

Chemo- and biostratigraphic correlation of the CPE (Carnian Pluvial Episode, Late Triassic) in the Western Tethys: Implications for environmental perturbation prior to the CPE[☆]

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ABSTRACT

The Carnian Pluvial Episode (CPE), characterized by global warming, enhanced hydrological cycle, and major biotic turnovers, represents a key Late Triassic interval of global carbon-cycle perturbation and climate change. Chemostratigraphy provides the principal framework for the global correlation of CPE successions, but inaccurate biostratigraphic calibration of carbon-isotope records can lead to miscorrelation of negative carbon isotope excursions (NCIEs). New bulk organic carbon isotope, microfacies, conodont, and foraminifer data from six successions in the Transdanubian Range (TR, Western Hungary), combined with revised biostratigraphic constraints, required the recalibration of previously published carbon-isotope curves. The revised framework shows that the lower Veszprém Formation, recording increased clastic input and the previously recognized CPE NCIE-1, belongs to the Julian 1 (*Aonoides* Zone). Microfacies and foraminiferal assemblages further indicate that the microbial-skeletal carbonate factory of the Wetterstein reef system remained active during the deposition of the lower Veszprém Formation. Consequently, this excursion is reinterpreted as a Pre-CPE NCIE, an interval of elevated terrestrial input but only moderate ecosystem disturbance. The onset of the CPE is placed at a pronounced NCIE in a higher stratigraphic position, formerly known as the CPE NCIE-2, coinciding with the final demise of the carbonate platform and major ecological reorganization. Peak environmental stress characterized by abundant hygrophytic palynomorphs, temporary collapse of marine microbiota or low-diversity stressed communities, was confined to the late Julian 2. Recovery began in the early Tuvanian with renewed shallow-water carbonate production despite continued minor carbon-cycle perturbations and fluctuating terrestrial input, indicating prolonged environmental instability, while the most severe biotic disruptions concentrated at the onset of the CPE and the end of Julian 2.

1. Introduction

The Carnian Pluvial Episode or CPE (Simms and Ruffell, 1989, 2018;

Dal Corso, 2025) in the Late Triassic was an interval (ca. 2.5 Myr) of pronounced global warming and C-cycle perturbation (Trotter et al., 2015). Massive injection of CO₂ and other greenhouse gases into the

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ocean-atmosphere system intensified the Triassic megamonsoon system, causing a seasonally wet climate with extreme rainfall and an accelerated hydrological cycle. Enhanced continental weathering and runoff increased the siliciclastic influx into marine basins across the wider Tethys realm during the late Julian and early Tuvallian (Fig. 1A). The C-cycle perturbation and its associated climatic feedback mechanisms (global warming, enhanced hydrological cycle, elevated clastic input, anoxia in marine basins, and deposition of organic-rich sediments) subjected marine ecosystems to severe stress, leading to extinctions across many clades e.g., ammonoids and conodonts (Rigo et al., 2007, 2018; Balini et al., 2010; Jenks et al., 2015; Chen et al., 2016; Sun et al., 2016; Tomimatsu et al., 2023), diversity declines (Forel et al., 2020; Tóth et al., 2024; Li et al., 2025), and a major reduction in microbial-dominated carbonate production in the shallow marine realm (Gattolin et al., 2015; Jin et al., 2020). On land, vegetation underwent substantial reorganization, with the expansion of hygrophytic floras (ferns, lycopsids) and wet habitats during the Julian 2 in many regions. However, the absence of comparable hygrophyte proliferation in parts of the Germanic Basin and Western Europe suggests that the climatic response was likely spatially heterogeneous (Visscher et al., 1994; Lindström et al., 2017; Franz et al., 2018; Baranyi et al., 2019a). Consequently, the general pattern of floral turnover across the CPE could be interpreted either as the intensification of the monsoon circulation leading to climatic extremities and episodic heavy rainfall (Baranyi et al., 2025) or as oscillations between arid and more humid periods, and abrupt climate swings (Alverà et al., 2026). The evolutionary significance of the CPE lies in its close temporal proximity to the diversification of dinosaurs, key plant groups (bennettites, modern fern groups, Pinaceae, Cupressaceae conifers), modern reef-forming corals, and pelagic calcifiers (Bernardi et al., 2018; Kustatscher et al., 2018; Dal Corso et al., 2020, 2021). Despite its pivotal role in the evolution of Triassic ecosystems, the exact patterns of climate change during the CPE, the C-cycle perturbation and their impact on the biosphere are still only coarsely understood (Dal Corso, 2025).

The C-cycle perturbation is widely attributed to the emplacement of the Wrangellian Terrane Large Igneous Province (Furin et al., 2006; Dal Corso et al., 2012; Tomimatsu et al., 2021; Jin et al., 2023). Multiple, likely globally synchronous, negative carbon isotope excursions (NCIEs) have been recognized with magnitudes of 2–4‰ in marine as well as in terrestrial sedimentary archives starting across the Julian 1–Julian 2 boundary and terminating at the base of the Tuvallian 2 (e.g., Miller et al., 2017; Dal Corso et al., 2020). In the Carnian strata of the Western Tethys (Fig. 1A), four major negative carbon isotope excursions have been recognized (Dal Corso et al., 2015, 2018, 2020; Pecorari et al., 2023; Dal Corso, 2025), several of which are also reproduced in the Eastern Tethys realm (e.g., Sun et al., 2016; Shi et al., 2019; Lu et al., 2021; Jin et al., 2022; Li et al., 2022; Ke et al., 2023, 2026; Hasebek et al., 2025) establishing them as robust chemostratigraphic markers on a global scale.

The sedimentological expression of the CPE is particularly well developed in the carbonate-dominated successions of the Western Tethys including the Dolomites, Julian Alps, Northern Calcareous Alps (Lunz area), and the Transdanubian Range, where a sudden increase in siliciclastic input reflects major changes in the depositional style and regional climate (e.g., Hornung et al., 2007; Haas et al., 2012; Gattolin et al., 2015). In the Alpine Realm, the first NCIE occurs across the Julian 1–2 boundary (i.e., boundary between the *Trachyceras aonoides* and *Austrotrachyceras austriacum* Ammonoid Zone), the second NCIE within the Julian 2, the third NCIE across the Julian 2–Tuvallian 1 boundary (i.e., boundary between the *Austrotrachyceras austriacum* and *Tropites dilleri* Ammonoid Zone) and the fourth NCIE at the base of the Tuvallian 2 (i.e. *Tropites subbullatus* Ammonoid Zone) (Dal Corso et al., 2018, 2020; Dal Corso, 2025). To date, only two of these excursions have been reported from the Transdanubian Range (Dal Corso et al., 2015, 2018). The first NCIE from the TR, recorded in the lowermost part of the Veszprém Marl Formation, has been correlated to the CPE NCIE-1

recording the globally synchronized onset of the CPE at the Julian 1–2 boundary (Dal Corso et al., 2015, 2018).

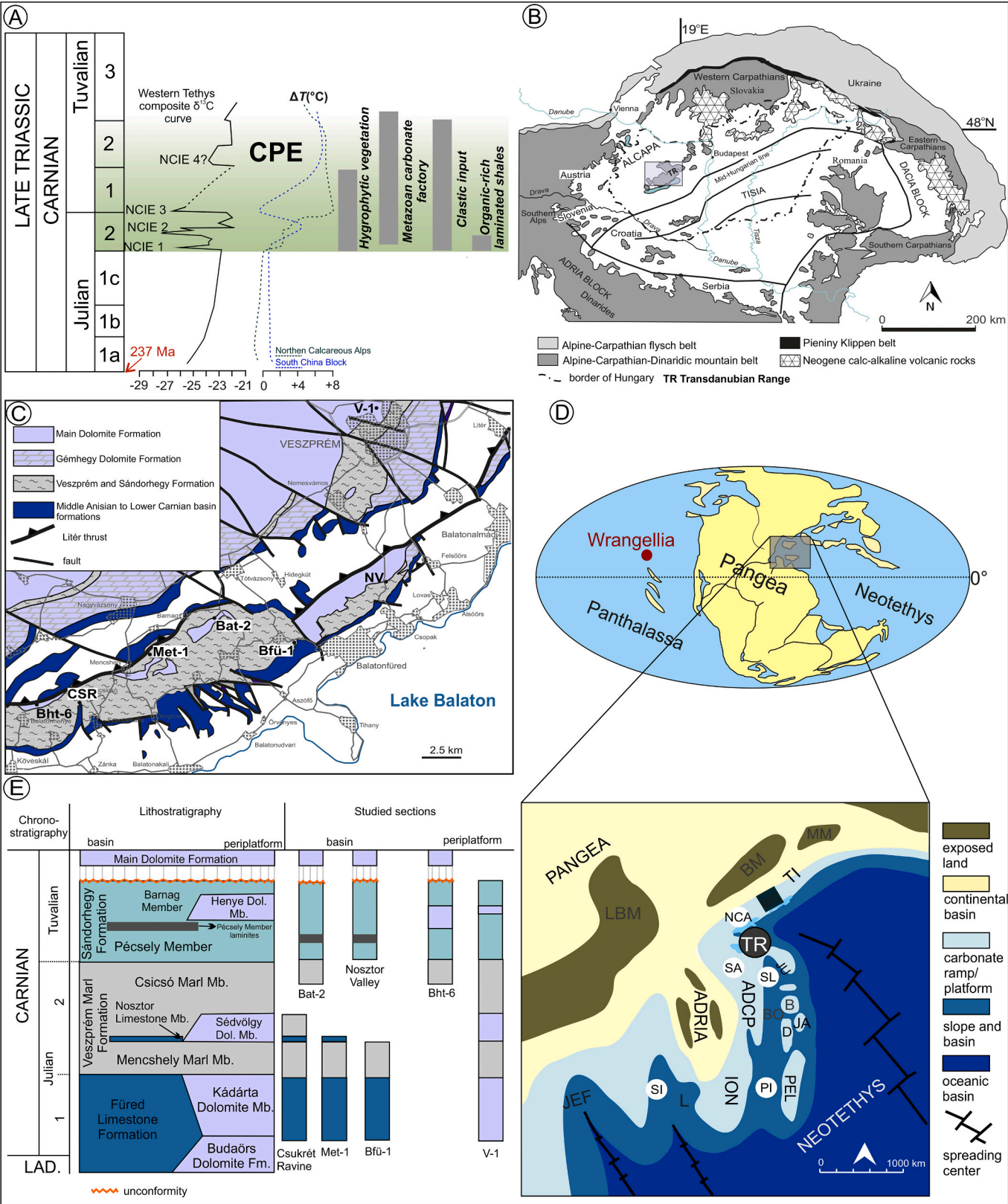
However, dating the onset of the increase in siliciclastic influx (i.e., deposition of marls) is hindered by the scarcity of stratigraphically robust index fossils, particularly ammonoids and conodonts, in the mixed carbonate-clastic sediments, and by the lack of up-to-date taxonomic revision of key ammonoid specimens. The present study extends the carbon isotope record from the TR with bulk organic carbon isotope data from the Julian 1, Julian 2, and early Tuvallian strata of three boreholes and two outcrops, reaching it to the top of the Sándorhegy Formation, the uppermost lithostratigraphic unit encompassing the CPE interval in the TR. New conodont, microfacies, and foraminifer data integrated with the results of previous ostracod and palynological analyses provided new biostratigraphic anchors supporting a more precise correlation of the Carnian strata of the TR within the Western Tethys realm. The revised correlation of chemostratigraphy with microfacies and micropaleontological data also shed light on Carnian biotic events prior to and during the CPE in the Western Tethys realm.

