



Delayed onset of regional aridification during global climate cooling: insights from the Miocene Valjevo-Mionica Basin, southeastern Europe[☆]

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ABSTRACT

The Middle Miocene Climatic Transition (MMCT) was a period of increased global aridity marked by reinforced evaporation and suppressed precipitation, respectively. While this aligns with general terrestrial paleoclimatic trends in Europe, the influence of land-vs-sea distribution and mountain building on regional climatic variability remains understudied. In particular, existing research suggests that southeastern Europe experienced pronounced aridity in the Miocene, linked to a rain shadow caused by the uplift of the Dinarides. However, poor age constraints hamper the establishment of clear causal relationships. In this work, we investigate how regional tectonic processes modulated global climatic trends in southeastern Europe. We conducted a sedimentological analysis of the basin fill and U-Pb zircon dating of intercalated volcanoclastic deposits in the Valjevo-Mionica Basin in western Serbia, allowing us to correlate the basin evolution with global and regional climatic forcing mechanisms. Our results reveal significant lake expansion between 14.1 and 13.5 Ma, which suggests a rise in precipitation coeval with the tectonically driven expansion of the Central Paratethys. A subsequent phase of progressive aridification occurred between 13.5 and 12.1 Ma. We correlate this with continued global cooling following the Middle Miocene Climatic Transition, consistent with an intensification of the rain-shadow effect in the Dinarides driven by changes in atmospheric circulation patterns.

1. Introduction

The Cenozoic is characterized by a long-term climatic transition from Cretaceous greenhouse conditions to the late Cenozoic icehouse climate. Following peak warmth during the Early Eocene Climatic Optimum (~52–50 Ma), global temperatures show a continuous decline, superimposed by transient warming and cooling intervals (Westerhold et al., 2020). This long-term cooling was associated with declining atmospheric CO₂ concentrations, tectonically driven modifications of ocean gateways, reorganizations of oceanic and atmosphere circulation patterns, and expansion of the Antarctic ice sheet (Miller et al., 2020; Steinthorsdottir et al., 2021). The Miocene Climatic Optimum (~16.9–14.7 Ma; Holbourn et al., 2013, 2014; Steinthorsdottir et al., 2021) represents one of the most pronounced warming intervals within this cooling trend. During the MCO, global mean surface

temperatures increased by approximately 3–6 °C, accompanied by elevated atmospheric CO₂ concentrations and substantial retreat of the Antarctic Ice Sheet. Herpetological and paleofloral records indicate intensified hydrological cycling and reduced meridional temperature gradients (Böhme, 2003; Böhme et al., 2011; Pound et al., 2012). Within terrestrial environments this was accompanied by an increase in thermophilous floras and widespread lake expansion reflecting generally humid conditions (Steinthorsdottir et al., 2021). The subsequent Middle Miocene Climatic Transition (~14.7–13.8 Ma; Holbourn et al., 2013, 2014; Steinthorsdottir et al., 2021) marks a shift back to cooler conditions. This was characterized by step-wise global cooling which saw the establishment of a permanent East Antarctic Ice Sheet (Holbourn et al., 2013, 2014; Miller et al., 2020). This resulted in significant biogeographic changes, regional extinctions, and progressive aridification of mid-latitude regions (Böhme, 2003; Böhme et al., 2011).

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Lacustrine depositional systems are widely recognized as sensitive recorders of climatic forcing, and have been used to constrain the effects of the MCO and MMCT on terrestrial environments (Mandic et al., 2011; Jiménez-Moreno and Mandic, 2020). In intramountain basins, climate modulates the hydrological balance by influencing precipitation–evaporation ratios, runoff, and sediment supply, leading to corresponding shifts in lake level and depositional environments (Benavente and Bohacs, 2024). On the other hand, tectonics governs accommodation space, subsidence patterns and catchment configuration, thereby controlling basin morphology. In some settings, tectonically-driven hydrologic changes may produce depositional trends inconsistent with climatic forcing. This has been observed e.g. in the Eocene Lake Gosiute or the Miocene Andean foreland basin (Graf et al., 2015; Bucher et al., 2021). In addition to local tectonic controls, climatic signals expressed in depositional records may also reflect regional changes in land–sea distribution and associated atmospheric moisture transport, rather than global climatic forcing alone. In particular, Paleogene transgression–regression intervals of the eastern Paratethys Sea have been linked to humid and arid phases, respectively, in central Asia (Bosboom et al., 2011, 2014; Kaya et al., 2019). Consequently, combined sedimentological and chronostratigraphic constraints provide a basis for resolving local tectonic and regional vs global climate forcing mechanisms on lacustrine depositional systems.

In Europe, a robust mid-latitude paleoclimatic record has been established, which suggests increasing aridity and a shift from trade-wind to westerly dominated moisture sources during the middle Miocene (Böhme et al., 2011; Methner et al., 2020; Ballian et al., 2025). However, local paleoenvironmental variations remain poorly constrained owing to the scarce spatial coverage of available data. Significantly, the Oligocene–Miocene also saw changes in paleogeography with the rise of mountain ranges (e.g. Alps, Dinarides, Carpathians, Caucasus) and changing land–sea distribution which contributed to significant regional climate change and biodiversity hotspots (Kocsis et al., 2014; Neubauer et al., 2015; Kováč et al., 2016, 2017; Mandic et al., 2019a, 2019b, 2019c; Neiber et al., 2021; Recknagel et al., 2023). In the Dinarides, a rain-shadow is suggested to have existed during the early and middle Miocene, with humid conditions persisting in the western flank of the range, while the eastern, internal part recorded extensive regional aridity (Andrić-Tomašević et al., 2021, 2025; Pavelić et al., 2022). A chronostratigraphic scheme for the intramountain basins in the western part of the range has been established based on magnetostratigraphy and radiometric Ar–Ar and U–Pb dating (de Leeuw et al., 2010a, 2011; Mandic et al., 2011, 2012, 2026; Sant et al., 2018; Šamarija et al., 2026). Radiometric age constraints of correlative deposits from the eastern part of the Dinarides are mostly lacking, leading to uncertainties on the timing and progression of the Miocene arid phase. In order to resolve the influences of regional vs global climate forcing mechanisms, the precise dating of intramountain basins is of vital importance.

We contribute to this discussion by presenting a case study on the depositional setting and paleoenvironmental conditions of the Valjevo–Mionica Basin in western Serbia (Fig. 1). This basin hosts a mid-latitude stratigraphic record of Miocene paleoenvironmental evolution. Furthermore, the deposits of the Valjevo–Mionica Basin have yielded significant findings of fish, plant and mollusc fossils (Lazarević et al., 2013; Neubauer et al., 2016; Bradić-Milinović et al., 2019). We investigated the stratigraphy and sedimentological features of the Valjevo–Mionica Basin, together with radiometric U–Pb dating of intercalated volcanoclastic deposits. Integrating zircon morphological observations with U–Pb dating allowed for a more resolved age model and stratigraphic correlation. The new geochronological framework facilitates correlation of the depositional and biogeographic evolution to global climate change. Additionally, the modulating influence of mountain uplift (Andrić-Tomašević et al., 2021), and changing-land–sea distribution (Mandic et al., 2019a, 2019b, 2026) are discussed. By examining the interplay of tectonic activity and climate change on the development

of the Valjevo–Mionica Basin, this study provides new constraints on regional vs global forcing mechanisms on the paleoclimatic evolution of southeastern Europe during the middle Miocene.

2. Geological setting

2.1. Regional setting

The Dinarides are a mountain range located in SE Europe (Fig. 1), formed as a result of the long-lasting convergence between Adria, occupying a lower plate position, and the Tisza and Dacia blocks in the upper plate position (Schmid et al., 2008, 2020; van Hinsbergen et al., 2020). The main phase of uplift commenced with the latest Cretaceous continental collision along the Sava suture zone (Ustaszewski et al., 2010; Stojadinović et al., 2022), whereafter deformation progressively migrated towards more external areas (Korbar, 2009; van Unen et al., 2019). During the early – middle Miocene, widespread extension driven by the roll-back of the European slab in front of the Carpathians resulted with the opening of the Pannonian Basin (Balázs et al., 2016; Handy et al., 2014). A late Oligocene onset of extension along the Sava suture zone has meanwhile been associated with roll back (Schefer et al., 2011) or detachment (Andrić et al., 2018) of a Dinaric slab. These events involved extensional reactivation of former thrust faults and core complex formation along the boundary of the Dinarides and the Pannonian Basin (e.g. Löwe et al., 2021; Stojadinović et al., 2017; Toljić et al., 2013; Ustaszewski et al., 2010). This gave rise to a series of basins known as the Serbian Lake System (SLS), spanning the NE part of the Dinarides and part of the Southern Carpathians, which accumulated up to several kms of early to middle Miocene syn- to post-extensional deposits (Marković et al., 2016; Sant et al., 2016; Rundić et al., 2019). Arid conditions recorded within the continental-lacustrine successions of the SLS have been linked to the possible presence of a rain shadow caused by high topography in the Dinarides (Andrić-Tomašević et al., 2021; Pavelić et al., 2022). Estimates of the Miocene paleotopography of the Dinarides are confined to the western, external part of the mountain range. The paleofloral associations derived from pollen data roughly constrain maximum elevations of between 1000 and 2000 m (Jiménez-Moreno et al., 2008, 2009; Jiménez-Moreno and Mandic, 2020), comparable to the present topography. The post-middle Miocene evolution of the Dinarides was marked by orogen-parallel wrenching and minor contraction associated with indentation of the Adriatic plate (Andrić et al., 2015; Bjelogrić et al., 2026; Korbar, 2009; van Unen et al., 2019; Tari, 2002).

2.2. Valjevo–Mionica Basin

The Valjevo–Mionica Basin occupies the western part of the Valjevo–Mionica–Belanovica Graben, which started forming in the late Early Miocene. The eastern, Belanovica segment was more involved in the subsequent inversion, whereas the Valjevo–Mionica segment underwent continuous subsidence and was ingressed by Paratethys marine-brackish waters in the Sarmatian. (Jovanović and Dolić, 1994; Marović et al., 2007; Obradović and Vasić, 2007). The Valjevo–Mionica Basin is characterized by a complex structural pattern. The basin geometry is primarily governed by E–W trending normal faults along its northern and southern margins, whereas subordinate NE–SW and NW–SE faults subdivide it into numerous smaller blocks (Marović et al., 2007). The northern basin rim is composed of Paleozoic units, represented by Devonian, Carboniferous, and Permian metamorphic to non-metamorphic rocks, and Lower Triassic clastics. The southern basin rim is meanwhile composed of Upper Triassic carbonates, which prevail in the south-eastern part, and the Upper Cretaceous Ljig flysch in the south-western part of this area (Fig. 1; Filipović et al., 1971; Mojsilović et al., 1975). Geophysical measurements indicate that the thickness of the Neogene basin infill may reach a thickness of up to 1000 m (Obradović and Vasić, 2007). This has been subdivided into six

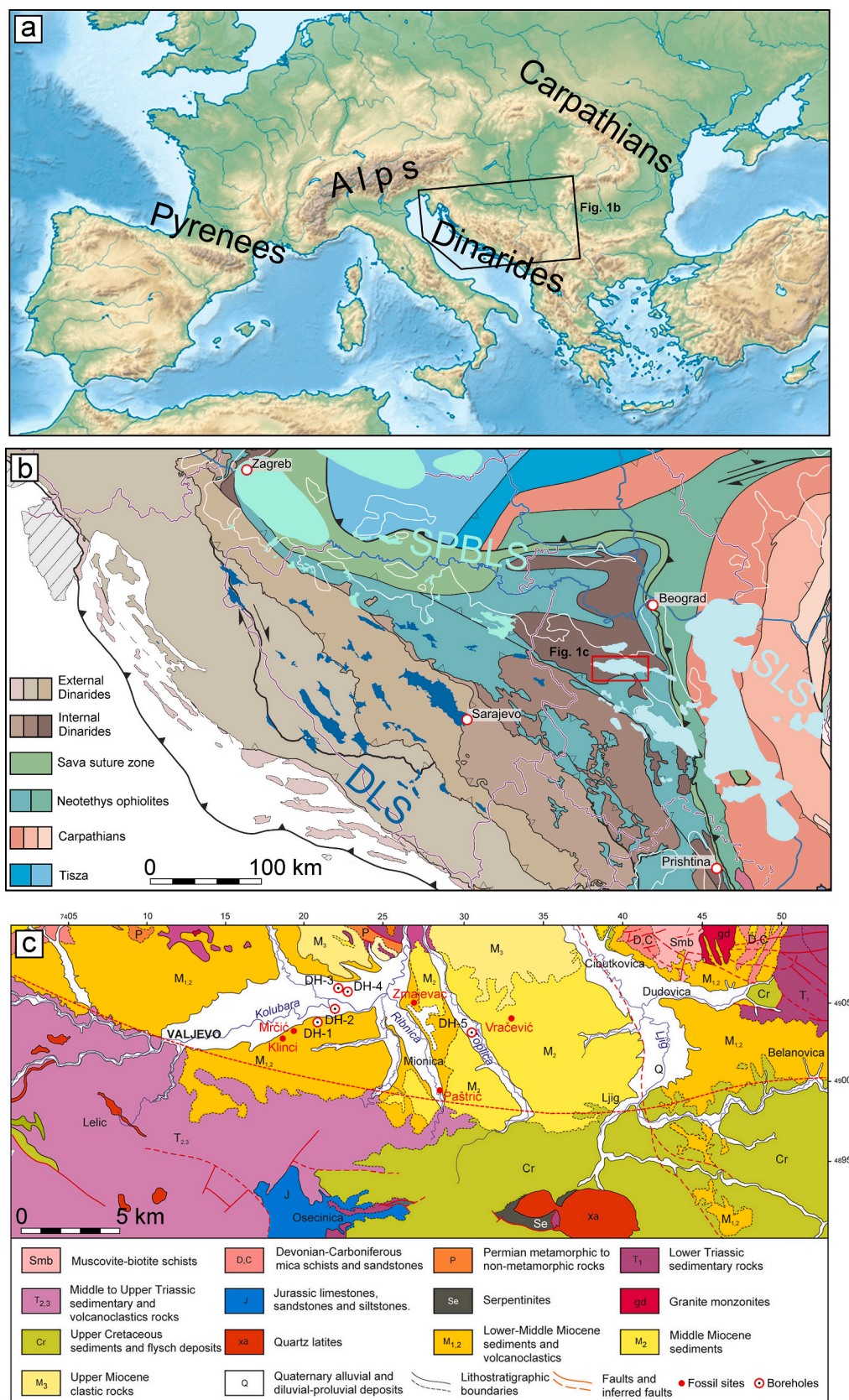


Fig. 1. a: Location of the Dinarides and the study area within Europe; b: Tectono-stratigraphic map of the Dinarides (after Schmid et al., 2020), showing the extent of the Dinarides Lake System (DLS), Serbian Lake System (SLS) and the Pannonian Basin Lake System (SPBLS), modified after Mandić et al. (2019c); c: Geological map of the Valjevo-Mionica Basin, modified after Brađić-Milinović et al., 2019.

formations, based on lithostratigraphic correlations from boreholes and field observations (Jovanović et al., 1994). The lower, lacustrine part of the basin infill comprises the pyrobituminous Mionica Fm. (including the “Bela Stena series”) with analcime and searlesite mineralisation, marly Valjevo Fm. and clastic Tabanovići Fm. (Jovanović et al., 1994; Obradović and Vasić, 2007; Lazarević et al., 2013; Simić et al., 2017). These are unconformably and transgressively overlain by Sarmatian (late Serravallian) marine-brackish deposits (Jovanović et al., 1994; Jovanović and Dolić, 1994) which laterally alternate with lacustrine sediments (Bradić-Milinović et al., 2021). Sarmatian deposits are mainly developed in the eastern part of the basin, and comprise the carbonate-clastic Mađarlija Fm. and marly Vračević Fm. (Neubauer et al., 2016; Bradić-Milinović et al., 2021). The youngest part of the basin infill is represented by the terrigenous Bogovada Fm. of Pannonian (Tortonian) age (Jovanović et al., 1994; Obradović and Vasić, 2007). The succession of the Valjevo-Mionica Basin is only weakly tectonised and is extensively covered by Quaternary alluvium and soil, severely limiting efforts to reconstruct the basin geometry and stratigraphic evolution based on field observations alone. Moreover, faunal endemism and uncertainties on the relative stratigraphic positions of the main fossil-bearing localities has impeded meaningful biostratigraphic age determinations. Lazarević et al. (2013) suggested an early Miocene age based on comparison of the paleofloral taxa retrieved from the Bela Stena series with other roughly coeval paleofloras from Serbia. Meanwhile, a late early Miocene to early middle Miocene age has been suggested for Klinci fossil fish fauna from the Valjevo Fm. (Bradić-Milinović et al., 2021). The age of the Sarmatian deposits has been more precisely determined, based on marine fossils (Jovanović and Dolić, 1994; Bradić-Milinović et al., 2018). Arid paleoenvironmental conditions with strong evaporation have been proposed based on sedimentological and geochemical constraints (Šajnović et al., 2008a, 2008b). However, paleofloral composition has been used to argue for a humid rather than arid climate (Lazarević et al., 2013).

