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Tectonic Forcing of Diachronous Salt Deposition During the Badenian Salinity Crisis Revealed by U–Pb Dating of Tephra Overlying Tuzla Basin Evaporites

Nevena Andrić-Tomašević[1] | Oleg Mandic[2] | Wout Krijgsman[3] | Armin Zeh[1] | Stjepan Ćorić[4] | Sejfudin Vrabac[5]

[1]Karlsruhe Institute of Technology, Institute of Applied Geosciences, Karlsruhe, Germany | [2]Geological-Paleontological Department, Natural History Museum Vienna, Vienna, Austria | [3]Paleomagnetic Laboratory Fort Hoofddijk, Department of Earth Sciences, Utrecht University, Utrecht, the Netherlands | [4]GeoSphere Austria, Vienna, Austria | [5]Faculty of Mining, Geology and Civil Engineering, University of Tuzla, Tuzla, Bosnia and Herzegovina

Correspondence: Nevena Andrić-Tomašević (nevena.tomasevic@kit.edu)

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ABSTRACT

During the Middle Miocene Badenian Salinity Crisis (BSC), extensive evaporites formed across different tectonic settings in the Central Paratethys. Limited age constraints hamper evaporite correlation and identification of driving mechanisms. Here, we use U–Pb dating of zircon by LA-ICP-MS from tephra overlying the Tuzla Basin evaporites. The results indicate cessation of evaporitic conditions at 13.88 ± 0.11 Ma, coeval with the Mi3b event-related global sea-level fall. In Tuzla, a backarc-extension-related sill controlled both evaporite formation and subsequent reflooding, significantly shortening the evaporitic phase. Conversely, flexural subsidence in the Carpathian Foredeep postponed restriction by ~0.5 Myr and prolonged evaporite deposition in deeper settings. We hypothesise that during the BSC, tectonically induced sills governed the timing and distribution of evaporites, as in the well-studied Mediterranean Messinian Salinity Crisis (MSC). Unlike the Gibraltar arc-dominated MSC, multiple, rapidly evolving sills of comparable influence controlled the BSC, producing diachronous and spatially heterogeneous evaporites across the Central Paratethys.

1 | Introduction

Giant evaporite deposits are spectacular geological phenomena characterised by the accumulation of hundreds of metres thick evaporites in marine realms within relatively short geological timescales (Hübscher et al. 2007; Camerlenghi and Aloisi 2020). These extreme depositional events profoundly affected marine ecosystems and ocean chemistry, and occurred throughout Earth's history, typically linked to ocean-domain opening and closure (Warren 2010; Wortmann and Paytan 2012). During the Cenozoic, several basins within the Africa–Eurasia collision zone underwent abrupt transitions to evaporitic conditions across different paleogeographic settings and at different times. Prominent examples include the Mediterranean Messinian Salinity Crisis (MSC, Hsü et al. 1973; Roveri et al. 2014; Krijgsman et al. 2024), the Badenian Salinity Crisis (BSC) in the Central Paratethys (Peryt 2006; De Leeuw et al. 2010), the large evaporites in the Red Sea (Stoffers and Kuhn 1974; Hughes and Johnson 2005) and still ongoing salt deposition in the Dead Sea (e.g., Sirota et al. 2016).

These giant evaporites form in marine basins after becoming partially isolated from the open ocean through the development of tectonic sills or gateways. Such restriction can be driven by tectonic uplift, variable basin subsidence patterns, or global and regional sea-level fluctuations that modify water exchange

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between basins and the open ocean (Flecker et al. 2015; Krijgsman et al. 2024). Once restriction is established, enhanced evaporation and limited replenishment of normal marine waters lead to hypersaline conditions and the precipitation of evaporitic minerals. The Messinian Salinity Crisis is one of the best-studied examples of such a system, where both tectonic processes and global sea-level changes likely contributed to the restriction of the Mediterranean-Atlantic gateways in the Gibraltar region and the Alboran Basin (Roveri et al. 2014; Flecker et al. 2015; Krijgsman et al. 2024). Disentangling tectonic and climatic controls on restriction is challenging because gateway and shallow-water regions are prone to erosion, whereas salts accumulated in deeper-basin settings are better preserved.

The BSC of the Central Paratethys has received less study compared to the MSC, although its tectonic framework is comparatively well constrained (Krézsek and Bally 2006; Schmid et al. 2020; Fodor et al. 2021; Tămaș et al. 2025). Most age constraints come from the Carpathian Foredeep in Poland and Romania (Figure 1), where the onset of evaporite deposition has been linked to the global sea-level fall associated with the Mi3b event (De Leeuw et al. 2010, 2018). The broader paleogeographic evolution of the region, including local tectonic activity and global climate deterioration during the Middle Miocene Climatic Transition, remains poorly understood, particularly regarding the processes governing the timing, distribution, and development of BSC evaporite deposition.