2. Geological setting

The Transdanubian Range unit (TR) forms the uppermost structural unit of the Austroalpine nappe system within the Alpine–Carpathian–Pannonian (ALCAPA) megaunit (Fig. 1B, e.g., Tari and Horváth, 2006). It is characterized by a SW–NE oriented syncline structure formed by mid-Cretaceous Eoalpine compression. The study area in the Balaton Highland occupies the southeastern limb of this structure, where Paleozoic and Triassic rocks constitute the pre-Cenozoic basement (Fig. 1C, Budai et al., 1999; Héja et al., 2024). During the Mesozoic, the TR was situated on the western Neotethys shelf (Fig. 1D) between the Northern Calcareous Alps (NCA) and the Southern Alps (Haas et al., 1995).

In the Middle Triassic, extensional tectonics related to the Neotethys rifting fragmented an earlier carbonate ramp into a horst-and-graben topography, creating structural highs and hemipelagic basins in the Balaton Highland (Budai and Vörös, 1992, 1993), as well as in other parts of the western Neotethys margin (Bertotti et al., 1993; Gaetani, 2010; Gawlick et al., 2012, 2021). A relative sea-level rise together with volcanic activity is recorded in the late Anisian (Budai and Vörös, 2006; Karádi et al., 2022; Budai et al., 2024). The Middle Triassic basins reached their maximum depths during the Ladinian (Buchenstein Formation), while platforms also started to grow (Budaörs Dolomite Formation) establishing a complex dissected platform-basin system that persisted in the Carnian. The Carnian sedimentary succession records the progressive infilling of these basins due to a drastic increase in the siliciclastic input from the Julian onward represented by the transition from the Füred Limestone Formation to the mixed carbonate-clastic Veszprém Marl Formation (Haas and Budai, 1999; Rostási et al., 2011; Haas et al., 2012). The several-hundred-metre-thick Veszprém Marl Formation comprises alternating clayey marl, marl to calcareous marl, and dolomitic marl units interbedded with platform carbonates in periplatform settings or pelagic carbonates in basinal areas. It is subdivided into a lower (Mencshely Marl Member, MMM) and upper (Csicsó Marl Member) marl units (Fig. 1E), which are lithologically very similar, separated either by the basinal Nosztor Limestone Member or by platform-related units (Sédvölgy Dolomite Member of the Gémhegy Formation) depending on depositional setting (Fig. 1E).

The overlying Sándorhegy Formation records the establishment of a shallow marine ramp system, with marls, limestones and bituminous laminated limestone with subtidal algal mats and pseudomorphs after dissolved gypsum (Pécse Member) in its lower part linked to relative sea-level fluctuation, restriction, and freshwater input (Nagy, 1999; Tóth et al., 2024). The upper part (Barnag Member) is represented by fossil-rich limestone beds of variable thickness, marl intercalations, marly limestone and cherty limestone beds (Nagy, 1999; Nagy and Csillag, 2002). The upper shallow marine environment preserves a



(caption on next page)

Fig. 1. Environmental perturbation associated with the CPE in the Western Tethys Realm and the geological and stratigraphical framework of the study area in the Triassic. (A) Composite carbon isotope curve and key environmental changes in the Western Tethys during the CPE after Dal Corso et al. (2018, 2020). (B) Tectonic position of the Transdanubian Range unit (TR) in the Alpine–Carpathian–Dinaridic orogen system (after Csontos and Vörös, 2004). The rectangle shows the position of the map in Fig. 1C. (C) Pre-Cenozoic geological map of the Balaton Highland within the Transdanubian Range showing the extension of the middle Anisian to mid Carnian formations (after Héja et al., 2024) and the location of the studied boreholes and outcrops. Uncoloured part of the map area is covered by middle Anisian platform carbonates or older formations. Cored wells: Balatonfüred Bfű-1; Balatonhenye Bht-6; Barnag Bat-2; Mentshely Met-1; Veszprém V-1. Outcrops: CSR – Csukrét Ravine; NV – Nosztor Valley. (D) Paleogeographic setting of the Transdanubian Range unit (TR) during the Late Triassic (after Haas et al., 1995). The rectangle on the paleoglobe shows the paleogeographic position of the Western Tethys Realm. Abbreviations: LBM – London-Brabant Massif, BM – Bohemian Massif, MM – Malopolska Massif, NCA – Northern Calcareous Alps unit, WC – West Carpathian units, TI – Tisza unit, TR – Transdanubian Range unit, SA – South Alpine unit, SL – Slovenian Basin, JU – Julian Alps, B – Bükk unit, ADCP – Adriatic Dinaridic Carbonate Platform, BO – Bosnian Zone, D – Drina–Ivanjica unit, JA – Jadar Block, SI – Sicilian Basin, L – Lagonegro Basin, JEF – Jefra Basin, PI – Pindos Basin, PEL – Pelagonian–Subpelagonian units. (E) Simplified lithological log of the Carnian formations of the TR with their previous biostratigraphical age constraints (Budai et al., 1999) and the stratigraphic range of the studied successions. Dol. = Dolomite, Mb. = Member, Fm. = Formation. For detailed logs see Fig. 7.

diverse metazoan carbonate factory with encrusting binding organisms, molluscs, foraminifers, green algae, echinoderms, and sponges, occupying different microenvironments from distal lagoons to transitional, proximal settings in relation to the existing platform areas leading to heterogeneous facies and varied lithologies (Nagy, 1999; Nagy and Csillag, 2002). Platform progradation occurred during the latest Julian–early Tuvallian (Hénye Dolomite Member, Budai and Haas, 1997) followed by an unconformity and the establishment of a regionally extensive carbonate platform system (Main Dolomite Formation) later in the Tuvallian (Haas and Budai, 1995; Budai and Haas, 1997).

2.1. Previous biostratigraphic age constraints: Overview of published data

Key Triassic biostratigraphic markers (ammonoids, radiolarians, conodonts) occur only sporadically in the Carnian mixed siliciclastic–carbonate deposits of the Balaton Highland, hampering precise biostratigraphic dating and requiring the use of alternative proxies such as palynomorphs, benthic foraminifers, or chemostratigraphy. Fossils from the Füred Limestone Formation below the Veszprém Marl Formation indicate a late Ladinian–early Carnian age (Dosztály et al., 1989; Budai et al., 1999; Budai et al., 2002). The most reliable biostratigraphic anchors of an early Carnian (Julian 1) age are a single finding of *Trachyceras aon* and a diverse radiolarian assemblage found in an abandoned quarry (Száká-hegy) near Balatonfüred (Dosztály, 1991; Vörös, 1998). This ammonoid indicates the *Aon* Subzone of the *Aonoides* Zone according to Krystyn (1978). Carnian conodonts from this formation were documented from here and also in an abandoned quarry in the Nosztor Valley near Csopak (Budai et al., 2002). Further support for an early Carnian age comes from the *Trachyceras aon* specimen reported by Lóczy (1916) from the lowermost part of the Mentshely Marl, directly overlying the Füred Limestone on the Csákány Hill, near Csopak. This specimen was illustrated by Frech (1912). Krystyn (1978) and later Urlichs (1994) considered this specimen as characteristic for the *Aon* Subzone, thus it represents a robust age constraint for the transition between the Füred and Veszprém Formation. By contrast, the biostratigraphic framework adopted in previous carbon-isotope studies (Dal Corso et al., 2015, 2018) relied primarily on two questionably identified ammonoids, *Sirenites?* sp. and *Neoprotrachyceras?* sp., first reported by Vörös (1998), who clearly indicated the uncertainties of the classification even on the genus level. Consequently, the latter ammonoid data remain highly questionable. The illustrated *Neoprotrachyceras?* sp. is most likely misidentified and likely belongs to the genus *Trachyceras*, characteristic of the *Aonoides* Zone (L. Krystyn, University of Vienna, personal communication, 2024). Although benthic foraminifers and other microfossil assemblages provide less robust biostratigraphical constraints, Góczán et al. (1991) noted that the assemblage from the lower Mentshely Marl Member closely resembles that of the San Cassiano Formation, supporting an early Julian age. Collectively, the revised biostratigraphic evidence places the Füred Limestone–Veszprém Marl transition in the Julian 1, corresponding to the *Aon* Subzone. This older age assignment also makes the age of the previously recognized NCIE-1 (Dal Corso et al., 2015) in the lower part of

the Veszprém Formation highly questionable.

Other reliable findings indicating the Julian 2 *Austriacum* Zone, *Austrotrachyceras austriacum* or *Sirenites* div. sp., were only found in the Nosztor Limestone Member (“*austriacum* limestone” Lóczy, 1916), the fossil-rich periplatform facies of the Buhimvölgy Breccia Member, and in the Csicsó Marl Member from the middle-upper part of the Veszprém Formation. Vörös (1998) further documented *Neoprotrachyceras baco-nicum* from the Csicsó Marl Member in the Csukrét Ravine at Balatoncsicsó, and *Paratrachyceras* cf. *hofmanni* from the Nosztor Limestone Member in the Mentshely Met-1 core (from 34 m depth), both assigned to the *Austriacum* Zone. Palynological assemblages (Góczán et al., 1991; Góczán and Oravecz–Scheffer, 1996a, 1996b; Baranyi et al., 2019b, 2025) from the Csicsó Marl Member and Sándorhegy Formation were previously assigned to the Julian 2 *Aulisporites astigmatus* assemblage sensu Roghi et al. (2010) and the Julian 2–early Tuvallian *Duplicisporites continuus* assemblage sensu Roghi (2004) based on the presence of *Aulisporites astigmatus*, *Lagenella martinii*, and *Duplicisporites continuus*. By contrast, the palynostratigraphic assignment of the Mentshely Marl Member is less well-constrained as typical early Julian taxa like *Concentricisporites bianulatus* (Roghi, 2004) are extremely rare, yet typical elements of Julian 2 assemblages from the Alps like *Aulisporites*, *Lagenella*, *Aratrisporites* spp. (Roghi, 2004; Roghi et al., 2010; Mueller et al., 2016) occur as well, albeit sporadically. The assemblage correlates best with the *vigens-densus* phase of Van der Eem (1983) described from the San Cassiano Formation from the Dolomites but contains elements mixed in from the younger *densus-maljawkinae* phase that has also been noted in the Alps (Broglia Loriga et al., 1999; Roghi, 2004). The Julian–Tuvallian boundary is tentatively placed in the lower Barnag Member of the Sándorhegy Formation (Góczán et al., 1983, 1991; Góczán and Oravecz–Scheffer, 1996a, 1996b; Baranyi et al., 2025). The uppermost part of the formation is still early Tuvallian, as indicated by characteristic palynomorph assemblages and the absence of diagnostic middle–late Tuvallian taxa such as *Granuloperculatipollis rudis* (Baranyi et al., 2025).