3. Materials and methods

A detailed sedimentological analysis was performed on the DH-1 and DH-2 boreholes. Additionally, boreholes DH-3, DH-4 and DH-5 were observed, augmented by comparison with boreholes DH-1 and DH-2, in order to gain insight into lateral differences of the depositional facies. For U-Pb, samples from different depths from all investigated boreholes were taken.

3.1. Sedimentological analysis

Sedimentological characteristics were identified by core logging and the study of 46 thin-sections. In order to determine the mineralogical composition, XRD was performed with a D8 Discover instrument (Bruker AXS GmbH). Two samples were selected from the DH-2 borehole, from a depth of 13.5 and 23.85 m, respectively. Each sample was ground by hand, using an agate mortar. Powder XRD patterns (ESM S6) were collected at ambient conditions in the 2θ range from 2 to 82° , using a step size of $0.02^\circ/2\theta$ and a counting time of 4 s per step. EVA software (Bruker AXS GmbH) was used for phase analysis. In addition, a rock cutting from the shallower sample was used for petrographic SEM imaging and EDX elemental mapping (ESM S7), using a Hitachi FlexSEM 1000. 26 lithofacies were distinguished based on colour, texture and structure (Table 1). These were grouped into 10 facies associations according to their predominant respective lithofacies. Detailed borehole logs are presented in ESM S5.

3.2. U-Pb geochronology

Tephra samples were collected from different depth intervals across the investigated boreholes (Fig. 1, Table 2). About 0.5–1 kg per sample were collected for heavy mineral separation. All samples were dried and

Table 1

List of identified lithofacies, their sedimentological characteristics and interpretations of their depositional processes.

Lithofacies	Description	Depositional processes
F1.	Clast-supported conglomerate. Moderate sorting. Granule to cobble-sized subangular to subrounded quartz, biotite, K-feldspar and volcanic clasts. Occasionally comprises tufa fragments. Forms distinct fining-upward sequences, sometimes together with F2.	Deposition from sheetfloods. Clast composition indicates erosion of a volcanic source lithology. Tufa clasts point to destruction and reworking of coeval tufa deposits.
F2.	Clast to matrix-supported sandstone. Moderate to poor sorting. Composed mostly of quartz and fragments of older volcanic rocks. Forms distinct fining-upward sequences, sometimes together with F1.	Deposition from sheetfloods. Clast composition indicates erosion of a volcanic source lithology
F3.	Dark, matrix-supported sandstone, comprising poorly sorted, angular clasts of older volcanic rocks within a brown clayey matrix. Sporadic tufa-derived pebbles. Includes mollusc fragments and dispersed organic matter.	Deposition from cohesive debris flows. Clast composition indicates erosion of volcanic and tufa lithologies. Presence of dispersed organic matter and mollusc fragments imply reworking of the nearshore lake environment during flow passage/deposition
F4.	Tufa, porous with frequent root moulds	Chemogenic calcite precipitation, possibly at least partially hydrothermally sourced. The tufa could have accumulated in small ponds from these high-Ca waters, and partly enveloped vegetation roots.
F5.	Orange to beige homogenous micrite. Contains carbonate concretions, dewatering structures and authigenic sulfide aggregates	Particle settling from water column in an anoxic environment. Dewatering structures may imply sporadic dessiccation due to subaerial exposure. Sulfides formed after burial in a reducing environment.
F6.	Dark brown clayey micrite with mollusc shell fragments	Suspension settling from water column paired with biogenic carbonate production.
F7.	Banded to massive olive green micrite with abundant sulfide aggregates. Transitions between bands is gradual.	Settling of micrite from the water column and subsequent bioturbation. Sulfides formed post-depositionally due to the activity of sulfate reducing bacteria.
F8.	Light beige to white porous laminated to banded marlstone. Occasional microbial mat intraclasts and peloids. Sometimes contains organic matter flakes.	Suspension settling from water column. Sporadic formation of microbial mats and their reworking by wave action.
F9.	Laminated grey marlstone with microbial mats, ranging in thickness from 0.1 mm to 5 mm. Dispersed sulfides present in variable amounts	Microbial carbonate precipitation in an oxygenated environment.
F10.	Grey to dark green laminated calcareous marlstone. Contains dispersed organic matter flakes. Laminas homogenous with gradual boundaries. Includes up to 1 cm thick calcarenite intercalations with erosive bases. These comprise micrite intraclasts, quartz and K-feldspar grains. Both the marlstone and calcarenite may also contain ostracod shells and microbial mat fragments.	Particle settling and bioturbation in an oxygenated calm environment. Calcarenite intercalations resulted from periodic low-density turbidity currents

(continued on next page)

Table 1 (continued)

Lithofacies	Description	Depositional processes
F11.	Massive light beige to yellow micrite, internally homogenous. Forms distinct, up to 5 cm thick intercalations with sharp boundaries. Contains small, dispersed sulfide aggregates.	Increased carbonate production and bioturbation during periods of better oxygenation and/or redeposition from low-density turbidity currents.
F12.	Marlstone with alternation of light grey, brown and dark laminae. These have sharp to gradual boundaries. Contains rare calcite pseudomorphs and sulfides.	Particle settling in a calm, anoxic environment below the storm wave base. Precipitation of soluble salts from saline-alkaline pore waters, later replaced with calcite. Sulfides point to reducing conditions.
F13.	Banded dark brown marlstone. Contains varying amounts of dark sulfides. Rare recrystallized sparitic lenses and intercalations. Contains ostracod shell fragments.	Settling of carbonate particles and organic matter from the water column. Lack of lamination and ostracod fragments suggest bioturbation, or alternatively deposition from low-density turbidity currents. Abundant sulfides and organic matter indicate anoxic, reducing conditions. Sparitic material possibly formed from dissolution and replacement of soluble salts by calcite.
F14.	Massive to indistinctly laminated clayey olive marlstone with rare silt-sized grains and sulfides. Forms distinct, up to 4 m thick intervals.	Settling of micrite, clay and organic matter from hypopycnal plumes below the storm wave base, during periods of increased fluvial input.
F15a.	Indistinctly laminated dark or rarely light grey siltstone with clayey-micritic matrix. Dispersed sulfides aligned parallel with bedding. Frequently alternates with F13 at mm to cm-scale, forming distinct intervals up to 3 m thick.	Particle settling from water column or episodic hypopycnal plumes. Sulfides formed under reducing conditions.
F15b.	Massive dark grey siltstone, with dispersed sulfides, occasionally forming distinct flakes which can additionally have an orange hue.	Particle settling from hypopycnal plumes. Alternatively, the massive structure may result from bioturbation of previously laminated siltstone (F16a). Sulfides formed under reducing conditions.
F16.	Alternation of laminated dark brown, organic-rich dolomarlstone and lighter siltstone laminae. Sometimes contains clayey orange laminae with analcime. Laminae are often wavy and disrupted. Contains small, dispersed searlesite aggregates and calcite pseudomorphs.	Dolomite precipitation from Mg-enriched water. High organic matter content reflects anoxic conditions. Siltstone reflects periodic gravity flows possibly during storms. Orange laminae reflect detrital clay input. Searlesite, analcime and calcite pseudomorphs of soluble salts suggest precipitation from saline-alkaline pore waters.
F17.	Banded to massive dark brown to beige dolomarlstone. Dispersed flakes of clayey material and associated analcime. Rare ostracod shell fragments. Sulfides are rare.	Dolomite precipitation from Mg-enriched water. Analcime precipitation from saline-alkaline pore waters aided by detrital clay input. Sulfides suggest reducing conditions.
F18.	Siltstone to fine sandstone with a grey to orange clayey matrix. Additionally contains calcite pseudomorphs, analcime and albite (ESM S6). Low-angle cross-bedding is present. Contains flakes of organic matter.	Current and/or wave action in shoreface setting. Organic matter may stem from plants along the lake margin. Precipitation of soluble salts, analcime and albite from saline-alkaline pore waters. Replacement of soluble salts with calcite.
F19.	Orange to grey weakly laminated to massive fine sandstone with clayey matrix. Commonly with slightly erosional lower	Tb interval of the Bouma sequence. Formed by deposition of clastic material from

Table 1 (continued)

Lithofacies	Description	Depositional processes
	boundaries but shows no grading. Contains dark red clayey intercalations with abundant analcime.	hyperpycnal flows during strong storm-related floods.
F20.	Laminated beige to grey marls, prominently featuring dewatering structures and reddish mottling.	Sporadic subaerial exposure of facies F13 or F17, leading to dessication and pedogenesis.
F21.	Finely laminated dolomarlstone. Consists of an alternation of beige, brown and grey laminae. Rare intercalations of orange, clayey material. Prominently features spherulitic and acicular searlesite (ESM S6, S7), often forming distinct, up to 1 cm thick intercalations. When present, searlesite leads to wavy, deformed or disturbed lamination.	Dolomarlstone and organic matter deposition within anoxic conditions. Searlesite formed by replacement of clayey material and/or directly from porewaters under conditions of increased alkalinity and salinity
F22.	Banded to massive, beige to light grey dolomarlstone. Contains dispersed, small searlesite and sulfide aggregates.	Bioturbation under relatively more oxygenated conditions. Searlesite suggests conditions of increased alkalinity and salinity. Sulfides suggest reducing conditions
F23.	Light grey laminated dolomarlstone intercalated with thin orange grainy Fe-rich material. Rarely Mn crusts (filling fractures as well). Lamina boundaries are sharp. Includes sporadic carbonate concretions.	Dolomarlstone and organic matter precipitation within anoxic conditions.
F24.	Grey laminated to banded dolomarlstone. Contains abundant sulfides forming distinct intercalations.	The banded structure reflects bioturbation. Sulfides likely reflect reducing conditions.
F25.	Yellow homogenous, well-sorted sandstone dominated by quartz grains	Deposition from hyperpycnal flow during storms.
F26.	Coarse poorly sorted breccia-conglomerate with a grey marly matrix. Composed of tufa intraclasts, and fragments of older limestones, clastites and volcanic rocks. Forms up to 50 cm thick intervals.	Deposition from debris flows.

powdered with a disc mill for 120 s, and subsequently the heavy minerals were concentrated with a gold-wash pan. Individual zircon grains were handpicked under ethanol, pipetted on double-sided adhesive tape, sputtered with Au for 15 s, and imaged for their morphologies by scanning electron microscopy (SEM) using a TESCAN VEGA2 electron microscope at the Department of Mineralogy and Petrology at the Karlsruhe Institute of Technology (KIT), Germany. All grains were numbered and the Degree of Roundness (DOR) and typologies determined, applying the classification scheme of [Zeh and Cabral \(2021\)](#) and [Pupin \(1980\)](#), respectively. Subsequently, the grains were embedded in epoxy, grinded to expose their centre parts, and investigated by cathodoluminescence (CL) imaging to gain information about their internal zoning patterns. The CL images were produced using a ThermoFisher Scientific Quattro S Environmental Scanning Electron Microscope (ESEM) at Institute of Functional Interfaces at KIT. The results are shown in [Figs. 6 & 7](#).

Uranium-Th-Pb analyses were performed by laser ablation-sector field-inductively coupled plasma mass spectrometry (LA-SF-ICP-MS) during 2 sessions, using a 193 nm ArF Excimer laser (Analyte Excite+, Teledyne Photon Machines) coupled to a Thermo-Scientific Element XR instrument at KIT. Zircon grains of unknown age were analyzed together with the reference zircons BB (primary reference material), Plešovice, KA, and SING (secondary reference material). Detailed information

Table 2

Results of U-Pb dating of zircon grains from volcanoclastic deposits in boreholes of the Valjevo-Mionica Basin.

Sample	Borehole	Depth (in m)	Age (Ma) ⁽¹⁾	MSWD, Prob. ⁽²⁾	n ⁽³⁾
DH-1-1	DH-1	180.9	13.149 ± 0.110/ −0.069*	–	32
DH-1-2	DH-1	196.7	13.384 ± 0.110/ −0.055*	–	31
DH-1-3	DH-1	212.8	13.464 ± 0.048	0.97, 0.52	36
DH-1-4	DH-1	231.25	13.860 ± 0.160	0.24, 0.92	5
DH-1-5	DH-1	451.6	14.358 ± 0.059	1.11, 0.31	29
DH-2-1	DH-2	108.1	13.030 ± 0.150	0.95, 0.41	4
DH-2-2	DH-2	139.7	13.367 ± 0.079/ −0.048*	–	28
DH-2-3	DH-2	158.0	13.458 ± 0.049	0.70, 0.87	28
DH-2-4	DH-2	179.1	13.659 ± 0.088	0.78, 0.63	10
DH-2-5	DH-2	398.5	14.420 ± 0.150/ −0.180*	–	22
DH-3-1	DH-3	308.8	14.272 ± 0.039/ −0.096*	–	29
DH-4-1	DH-4	294.3	14.270 ± 0.100/ −0.130*	–	25
DH-5-1	DH-5	410.6	14.144 ± 0.140/ −0.090*	–	34
DH-5-2	DH-5	426.8	14.346 ± 0.054/ −0.140*	–	32
DH-5-3	DH-5	440.1	14.346 ± 0.050/ −0.066*	–	33

(1) Weighted mean ²⁰⁶Pb/²³⁸U ages with 2 sigma error, or *-robust median ages.

(2) MSWD, Prob. - Mean standard weighted deviation, Probability of fit (for weighted mean ages).

(3) Number of analyses used for age calculation.

about instrument conditions are presented in electronic supplement materials (ESM-Table S1), and results of reference and unknown zircon measurements in Table S2. From each sample between 35 and 112 zircon grains were picked for U-Th-Pb analyses (Table S2). Several grains were analyzed multiply, up to 5 analyses per grain, in order to check for age variations.