This study focuses on the Tuzla Basin, an intermontane basin that differs fundamentally from the Carpathian Foredeep in both tectonic configuration and marine connectivity (Ćorić et al. 2007). Rather than being directly linked to the foredeep system, the Tuzla Basin was connected to the Mediterranean through the Slovenian Gateway along the Alps-Dinarides junction (Mandic et al. 2019). The recent discovery of a tephra layer in the Tuzla Basin offers new opportunities to apply high-resolution chronostratigraphic constraints to the evaporitic succession. These constraints place the Tuzla evaporites within the broader temporal and tectonic framework of the Paratethyan evaporites, shedding new light on the interplay among basin tectonics, marine connectivity, and large-scale salt deposition.

2 | The Badenian Salinity Crisis in the Paratethys

The Middle Miocene evolution of the Central Paratethys, a semi-isolated inland sea, was marked by the BSC, a major environmental and ecological disruption. The BSC is relatively well-constrained only in the Carpathian Foredeep, where chronostratigraphic and biostratigraphic data place it between 13.81 and 13.32 Ma (De Leeuw et al. 2010, 2018). The crisis has been linked to tectonically driven gateway restriction amplified by the glacio-eustatic sea-level fall associated with Antarctic ice-sheet growth (Peryt 2006; De Leeuw et al. 2010; Palcu et al. 2017, 2023). This event is characterised by widespread precipitation of gypsum and halite, forming more than 100 m thick successions across basins formerly connected to the Paratethys Sea (Figure 1a; Carpathian foredeep, East Slovak Basin, the Transcarpathian Trough, Transylvanian Basin, Vienna Basin, and the Tuzla Basin, Venglinskij 1975; Kováč et al. 1995, 1996; Filipescu 2001; Krézsek and Filipescu 2005; Bąbel and Becker 2006; Peryt 2006; Bukowski et al. 2007, 2010;