3. Material and methods

3.1. Studied sections

Four borehole successions and two representative outcrops were selected for integrated chemo- and biostratigraphic analyses (Figs. 1C and E). The Csukrét Ravine (46°55′15.79″ N, 17°39′32.84″ E), the Mentshely Met-1 (46°57′18.97″ N 17°43′10.46″ E), the Nosztor Valley (47°00′03.45″ N, 17°54′53.42″ E), and the Barnag Bat-2 (46°58′44.61″ N, 17°46′21.23″ E) successions represent Carnian basin profiles, while the Veszprém V-1 (47°6′44.139″ N, 17°54′20.21″ E) and the Balatonhenye Bht-6 (46°55′20.23″ N, 17°37′35.11″ E) cores expose periplatform successions (Figs. 1C and E). Detailed lithological and facies characteristics of the Mentshely Met-1, Veszprém V-1, Balatonhenye Bht-6, Barnag Bat-2 boreholes are described in Nagy and Csillag (2002), Rostási et al. (2011), Dal Corso et al. (2015, 2018), Tóth et al. (2024), and Baranyi et al. (2019b, 2025). The Supplementary Material 1

provides a detailed description for the Csukrét Ravine and the Nosztor Valley outcrop is described based on Nagy (1999).

3.2. Conodont sample preparation

Ten samples consisting of three to five kg of rock material have been collected from the Csukrét Ravine for conodont analysis (Figs. 2–3). An additional 21 samples have been processed from the cores Balatonhenye Bht-6, Barnag Bat-2, Veszprém V-1 and the Nosztor Valley outcrop, but only the Csukrét Ravine yielded conodont remains. The samples were processed by soaking them in 10% diluted acetic acid. The washing residues were collected on a 125-μm-mesh sieve. The scanning electron micrographs of microfossils were taken at the Department of Petrology and Geochemistry of the Eötvös Loránd University (Budapest) using an Amray 1830 I Scanning Electron Microscope (SEM).

3.3. Microfossils, microfacies, and palynology

Ostracod and palynological data have been obtained from the published works of Tóth et al. (2024) and Baranyi et al. (2019b, 2025).

Extending the datasets of Baranyi et al. (2019b, 2025), 15 samples from the Nosztor Valley outcrop were selected and prepared for palynological analysis but all of them were barren and contained no autochthonous sedimentary organic matter (see preparation techniques in Baranyi et al., 2025).

Microfacies and foraminiferal assemblages (Figs. 4–6) of Carnian deposits (Supplementary Material 2) from the TR have been previously studied by Oravecz-Scheffer (1987), Góczán et al. (1983, 1991), Góczán and Oravecz-Scheffer (1996a, 1996b), Nagy (1999), and Nagy and Csillag (2002). A total of 213 thin sections have been re-investigated from these previous works now archived in the collections of the Hungarian Geological Institute (currently part of the Supervisory Authority for Regulatory Affairs, SARA-SZTFH) covering the Mentshely Met-1, Veszprém V-1, and the Barnag Bat-2 cores. Slides from the Met-1 and V-1 have been selected for further detailed microfacies study and determination of foraminifers as the latter dataset was missing from this core. For Met-1, 137 thin sections were available from the interval between 424 m and 19.7 m, and for the V-1 borehole, 7 thin sections from the interval of 555–163.5 m. For the Bat-2, microfacies data from 69 thin sections from 198 to 19.6 m – already published in Nagy and Csillag

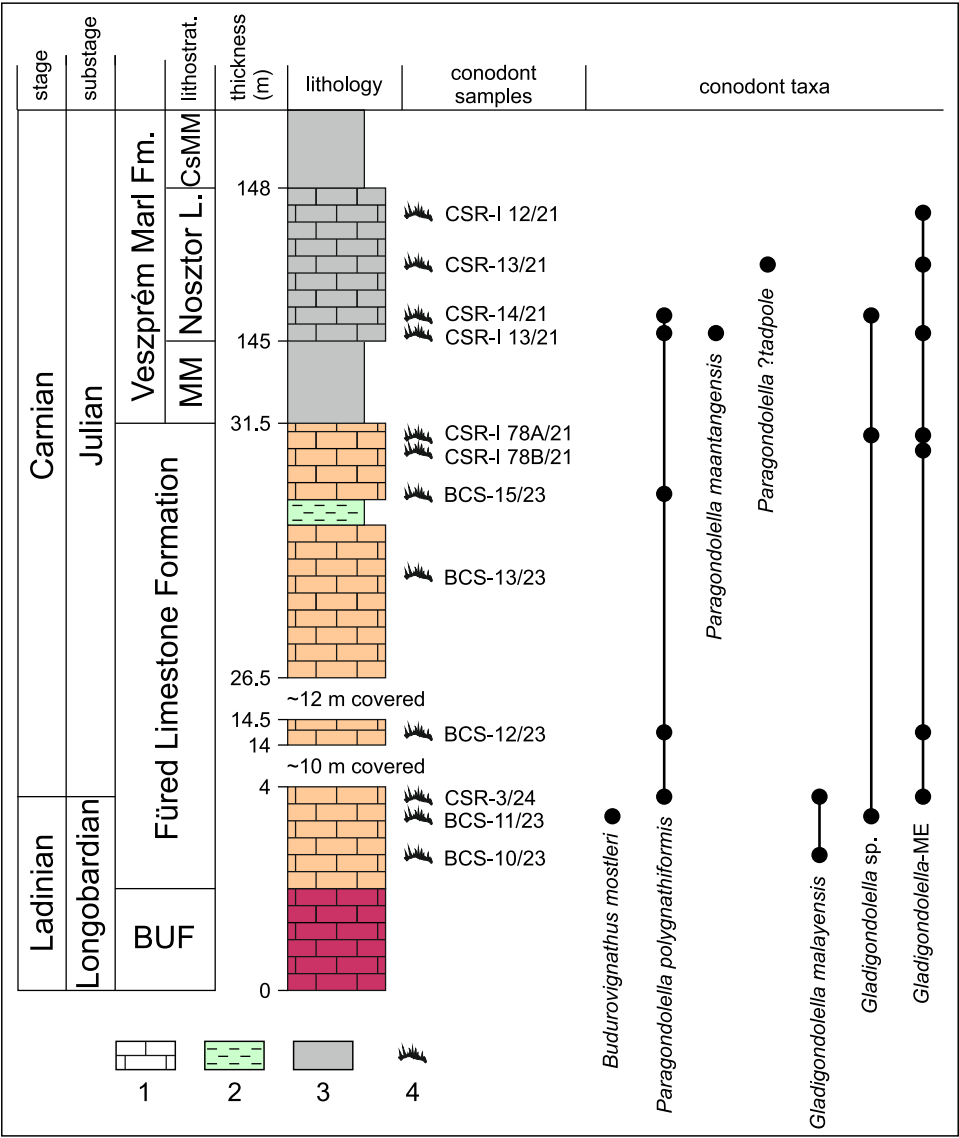


Fig. 2. Stratigraphic log of the Csukrét Ravine outcrop showing the conodont sample positions and the ranges of the conodont taxa. Note that the thickness of the Mentshely Marl Member is not illustrated to scale as this interval was not sampled for conodonts. Legend: 1. limestone, 2. strongly weathered greenish clay, 3. marl, 4. conodont sample position. BuF=Buchenstein Formation; MM = Mentshely Marl; L = Limestone; CsMM = Csicsó Marl Member.

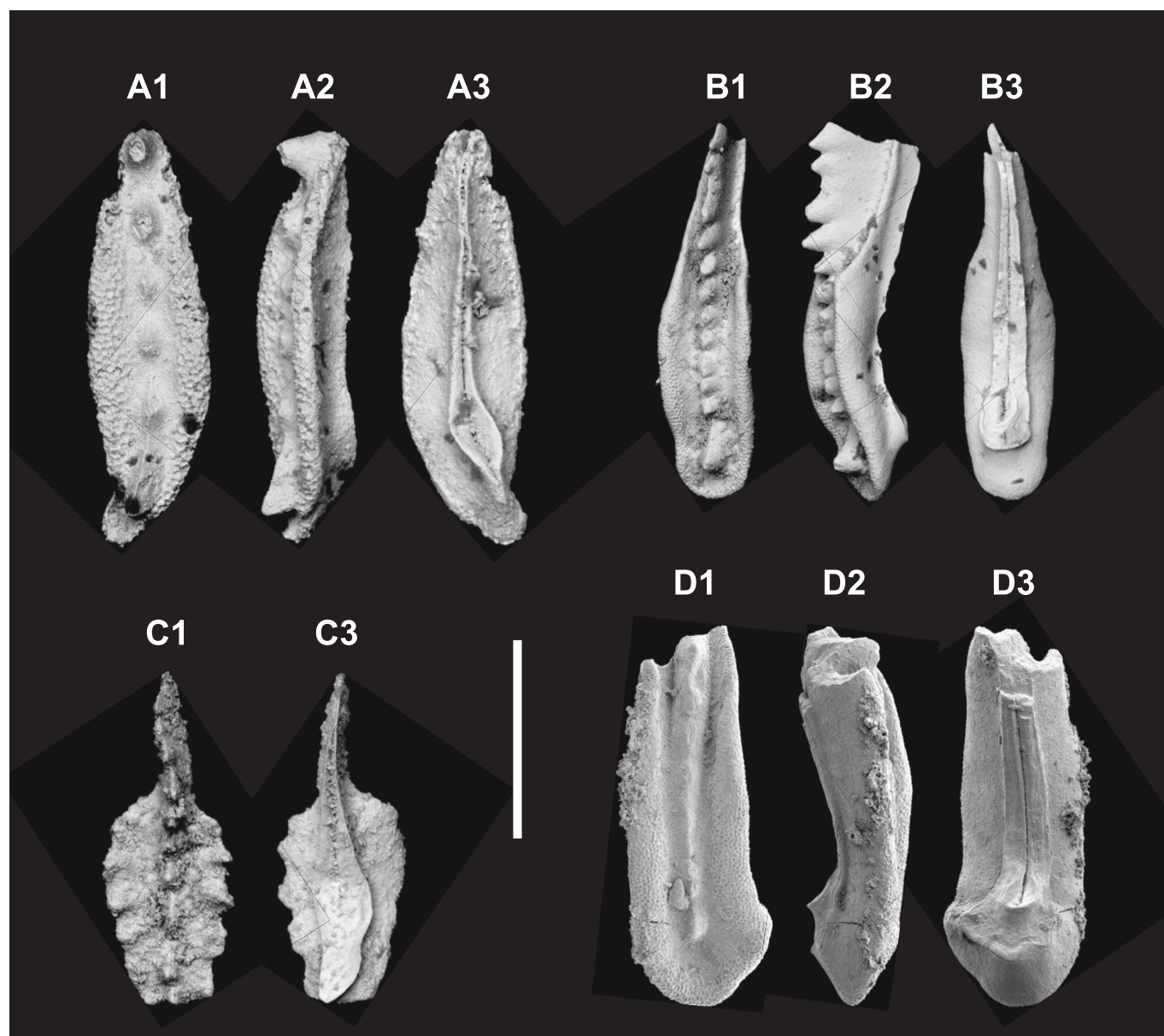


Fig. 3. SEM micrographs of characteristic conodonts from the Csukrét Ravine outcrop. Scale bar is 500 μm and all specimens are on the same scale. 1: upper view, 2: lateral view, 3: lower view. A. *Gladigondolella malayensis*, sample BCS10/23. B. *Paragondolella polygnathiformis*, sample CSR3/24. C. *Budurovignathus mostleri*, sample BCS11/23. D. *Paragondolella maantangensis*, sample CSR-1/13/21.