All raw data were corrected offline using an in-house MS Excel® spreadsheet program (Gerdes and Zeh, 2006, 2009). A common Pb correction based on the interference and background corrected ²⁰⁴Pb signal and a model Pb composition (Stacey and Kramers, 1975) was only applied to inherited grains older than 200 Ma when the common Pb uncorrected age was significantly outside the error of the corrected age. The ages of tephra zircon populations are presented in ranked isotope plots (Fig. 6). For ²⁰⁶Pb/²³⁸U age calculation analyses with a concordance level ranging from 1 to 199% were used, excluding grains with the highest amount of common Pb. Weighted average ages are presented for samples with MSWD < 1.3 (mean standard weighted deviation) and a probability of fit > 0.05. Otherwise, robust median ages are shown (Table 2, Fig. 6, Table S2). All ages were calculated by using the software ISOPLOT v.3.75 (Ludwig, 2012).

4. Results

4.1. Lithological description

Based on our sedimentological analysis, 26 lithofacies were distinguished (Table 1). These are grouped into 10 facies associations based on their stratigraphic position and depositional environments.

4.1.1. Facies association 1 (FA 1)-Distal alluvial fan

4.1.1.1. Description. This unit is dominated by clast-supported conglomerate, and clast- to matrix-supported sandstones (F1, F2, F3; Table 1). Conglomerates (F1; Figs. 2h, 4a) and clast-supported sandstones (F2 Figs. 2f; 4b) may form fining-upwards sequences ranging in

thickness from 0.2 to 3 m. Conglomerates may alternatively form 0.5–1 m thick, ungraded intercalations within sandstones (F2, F3). The F2 sandstones are sometimes reddish and show mottling, suggestive of soil development. On the scale of the borehole sample, the lower contacts are flat and sharp without clearly visible incision. Clasts mostly comprise sub-angular to sub-rounded volcanic-derived material and rarely tufa fragments (Table 1). Additionally, matrix-supported sandstones (F3) contain mollusc fragments (Table 1). This unit is well-developed in all analyzed boreholes, with a thickness of over 100 m attested at DH-1. It is overlain by FA 2 in drill hole DH-1, and by FA 3 in drill holes DH-2, DH-3, DH-4 and DH-5.

4.1.1.2. Interpretation. This unit is interpreted to have been formed in an alluvial fan environment. The conglomerate-sandstone intervals suggest deposition from sheet-floods, based on their structural characteristics (Blair and McPherson, 1994). The reddish colour and soil development indicate that sandstone beds sometimes remained sub-aerially exposed for prolonged periods in-between individual depositional events, likely due to periodic flash-floods (McCarthy et al., 1997). The tufa and mollusc fragments indicate periodic reworking of marginal lake deposits or intermittent ponds/marshes. The presence of tufa suggests freshwater input, encrustation of vegetation by carbonate precipitation from cold spring waters (Gierlowski-Kordesch, 2010) in areas protected from clastic input. Considering the unit's vicinity from the basin bounding fault cross-cutting Triassic carbonate units in bedrock (Fig. 1), precipitation from cooled thermal spring waters (Andrić-Tomašević et al., 2024) cannot be excluded. In the upper part of FA 1, the co-occurrence of tufa with F5 and F7 suggests that it also occupied the margins of small, intermittent ponds or marshes.

4.1.2. Facies association 2 (FA 2)-marginal lacustrine carbonates

4.1.2.1. Description. This unit consists of tufa and homogeneous micrites (F4, F5, F6, F7). Tufa ranges in thickness from 0.8 to 5.6 m and shows sharp upper and lower boundaries. Micrites often contain carbonate concretions and dewatering structures (F5; Table 1 Fig. 4e) and mollusc remains (F6, Table 1, Fig. 4f). Authigenic sulfides occur in F7, and to a lesser degree throughout F5. Sulfides in F5 cross-cut all other sedimentary structures (Fig. 4e). FA 2 forms a 15 m thick interval in DH-1, whereas its presence in the remaining boreholes is unclear. This unit is present only in DH-1 (Fig. 8). In vertical succession FA 2 is underlain by FA 1, and overlain by FA 3 (Fig. 8).

4.1.2.2. Interpretation. This unit formed in a marginal lacustrine environment with periodic subaerial exposure, such as small, intermittent ponds or marshes. The predominantly dark colour of the micrites indicates a high organic-matter content, possibly pointing to the proximity of terrestrial vegetation and local or periodic anoxic environments. However, the cross-cutting relationships of authigenic sulfides with all other sedimentary structures (Fig. 4e) suggests that they developed during diagenesis. Intervals with abundant mollusc fauna additionally suggest periodic freshwater input by rivers or streams (Benavente and Bohacs, 2024). Carbonate concretions suggest periodic desiccation and subaerial exposure during lake-level falls (Alonso-Zarza and Wright, 2010). The presence of tufa suggests freshwater input and encrustation of vegetation by carbonate precipitation from cold spring waters (Gierlowski-Kordesch, 2010) in areas protected from clastic input. Considering the vicinity of the basin bounding fault cross-cutting Triassic carbonate units in bedrock (Fig. 1), precipitation from cooled thermal spring waters (Andrić-Tomašević et al., 2024) cannot be excluded. Moreover, the co-occurrence of tufa with F5 and F7 suggests that it occupied the margins of small, intermittent ponds or marshes.

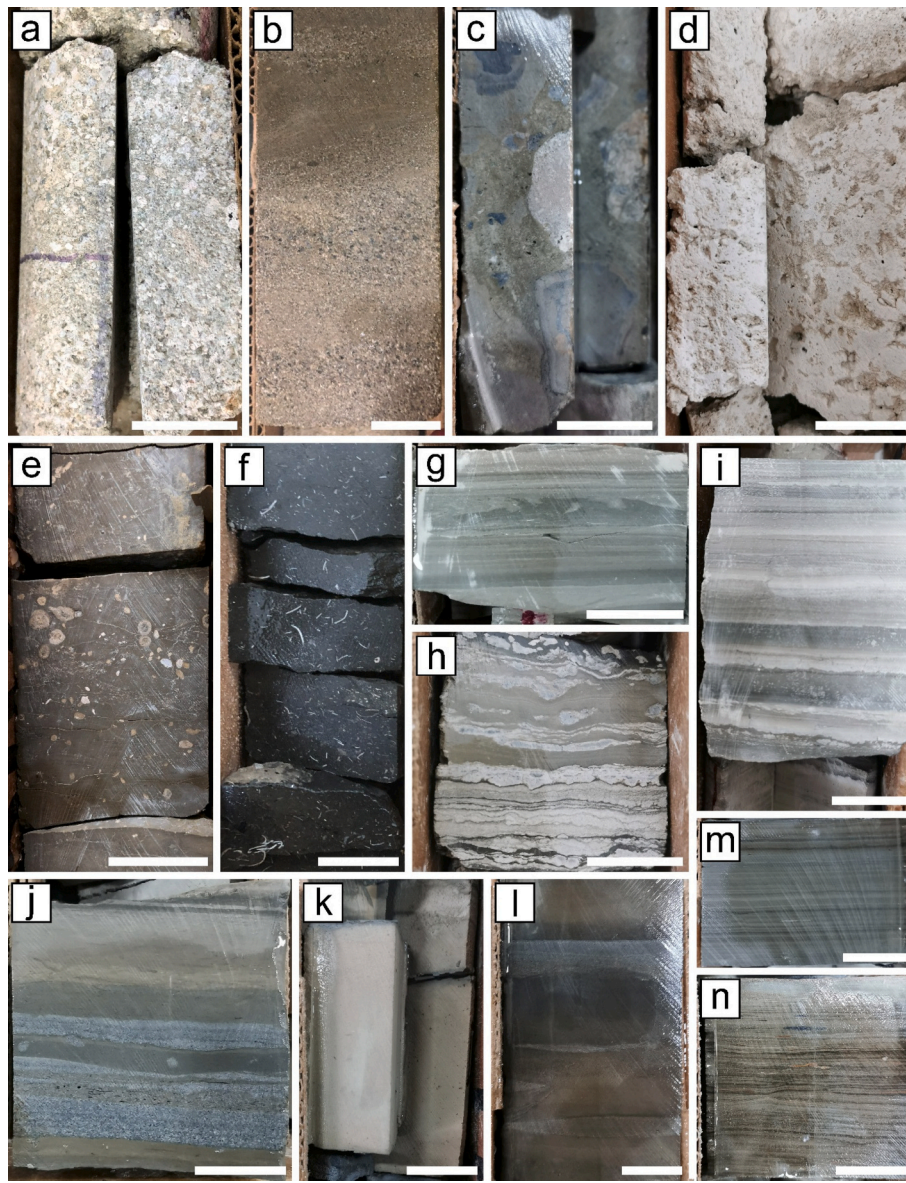


Fig. 2. Drill cores samples, showing typical lithofacies of the Valjevo-Mionica Basin. a) Clast-supported conglomerate (F 1), DH-1 core, 607.0 m depth; b) Clast-supported sandstone (F 2), DH-1 core, 524.7 m depth; c) Dark, matrix-supported sandstone with tufa pebble (F 3), DH-2 core, 446.4 m depth; d) Tufa (F 4), DH-2 core, 497.5 m depth; e) Beige micrite with carbonate concretions (F 5), DH-1 core, 460.8 m depth; f) Dark brown clayey micrite with mollusc fragments (F 6), DH-1 core, 499.5 m depth; g) Banded to massive olive green micrite with abundant sulfide aggregates (F7), DH-2 core, 342.8 m depth; h) Laminated grey marlstone with microbial mats (F 9), DH-2 core, 334.1 m depth; i) Banded to laminated marlstone with reworked microbial mat fragments (F 8), DH-2 core, 336.5 m depth; j) Grey to green laminated marlstone with calcarenite intercalations (F 10), DH-2 core, 296.1 m depth. k) Massive light beige micrite (F 11), DH-2 core, 188.6 m depth; l) Banded dark brown marlstone (F 13), DH-2 core, 51.1 m depth; m, n) grey-beige laminated marlstone (F 12), DH-2 core, 99.7 and 97.0 m depth, respectively. Scale bar = 2 cm. For facies descriptions, see [Table 1](#). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.1.3. Facies association 3 (FA 3)-Littoral marlstones with microbial mats

4.1.3.1. Description. This unit features banded to massive green marlstone with sulfide aggregates (F7), lighter colored marls with pelloids and microbial mat intraclasts (F8), and dark laminated microbial mats (F9; Tb.1, [Fig. 4h, i, j, k](#)). Slumps are occasionally observed within this unit.

4.1.3.2. Interpretation. These unit is interpreted to represent a shallow, low-energy environment with sustained microbial activity and carbonate precipitation, associated with oxygenated littoral settings with low siliciclastic input ([Gierlowski-Kordesch, 2010](#)). Microbial mats (F9) possibly formed small bioherms. Intraclasts and pelloids derived from

microbial mats indicate periodic reworking, possibly by storms and/or wave action ([Flügel, 2004](#); [Gierlowski-Kordesch, 2010](#)). This resulted in the formation of F8 more distally. The banded to massive marls (F7) imply bioturbation in an oxygenated environment. Fluctuating redox conditions enabled microbial sulfate reduction. Slumps suggest sediment transport on an inclined slope stemming either from seismic shocks ([Alsop and Marco, 2011](#); [Mabrouk et al., 2021](#)) or pore water overpressure ([Moernaut et al., 2017](#)).

4.1.4. Facies association 4 (FA 4)-Sublittoral marlstones with calcarenite intercalations

4.1.4.1. Description. This unit includes green calcareous, laminated to

banded marlstone with calcarenite intercalations and ostracods (F10), yellow micrite intercalations (F11), and laminated to banded carbonaceous marls (F12, F13, Table 1). Slumps featuring microbial mat fragments are present throughout this unit. Up to 50 cm thick debrite intercalations composed of various intra- and extraclasts (F26) were observed in DH-3 and DH-4.

4.1.4.2. Interpretation. This unit suggests a deposition within a sublittoral environment. Frequent gravity-flow deposits and slumps indicate deposition on an inclined lake bottom. This enabled the transport of shallow-water material towards deeper parts of the basin. Shallow-water derived microbial mat fragments suggest the relative proximity to a lake margin carbonate-producing environment. Debrites (F26) within DH-3 and DH-4 additionally attest to the input of coarse, extrabasinal clastic material, possibly induced by seismic shocks. The yellow micrite intercalations suggest periods of increased carbonate production and bioturbation, whereas the overall predominance of laminated, organic rich facies (F10 and F12) suggests deposition within calm sublittoral settings with low oxygenation. Therefore, this lithological unit likely corresponds to the slope of a lacustrine bench platform (Platt and Wright, 1991; Gierlowski-Kordesch, 2010), which distally transitioned into Unit 5.

4.1.5. Facies association 5 (FA 5)-Profundal clayey marlstones

4.1.5.1. Description. This unit comprises thick intervals of clayey marls (F14) and weakly laminated carbonaceous siltstones (F15a). These alternate with intervals consisting of laminated to banded carbonaceous marls (F12, 13), or of a mm- to cm-scale alternation of F15a and F12. Distinct intercalations of yellow micrite (F11) are occasionally present within F14. This unit gradually transitions upwards into FA 6.

4.1.5.2. Interpretation. The predominance of fine-grained laminated deposits points to sedimentation within low energy anoxic conditions within a stratified lake, corresponding to the profundal zone (Gierlowski-Kordesch, 2010; Buchheim et al., 2011). The organic-rich marls (F14) and siltites (F15a) of this unit reflects fine-grained clastic input during humid phases derived from hypopycnal flows (Renaut and Owen, 2023). The carbonate rich intervals (F11, F13) meanwhile formed during drier phases with less clastic input and/or lake level falls. This would have reduced clastic input and enabled more oxygen and sunlight to reach the lake bottom, promoting carbonate production and bioturbation. Variations in carbonate and terrigenous input suggest periodic runoff fluctuations.

4.1.6. Facies association 6 (FA 6)-Sublittoral marlstones

4.1.6.1. Description. This unit primarily consists of banded dark brown marlstone with sulfides and occasional ostracod fragments (F13). Contacts between bands are gradual. This facies alternates with marls comprising light, brown, and dark laminas and small sulfide minerals (F12). These additionally sometimes contain calcite pseudomorphs of soluble salts (Fig. 4o). Intercalations of massive to laminated siltstone are common (F15a). Soft-sediment deformations suggestive of slumping are frequent in this unit.

4.1.6.2. Interpretation. The predominance of banded marlstone (F13), suggestive of bioturbation, indicates deposition within a calm, sublittoral environment with a low clastic input. The occurrence of sulfides in varying amounts suggests periodic redox shifts, consistent with lacustrine settings with pronounced seasonal or climatic variability (Buchheim et al., 2011). Calcite pseudomorphs of soluble salts are suggestive of rising lake water salinity. Slumping suggest mass-movement along an inclined depositional slope triggered either by seismic shocks or overpressure. High sediment load is excluded as there

is a lack of clastic input in this unit.

4.1.7. Facies association 7 (FA 7)-Littoral to sublittoral dolomarlstones with analcime and searlesite

4.1.7.1. Description. This unit predominantly consists of laminated (F16, F21) and banded to massive (F17, F22) dolomarlstone with analcime and searlesite aggregates. Rare ostracod fragments are present (Fig. 5h). Siltstone to sandstone intercalations occur throughout this unit (F15b, F18, F19). Soft-sediment deformations and small faults associated with slumping are likewise frequent.

4.1.7.2. Interpretation. This unit formed in a littoral to sublittoral environment. The alternation of laminated (F16, F21) and banded (F17, F22) dolomarlstones is characteristic for environments with fluctuating oxygenation, where bioturbation occurs during periods of improved oxygen supply. This is in agreement with the finding of ostracod fragments in F17 (Fig. 5h). Moreover, the fine-grained texture of dolomarlstones points to primary dolomite formation in an alkaline and/or saline lake (Guo et al., 2023). Such conditions are additionally suggested by the presence of soluble salt pseudomorphs, analcime and searlesite (Surdam, 1977; Pavelić et al., 2022; Li et al., 2023). The massive siltstones (F15b) reflect particle settling from hypopycnal plumes associated with episodic floods, a process characteristic for an arid environment with intermittent rainfall (Gierlowski-Kordesch, 2010; McGlue et al., 2012; Renaut and Owen, 2023). The sandstone intercalations (F18, F19) possibly reflect distal fluvial input. Slumping suggests deposition on an inclined lake bottom.