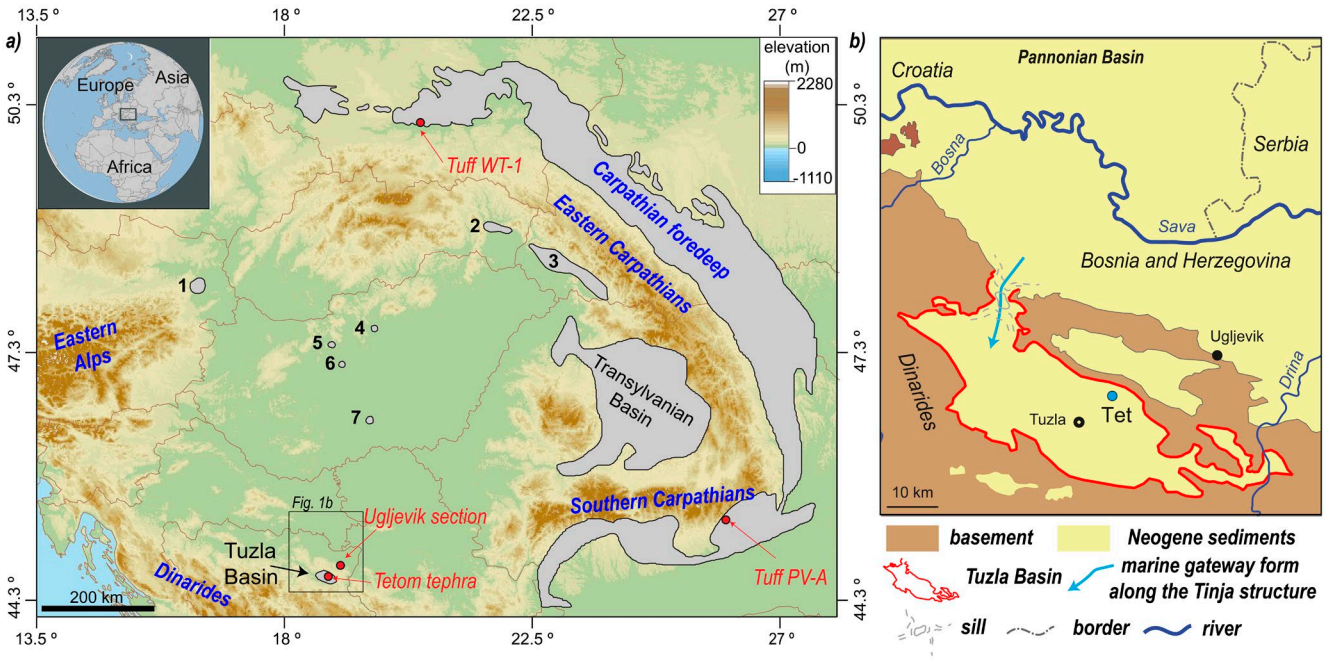


FIGURE 1 | (a) Geographical location of the study area and distribution of Badenian salt deposits in the Paratethys domain (modified after Baldi et al. 2017). 1—Vienna Basin; 2—East Slovak Basin; 3—Transcarpathian Basin; 4—Paleogene Basin; 5—Zsámbék Basin; 6—Adony Basin; 7—Soltvadkert trough. Locations of Tuff WT-1 and Tuff PV-A are from De Leeuw et al. (2010, 2018). DEM from Topomap (Tozer et al. 2019); (b) Simplified geological map of the southwestern Central Paratethys margin including the Tuzla Basin (modified after Čičić et al. 1990, 1991; SFR Yugoslavia 1974). Blue dot marks the location of the Tetima borehole where the TETOM tephra sample was taken. The borehole is located 12 km northeast of Tuzla. [Colour figure can be viewed at wileyonlinelibrary.com]

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Sliwinski et al. 2012; Baldi et al. 2017; Harzhauser et al. 2018, Galamay et al. 2021). Because these basins developed in different tectonic settings, they provide an opportunity to investigate how regional tectonics influenced the development and timing of evaporitic conditions.

3 | Miocene Evaporites of the Tuzla Basin

The Tuzla Basin (Bosnia and Herzegovina), a marginal basin of the Central Paratethys, preserves a 3.5 km thick sedimentary succession spanning from Oligocene to Upper Miocene (Figure 2, Čičić et al. 1977, 1990, 1991; Čičić 2002). The basin formed during the Oligocene as an isolated intramontane system characterised by continental sedimentation. During Miocene times, its evolution was likely controlled by NW-SE trending faults (e.g., Hrvatović 2022) related to regional NE-directed extension in the Pannonian Basin System (e.g., Fodor et al. 2021), also affecting the Dinarides (e.g., Andrić et al. 2017). Previous studies recorded regional changes towards the (N)W-(S)E directed stress field during later extensional phases (e.g., Tomljenović and Csontos 2001; Ilić and Neubauer 2005; Andrić-Tomašević et al. 2024), leading to (N)E-(S)W oriented faults, which were active also during the Late Miocene–Pliocene transpressional phase. These faults connect intramontane basins in the hinterland with the Central Paratethys domain. In the case of the Tuzla Basin, this relates to the Tinja fault line, which connects it to the Slavonia-Srijem Basin, a subbasin of the Central Paratethys (e.g., Soklić 1963; Hrvatović 2022). Fluvial-to-lacustrine deposits dominate the Oligocene–Middle Miocene, with freshwater faunas and coaly-sandy intercalations. Its topmost part is represented by the Red and overlying Variegated ('šarena serija') Series. The former proluvial-limnic, playa-type deposits include red siliciclastites, nodular limestones, limestones, and gypsum, whereas the latter comprises lacustrine and deltaic conglomerates, sandstones, thin-bedded and laminated marls, some nodular limestones, and pyroclastic deposits. Remains of the mammal *Gomphotherium angustidens* place the maximal age of these deposits close to the Langhian–Serravallian transition at ~13.8 Ma (Göhlich 2020; Raffi et al. 2020).

Zircon U–Pb ages from an intercalated tephra suggest that continental sedimentation persisted until at least 14.12 ± 0.13 Ma (Mandic et al. 2026). Marine conditions rapidly established during the Badenian transgression and are represented by massive marls bearing planktonic foraminifera (Ćorić et al. 2018). The basinal restriction is marked by the Salt Fm., which is represented by the overlying Banded Series containing up to 600 m of halite, glauberite, and anhydrite. The upper Salt Formation grades into platy limestones, halite, and glauberite, overlain by dark limestones and marlstones, suggesting restricted marine conditions. The overlying echinoid-bearing marlstones and