(2002) – were re-illustrated in the present study extended with the revision of the foraminifer data.

3.4. Bulk organic stable carbon isotope and TOC analysis

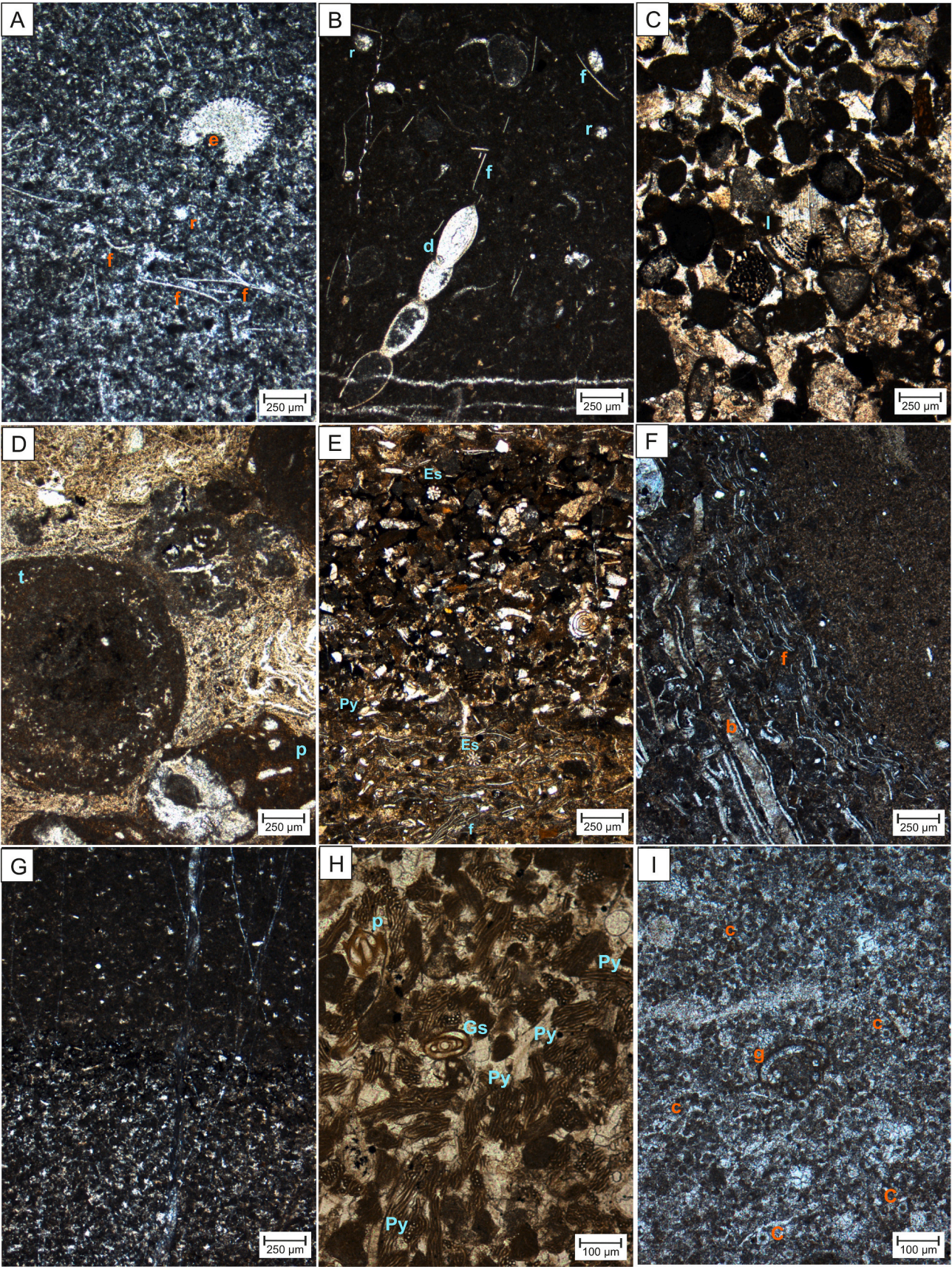
One hundred and seventy-seven bulk rock samples were collected from CPE successions in the Balaton Highland for bulk organic carbon-isotope analysis and total organic carbon (TOC) measurements (Csukrét Ravine: 60 samples, Veszprém V-1: 49 samples, Nosztor Valley: 26 samples, Balatonhenye Bht-6: 20 samples, Barnag Bat-2: 22 samples). Samples from the cores have been obtained from the Szépvízér core repository of the Hungarian Geological Institute. For the V-1 core, only a limited number of core segments (19 samples) were available for sampling between 356 m and 141 m, as part of the core material was lost/used and a long interval was drilled without coring during the original preparation of the borehole (~255–175 m). The sampling resolution in the Barnag Bat-2 and Balatonhenye Bht-6 cores was influenced by the

preservation state of the core segments at the repository and only those intervals were sampled where cross-contamination or mixing of samples could be excluded. TOC and bulk organic carbon-isotope analyses have been performed at the Institute for Geological and Geochemical Research (IGGR), Research Centre for Astronomy and Earth Sciences, HUN-REN (IGGR, RCAES, HUN-REN, Hungarian Research Network), State Key Laboratory of Continental Shale Oil (Daqing), China University of Geosciences (Wuhan), and by the ISOLAB b.v. Details of the analytical techniques are given in the Supplementary Material 1. Isotope ratios are reported in per mil vs. VPDB listed in the Supplementary Material 3.

4. Results

4.1. Conodont data

Conodonts were recovered only from the Csukrét Ravine outcrop



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Fig. 4. Main microfacies types of the Füred Limestone Formation and Mencshely Marl and Nosztor Limestone members (Veszprém Formation). (A) Peloidal bioclastic packstone with filaments, radiolarians and echinoderm fragment (MF 1, Füred Limestone, Met-1420 m). (B) Bioclastic wackestone with foraminifera (*Dentalina*), filaments (MF 2, Füred Limestone, Met-1384.5 m). (C) Bioclastic aggregate-grain grainstone with *Lamelliconus multispira* (MF 3, Mencshely Marl, Met-1332.5 m). (D) Bioclastic-oncolithic floatstone with *Palaeonubecularia gregaria* and *Tubiphytes* surrounded by *Plexoramea* (MF 3, Mencshely Marl, Met-1326.1 m). (E–F) Micrite alternating with skeletal debris flow derived skeletal layer (E - echinoid spines, filaments, cyanobacterial *Pycnoporidium*, -, F - filaments brachiopod shell fragments) (MF 3, Mencshely Marl, Met-1196.3 m). (G) Quartz-peloidal packstone/wackestone (MF 4, Mencshely Marl, Met-1191 m). (H) Grainstone densely packed with tubular porostromate calcimicrobes (*Pycnoporidium*) (MF 3, V-1338 m). (I) Bioclastic packstone densely packed with calcispheres and a foraminifer (*Glomospirella* sp.) (MF 5, Nosztor Limestone, Met-1 43.9 m). Abbreviations: f – filaments, r – radiolarians, e – echinoderm fragments, d – *Dentalina*, l – *Lamelliconus multispira*, t – *Tubiphytes*, p – *Palaeonubecularia gregaria*, Es – echinoid spines, Tr – *Triadodiscus*, Py – *Pycnoporidium*, b – brachiopod shell fragment, Gs – *Gsollbergella spiroloculiformis*, c – calcisphaeres, g – *Glomospirella*.

from the Füred Limestone Formation, and the Nosztor Limestone Member of the Veszprém Formation (Figs. 2–3). The lower part of the Füred Limestone Formation, samples BCS-10/23 and BCS-11/23 yielded *Budurovignathus mostleri*, *Gladigondolella malayensis*, and *Gladigondolella multielements* (ME). This interval is placed in the upper Longobardian (uppermost Ladinian) *Diebeli* conodont Zone of Krystyn (1983) and Karádi et al. (2022). The first appearance of *Paragondolella polygnathiformis*, the conodont species marking the base of the Carnian is recorded higher, in sample CSR-3/24, which is therefore assigned to the *Polygnathiformis* Zone of Rigo et al. (2018). Samples from BCS-12/23 to BCS-15/23 contain the same assemblage with *P. polygnathiformis* accompanied by *Gladigondolella* sp. and *Gladigondolella* ME. Clay content of the formation significantly increases upsection in the Füred Limestone Formation (CSR-1/78 A and CSR-1/78B) accompanied by a decrease in conodont abundance. The samples from the topmost part of the Füred Limestone contain only *Gladigondolella* sp. and *Gladigondolella* ME. Species of the genus *Paragondolella* (*P. polygnathiformis*, *P. maantangensis*, *P. tadpole*) dominate the samples from the Nosztor Limestone Member (Fig. 2) accompanied by the multielement apparatus of *Gladigondolella*. All conodonts show a color alteration index (CAI) value of 1.