4.1.8. Facies association 8 (FA 8)-Mudflats

4.1.8.1. Description. This unit is found only in DH-1. It is characterized by the frequent alternation of laminated to banded marlstone (F12, 13), and dolomarlstone (F16, 17) with laminated marls featuring pedogenic features and dewatering structures (F20). Rarely, banded to massive, greenish marls similar to F7 are also observed.

4.1.8.2. Interpretation. This unit is interpreted to reflect pedogenic alteration of marlstones and dolomarlstones within a marginal setting characterized by frequent frequent water-level oscillations and coastline shifts (Alonso-Zarza and Wright, 2010; Gierlowski-Kordesch, 2010).

4.1.9. Facies association 9 (FA 9)-Sublittoral dolomarlstone with sulfides and Fe-Mn crusts

4.1.9.1. Description. This unit comprises laminated dolomarlstone with Fe-Mn rich crusts (F23), and laminated to banded dolomarlstone with sulfides (F24). It is found within the top 20 m of DH-1, above Unit 9. Dolomarlstones are often intercalated by coarse to medium grained yellowish sandstone intercalations containing mostly well-sorted, rounded quartz grains (F25).

4.1.9.2. Interpretation. This unit formed in a sublittoral environment. Dolomarlstone suggests elevated salinity and/or alkalinity. Nevertheless, the absence of searlesite and analcime suggests a decrease in lake water salinity compared to FA 7. Additionally, the presence of Fe-Mn crusts suggests oxygenated bottom waters. Sandstones indicate greater clastic input, likely due to progradation of alluvial or deltaic systems surrounding the lake under conditions of increased humidity, with dominance of well-sorted, rounded quartz grains pointing to greater transport distances or wave action.

4.1.10. Facies association 10 (FA 10)-Littoral sandstones and clays

4.1.10.1. Description. This unit appears in the upper 220 m of DH-5,

transitioning gradually from the underlying FA 5. It is represented by an alternation of up to 1 m thick packages of banded and laminated marls (F12, F13), greenish-brown claystone (F14), cross-bedded (F18) and homogenous sandstone (F25) and rarely intraclastic breccia (F26). Sandstones are well-sorted, as opposed to intraclastic breccias which comprise centimetre-sized clasts in a sandy matrix.

4.1.10.2. Interpretation. The predominance of siliciclastics suggests proximity to the lake margin, probably reflecting fluvial input into the basin. A relatively shallow, littoral environment is reflected by cross-bedded sandstone (F18), which suggests reworking of the clastic material by wave action. The alternation of marly (F12, F13), clayey (F14) and sandy (F18, F25) intervals may further suggest periodic variations in the amount of clastic input. Intraclastic breccia intercalations (F26) suggest reworking of older lacustrine deposits, possibly during lake-level lowstands.

4.2. Zircon shapes and formation temperatures

Zircon populations were dated from fifteen tephra samples from five boreholes of the Valjevo-Mionica Basin (Figs. 6, 7). In addition, zircon typologies, average zircon formation temperatures, and the degree of roundness (DOR) were determined, revealing significant differences among the samples (Figs. 7, 8a, b). Most zircon populations are dominated by perfect euhedral magmatic zircon grains (average DOR = 1.1–1.9), except two samples (DH-1-3 and DH-2-3) with av. DOR = 2.6–3.0 (see Table 2). Zircon populations of most samples show a wide range in typologies (Table S3, S4), and average formation temperatures, ranging between 710 °C and 860 °C. Considerable overlap exists among the samples DH-1-5, DH-2-5, DH-3-1, DH-4-1, DH-5-1 and DH-5-3, dominated by the typologies S25, P4-P5 (av. $T = 807\text{--}820$ °C), and among the samples DH-1-2, DH-1-3, DH-2-1, DH-2-2 and DH-2-3, centered around the typologies S22-S25, P5, J4 (av. $T = 829\text{--}860$ °C). Samples DH-1-1 and DH-5-2 are dominated by typologies S3-S4, S7-S8, P2-P3 and show the lowest formation temperatures (av. $T = 710\text{--}743$ °C) (Figs. 6, 7).

4.3. Zircon internal zoning

Most of the investigated zircons display oscillatory, and/or sector internal zoning patterns in CL images suggesting a magmatic origin (e.g. Z494, Z684; Fig. 8c). Only a few grains display clear core-rim relationships, characterized by abrupt changes in brightness and/or zoning patterns (e.g. Z145; Fig. 8c). Some grains also contain cracks, inclusions and bright rims (Z686):

4.4. Results of U-Pb zircon dating

Zircon grains of most samples show a wide range of ages from the Miocene to the Neoproterozoic (Table S2). The predominant zircon populations in all investigated samples yield Miocene ages between $14.420 \pm 0.150\text{--}0.180$ to 13.030 ± 0.150 Ma, obtained from the deepest and shallowest tephra layers in borehole DH-1, respectively. Inherited zircon grains were found in all samples, comprising up to 50% of the population (Table S2). Half of the samples contained a small number of zircon grains with ages significantly younger than the predominant Miocene population (e.g., sample DH-2-2, Table S2). These younger ages perhaps result from a post-depositional, partial Pb-loss, related to laser ablation.

5. Discussion

5.1. Depositional ages

The results of this study indicate that the youngest zircon

populations in tuff layers from the Valjevo-Mionica Basin yield middle Miocene ages between $14.420 \pm 0.150\text{--}0.180$ to 13.030 ± 0.150 Ma, and become systematically younger from the bottom to the top of the succession. This suggests that deposition occurred over a period of at least ca. 1.4 Myr. However, the finding of inherited pre-Miocene zircon grains in all samples hints that the investigated tephra layers contain volcano-sedimentary detritus derived from different sources. Thus, for interpretation of the ages it is important to know when the different sources were mixed with each other. In general, two end-member scenarios may be considered: (1) All zircon grains, Miocene volcanic and inherited, originated from the same eruption center, and were transported by the same tephra cloud, (2) Miocene magmatic and inherited grains were mixed during post-air fall reworking. In the first scenario, the youngest volcanic zircon grains in the tephra layer represent the time of deposition, and in the second scenario a maximum depositional age, more or less close to the time of deposition. A predominately syn-eruptive mixing is supported by the relatively low amount of inherited zircon grains and minimal age variations (reflected by low MSWD's) in the analyzed samples (Table S2c). This suggests that ages derived from the youngest volcanic zircon populations in most, if not all samples represent the time of deposition, or are very close to it.

Finally, we note that a small number of zircon analyses in some samples yield U-Pb ages significantly younger than the predominant Miocene population (Table S2). This in particular holds true for sample DH-5-2, where some grains show $^{206}\text{Pb}/^{238}\text{U}$ ages down to 6.38 ± 1.27 Ma, much younger than the robust median age of $14.346 \pm 0.054\text{--}0.14$ (Table S2). Taking this, and the stratigraphic positions of the samples (Table 2; Fig. 8) into account, the youngest zircon ages most likely result from partial Pb loss, perhaps induced by laser ablation of weak or fractured zircon zones, and do not result from the admixture of younger detritus.

5.2. Correlation of tephra layers

U-Pb zircon ages obtained from the analyzed tephra layers provide the basis for the age model of the Valjevo-Mionica Basin. Nevertheless, some samples display ages which overlap within error, leading to ambiguities in the stratigraphic correlation of different boreholes. This is most pertinently displayed by the DH-5-2 and DH-5-3 ash layers (Fig. 6; Table 2). Zircon typology provides an additional, independent means of differentiating such layers and improving stratigraphic correlations. In this manner, we may group samples into distinct tephra horizons based on the U-Pb ages and zircon typology.

The lowermost ash layers across all boreholes (i.e. DH-1-5, DH-2-5, DH-3-1, DH-4-1 and DH-5-3) display overlapping U-Pb ages and similar typologies (Figs. 6, 7). This suggests that these samples represent products of one and the same volcanic eruption, provisionally named tephra horizon 1. Conversely, the DH-5-2 sample displays markedly different zircon typologies (Fig. 7), indicating that it represents the result of a distinct, slightly younger volcanic episode, assigned to tephra horizon 2. The DH-5-1 sample is somewhat younger (Fig. 6; Table 2), and likely represents another volcanic eruption (tephra horizon 3), although the zircon typologies are similar to sample DH-1-5, DH-2-5, DH-3-1, DH-4-1 and DH-5-3. For samples DH-1-4 and DH-2-4, unambiguous correlation was not possible due to the small number of zircon grains. We tentatively ascribe them to the same tephra horizon based on the similar stratigraphic position and overlapping ages. However, we consider the age of DH-1-4 more reliable based on the larger sample size (Fig. 6). Further upwards in the succession, U-Pb ages and zircon typologies show that samples DH-1-2 and DH-1-3 may be correlated with DH-2-2 and DH-2-3, respectively. Finally, the DH-1-1 and DH-2-1 ash layers yielded overlapping U-Pb ages but display significantly different zircon typologies (Fig. 7) indicating that they are not correlative, and were derived from different sources. This interpretation is backed by differences in stratigraphic position of the ash layers (Table 2; Fig. 8). Based on this, both ash layers likely represent distinct eruption events, (tephra

horizons 6 and 7, respectively).

5.3. Tephrostratigraphic implications

The early-middle Miocene saw extensive volcanic activity in the Pannonian Basin (Pecskay et al., 2006; Lukács et al., 2015, 2018; Lukács et al., 2022, 2024; Hencz et al., 2024). The resulting volcanoclastic deposits were deposited over a wide area, including intramontane basins in the Dinarides, the North Alpine Foreland Basin and the Apennine foredeep (Šegvić et al., 2014; Wotzlaw et al., 2014; Rocholl et al., 2018; Badurina et al., 2021; Brlek et al., 2023, 2024a, 2024b). The tephra layers of the Valjevo-Mionica Basin dated as part of this study likely represent products of the same volcanic activity.

Our tephra horizons 1 and 2 temporally overlap with the 14.3 ± 0.2 Ma age of the Harsany Member of the Bükk Foreland Volcanic Area (Lukács et al., 2018; Hencz et al., 2024). Ti-in-zircon, whole rock and glass composition data imply zircon formation temperatures of 640–750 °C for the Harsany Member (Lukács et al., 2021). This is slightly lower than our average zircon crystallization temperature estimates for tephra horizon 1 (807–820 °C; Fig. 6), but overlaps with the 743 °C temperature estimate for tephra horizon 2 (Fig. 6). This discrepancy could stem from inherent differences between zircon typology-based temperature estimates and independent geochemical constraints (Akin et al., 2019). On the other hand, geochemical and CA-ID-TIMS data indicate that the Harsany Member comprises multiple, temporally close but compositionally different volcanic eruptions (Lukács et al., 2022; Brlek et al., 2024a). Therefore, our tephra horizons 1 and 2 might both be associated with the Harsany Member, with the differences in zircon crystallization temperature reflecting compositional differences between individual eruptions.

The age of tephra horizon 3 overlaps with the 14.03 ± 0.04 Ma Pöls tuff from the Styrian Basin (Sant et al., 2020), and the 14.120 ± 0.130 Ma ČAK tuff from the Tuzla Basin reported by Mandić et al., 2026 (this issue). These ages also overlap with the onset of volcanic activity at the The Kráľová stratovolcano at ~ 14.1 Ma (Rybár et al., 2024). However, further research is needed to determine the specific sources of these tuffs.

Tephra horizon 4 may potentially be correlated with the 13.60 ± 0.07 Ma WT-3 tuff in the East Carpathians (de Leeuw et al., 2010b). For a similarly aged tuff in the Ugljevik Basin, Badurina et al. (2021) proposed a source in the Eastern Carpathians or Apuseni Mts.

Tephra horizons 5 and 6 may be correlated with similarly aged tuffs from the Apennines (RES tuff, 13.340 ± 0.018 Ma; Wotzlaw et al., 2014), North Alpine Foreland Basin (Zahling-1 tuff, 13.34 ± 0.39 Ma; Rocholl et al., 2018) and East Carpathians (PV-A tuff, 13.32 ± 0.07 Ma; de Leeuw et al., 2018). These were potentially sourced from coeval volcanism in the East Carpathians or Apuseni Mts. (Pecskay et al., 2006; Rocholl et al., 2018; Badurina et al., 2021).

Finally, tephra horizons 7 and 8 overlap in age with the 13.064 ± 0.065 Ma Dobi Member of the Bükk Foreland Volcanic Area (Karátson et al., 2025). Moreover, the estimated 710 °C zircon formation temperature of tephra horizon 8 (Fig. 7) overlaps with the 700 °C zircon saturation temperature obtained from the Lénárdaróc site (Lukács et al., 2024), which has been assigned to the Dobi eruption (Karátson et al., 2025). This suggests that tephra unit 8 may be correlated with the Dobi eruption. On the other hand, the different predominant typologies and high zircon formation temperature (860 °C) of tephra horizon 7 suggest a different source. For similarly aged tuffs in the Ugljevik Basin, Badurina et al. (2021) suggested a source in the East Carpathians or Apuseni Mts.

In total, we identified 8 distinct tephra horizons in the distal tephrostratigraphic record of the Valjevo-Mionica Basin. Further research is required to constrain the specific source areas of these tephra layers. Nevertheless, this demonstrates the potential of a distal tephrostratigraphic record for resolving discrete, temporally closely spaced volcanic eruptions.

5.4. Age model

The new U-Pb ages obtained from the Valjevo-Mionica Basin, allow us to constrain the time of sediment deposition, and to calculate the average sediment accumulation rates. Furthermore, by correlating tephra layers across the basin we gained new insights into the vertical and lateral differences in facies development. This forms the basis for a stratigraphic revision of the lacustrine infill of the Valjevo-Mionica Basin. The age of the succession in the western part of the basin is calibrated by the boreholes DH-1 and DH-2, which contain 5 ash layers each. Zircon ages of the five tephra layers in the DH-1 borehole reveal a successive younging in sediment deposition from the bottom to the top, as indicated by U-Pb age of 14.358 ± 0.059 Ma (ash layer DH-1-5 at 451.6 m depth), 13.860 ± 0.160 Ma (DH-1-4 at 231.25 m), 13.464 ± 0.048 Ma (DH-1-3 ash layer at 212.8 m), $13.384 \pm 0.110/-0.055$ Ma (DH-1-2 ash layer at 196.7 m), and $13.149 \pm 0.110/-0.069$ Ma (DH-1-1 ash layer at 180.9 m; Table 1; Table S2). Using the prominent DH-1-5 and DH-1-3 ash layers as tie-points, an average sediment accumulation rate of 27 cm/kyr may be inferred, spanning FA 3–5 (Figs. 8, 9). This sedimentation rate markedly decreases upwards, to 20 cm/kyr within the lower part of FA 6 as shown by the DH-1-3 and DH-1-2 ash layers (Figs. 8, 9). A further decrease to 7 cm/kyr is apparent in the middle part of FA 6, using the DH-1-1 ash layer as a tie-point. (Figs. 9, 10).