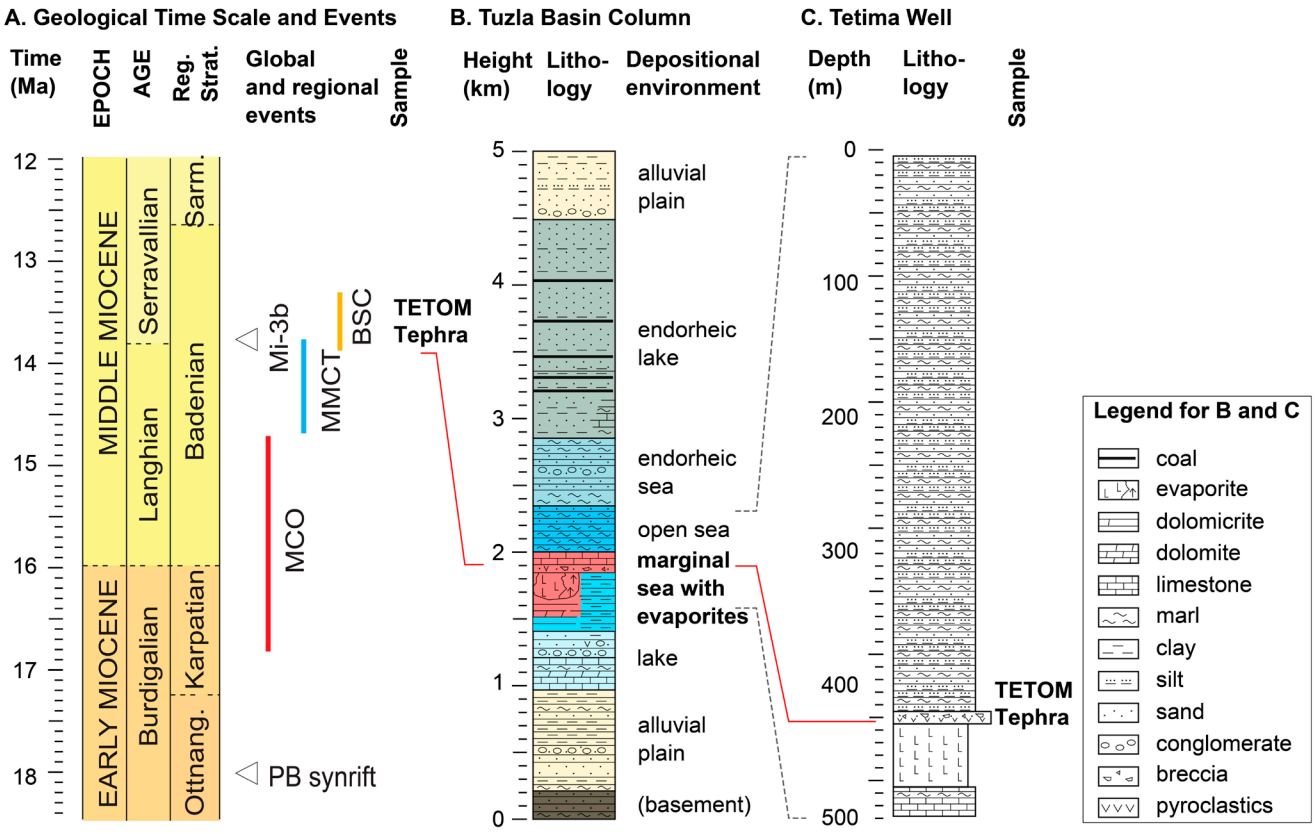


FIGURE 2 | Stratigraphic context of the Tuzla Basin. (A) Geological timescale after Raffi et al. 2020, with the main climatic and tectonic events affecting the study region. The red star delineates the position of the studied TETOM tephra. BSC, Badenian Salinity Crisis; MCO, Miocene Climatic Optimum; MMCT, Middle Miocene Climatic Transition; PB, Pannonian Basin. (B) General stratigraphic column of Tuzla Basin (Čičić et al. 1990, 1991); (C) Overview of the main stratigraphic units in Tetima borehole. Borehole Tetima (B-77), located 12 km NE ofa Tuzla. This rock salt deposit has a Dinaric direction of strike and an elliptical shape, 2 km long and 1 km wide. [Colour figure can be viewed at wileyonlinelibrary.com]

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sandstones indicate normal salinity and open-marine conditions (Vrabac et al. 2022).

The thick evaporite successions of the Tuzla Basin, formerly assigned an Early Miocene age, are currently correlated with the BSC based on marine microfossil evidence (Ćorić et al. 2007). The timing of halite precipitation remains poorly constrained. Regional correlations link it either to the early Serravallian (Baldi et al. 2017) or to the latest Langhian sea-level fall (Mandic et al. 2019). Both scenarios suggest salt deposition postdating the onset of normal marine conditions in the Tuzla Basin, in contrast to earlier studies implying predating them (Čičić et al. 1977, 1990, 1991; Čičić 2002; Ćorić et al. 2018; Vrabac et al. 2022).