4.2. Microfacies and foraminiferal assemblages

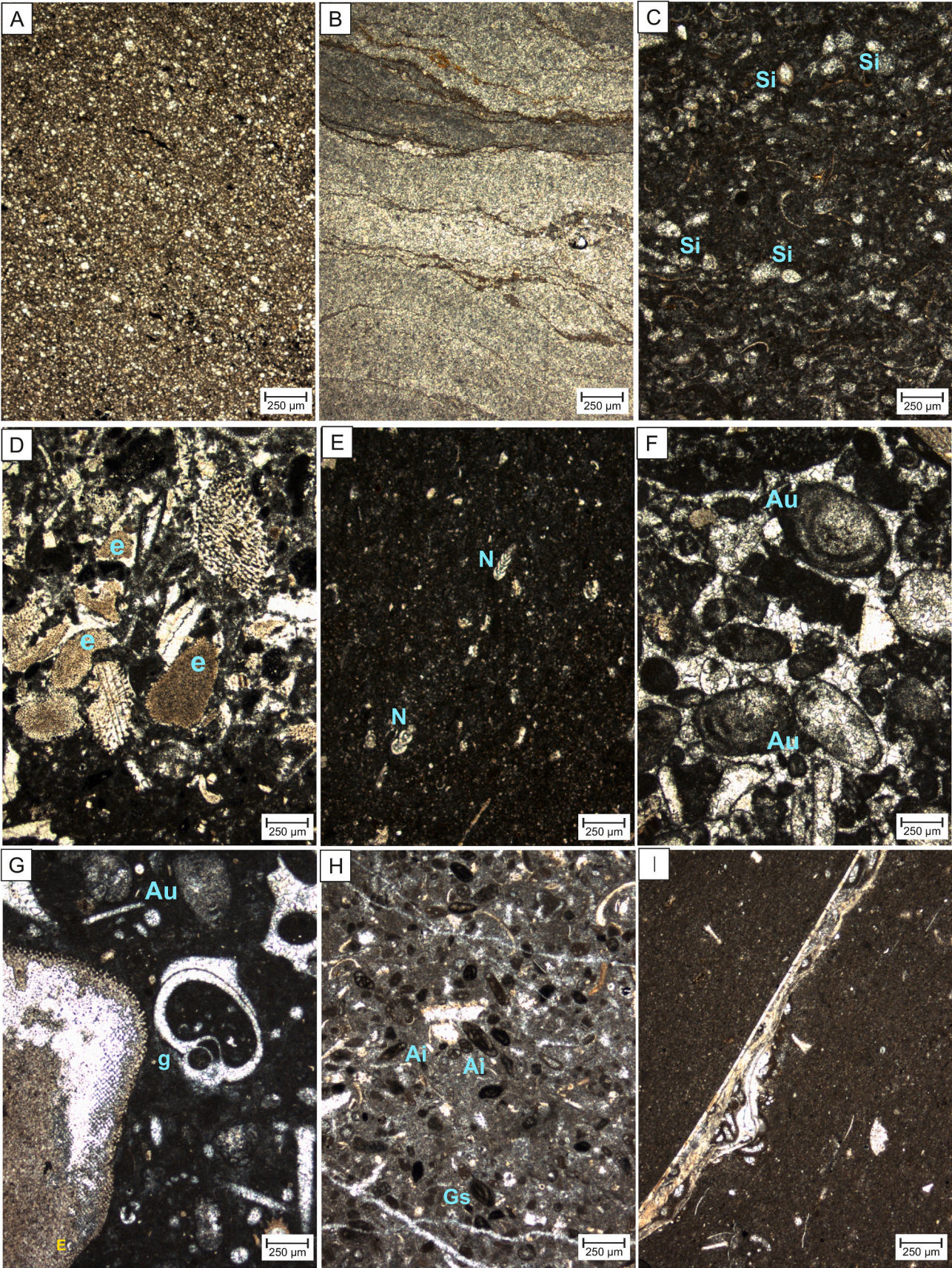
Nine microfacies types are distinguished (MF 1–9) from the Carnian successions of the Met-1, V-1, and Bat-2 cores, and a total of 55 foraminifer taxa are determined (Figs. 4–6, Supplementary Material 2, Figs. S1–S3). In Met-1 (424–384.5 m), microfacies of the Füred Limestone is pelagic peloidal bioclastic packstone (MF 1, Fig. 4A) and wackestone (MF 2, Fig. 4B) with varying amounts of recrystallized radiolarians, thin-shelled bivalve filaments and some shallow-marine bioclasts indicating open marine hemipelagic sedimentation with weak currents in the basin. The amount of foraminifers is negligible in the basin sediments represented by microfacies MF 2, but few ophthalmidiid miliolids (*Ophthalmidium*, *Gsollbergella*), nodosariids (e.g., *Austrocolomia*) or ammodiscids (*Glomospirella*) are present in MF 1 which seems to contain transported material from the shallower marine environments (Fig. S1). The pelagic bioclastic wackestone microfacies type (MF 2) is characteristic in the entire Mencshely Marl Member (Met-1, 372–65.8 m, V-1583.8–512.3 m, Figs. S1–S2) where it is alternating with calciturbidites derived from the adjacent platforms (MF 3, Figs. 4E–F and H) and debris flows (MF 4, Fig. 4G). Calciturbidite and skeletal debris flow units represented by various microfacies types (bioclastic aggregate-grain grainstones, bioclastic oncolithic floatstones, and bioclastic packstones) of MF 3 frequently occur in the lower part of the Mencshely Marl Member until 196.3 m alternating with MF 2 (Fig. S1). This microfacies is characterized by rich reef-derived bioclast association: cyanobacterial *Tubiphytes* and foraminifers (*Palaeonubecularia gregaria*, Fig. 6O) forming oncoids and other calcimicrobes such as *Cayeuxia*, with a typical Triassic platform dweller foraminiferal association: involutinids represented by the taxa *Lamelliconus* and *Triadodiscus*, some litiolids (e.g., *Trochammina*) and miliolid *Gsollbergella* (Fig. S1). Other bioclasts occur regularly e.g., echinoid spines, bivalve filaments, and crinoid ossicles. Increase of terrestrial influx is indicated by the arrival of a large amount of terrigenous quartz grains represented by the quartz-peloidal packstone-wackestone of MF 4 (Fig. 4G) mainly in

the upper part of the Mencshely Marl Member (Met-1, 264.4–60.6 m, Fig. S1). Pyritized grains also occur as clasts in this microfacies type. The detrital component is so high in the sediments from 160 m to 70 m in Met-1 that no thin sections were prepared from this marly interval. The foraminiferal fauna is generally monospecific in the upper part of the Mencshely Marl (Figs. S1–S2), dominated exclusively by small representatives of the miliolid *Gsollbergella spiroloculiformis* (Figs. 6J–K, S1). The Nosztor Limestone Member (Met-1, 59.8–41 m) is represented mainly by a unique open-marine microfacies (MF 5, Fig. 4I, S1) with bioclastic wackestone–packstone texture where calcispheres occur in rock-forming quantities, along with few radiolarians. Foraminifers are represented by only few nodosariids.

In the V-1 core the interval between ~350–338 m, originally considered as part of the Csicsó Marl Member immediately above the platform dolomites of the Sédvölgy Member, is rich in carbonates and exhibits the MF 3 microfacies (Fig. S2). This peculiar type of grainstone is densely packed with tubular porostromate calcimicrobes (*Pycnoporidium*), as well as endothyrid (*Endotabanella*, Fig. 6B) and duostominid foraminifers (*Diploremmina* and *Variostoma*), which are often associated with cyanobacterial mats (Fig. 4H, S2). Above 338 m in the V-1 core, the sediments are gradually enriched in detrital components characteristic for the Csicsó Marl Member. The microfacies of this lithostratigraphic unit is quartz-peloidal wackestone/packstone occasionally exhibiting typical graded turbidite characteristics. The foraminiferal assemblage is very poor, only the specimens of *Gsollbergella* occur as bioclasts, e.g., in Bat-2 (198–185.5 m).

The various microfacies types of the Sándorhegy Formation in the Bat-2 core are characterized by increasing carbonate content and more metazoan bioclastic-skeletal components towards the Barnag Member (Figs. 5 and S3). The microfacies (MF 6, Fig. 5B–C) in the lower part of the Pécsely Member (167.2 to 146.3 m) is grey clayey mudstone and filament-rich wackestone followed by dark grey bituminous laminites with slump structures and evaporite hollows but negligible bioclast content. In the uppermost part of the laminites, the microfacies changes to a bioclastic peloidal packstone containing large quantities of ostracod (*Simeonella*) carapaces (Fig. 5C). There are no thin sections between 143.4 and 111.3 m, due to the presence of marls and clay marls suggesting stronger clastic influx. The upper calcareous marl series of the Pécsely Member (99.6–89.6 m) is characterized by a poorly sorted bioclastic peloidal wackestone-packstone microfacies with few skeletal debris containing foraminifers (*Gsollbergella* and some nodosariids), fragments of echinoderms, bivalves, and gastropods. Moreover, some neomorphic calcite or quartz grains also occur as lithoclasts.

The Barnag Member starts with a cherty limestone series (88 to 76.8 m) where the characteristic microfacies (MF 7) is wackestone with nodosarid foraminifer association, sponge spicules and some peloids and oncoids. In the upper part of the sequence (74.8 to 55.1 m) the characteristic microfacies types (MF 8, Fig. 5F) are coarse-grained intraclastic skeletal packstone/grainstone with foraminifers and dasycladaceans (*Poikiloporella duplicata*), gastropods, bryozoans, and skeletal aggregates and minor oncoids or coated grains. The foraminiferal assemblages are dominated by involutinid (*Aulotortus sinuosus*, Fig. 6C) and endothyrid (*Endotriada* and *Endotriadella*, Fig. 6A) benthic foraminifers. Above 50 m, quartz-peloidal wackestone with an increasing amount of brachiopod and bivalve shell fragments can be



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Fig. 5. Main microfacies types of the Csicsó Marl Member (Veszprém Formation), Pécsely and Barnag members (Sándorhegy Formation). (A) Packstone densely packed with quartz grains (MF 4, Csicsó Marl, Bat-2188.3 m). (B) Grey clayey mudstone with slumps (MF 6, Pécsely Member, Bat-2153.5 m). (C) Peloidal bioclastic packstone with ostracods (*Simeonella*) (MF 6, Pécsely Member, Bat-2143.4 m). (D) Poorly sorted bioclastic peloidal wacke-packstone with skeletal debris (echinoderm fragments) (MF 3, Pécsely Member, Bat-2 91.3 m). (E) Cherty wackestone with nodosariid foraminifera and sponge spicules (MF 7, Barnag Member, Bat-2 78.9 m). (F) Coarse-grained intraclastic skeletal grainstone with involutinid foraminifera (*Aulotortus sinuosus*) (MF 8, Barnag Member, Bat-2 70.3 m). (G) Poorly sorted bioclastic peloidal packstone with echinoderm fragments, gastropods and involutinid foraminifera (*Aulotortus sinuosus*) (MF 3, Barnag Member, Bat-2 68.3 m). (H) Bioclastic packstone with miliolid-brachiopod coquina containing *Agathammina iranica* (MF 9, Barnag Member, Bat-2 50.3 m). (I) Bioclastic wackestone with brachiopod shell fragment with microencrusters. Abbreviations: Si – *Simeonella*, e – echinoderm fragments, N – *Nodosaria*, Au – *Aulotortus sinuosus*, Ai – *Agathammina iranica*, g – gastropod shell, Gs – *Gsollbergella*.