The lacustrine deposits of the Valjevo-Mionica Basin are overlain by brackish deposits of the Paratethys, which were biostratigraphically determined to be of Sarmatian age (Jovanović and Dolić, 1994; Marković and Milivojević, 2010; Neubauer et al., 2016). Considering its geographic position, we regard borehole DH-1 as having drilled through the lowermost part of the Sarmatian deposits. We tentatively place the boundary of the saline lacustrine and Sarmatian restricted marine deposits at a depth of 20 m in DH-1, i.e. at the boundary of FA 7 and 9 (Fig. 10). This boundary coincides with the marked disappearance of searlesite and analcime mineralisation, pointing to a decrease in water salinity. The Sarmatian lasted from 12.65 to 11.6 Ma in the Central Paratethys (ter Borgh et al., 2013; Palcu et al., 2015; Mandić et al., 2019b). Depending on when the Sarmatian ingress occurred in the Valjevo-Mionica Basin, this constrains the sedimentation rates in the upper part of the lacustrine infill to between 32 and 10 cm/kyr. However, considering the late Sarmatian age proposed for the ingress horizon at the Zmajevac section (Jovanović and Dolić, 1994), we consider the lower end of the sedimentation rate estimates as more likely. However, further geochronological and biostratigraphic constraints are needed to test this age determination.

In the DH-2 borehole, the DH-2-5 ash layer at a depth of 398.5 m yielded an U-Pb age of $14.420 \pm 0.150/-0.180$ Ma. Upwards, the DH-2-4 ash layer at 179.1 m gave an age of 13.659 ± 0.088 Ma. Using the DH-2-5 and DH-2-4 ash layer as tie points, an average sedimentation rate of 28 cm/kyr can be obtained for the FA 3–5, comparable to values obtained from drill core DH-1. The DH-2-3 ash layer at 158.0 m depth yielded an age of 13.458 ± 0.049 Ma and, therefore, suggests a marked reduction of the sedimentation rate to about 10 cm/kyr. For sample DH-2-2 (at 139.7 m depth), an age of $13.367 \pm 0.079/-0.048$ Ma was obtained, resulting in an average sedimentation rate of 20 cm/kyr for the lower part of FA 6 (Fig. 9). Finally, sample DH-2-1 at 108.1 m depth yielded the youngest age of 13.030 ± 0.150 Ma, and points to a slow average sedimentation rate of 9 cm/kyr for the upper part of FA 6, which is comparable to the one obtained from the upper part of FA 6 in drill-core DH-1. Extrapolating the 9 cm/kyr sedimentation rate derived from the upper part of the FA 6 results in an age of 11.8 Ma for the uppermost part of borehole DH-2.

In the northwestern part of the basin, one ash layer was sampled from boreholes DH-3 and DH-4 (Table 2) each. These gave ages of $14.272 \pm 0.039/-0.096$ and $14.270 \pm 0.100/-0.130$ Ma, respectively. The ages and zircon typologies overlap with those from samples DH-1-5 and DH-2-5 (see Section 5.2). This suggests that the sedimentary succession drilled by the boreholes DH-3 and DH-4 is uplifted by ~ 100 m

relative to the succession penetrated by the boreholes DH-1 and DH-2 (Fig. 9).

Finally, data from borehole DH-5 allows us to constrain depositional rates for the FA 3 in the eastern part of the Valjevo-Mionica Basin. The two lowermost ash layers DH-5-3 (at 440.1 m) and DH-5-2 (at 426.8 m) gave overlapping U-Pb ages of $14.346 \pm 0.050/-0.066$ and $14.346 \pm 0.054/-0.140$ Ma, respectively, and sample DH-5-1 (at 410.6 m) a slightly younger U-Pb age of $14.144 \pm 0.140/-0.090$ Ma. Using samples

DH-5-3 and DH-5-1 as tie points results in an average sedimentation rate of 15 cm/kyr for FA 3 in borehole DH-5. Although no younger ash layers were found in this borehole, the proximity of Sarmatian deposits (e.g. Zmajevac and Vračević streams; Stevanović, 1953; Jovanović and Dolić, 1994; Marković and Milivojević, 2010; Neubauer et al., 2016) which occur some ~30 m above the top of DH-5 (Fig. 9), indicate a similar, ~500 m total thickness of the lacustrine strata as in the western part of the basin, and point to similar average sedimentation rates (Fig. 10).

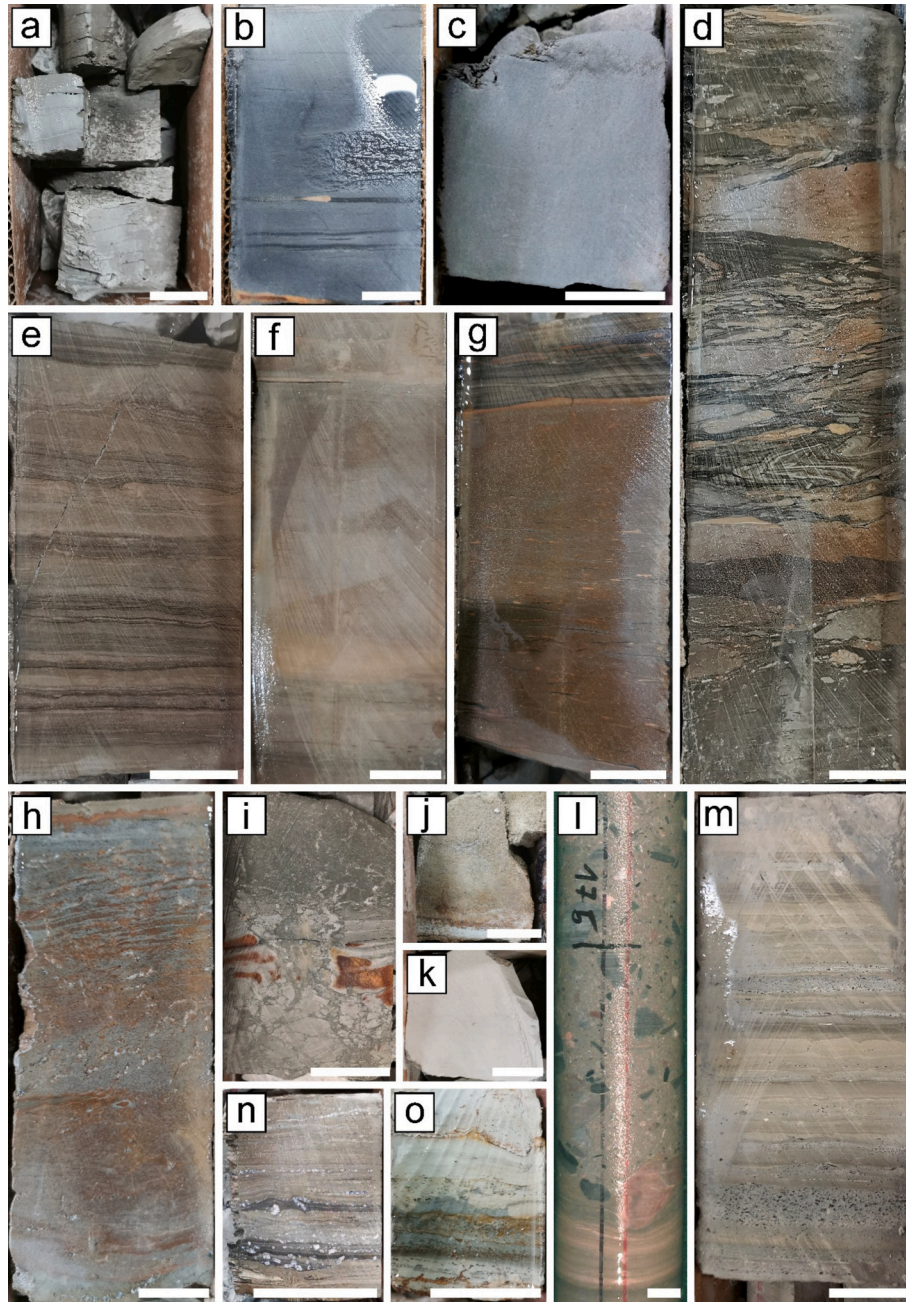


Fig. 3. Lithofacies of the Valjevo-Mionica Basin. a) Green massive to indistinctly laminated green clayey marlstone (F14), DH-2 core, 232.5 m depth; b) Grey indistinctly laminated siltstone with marly matrix (F15a), DH-2 core, 122.3 m depth; c) Massive dark grey siltstone (F15b), DH-2 core, 6.8 m depth; d) Slump within dolomarlstone (F17) with fine sandstone (F19) intercalations, DH-2 core, 40.9 m depth; e) Dark brown laminated dolomarlstone with siltstone laminae (F16), DH-2 core, 9.6 m depth; f) Banded to massive beige dolomarlstone (F17), DH-2 core, 43.1 m; g) Grey-orange weakly laminated to massive fine sandstone (F19), DH-2 core, 59.6 m depth; h) Grey-orange siltstone to fine sandstone with low-angle cross-bedding and calcite pseudomorphs (F18), DH-2 core, 52.4 m depth; i) Grey laminated marl with dewatering structures (F20), 106.3 m depth; j) Yellow homogenous sandstone (F25), DH-1 core, 7.6 m depth; k) Massive beige dolomarlstone (F22) with small searlesite and sulfide aggregates, DH-2 core, 9.4 m depth; l) Poorly-sorted breccia-conglomerate (F26), DH-4 core, 175 m depth; m) Grey banded dolomarlstone with sulfide aggregates (F24), DH-1 core, 19.1 m depth; n) Laminated dolomarlstone with searlesite aggregates (F21), DH-2 core, 7.7 m depth; o) Light grey laminated dolomarlstone with Fe-Mn crusts (F23), DH-1 core, 6.9 m depth. Scale bar = 2 cm. For facies descriptions, see Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.5. Diagenesis of authigenic minerals

The formation of authigenic minerals reflects the interplay of different depositional, paleoclimatic and diagenetic processes. In the Valjevo-Mionica Basin, these are represented by searlesite, analcime, pyrite, calcite pseudomorphs of soluble salts, and possibly albite (see below).

Searlesite occurs predominantly within the upper part of the FA 7 as dispersed spherulitic aggregates (Fig. 5l) or as closely packed, spherulitic aggregates and randomly oriented acicular grains, associated with dark, clayey laminae (Figs. 3n, 5k). Wavy and disrupted lamination surrounding these aggregates imply displacive growth from porewaters during early diageneses, whereas local cross-cutting relationships indicate partial replacement of clay-rich matrix during later diagenetic stages. Such textures are consistent with direct precipitation from highly alkaline, Na, B rich pore waters and/or alteration of matrix material

under arid climatic conditions within saline-alkaline lakes (Hay and Guldman, 1987; Larsen, 2008; García-Veigas et al., 2013; Li et al., 2023).

Analcime occurs within FA 7. It is not associated with pyroclastic material, which is a common precursor for analcime authigenesis (Surdam, 1977; Larsen, 2008; García-Veigas et al., 2013), but occurs either in association with searlesite (ESM S7), or abundantly within irregular, reddish, clayey patches (Fig. 5e). Common euhedral to subhedral morphologies (ESM S7) suggest formation through progressive alteration of matrix material, and/or by direct precipitation from saline-alkaline pore waters (English, 2001; Do Campo et al., 2007), rather than replacement of precursor silicates or glass shards which is associated with anhedral to globular analcime morphologies (Do Campo et al., 2007; Ozen and Goncuoglu, 2012).

Albite occurs within FA 7 (ESM S6). Authigenic albite formation usually occurs in the central parts of saline-alkaline lake deposits as an

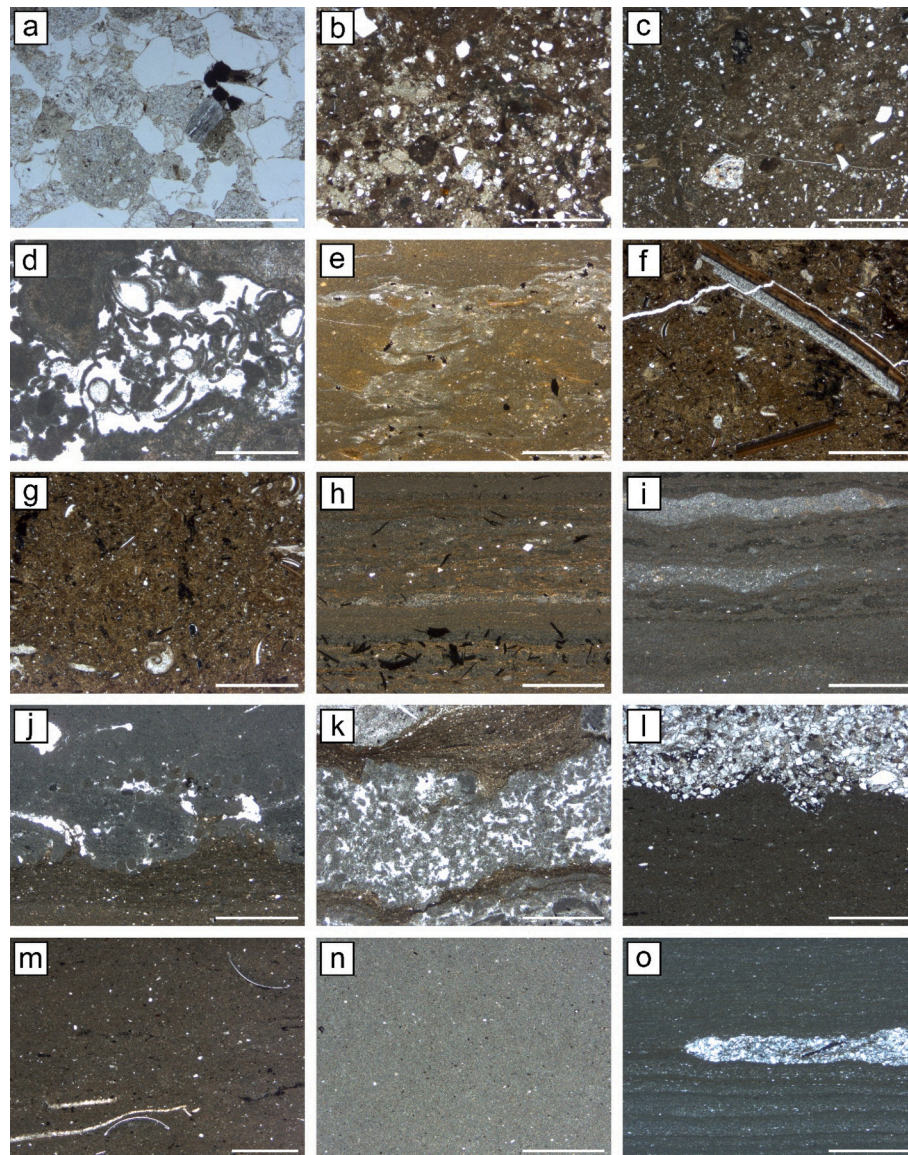


Fig. 4. Photomicrographs of lithofacies of the Valjevo-Mionica Basin: a) Clast-supported conglomerate (F 1), b) Clast to matrix supported sandstone (F 2), c) Matrix supported sandstone (F 3), d) Tufa showing root moulds (F 4), e) Beige homogenous micrite showing dewatering structure (F 5), g, f) Dark brown clayey micrite with mollusc shell fragments (F 6), h) Banded micrite with sulfide aggregates (F 7), i) Banded white marlstone with microbial mat fragments (F 8), j) Banded marlstone with peloidal grainstone-packstone interval showing erosive base (F 8), k) Microbial mats within laminated grey marlstone (F 9), l) Well-sorted, clast supported calcarenite with erosive base within F10, m) Fostracod shell fragments in grey to green marlstone (F10), n) Massive light beige micrite (F 11), o) Laminated marlstone showing calcite pseudomorph (F 12). Scale bar = 1 mm, except Fig. 4m=200 µm. For facies descriptions, see Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

end-member in the interaction of increasingly alkaline pore waters with pyroclastic or clayey material, replacing precursor silicates, or precipitating directly from pore waters (Surdam, 1977; Fishman et al., 1995; Larsen, 2008; Li et al., 2023). In the Valjevo-Mionica Basin, its association with analcime may support such a diagenetic origin (ESM S6), during periods of highly alkaline pore water percolation. However, as the sample in question is a sandstone, a detrital origin cannot be completely ruled out.