Here, we refine the chronological framework of the Tuzla evaporites by U–Pb radiometric dating of zircon from a tephra layer directly overlying the halite. The TETOM tephra was sampled from the Tetima (B-77) borehole (Figure 2C). In this region, the Salt Formation reaches 400 m in thickness with a maximum halite thickness of ~180 m (Vrabac et al. 2011). The base of the core consists of laminated to thin-layered alternations of marls, anhydrite, and halite. Higher in the succession, brecciated evaporites appear, capped by a crystallo-vitroclastic tephra (pelitic to psamitic texture). This tephra forms a basin-wide marker horizon (Vrabac et al. 2022). Overlying the tephra are ~90 m of massive marls containing *Ammonia viennensis–Nonion commune* assemblages, indicative of a marine littoral environment with normal salinity. The depositional age is assigned to the middle–late Badenian, corresponding to the middle Langhian to early Serravallian (Vrabac et al. 2022).

4 | Results and Discussion

U–Pb analyses of twenty-five zircon grains of perfect euhedral shape from the TETOM tephra define a regression line in the Tera-Wasserburg diagram with a lower intercept $^{206}Pb/^{238}U$ age of 13.88 ± 0.11 Ma (Figure 3 and Tables S1 and S2). Detailed information on methods and data is presented in the Supporting Information. Similar typologies of all zircon crystals ($n = 156$) found in sample TETOM (mostly P3–P5 according to Pupin 1980; see inset in Figure 3) suggest tephra supply from a single eruption centre during a single event. From the data available, there is neither evidence for xenocrysts nor for grains from admixed sources. However, an antecryst origin within the erupted magma chamber cannot be completely excluded. Thus, the obtained age is regarded as a maximum depositional age for tephra layer deposition. It is consistent with the biostratigraphically inferred age range (Ćorić et al. 2007) and overlaps, within uncertainties, with tuffaceous clays in the nearby Ugljevik Basin (sample Ugljevik 6; ca. 13.8 Ma; Mandic et al. 2019; Badurina et al. 2021) and tuffite WT-1 in the Polish Carpathian Foredeep (13.81 ± 0.08 Ma; De Leeuw et al. 2010). Furthermore, petrographic and geochemical evidence links the Ugljevik and WT-1 tephras to the same source (Badurina et al. 2021), indicating broadly coeval calc-alkaline volcanism in the Apuseni Mountains and/or Eastern Carpathians (Harangi et al. 2024).

This new age imposes a key constraint on the paleogeographic evolution of the Tuzla Basin within a broader regional framework (Figures 4 and 5). After its Oligocene to Early Miocene

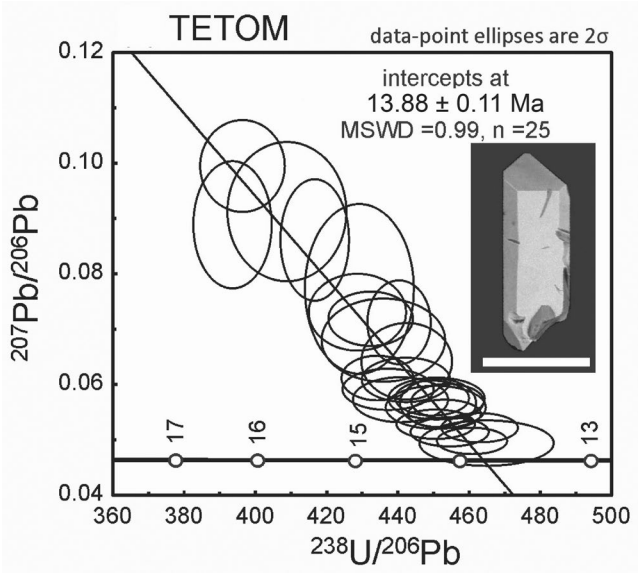


FIGURE 3 | Results of U–Pb dating of zircon grains from tephra sample TETOM are presented in Tera-Wasserburg diagrams. *Inset*: Representative euhedral zircon grains intergrown with apatite (grey minerals); white bar scale = 100 μm.