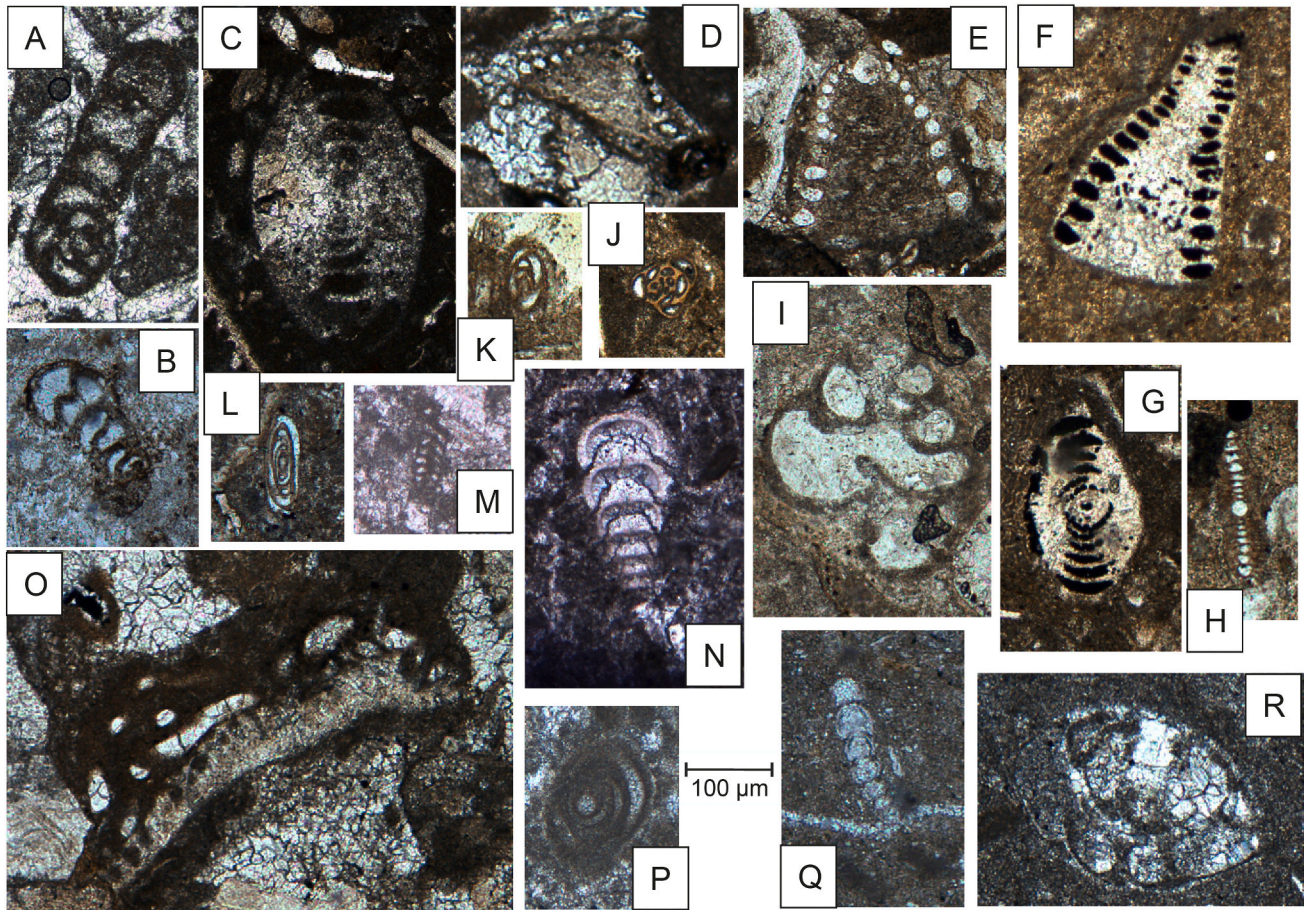


Fig. 6. Characteristic foraminifera from the studied Carnian sections. (A) *Endotriadella* sp., Barnag Bat-2 70.3 m. (B) *Endotabanella* sp., Mencshely Met-1 19 m. (C) *Aulotortus sinuosus*, Barnag Bat-2 66.4 m. (D) *Lamelliconus biconvexus*, Mencshely Met-1337.3 m. (E) *Lamelliconus multispira*, Mencshely Met-1314.5 m. (F) *Lamelliconus multispira*, Mencshely Met-1325.2 m. (G) *Triadodiscus eomesozoicus*, Mencshely Met-1287.2 m. (H) *Triadodiscus eomesozoicus*, Mencshely Met-1314.5 m. (I) *Trochammina almtalensis*, Mencshely Met-1324.9 m. (J) *Gsollbergella spiroloculiformis*, Mencshely Met-1296.3 m. (K) *Gsollbergella spiroloculiformis*, Mencshely Met-1314.5 m. (L) *Agathammina austroalpina*, Mencshely Met-1196.3 m. (M) *Turritellina carnica*, Mencshely Met-1389.3 m. (N) *Austrocolonia marschalli*, Mencshely Met-1416 m. (O) *Palaeonubecularia gregaria*, Mencshely Met-1337.3 m. (P) *Ophthalimidium exiguum*, Mencshely Met-1 35.7 m. (Q) *Nodosaria raibliana*, Mencshely Met-1 65.8 m. (R) *Duostomina* sp., Mencshely Met-1 55 m.

observed in the microfacies. In the foraminifera fauna, the *Agathammina*-*Gsollbergella* miliolid association appears accompanied by nodosariids and ammodiscids. The representatives of microgranular endothyrids are still present, the involutinids are completely absent from the sequence. The miliolid foraminifera and brachiopod shells sometimes form coquinas (MF9, Fig. 5H).

4.3. Bulk organic carbon isotope ($\delta^{13}C_{TOC}$) and total organic matter (TOC)

Bulk organic carbon isotope analysis was performed on a total of 177 samples (Fig. 7); all measured carbon isotope and TOC data are available in the supplementary material (Supplementary Material 3). From the Csukrét Ravine 60 samples have been collected on multiple sampling

campaigns during 2022–2025 as outcrop conditions are largely dependent on water level in the ravine. Samples have been obtained from the Füred Limestone Formation, transition between the Füred and Veszprém Formation, the Mencshely Marl, and the Nosztor Limestone Member (Fig. 7). The transitional interval between the Füred and Veszprém formations is not well exposed in the Csukrét Ravine, therefore the lower 10 m of the studied interval could only be sampled in lower resolution. The upper marl unit of the Veszprém Formation (Csicsó Marl Member) is also poorly exposed; it is largely covered by vegetation and Quaternary sediments. The $\delta^{13}C_{TOC}$ values of the Füred Limestone Formation range from -24.2‰ to -26.4‰ with a slight negative shift represented by BCS-13/23 but due to the low resolution a clear trend cannot be established. TOC values are generally low with a few distinct peaks in BCS-15/23 (1.34 wt%) and CSR-1/78A (1.96 wt%) with no linear

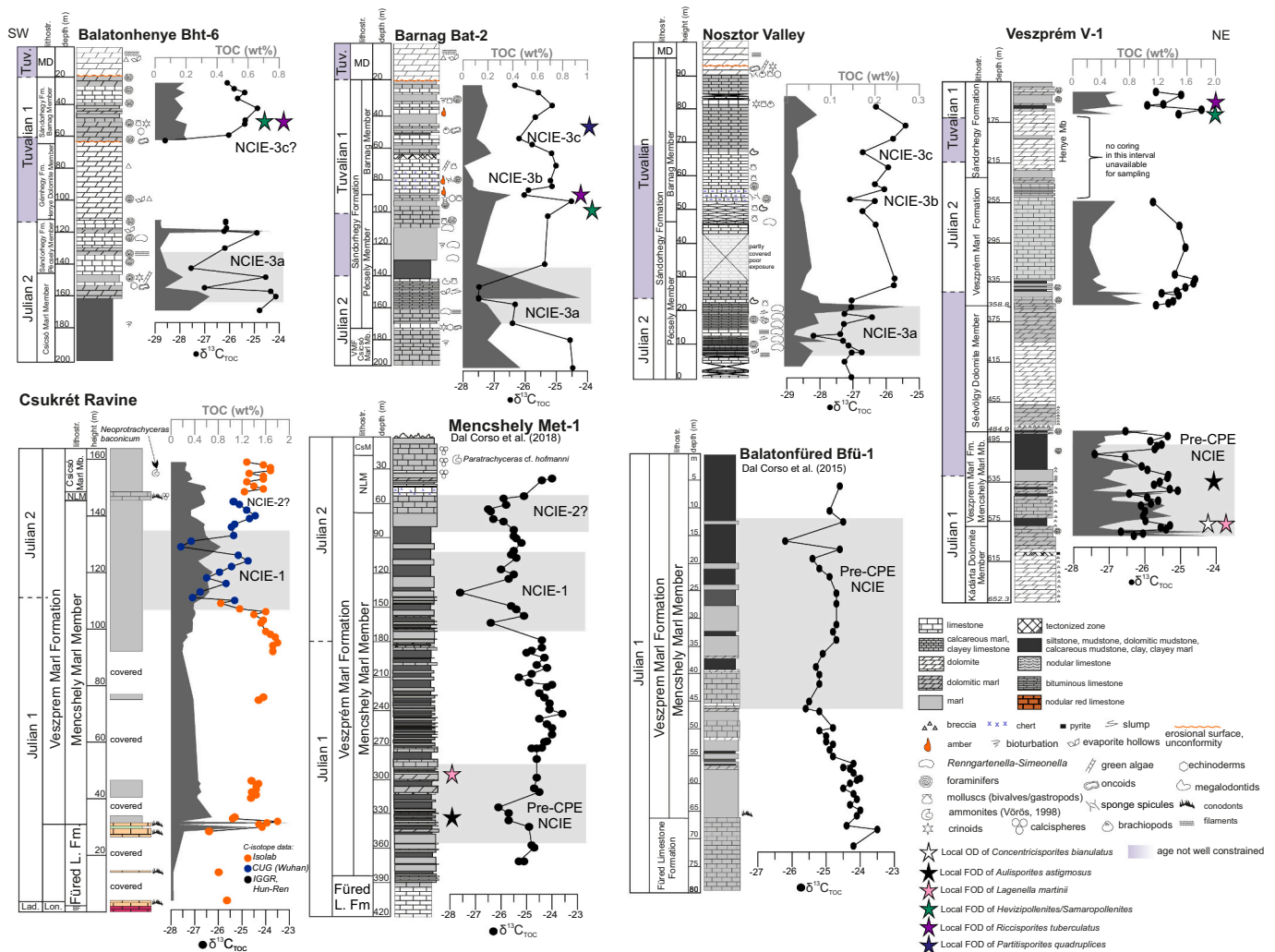


Fig. 7. Lithology, sedimentology, and biostratigraphic constraints of the studied Carnian successions from the Balaton Highland (Transdanubian Range) together with the carbon isotope composition of total organic carbon ($\delta^{13}\text{C}_{\text{TOC}}$) and TOC (wt%) data. All curves are produced in this study except for those of the Mentshely Met-1 and Balatonfüred Bfü-1 cores which are from Dal Corso et al. (2015, 2018). Lithological, sedimentological, and paleontological data are summarized from Nagy (1999), Budai et al. (1999), Nagy and Csillag (2002), Rostási et al. (2011), Tóth et al. (2024), Baranyi et al. (2019b, 2025). Purple areas in the biostratigraphy represent intervals of uncertain age constraints. Abbreviations: Lad. = Ladinian, BuF = Buchenstein Formation, NLM = Nosztor Limestone Member, FL = Fured Limestone Formation, MD = Main Dolomite Formation (Dolomia Principale equivalent), Tuv. = Tuvalian. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

correlation between TOC and isotope values ($R^2 = 0.03$). The $\delta^{13}\text{C}_{\text{TOC}}$ data from the lower part of the Mentshely Marl Member show generally more positive values -24.0 to -25.4‰ with generally low TOC. In the Csukrért Ravine, two peaks are observed between samples CSR-I/52 and CSR-I/28 forming a clear negative isotope excursion (NCIE) of -3.6‰ in the upper part of the Mentshely Marl Member. Data from the overlying (poorly exposed) part of the Csicsó Marl Member show a positive trend with values between -24.9‰ and -23.8‰ with generally low TOC ($<0.6\text{ wt\%}$).