Calcite pseudomorphs replacing soluble salts occur frequently in FA 7 and FA 8, and rarely in FA 6, either as small dispersed aggregates, or parallel to lamination (Figs. 4o, 5d). They are primarily filled with coarse sparite grains filling irregular voids, although cone-in-cone structures are also observed (Fig. 5a). Common soft-sediment deformation features around calcite-filled voids, such as wavy lamination (Fig. 4o), suggest displacive salt growth during early diagenesis, probably close to the sediment-water interface. Subsequent oscillations in

water chemistry resulted in their dissolution and replacement with calcite. Small amounts of gypsum and halite recorded in F18 (ESM S6) may reflect remnants of original void-filling salts. Obradović et al. (1997) additionally reported findings of shortite and trona.

Dispersed sulfides occur throughout most lacustrine deposits of the Valjevo-Mionica Basin, but are especially common within organic-rich marlstones of FA 3–6 (e.g. Fig. 4h). Their origin is related to bacterial sulfate reduction, producing hydrogen sulfide that reacts to form sulfide minerals, e.g. pyrite. This suggests anoxic lake-bottom conditions (Jagniecki and Lowenstein, 2015). However, sulfide-bearing, bioturbated marls (Fig. 5a, l) indicate oxygenated bottom waters, suggesting pore-water chemistry as the dominant control on bacterial sulfate reduction. Sulfides also rarely co-occur with searlesite and analcime (Fig. 5l; ESM S7). As sulfides commonly form close to the sediment-water interface (Wright, 1999), this relationship may support an early diagenetic origin of this mineral association. Bacterial sulfate reduction

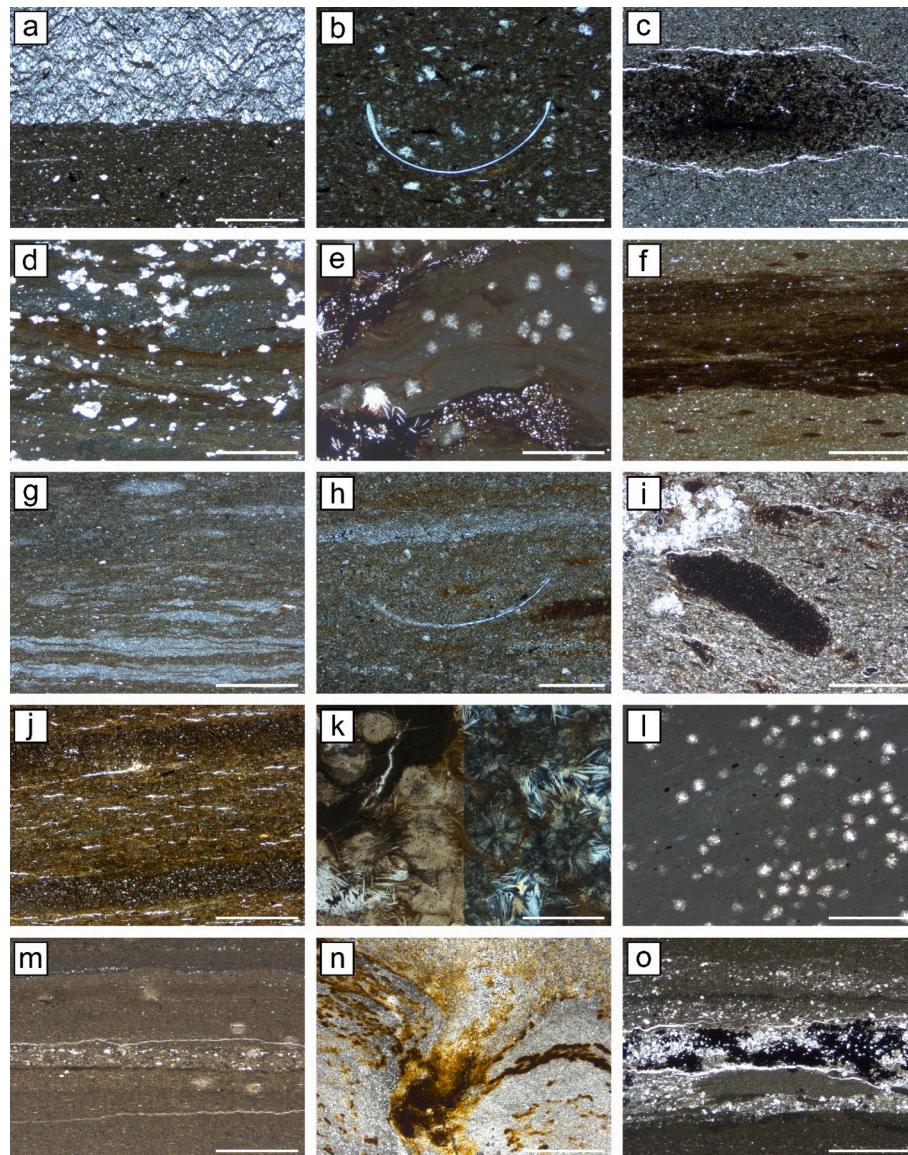


Fig. 5. Photomicrographs of lithofacies of the Valjevo-Mionica Basin: a) Banded dark marlstone with dispersed sulfides and calcite pseudomorph showing cone-in-cone texture (F13), b) Ostracod fragment in F 13, c) Sulfide aggregates within F15a, d) Dolomarlstone with calcite pseudomorphs (F 16), e) Dolomarlstone with searlesite aggregates and lenses of clayey material with analcime (F 16), f) Banded dolomarlstone showing orange clayey intercalation with analcime (F17), g) Banded dolomarlstone with dolomite microspar lenses (F17), h) Ostracod fragment in F17, i) Fine sandstone with calcite pseudomorphs and clayey intraclast (F 18), j) Orange clayey sandstone with dark intervals with analcime (F19), k) Laminated dolomarlstone with searlesite aggregates in PPL (left) and XPL (right), F 21, l) Massive grey dolomarlstone with searlesite and sulfide aggregates (F 22), m, n) Laminated dolomarlstone with Mn-crusts (F 23), o) Banded dolomarlstone with sulfide aggregates (F 24). Scale bar = 1 mm, except b, h) = 200 μm. For facies descriptions, see Table 1.

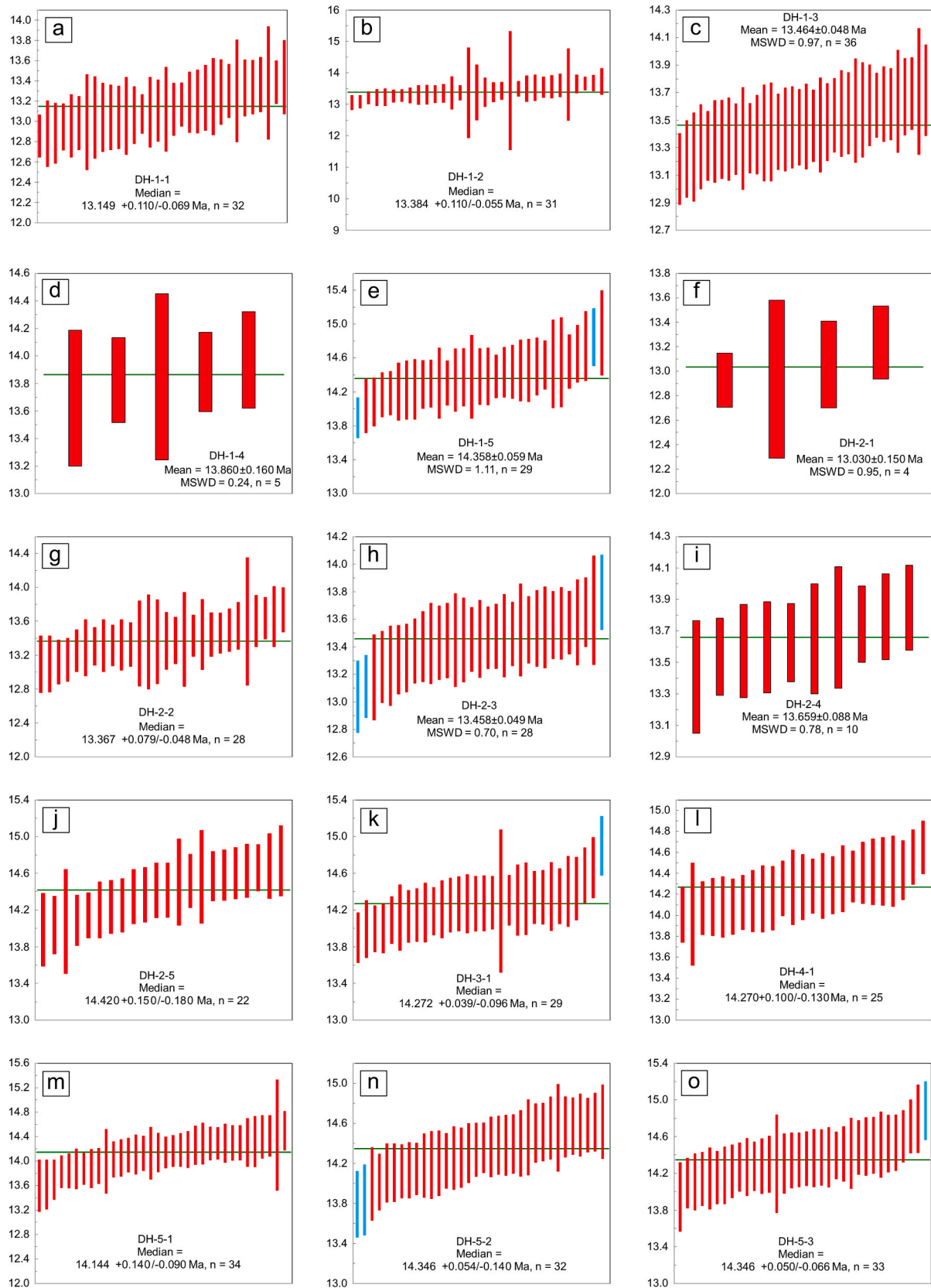


Fig. 6. Results of zircon U-Pb dating of volcanoclastic layers from the Valjevo-Mionica Basin. a) DH-1-1, b) DH-1-2, c) DH-1-3, d) DH-1-4, e) DH-1-5, f) DH-2-1, g) DH-2-2, h) DH-2-3, i) DH-2-4, j) DH-2-5, k) DH-3-1, l) DH-4-1, m) DH-5-1, n) DH-5-2, o) DH-5-3. Weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age are presented for datasets with $\text{MSWD} < 1.3$, and robust median ages for all other samples. Data-point error symbols are 2σ . Data-point error symbols in red represent analyses used in the calculation, whereas those in blue represent rejected analyses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

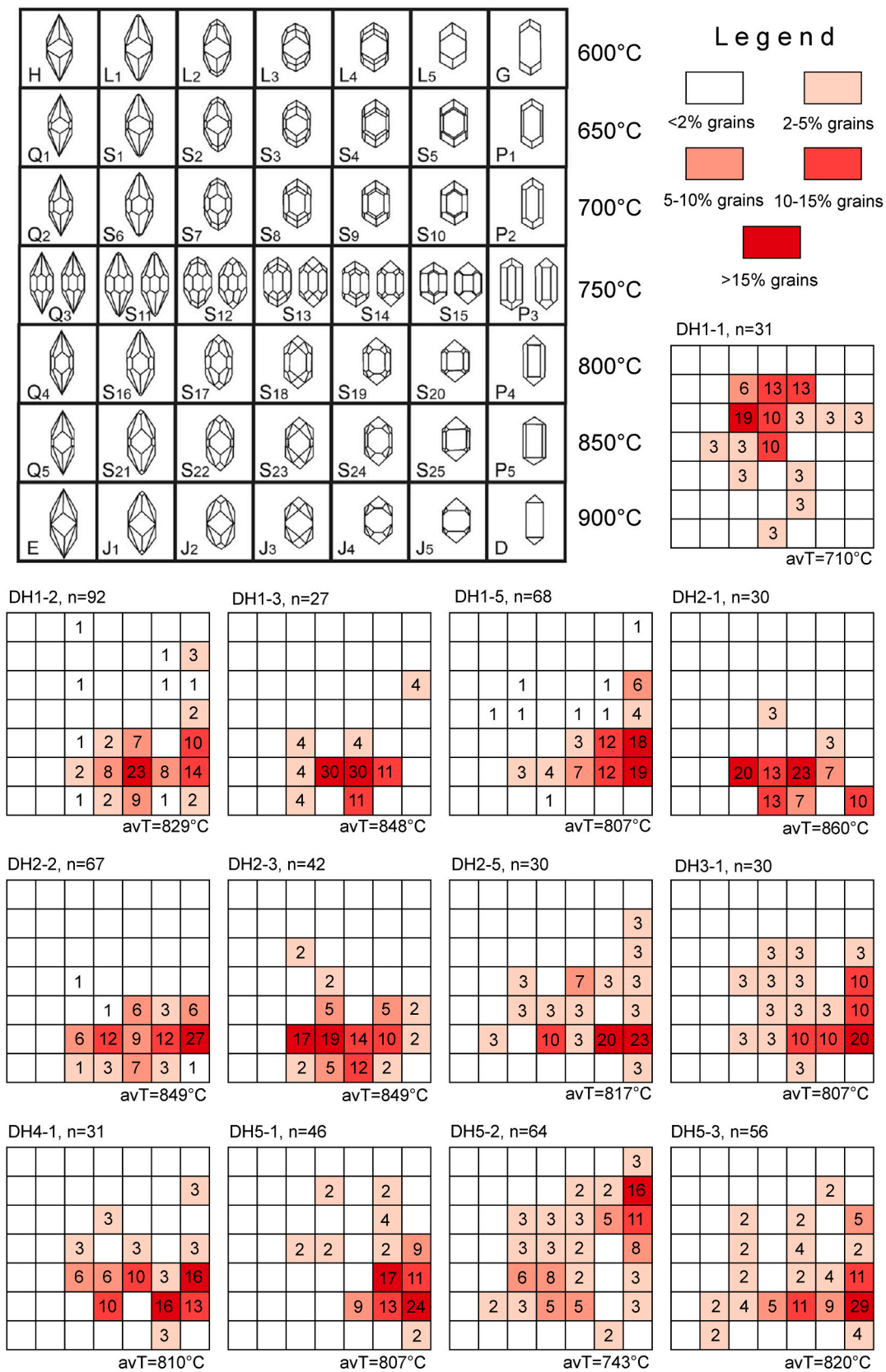


Fig. 7. Typologies and average temperatures of zircon populations in tuff layers of the Valjevo-Mionica Basin, after Pupin (1980).