development as an isolated intramontane basin, the basin was affected by a marine transgression at ~14.12 Ma (Mandic et al. 2026). This event corresponds to the final Langhian transgression pulse (green arrow on Figure 5) and was likely facilitated by tectonic subsidence associated with back-arc extension across the Pannonian Basin System (e.g., Fodor et al. 2021). A contemporaneous rotation in the stress field likely promoted the opening of local marine gateways along structures perpendicular to or at an angle to the basin-bounding faults (Mandic et al. 2026; Andrić-Tomašević et al. 2024; Schefer et al. 2011; Ilić and Neubauer 2005). This deformational phase generated NE–SW striking faults that cross-cut earlier basin-forming structures (Hrvatović 2022), and provided pathways for seawater to enter the Tuzla Basin, probably via a connection along the Tinja River (marked as a gateway in Figure 1b) and the Slavonia-Srijem Basin part of the Paratethys Sea. During the middle Badenian, the Tuzla Basin became restricted, leading to evaporite deposition. Differential syn-rift subsidence generated a structural high along the footwall crest, where reduced subsidence relative to the rapidly subsiding hangingwall promoted the formation of a sill separating the Tuzla Basin from adjacent basins (Figure 4a). At the same time, a ~50 m global sea-level fall associated with the Mi3b event (Miller et al. 1991, 2020), dated at 13.82 ± 0.003 Ma in the Mediterranean (Abels et al. 2005), progressively restricted the basin from the Paratethys Sea. Once the rate of sea-level fall exceeded local subsidence, the sill effectively isolated the Tuzla Basin. A negative hydrological balance across the Paratethys (Simon et al. 2019) further facilitated widespread evaporite deposition, despite a 2°C–3°C drop in sea-surface temperatures inferred from faunal assemblages in non-evaporitic domains (Harzhauser and Piller 2007). Our new U–Pb age from the TETOM tephra indicates that halite deposition in the Tuzla Basin ceased at 13.88 Ma. Although the start and duration remain uncertain, evaporite deposition likely began with the onset of the global sea-level fall at 13.95 Ma (black arrow in Figure 5) and lasted only ~70–180 kyr (including uncertainties)

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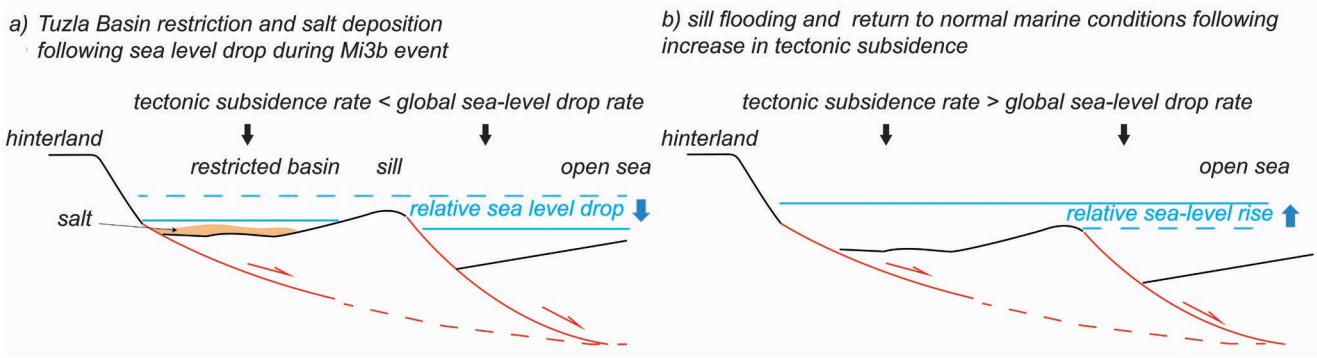


FIGURE 4 | Schematic representation of the gateway evolution along the extensional SW margin of the Central Paratethys. (a) The compartmentalisation of the basin bathymetry, controlled by variable subsidence rates in asymmetric syn-rift subbasins. Sill forms in the area where sea level drops, outpacing local subsidence, leading to the isolation of the intramontane basin from the open sea and the development of evaporites in the Tuzla embayment under global arid climatic conditions. (b) The subsequent tectonic subsidence outpaced the globally low sea level and led to reflooding of the Tuzla Basin at 13.88 Ma. [Colour figure can be viewed at wileyonlinelibrary.com]