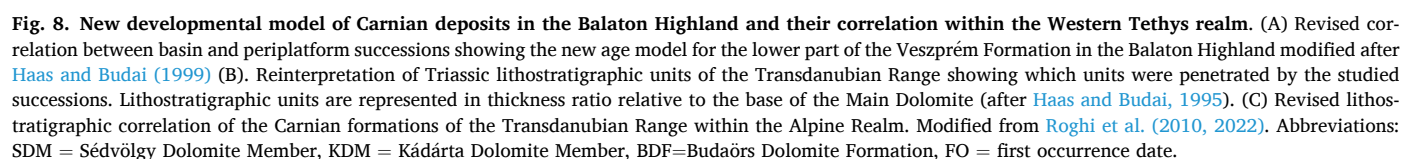
Isotope values from the Veszprém V-1 core (Fig. 7) from the Mentshely Marl Member show more variation with frequent negative and positive oscillations from -24.4‰ to -27.4‰ and with TOC values between $0.11\text{ wt\%}$ and $1.91\text{ wt\%}$ with four smaller negative peaks at 584.4 m , 545.9 m , 506.1 m , and at 483 m . The interval between $\sim 530\text{ m}$ and 506.1 m is characterized by the most prominent negative shift of -2.1‰ in the entire Mentshely Marl Member from the V-1 succession culminating in a pronounced NCIE at 506.1 m . The negative peaks at 584.4 m , 545.9 m , and 483 m are associated with increases in the TOC values ($1.91\text{--}1.05\text{ wt\%}$), but there is no significant linear correlation between TOC and carbon isotope values in the V-1 core ($R^2 = 0.32$).

Isotope ratios from the overlying marly unit ($356\text{--}252\text{ m}$) range from -24.6‰ to -25.8‰ showing a broad overall positive trend interrupted by a slight shift towards more negative values at the top of the sampled interval. TOC values are varied but remain lower ($0.23\text{--}0.99\text{ wt\%}$). The third sampled unit in the Veszprém V-1 borehole, assigned to the Tuvalian part of the Sándorhegy Formation ($163.5\text{--}141\text{ m}$), is characterized by isotope ratios ranging from -24.4‰ to -25.9‰ and relatively low TOC values $<1\text{ wt\%}$ without showing a clear trend.

$\delta^{13}\text{C}_{\text{TOC}}$ values in the Nosztor Valley outcrop representing the Julian–Tuvalian transition (Fig. 7) start around -27‰ with a clear negative excursion of -28.2‰ at 12.5 m (Bed 7). The TOC values are generally low between $0.02\text{ wt\%}$ and $0.27\text{ wt\%}$ with no correlation between TOC and isotope values ($R^2 < 0.0005$). The upper part of the section ($\sim 20\text{--}80.5\text{ m}$) is characterized by an overall positive trend in the $\delta^{13}\text{C}_{\text{TOC}}$ (around -27 to -25‰) with two minor negative shifts (Fig. 7).

In the Barnag Bat-2 core a pronounced negative carbon isotope excursion is recorded at $154.5\text{--}147\text{ m}$ up to -27.5‰ in the lower part of the Sándorhegy Formation (Fig. 7). TOC values associated with the NCIE are varied ranging from $0.09\text{ wt\%}$ to $0.94\text{ wt\%}$ with the relatively higher TOC values occurring in the bituminous limestone unit of the Pécsely

In the Balatonhenye Bht-6 core (Fig. 7) an NCIE is recorded at the transition between the Csicsó Marl Member (Veszprém Formation) and the Pécsely Member (Sándorhegy Formation) at 154.8–142.4 m (from –27.0‰ to –27.6‰) and probably a second one on top of the platform progradation unit (Henyé Member) at 61.5 m (–28.6‰). As parts of the core were not available anymore for sampling, a clear trend cannot be



established but the upper part of the Sándorhegy Formation (58–24.9 m) is characterized by more positive values (between -26.1‰ to -24.9‰). Variation in TOC (0.32–0.74%) has no significant influence on the $\delta^{13}\text{C}_{\text{TOC}}$ values ($R^2 = 0.03$). Like on the Barnag Bat-2 isotope curve, the topmost part of both boreholes records a negative shift, but the development of a true excursion is not evident due to an erosional surface and hiatus (Fig. 7).

5. Discussion

5.1. The age of the Füred Limestone and Veszprém Marl Formation

Robust stratigraphical markers are scarce in the Carnian strata of the Balaton Highland and widely accepted reliable biostratigraphical anchors were available only from the middle part of the Füred Limestone Formation (*Trachyceras aon* in Dosztály, 1991; Vörös, 1998) indicating Julian 1 age. Ammonoids from the middle and upper part of the Veszprém Formation (Nosztor Limestone and the Csicsó Marl Member) confirmed a Julian 2 age (*Austriacum* Zone). Previous studies have based the correlation of the Veszprém Formation on less reliable biostratigraphical data such as the *Sirenites?* sp. and *Neoprotrachyceras?* sp. from the upper part of Füred Formation that seemed to indicate a Julian 2 age. However, the occurrence of the *Trachyceras aon* specimen from the Csákány Hill in the basal part of the Veszprém Formation and the revision of the specimen previously known as *Neoprotrachyceras?* sp. (L. Krystyn, University of Vienna, personal communication, 2024) place the transition between the Füred-Veszprém Formation into the early Julian, *Aon* Subzone (Krystyn, 1978). Consequently, the exact level of the Julian 1–Julian 2 boundary remains uncertain, most likely placed in a higher stratigraphic position within the Mentshely Marl Member. This makes the age constraints and correlation of the CPE NCIE-1 of Dal Corso et al. (2015) recorded in the TR successions highly debatable.

The first occurrence of the conodont *Paragondolella polygnathiformis* marking the base of the Carnian is observed within the lower part of the Füred Limestone Formation in the Csukré Ravine. The first occurrence of this species is recorded in the Partnach Beds, a mixed carbonate-siliciclastic formation, in the Mendlingbach section (Lein et al., 2012) and in the San Cassiano Formation in the Prati di Stuares/Stuares Wiesen section (Mietto et al., 2012). The same conodont occurrences and the lithological similarity confirm that the Füred Limestone Formation of the TR is age equivalent with parts of the Partnach Formation of the Northern Calcareous Alps and the lower San Cassiano Formation of the Dolomites (Fig. 8). The upper Partnach Formation and the upper Reifling Formation are dated by conodonts as late Julian 1 *Aonoides* Subzone (Krystyn, 1978, 1991; Hornung et al., 2007) further hinting at an older age for the Füred-Veszprém Formation transition and the earlier onset of siliciclastic influx.

The Carnian evolution of the Western Tethys realm is largely determined by the evolution and demise of the Wetterstein carbonate platform cycle (Keim et al., 2006; Hornung et al., 2007; Krystyn et al., 2008; Missoni et al., 2012; Gawlick et al., 2017; Mrdak et al., 2023). During its developmental phase, carbonate debris of the prograding platform is regularly transported into basin successions. Levels with enhanced input of carbonate platform facies with sparite cement, breccias, characteristic shallow-water foraminifers (*Lamelliconus-Triadodiscus* assemblage, M3 microfacies, Figs. 4C–F) including clasts of microbial origin (*Tubiphytes* and *Cayuexia*), are frequent in the Mentshely Marl Member interbedded between more micritic and marly layers. The Wetterstein Platform has a characteristic fossil assemblage, microbial and skeletal (e.g., Mircescu et al., 2025), which can be traced in the whole Western Tethys Realm. The involutinid *Lamelliconus* and *Triadodiscus* dominated shallow-water foraminiferal assemblages accompanied by cyanobacteria such as *Tubiphytes*, which occur in the calciturbidites of the Mentshely Marl in the Met-1 core, are characteristic of the Ladinian–early Carnian Wetterstein Platform (NCA, Austria: Koehn-Zaninetti, 1969; Resch, 1979; Bradner and Resch, 1981; Rüffer

and Zamparelli, 1997; Lesno Brdo, Slovenia: Oblak, 2001; Gale et al., 2018; West Carpathians: Salaj et al., 1983). The cyanobacterial *Tubiphytes* and *Tubiphytes*-like organisms are frequent in Ladinian–Carnian Wetterstein reefs of the Alps but less significant in other, Anisian or Norian–Rhaetian reefs (e.g., Senowbari-Daryan, 2013). The stratigraphic range of the identified involutinid taxa such as *Lamelliconus cordevolicus*, *L. biconvexus* (Fig. 6D), *L. multispira* (Fig. 6E), and *Triadodiscus eomesozoicus* (Figs. 6G–H) is also limited to the Ladinian to lower Carnian (e.g., Trifonova, 1993; Rettori, 1995). The presence of duostominids *Duostomina*, (Fig. 6R) and *Diplotremina*, in the Mentshely Marl Member suggests also upper Ladinian–early Carnian age (e.g., Koehn-Zaninetti, 1969; Resch, 1979). Moreover, the occurrence of *Turriplomina carnica* (Fig. 6M) in the Füred Limestone Formation and the lower part of Mentshely Marl (Met-1, 389 m) also supports the time interval of the Wetterstein-type platform evolution as the representatives of the *Turriplomina* group have been found in basinal and slope deposits of the Reifling Formation, as well as in the Wetterstein Platform in the NCA (e.g., Zaninetti et al., 1990). In the Dolomites, a facies (marls alternating with calciturbidites) and microfacies similar to MF 2 and MF 3 from the Met-1 core and foraminiferal fauna with *Lamelliconus*, *Triadodiscus* and duostominids, are recorded in the basin sediments of the San Cassiano Formation at Tamarin (Di Bari and Baracca, 1998). That section was correlated to the upper part of *Aonoides* Subzone and is coeval with the carbonate platform facies of the Upper Cassian Dolomite (Cordevolian; Urlichs, 1994; Bizzarini, 1996).