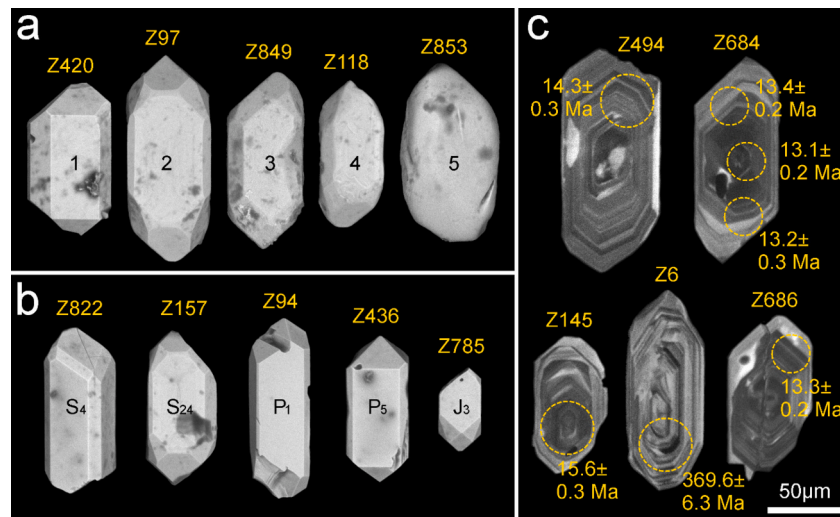


Fig. 8. Common external morphologies and internal zoning patterns of the analyzed zircon grains. a) SEM images of zircon grains displaying all degree of roundness (DOR) categories according to Zeh and Cabral, 2021; 1-perfect euhedral, 2-slightly rounded, 3-edges significantly rounded, 4-relic primary faces, 5-completely rounded). b) SEM images of common zircon typologies (after Pupin, 1980). c) CL images showing internal zoning patterns of Miocene zircons and laser spot placement.

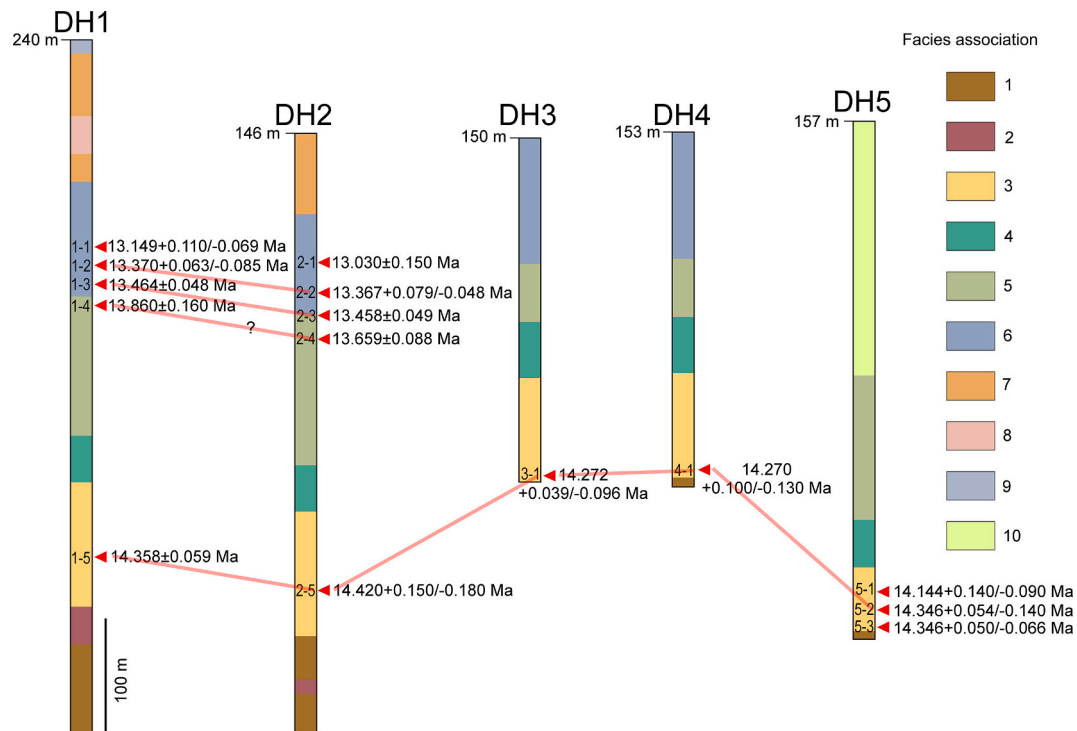


Fig. 9. Schematic core logs showing Facies associations and U-Pb ages of samples tephra ash layers. The topographic height of the drill holes is indicated. Facies associations are indicated with numbers: 1- Distal alluvial fan, 2- Marginal lacustrine carbonates, 3- Littoral marlstones with microbial mats, 4- Sublittoral marlstones with calcarenite intercalations, 5- Profundal clayey marlstones, 6- Sublittoral marlstones, 7- Littoral to sublittoral dolomarlstones with analcime and searlesite, 8- Mudflats, 9- Sublittoral dolomarlstone with sulfides and Fe-Mn crusts, 10- Littoral sandstones and clays.

also increases pore-water alkalinity (Jagniecki and Lowenstein, 2015), possibly aiding dolomitization in FA 7 (Wright, 1999) and promoting searlesite and analcime precipitation.

Overall, the authigenic mineralogy of the Valjevo-Mionica Basin correlates well with depositional environments. Sulfides are most common within organic-rich intervals of FA 3–5, whereas calcite pseudomorphs of soluble salts occur in FA –8, consistent with sedimentological evidence of lake shallowing and evaporation-driven salinity increase. Authigenic silicates, comprising searlesite, analcime and possibly albite,

occur predominantly within FA 7, but are absent from contemporaneous mudflats (LU8) and marginal areas with high clastic input (FA 10). This is broadly consistent with patterns observed across saline-alkaline lakes, where authigenic silicates form mainly in perennial lacustrine settings and reflect increasing salinity and alkalinity towards the basin centre (Do Campo et al., 2007; Larsen, 2008; Surdam, 1977). Together, these observations suggest that interstitial brine composition enabling authigenic silicate growth was controlled by evaporation under an arid climate (Larsen, 2008), with fine-grained siliciclastic detritus providing

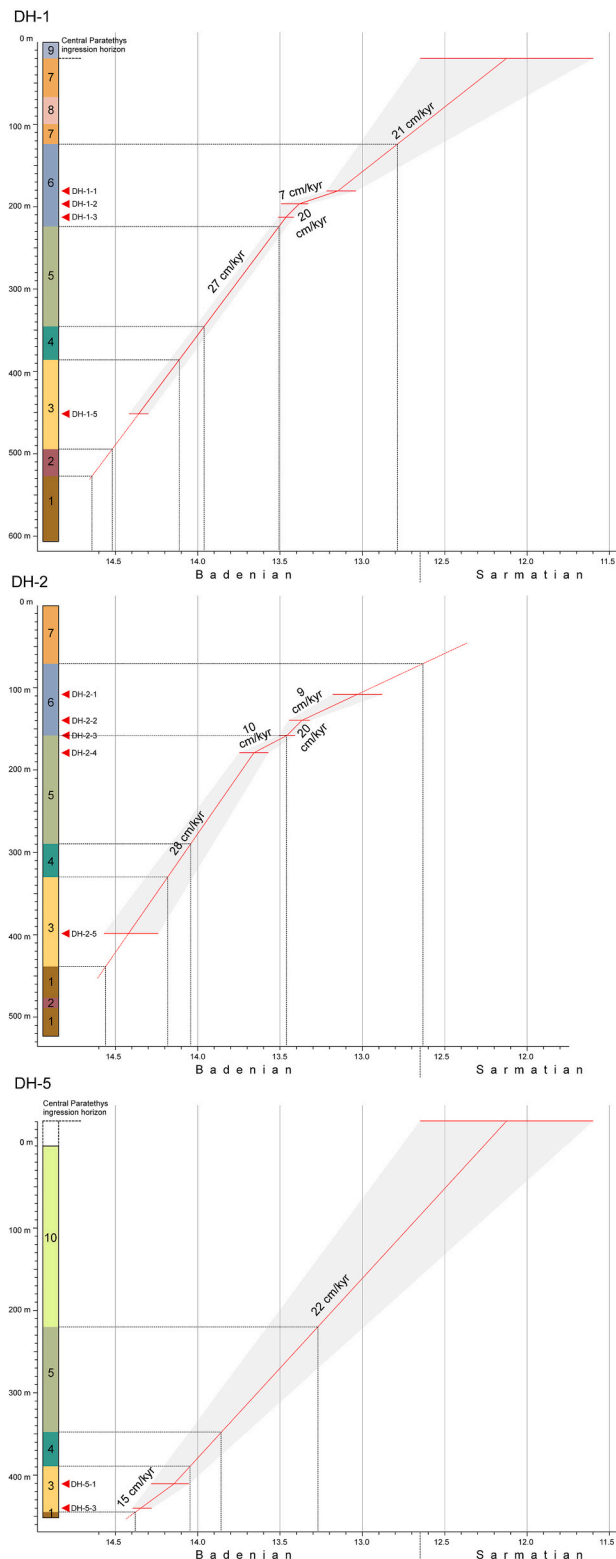


Fig. 10. Age models and average sedimentation rates based from boreholes DH-1, DH-2 and DH-5 based on U-Pb zircon dating. Red horizontal bars show age errors of individual ages. The red lines indicate the age-depth correlation, based on weighted mean and robust median ages, from which average sedimentation rates are calculated. Dashed red lines indicate extrapolations of age-depth correlations based on calculated sedimentation rates. Dashed black lines show correlation of main facies changes and their respective ages inferred from the age model. Numbering of facies associations as in Fig. 9. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reactive aluminosilicate material (ESM S7).

5.6. Depositional evolution

The evolution of the Valjevo-Mionica Basin comprises 3 stages based on lithological and chronostratigraphic information. Moreover, correlation with geochemical data (Šajnović et al., 2008a, 2008b; Šajnović et al., 2009) offers additional constraints on the paleoenvironmental evolution.

5.6.1. Stage 1: >14.6 Ma

At this stage, deposition was characterized by coarse alluvial clastics (FA 1) derived by streams draining from the surrounding Cretaceous flysch and Triassic carbonates (Fig. 11). Between these fans in areas with less clastic input, small freshwater ponds developed during periods of increased runoff. Precipitation dependent oscillations in water level led to formation of palustrine carbonates. These ponds also occasionally hosted tufa near their shorelines (Fig. 11). Tufa precipitation may have been aided by input of cooled thermal water, sourced from basin-bounding faults (Andrić-Tomašević et al., 2024). This evolutionary stage was coeval with widespread early-middle Miocene asymmetric extension affecting the Internal Dinarides following the roll-back of the Carpathian slab (Matenco and Radivojević, 2012; Löwe et al., 2021). The is also documented in the Bukulja Mt. To the NE of the VMB (Stojadinović et al., 2013; Mladenović et al., 2025). The subsidence in the southern part of the basin was likely controlled at this stage by a normal-fault cross-cutting the Triassic and Cretaceous bedrock and likely linked to the rise of the Bukulja dome. The exhuming bedrock units supplied the basin with clastic material. Based on current datasets we cannot say that the VMB was a breakaway basin of the regional-scale detachment exposed in Bukulja, as its continuation below the basin infill is unclear.

5.6.2. Stage 2: 14.6–13.5 Ma

At 14.6–14.5 Ma, shallow, perennial lacustrine conditions were established in the western part of the basin, and slightly later at 14.4 Ma in the eastern part (Fig. 10). This lake was characterized by fine-grained carbonate sedimentation featuring microbial mats formed in a littoral environment (FA 3). The drop in coarse-grained clastic supply and the overall retrogradational depositional trend point towards a decrease in tectonic activity and the lack of source area rejuvenation. Geochemical data indicate alkaline conditions for these initial lacustrine deposits (Šajnović et al., 2008a, 2008b). Based on the relatively most precise age model from DH-1 (Fig. 10), at 14.1 Ma a rapid deepening occurred, as shown by the development of sublittoral marls with calcarenite intercalations (FA 4). An increase in carbonate content (Šajnović et al., 2008a) and ostracod remains (Fig. 4m) suggest increased bio-productivity. The coeval presence of littoral environments with microbial mats is attested through resedimented microbial mat fragments. Basinward, the sublittoral marls transitioned into a profundal facies association (FA 5) consisting of clayey marls and laminated carbonaceous marls (Fig. 11). The prevalence of these deposits after 14 Ma points to an increase in fine-grained clastic input. The cyclicity of depositional facies in FA 5 suggests that the lake environment was sensitive to climatic forcing. Subsidence rates were relatively high during this time period at 27–28 cm/kyr (Fig. 8). The deepening of the lake may have resulted either from tectonic subsidence and/or from the establishment of more favourable climatic conditions. Coarse debrites with extrabasinal clasts in FA 4 in DH-3 and DH-4, together with differences in the thickness of FA 5 indicate pulses of tectonic subsidence. Nevertheless, progradation of large fan-deltas which is common in tectonically-controlled basins (Andrić et al., 2017; Budai et al., 2019; Jia et al., 2021) has not been observed. On the other hand, increased bio-productivity in the littoral zone, paired with increased fine-grained clastic input in the profundal zone suggest increased runoff and hence relatively more humid conditions favourable for lake expansion during

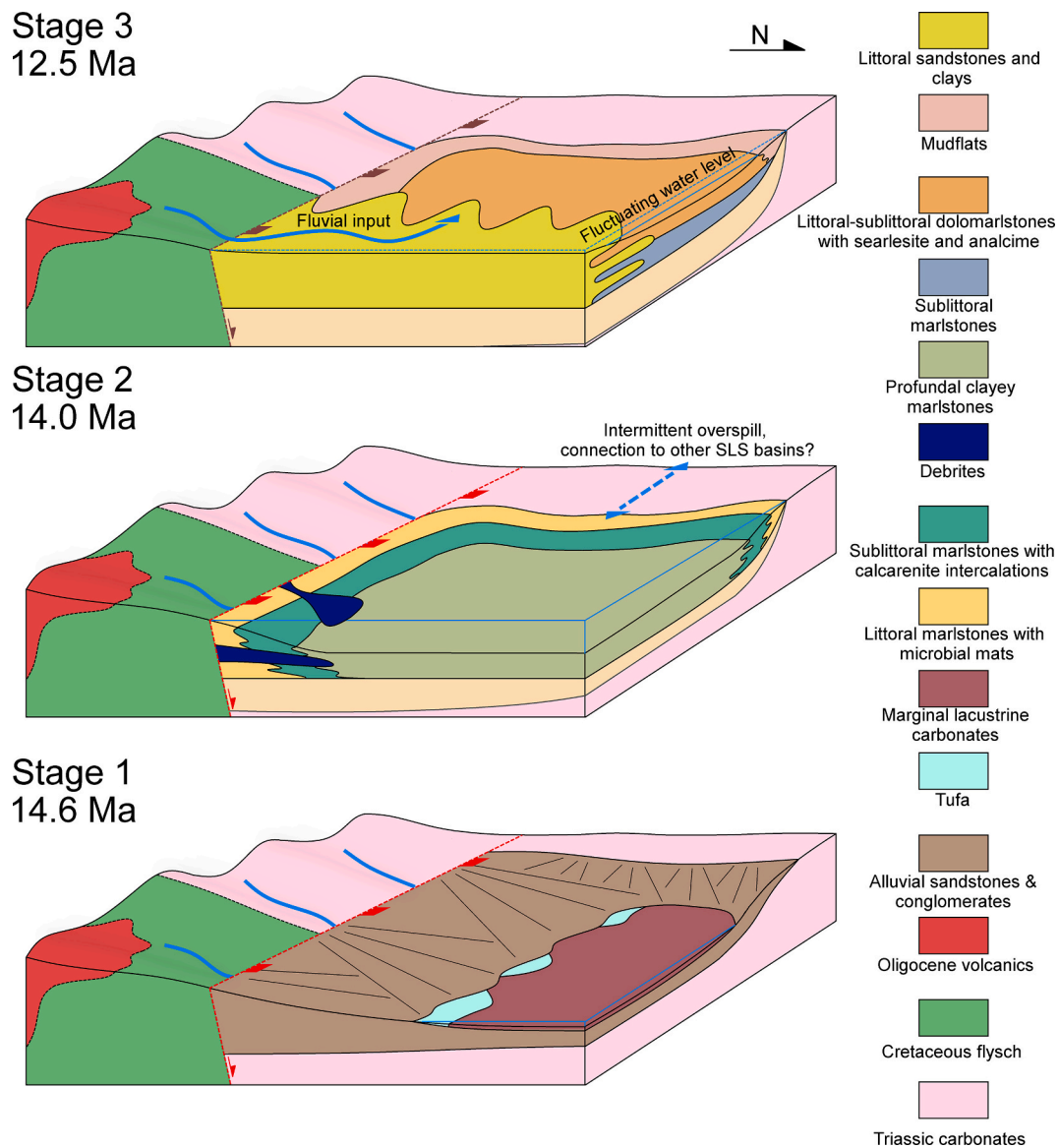


Fig. 11. Block diagrams showing the evolution of the Valjevo-Mionica Basin during three different stages.

the beginning of the Middle Miocene Climatic Transition (MMCT). The Valjevo-Mionica Basin remained in a balance-filled state (Benavente and Bohacs, 2024) characterized by cyclic profundal deposition until 13.5 Ma.