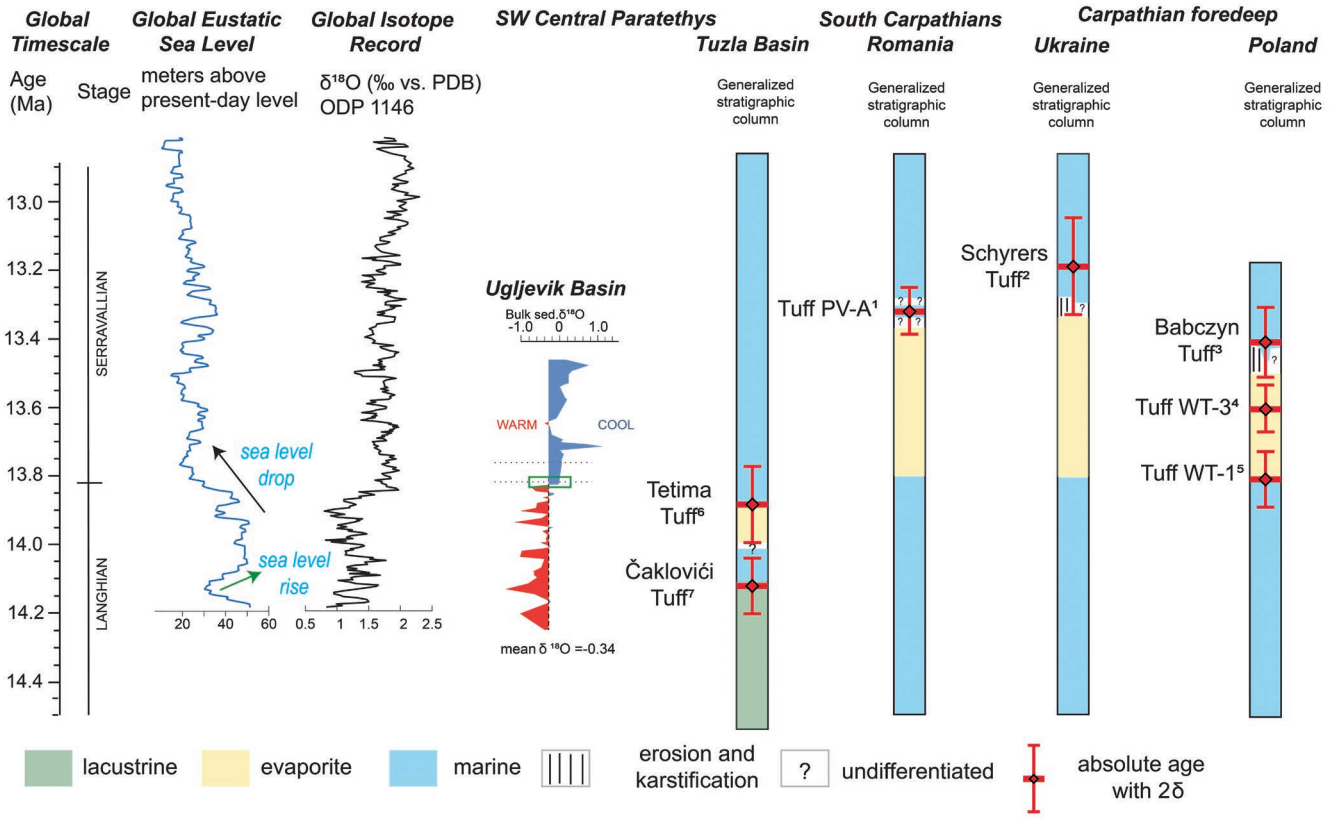


FIGURE 5 | Stratigraphic positions of the dated Badenian deposits across Paratethys. Global δ^{18} benthic foraminifera record and sea level variations are from van de Wal et al. (2011). Oxygen isotope data in the Ugljevik basin (Mandic et al. 2019). The green rectangle marks the tentative onset of salt precipitation. Results of tephra dating from: 1—De Leeuw et al. (2018); 2—Nejbert et al. (2012); 3—age recalculated by De Leeuw et al. (2018); 4 and 5 De Leeuw et al. (2010); 6—this study; 7—Mandic et al. (2026). [Colour figure can be viewed at wileyonlinelibrary.com]

until 13.88 Ma (Figures 3 and 5). The return to normal marine conditions at ca.13.88 Ma is likely induced by steady tectonic subsidence rates outpacing globally low sea-level (Figures 4b and 5), which facilitated the entry of Mediterranean waters into the Tuzla Basin via the Slovenian Gateway and the southern Pannonian Basin Trough.

The proposed evolutionary model based on our results and previous data highlights that the timing and duration of evaporitic conditions during the BSC were governed by a complex interplay between global sea-level change and local tectonics. In both the Tuzla Basin and the Carpathian Foredeep, evaporite deposition was initiated by the aforementioned Mi3b global cooling event. This glacioeustatic base-level drop restricted the exchange of dense bottom waters in semi-isolated basins of the Central Paratethys, promoting salinity build-up and evaporite formation (De Leeuw et al. 2010). However, the precise timing of evaporitic conditions was modulated by local sill dynamics, resulting in

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diachronous development across the region. The onset of evaporite deposition in the Tuzla Basin is estimated at 13.95 Ma, while in the Carpathian Foredeep of Poland it is dated at 13.81 ± 0.08 Ma (De Leeuw et al. 2010). In Tuzla, reflooding terminated evaporite deposition at 13.88 ± 0.11, about 0.5 Myr earlier than in the Carpathian foredeep of Romania (De Leeuw et al. 2018). The observed diachrony between Tuzla and the Carpathian Foredeep reflects differences in local tectonic configuration, sill evolution, and proximity to marine gateways. While the Slovenian gateway along the Dinarides–Alpine junction allowed initial Serravallian transgression from the Mediterranean to reach the Pannonian Basin, the Carpathian Foredeep remained tectonically isolated for an additional ~0.5 Myr (Figure 5). Middle Miocene thrusting east of the Vienna Basin likely severed connectivity to the Mediterranean, leaving the Carpathian Foredeep primarily linked to the Eastern Paratethys (Kováč et al. 2017).

Integration of our results with the previous stratigraphic data implies that evaporite deposition was controlled primarily by the evolving configuration of marine gateways rather than a single climate-driven isolation event. In this context, regional tectonic activity including back-arc extension in the Pannonian Basin domain and shortening in the Carpathian Foredeep, likely segmented the region into a series of sub-basins separated by multiple transient topographic barriers and sills. Temporal and spatial variations in tectonic activity, superimposed on sea-level variations, not only drove diachronous restriction but also controlled intermittent reflooding from the Mediterranean and Eastern Parathethys. In the Carpathian Foredeep, thick evaporites accumulated in deep settings, while neighbouring sectors along strike such as the Vienna Basin, experienced shallower depositional conditions (Harzhauser et al. 2018), due to locally elevated sills and modulated basin connectivity. Previous tectonostratigraphic works (e.g., Meulenkamp et al. 1996; Jipa 2018; De Leeuw et al. 2020) and recent forward stratigraphic and geodynamic modelling studies (e.g., Eskens et al. 2025; Maiti et al. 2026, Piccolo et al. 2026) provide a potential mechanism for generating such regional patterns by demonstrating that slab tearing can produce substantial lateral variations in uplift and subsidence rates along the strike, leading to variations in depositional systems and changes in basin connectivity through time. In this framework, isostatic rebound following slab detachment along the Carpathian arc may have caused uplift and basin shallowing in certain areas of the Paratethys. In contrast, domains affected by an attached slab experienced continued flexural subsidence (e.g., Maiti et al. 2024), likely prolonging restricted conditions for up to ~0.5 Myr. By comparison, the southwestern Paratethys was characterised by patchy, shallow evaporite deposition, reflecting spatial and temporal variations in subsidence, typical of syn-rift, back-arc settings (e.g., Faccenna et al. 2016; Balázs et al. 2016). The changes in slip rates along the normal faults and the associated accommodation space created (e.g., Gupta et al. 1998; Cowie and Roberts 2001) lead to transient barriers and sills, and frequent reorganisations of marine gateways and connections between subbasins (Mandic et al. 2026). These results highlight that multiple, evolving sills played a key role in regulating both restriction and reflooding during BSC. Unlike the MSC, which was largely controlled by the Gibraltar sill, with a secondary role for the Sicily sill (Aloisi et al. 2024; Krijgsman et al. 2024), we hypothesise that the BSC was governed by a network of sills of comparable importance, producing a highly variable and diachronous evaporite record across the Paratethys. By identifying this previously unexplored tectonic end-member model, our study points to tectonics as the first-order control on the basin restrictions and giant evaporite deposition, which should be considered when doing large-scale paleoenvironmental reconstructions. Further studies will certainly be essential to test, refine, or modify this model at the scale of the entire Central Paratethys.

5 | Conclusions

A new U–Pb age of 13.88 ± 0.11 Ma for a tephra layer directly overlying the halite of the Tuzla Basin provides new constraints on the timing of basin restriction and evaporite formation. Combined results indicate that restriction of the Tuzla Basin and the associated salinity crisis were triggered by a sea-level fall during the Mi3b event and terminated by a regional transgression. The precise timing of evaporitic conditions was modulated by local sill dynamics, resulting in diachronous development of BSC evaporites across the Central Paratethys. In particular, restriction of the SW margin, including the Tuzla Basin, occurred earlier and was shorter-lived than in the Carpathian Foredeep. This spatial and temporal variability in evaporite deposition reflects differences in the tectonic setting of the Central Paratethys Basin System, with extensional regimes prevailing in the south and southwest and compressional tectonics in the Carpathian Foredeep, which delays gateway closure and prolongs basin restriction.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Material of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Operating conditions for the LA-ICP-SF-MS equipment for U-Th-Pb isotope analysis. **Table S2:** (a) Results of U–Pb zircon dating of sample TETOM, (b) Results of U–Pb dating of reference material.

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