5.6.3. Stage 3: 13.5–12.1 Ma

From 13.5 Ma, there is a decrease in clastic input in DH 1 and DH-2 (FA 6, Figs. 10, 11). Bioturbated intervals and ostracod remains also suggest a somewhat shallower setting compared to FA 5. Rare calcite pseudomorphs of soluble salts suggest episodic saline-alkaline conditions. After 12.8–12.6 Ma (Fig. 10), the predominance of littoral dolomarlstones with analcime and searlesite (FA 7) suggest persistent saline-alkaline lake conditions. This was coupled with periodic exposure and pedogenetic alteration of lake-margin marls (FA 8). In the eastern part of the basin, shallowing resulted in progradation of littoral clastics (FA 10) over the profundal facies association (FA 5) after 13.3 Ma, although note the error range in the age model (Figs. 10, 11). This was possibly derived from erosion of the Ljig flysch and neighboring Oligocene volcanics (Fig. 11). Geochemical data indicate a reduction in Al_2O_3 content reflecting lower terrigenous input. On the other hand, MgO , Na_2O and organic carbon contents gradually increase (Sajnović et al., 2008b). This

time interval was therefore characterized by a transition towards an underfilled, hydrologically closed lake (Benavente and Bohacs, 2024) with high evaporation, unstable water levels and a stratified water column. Organic matter geochemistry indicates the primary contribution of algal biomass to the organic matter content in this interval (Sajnović et al., 2008a). Upwards, a marked decrease in water salinity is suggested by the sedimentological characteristics of FA 9.

5.7. Tectonic vs climatic control on regional aridity

Our present study demonstrates that the Valjevo-Mionica Basin saline lake succession developed after the MCO (i.e. after 14.7 Ma), in contrast to previous interpretations (Andrić-Tomašević et al., 2021). Still, an older phase cannot be excluded as older deposits contemporaneous with the MCO were not accessible in this study.

The initial formation of an alkaline lake around 14.6–14.3 Ma slightly post-dates the Mi-3a glaciation and the onset of the MMCT (Miller et al., 2020), but coincides with the timing of significant continental mid-latitude cooling (Methner et al., 2020). This cooling could have reduced evaporation rates enabling the establishment of lacustrine conditions. The studied sedimentary succession implies significant lake

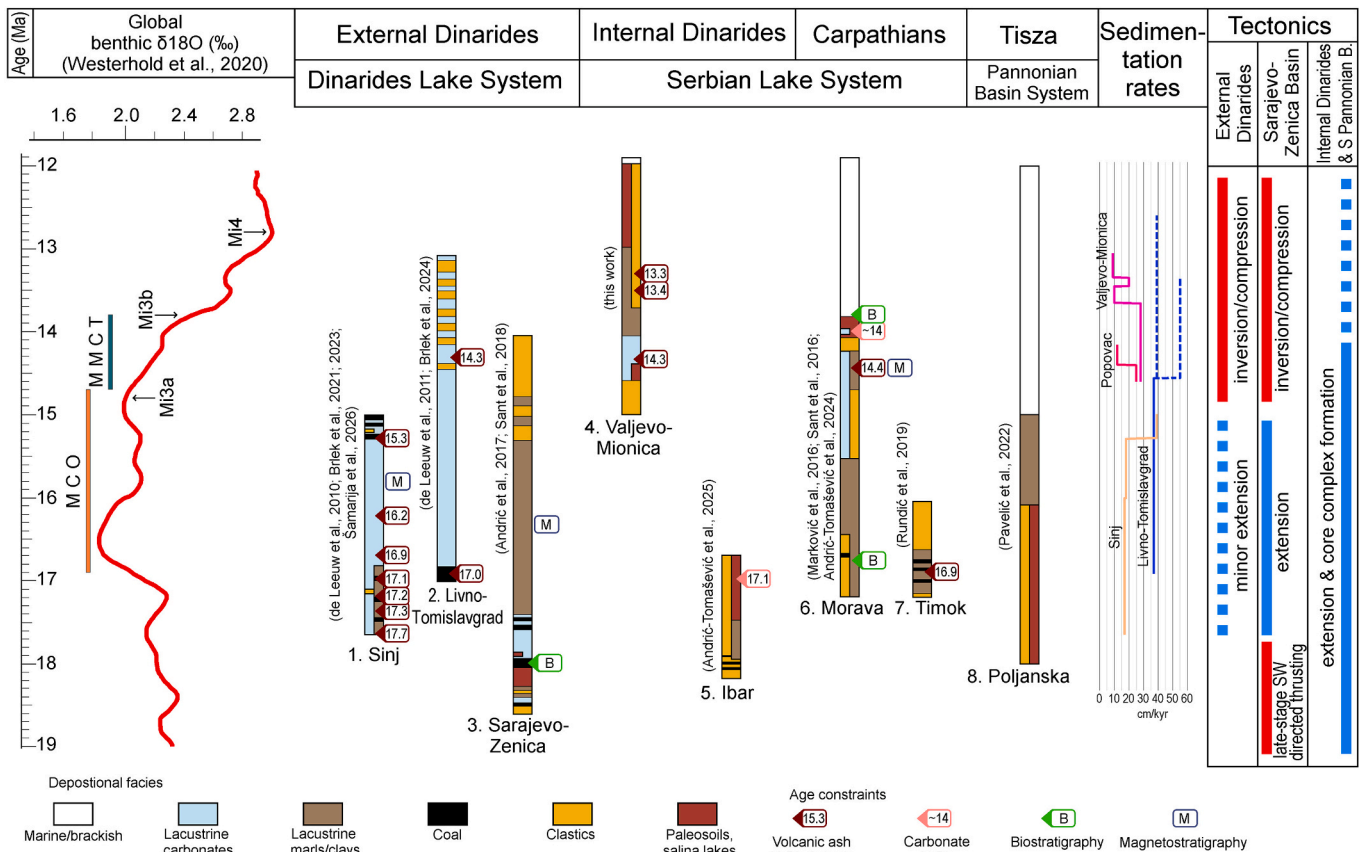


Fig. 12. Stratigraphic correlation of selected DLS and SLS basins, global climate and regional tectonics. MCO-Miocene Climatic Optimum, MMCT-Middle Miocene Climatic Transition, major $\delta^{18}O$ increases (Mi events) after Miller et al. (2020). Major intramontane basin sedimentation rates after: Sinj (de Leeuw et al., 2010a; Šamarija et al., 2026), Livno-Tomislavgrad (de Leeuw et al., 2011), Popovac (Sant et al., 2016), Valjevo-Mionica (this study). Tectonic evolution summarized after de Leeuw et al. (2011, 2012); Matenco and Radivojević (2012); Sant et al. (2016, 2018); Andrić et al. (2017); Šamarija et al. (2026).

deepening starting at 14.1 Ma (Figs. 11, 12) reflecting a positive water balance. A good temporal overlap of this facies change across the boreholes, considering the age model error (Fig. 10), suggests an extrabasinal forcing mechanism. This deepening contrasts the overall decreasing temperature and precipitation rates in Europe between 15 Ma and 11.6 Ma (Böhme et al., 2011; Methner et al., 2020). However, acceleration of tectonic activity (ter Borgh et al., 2013; Balázs et al., 2016) in the neighboring Pannonian Basin System provided accommodation space for a south-eastwards expansion of the Central Paratethys (Mandic et al., 2019a; Mandic et al., 2026). It reached the area to the north of the Valjevo-Mionica Basin by 14.1–14.0 Ma (Sant et al., 2017; Mandic et al., 2019a; Mandic et al., 2026; Rundić et al., 2024). The increasing areal extent of the Central Paratethys and its proximity to the Valjevo-Mionica Basin may have provided a moisture source to foster lake expansion and delay aridification controlled by global cooling trends (Miller et al., 2020; Steinhorsdottir et al., 2021).

During the Mi3b glaciation (dated at 13.82 ± 0.003 Ma; Abels et al., 2005), the Paratethys sea-level dropped by 50 m (Harzhauser and Piller, 2007). A sea-surface temperature drop of 2–3 °C has also been suggested based on gastropods and foraminifera (Harzhauser and Piller, 2007). This event also resulted in the Badenian Salinity Crisis due to the Carpathian foreland basin isolation, lasting from 13.8 to 13.4 Ma (de Leeuw et al., 2010b, 2018). Even though this extreme event affected the regional moisture source, the southern Central Paratethys was unaffected (Mandic et al., 2019b). Consequently, the Valjevo-Mionica Basin records relatively humid conditions, as suggested by high terrestrial input indicating high runoff and mixed algal-terrestrial organic matter composition (this study; Šajnović et al., 2008a, 2009).

The Valjevo-Mionica Basin records the start of an arid phase after

13.5 Ma. Stratification of the water column with pronounced anoxic episodes is attested from laminated, organic-rich marlstone with sulfide mineralisation, whereas the reduction in clastic input suggests decreased runoff (FA 6). At this time, calcite pseudomorphs, replacing soluble salts, start appearing (Fig. 4o). The establishment of a saline-alkaline lake after 12.8–12.6 Ma reflects further aridification, possibly correlated with the Mi-4 glaciation at 12.8 Ma (Miller et al., 2020; Fig. 11). Saline-alkaline conditions and aridification are also supported by geochemical constraints from the uppermost 200 m of the lacustrine succession (Šajnović et al., 2008a, 2008b, 2009). The final disappearance of the Dinarides Lake System (DLS) between 14 and 13 Ma (de Leeuw et al., 2011; Sant et al., 2018; Mandic et al., 2020; van der Made, 2020) suggests that aridification possibly affected both flanks of the Dinarides during the MMCT cooling (Fig. 12).

Nevertheless, whereas the SLS basins (e.g. Morava, Valjevo-Mionica) show decreasing sedimentation rates during MMCT cooling, sedimentation rates in DLS basins (e.g. Sinj and Livno-Tomislavgrad) increased (Fig. 12). This could indicate an additional, tectonic forcing on the demise of the DLS, related to post-15 Ma renewed compression in the External Dinarides (e.g. Bjelogrić et al., 2026; de Leeuw et al., 2011, 2012; Andrić et al., 2017; Sant et al., 2018).

In addition, regional aridity may have been driven by changes in atmospheric circulation patterns. Quan et al. (2014) suggested that the shift towards a westerly-dominated precipitation pattern in Europe occurred at least by 11.6 Ma. Ballian et al. (2025) suggested the existence of a westerly dominated Mediterranean climate in south-eastern France between 14.2 and 13.8 Ma, followed by a return to northeasterly-driven moisture transport between 13.8 and 13 Ma. On the other hand, results from the Ili Basin in central Asia suggest

increased westerly strength between 13.4 and 12.9 Ma (Frisch et al., 2019). In the Valjevo-Mionica Basin, the persistence of arid conditions between 13.5 and 12.1 Ma (Fig. 12) is in agreement with a rain shadow imposed by high topography in the Dinarides (Andrić-Tomašević et al., 2021). The middle Miocene paleotopography of the Dinarides is poorly constrained. Available palynological constraints suggest maximum elevations comparable to the present day, i.e. between 1000 and 2000 m (Jiménez-Moreno et al., 2008, 2009; Jiménez-Moreno and Mandić, 2020). However, this is also comparable to the elevation of the Pindos Mts. in Greece which offer an example of a recent rain shadow in South-eastern Europe (Dotsika et al., 2010; Sindosi et al., 2015). While the western coast of Greece has a humid climate, the eastern coast shows a semi-arid climate (Koutsogiannis et al., 2008) and hosts alkaline-saline lakes (e.g. Pikrolimni; Dotsika et al., 2009). Therefore, the severity of the Miocene rain shadow in the Dinarides could have been an expression of the dominant moisture-bearing wind direction, and sufficient surface temperature to foster evaporation. Prevailing northerly winds would have brought moisture towards the Internal Dinarides, whereas the mountain range would have blocked moist air from reaching the interior during periods of a westerly-dominated wind field.

Finally, saline-alkaline conditions in the Valjevo-Mionica Basin after 13.5 Ma may have also been driven by hydrologic changes which modulated the balance of freshwater input and evaporation (cf. Graf et al., 2015). While direct evidence for this option is lacking, hydrologic changes may be suggested based on the Miocene tectonic evolution of the Internal Dinarides. The initial early-middle Miocene extension in the Valjevo-Mionica Basin (this study; Mladenović et al., 2025) possibly promoted the formation of an internally drained basin with a wide catchment area. Some of the inflowing rivers could have been subsequently re-routed towards the Morava graben to the southeast, where extension peaked in the late Badenian – early Sarmatian (Matenco and Radivojević, 2012; Mandić et al., 2026).

We recognize the need for future research in order to provide more robust paleoenvironmental correlations across the Dinarides, as the current geochronological framework of the SLS is still incomplete, most notably in the time frame between 16 and 15 Ma. Nevertheless, our current work highlights the role of regional tectonics, changing land-sea distribution, and prevailing wind direction on modifying or delaying the response of terrestrial environments to global climate forcing.

6. Conclusions

Lacustrine deposition in the Valjevo Mionica Basin occurred between 14.6 and 12.1 Ma, as indicated by the results of U-Pb dating of zircon populations from different boreholes across the basin. Dating of the ash layers combined with their typological comparison enabled the identification of 8 distinct tephra horizons. The sedimentological analysis enabled us to recognize 10 Facies associations, ranging from alluvial clastics to fine-grained lacustrine marls and carbonates. Lake expansion between 14.1 and 13.5 Ma, contrasting with global climate cooling, was likely driven by a regional increase in precipitation derived from the eastwards expansion of the Central Paratethys. A highly saline-alkaline environment is evident after 13.5 Ma, as shown by the dolomite, analcime and searlesite mineralisation. The rise in salinity coincides with a shallowing of the lake and a decrease in the rate of deposition from an average of 27–28 cm/kyr to 10–15 cm/kyr. Progressive aridification between 13.5 and 12.1 Ma was likely driven by the combined effects of continued global cooling, a switch from northerly to westerly-derived moisture which resulted in a strengthening of the rain shadow in the Dinarides, and/or hydrologic changes.

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CRedit authorship contribution statement

Robert Šamarija: Writing – original draft, Visualization,

Methodology, Investigation, Formal analysis, Conceptualization. **Nevena Andrić-Tomašević:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Oleg Mandić:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition. **Armin Zeh:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis. **Branislav Potić:** Supervision. **Ana Arifović:** Supervision. **Matthias Schwotzer:** Methodology.

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

All data generated and used in this study are included in the Supplementary Material.

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