Carbonate platform-derived microfacies (MF 2) and Wetterstein-type foraminiferal assemblage occur consistently in the lower Mentshely Marl Member, extending to ~260 m in the Met-1 core (Figs. 4–5, S1–S2), followed by a transient interval with more detrital input, but platform components still return in smaller quantities until ~190 m when quartz grains become the dominant components in the microfacies. These observations indicate that shallow-water carbonate production and platform shedding remained active during the deposition of the lower Mentshely Marl Member. Taking into consideration the occurrence of the *Trachyceras aon* specimen from the Csákány Hill, together with the microfacies and foraminifer data documenting elements of the Wetterstein reef facies in the lower part of the Mentshely Marl Member, a revision of the Carnian evolution of the Balaton Highland and its litho- and biostratigraphic correlation with sections in the Southern and Northern Calcareous Alps is justified (Fig. 8). Across the Western Tethys, the demise of the Wetterstein platform is consistently placed within the *Mazzaella carnica* Conodont Zone, equivalent to the uppermost *Aonoides* to lowermost *Austriacum* Ammonoid Zone (Hornung et al., 2007; Lein et al., 2012; Lukeneder et al., 2012; Mueller et al., 2016; Mrdak et al., 2023). Consequently, the Wetterstein-type platform microfacies and microfauna in the lower Veszprém Formation clearly predate carbonate platform demise. In the Southern Alps, the demise of the Wetterstein platform cycle occurred between the deposition of the San Cassiano and Heiligkreuz Formation (Gattolin et al., 2015; Dal Corso et al., 2015, 2018; Alverà et al., 2026). The San Cassiano Formation spans the late Ladinian–early Carnian (*Regoledanus*–*Aonoides* zones), whereas the age of the basal Heiligkreuz Formation is uncertain according to the most recent studies, as it is assigned either to the uppermost *Aonoides* Zone (see Fig. 2 in Alverà et al., 2026) or to the lowermost *Austriacum* Zone (see Fig. 3B in Alverà et al., 2026). Unlike the Mentshely Marl Member, the basal Heiligkreuz Formation (Alpe di Specie Member), marking the onset of the Carnian Pluvial Episode (CPE), lacks calcarenite intercalations due to carbonate platform demise (Alverà et al., 2026). Overall, the revised age constraints of the lower Veszprém Formation and the microfacies observations question the correlation of the lower Mentshely Marl Member with the lower part of the Heiligkreuz Formation and consequently the onset of the CPE. The lower part of the Mentshely Marl member is more likely correlated to the San Cassiano Formation, particularly based on their similar microfaunal assemblage (Góczán et al., 1991).

The demise of the Wetterstein Platform in the Alpine Realm has been

linked to the “Reingrabener Wende” or Reingraben Event (Schlager and Schöllnberger, 1974) that corresponds with the CPE or slightly precedes it (Hornung and Brandner, 2005; Dal Corso et al., 2018). In the Lunz area of the Northern Calcareous Alps it is represented by the dark grey limey marls and turbiditic limestones of the Göstling Member (uppermost Reifling Formation) in the basal Julian 2 (*Austriacum* Zone), which is overlain by the Reingraben Formation of Julian 2 age and subsequently by the terrestrial-marine clastic Lunz Formation (Lein et al., 2012; Roghi et al., 2010; Mueller et al., 2016; Lukeneder et al., 2024). The available lithological and microfacies evidence indicates that the upper Mencshely Marl and the Nosztor Limestone members are deposited after the demise of the Wetterstein-type carbonate platform, and are likely age-equivalent to the Göstling Member (Fig. 8). This contrasts with the prevailing hypotheses that the Nosztor Limestone Member records the highstand shedding from the prograding Sédvölgy Platform, separating the Mencshely and Csicsó Marl members of the Veszprém Formation in previous lithostratigraphic works (Fig. 1A, Budai and Haas, 1997). However, the Nosztor Limestone Member lacks platform-derived material (Fig. 4I), inconsistent with deposition during active platform growth. Furthermore, the presence of a platform carbonate unit within the Julian 2 would conflict with the general idea of the biotic consequences of the CPE, namely carbonate platform demise. This discrepancy is reconciled by the revised microfacies data of the V-1, which suggest that the platform carbonate unit of the Sédvölgy Dolomite Member, penetrated by the core, is equivalent to the Wetterstein platform (Figs. 8, S2). Noteworthy, the microfacies of the interval ~350–338 m in the V-1 core above the Sédvölgy Dolomite Member still contains large amount of carbonate debris and platform-related bioclasts including Wetterstein-type reef dweller *Lamelliconus-Triadodiscus* foraminiferal assemblage, indicating that the final demise of carbonate factories is placed above that in this periplatform setting (Figs. 8–9, S2). Our new correlation thus strongly implies that the Sédvölgy Dolomite Member penetrated by the V-1 core predates the CPE and the carbonate factory crises, and it is clearly older than the Nosztor Limestone Member. In the V-1, the onset of the CPE is marked above ~334 m by a pronounced increase in hygrophytic palynomorphs (Baranyi et al., 2019b, 2025) and elevated H/X and I/X ratios (Fig. 9). This palynoflora corresponds to the *Aulisporites*–*Aratrisporites* assemblages that characterizes the onset of the CPE throughout the Alpine realm, including the Reingraben Formation of the Lunz area, upper part of the Conzen Formation-lower part of the Tor Formation, and lower Heiligkreuz Formation in the Dolomites (Roghi et al., 2010, 2022; Mueller et al., 2016).

5.2. Julian chemostratigraphic correlation and the evidence of a Pre-CPE NCIE

The chemostratigraphic application of bulk organic carbon stable isotope data requires that the measured values preserve a primary geochemical signal and thus represent reliable paleoenvironmental archives (Bornemann et al., 2023). Therefore, assessing the degree of diagenetic alteration is a prerequisite for chemostratigraphic interpretation to ensure the reliability of the isotopic record. Independent thermal maturity proxies indicate negligible diagenetic overprint in the studied successions. Sporomorph color variation (Baranyi et al., 2019b, 2025) and conodont color alteration indices (CAI = 1) both indicate low thermal maturity degree. This interpretation is supported by the widespread occurrence of poorly ordered mixed-layer illite/smectite (60–70% expandability) in the clay mineral assemblage of the Veszprém Formation in the Met-1 and Bfü-1 core (Rostási et al., 2011). Similarly, vitrinite reflectance measurements (Laczó, 1984) of the Veszprém and Sándorhegy Formation samples point to predominantly immature organic matter. Overall, the aforementioned independent diagenetic data indicate that the stable isotope geochemical record preserves a primary signal and has not been significantly modified by diagenesis.

The Carnian Pluvial Episodes was accompanied by a major

perturbation of the global carbon cycle, manifested by multiple negative carbon isotope excursions (NCIEs) in marine and terrestrial sedimentary archives (Dal Corso et al., 2012, 2015, 2018). The composite bulk organic carbon isotope curve from the Western Tethys realm indicates the presence of four negative isotope excursions (Fig. 1A), with NCIE-1 marking the Julian 1–2 boundary and the onset of the CPE (Dal Corso et al., 2015, 2018). However, the revised stratigraphical framework of the Füred Formation and lower Veszprém Formation challenges the correlation of the NCIE-1 previously identified by Dal Corso et al. (2015, 2018) in the lower Mencshely Marl Member (lower Veszprém Formation).

In the Northern Calcareous Alps, the CPE NCIE-1 has been consistently recorded from the Göstling Member (Dal Corso et al., 2015; Mueller et al., 2016), which correlates with the upper Mencshely Marl and Nosztor Limestone members in the Transdanubian Range (Fig. 8). The NCIE-2 of the CPE, so far identified only in the Dolomites and the Transdanubian Range, was recorded in the upper part of the Mencshely Marl Member according to Dal Corso et al. (2018). Yet the age constraints, together with the microfacies and micropaleontological evidence could imply that at least the lower part of the Mencshely Marl is still Julian 1. A negative isotope excursion in similar stratigraphic position as the NCIE-2 is also recognized in the Csukrét Ravine (~130–110 m, Fig. 7) enabling a robust correlation between the sequences of Met-1 and the Csukrét Ravine outcrop. This excursion, which postdates the carbonate platform demise, also coincides with pronounced changes in microfossil assemblages (Fig. 9). These observations suggest that the onset of the CPE, and thus the Julian 1–2 boundary, is positioned higher in the Transdanubian Range succession than previously proposed. Accordingly, the negative isotope excursion in the upper Mencshely Marl Member, originally interpreted as NCIE-2 by Dal Corso et al. (2018), is more likely to represent NCIE-1 and the onset of the CPE.

Following the new correlation, the negative carbon isotope excursion in the lower part of the Mencshely Marl Member, recorded in the Mencshely Met-1, Balatonfüred Bfü-1 (identified as NCIE-1 by Dal Corso et al., 2015, 2018) and tentatively recognized in the Csukrét Ravine (around 30 m) predates the onset of the CPE and is reinterpreted now as a Pre-CPE NCIE (Figs. 7–8). The same excursion might be also present in the V-1 core around 518–506 m in the lower part of the Mencshely Marl Member (Fig. 7). The data of Mueller et al. (2016, Figs. 4 and 7) reported a more negative carbon isotope value from the Julian 1 in the Partnach Beds at the base of their investigated succession. Although the low sampling resolution between this interval and the Göstling Member precludes detailed interpretation, these data suggest greater variability in the early Carnian carbon isotope record than previously recognized. Likewise, recent records from the Eastern Tethys (e.g., Zhao et al., 2025; Chen et al., 2026; Li et al., 2026) document some variation in the carbon isotope values signaling the growing instability of the thermally sensitive carbon sources before the onset of the CPE. However, their stratigraphic significance remains uncertain because of persistent biostratigraphic and correlation challenges between Western and Eastern Tethyan successions. The causes of a potential early Julian carbon cycle perturbation remain also unresolved but it might be linked to an early phase of the Wrangellia LIP volcanism. This is consistent with the available Os-isotope data (Tomimatsu et al., 2021) and positive $\Delta^{199}\text{Hg}$ shift with Hg peaks from the Panthalassa region (Jin et al., 2023) indicating volcanic activity beginning already in the early Carnian. Evidence for local or regional Tethyan-scale volcanism from early Julian is still equivocal mainly related to the uncertainty and large errors in the radiometric ages. Nevertheless, a possible multiphase magmatic activity is documented in the Dolomites, including the Predazzo Magmatic Complex, where monzonite and syenite bodies yielded ages of 238.1 ± 1.8 to 230.1 ± 0.6 Ma, while the main calc-alkaline-shoshonitic magmatism has been dated to 238.190 ± 0.055 – 235.8 ± 1.8 Ma (Visonà et al., 2025). In addition, Mazaheri-Johari et al. (2021) demonstrated elevated sedimentary Hg loadings in the Füred Limestone Formation and the lower part of the Mencshely Marl Member, which could suggest the

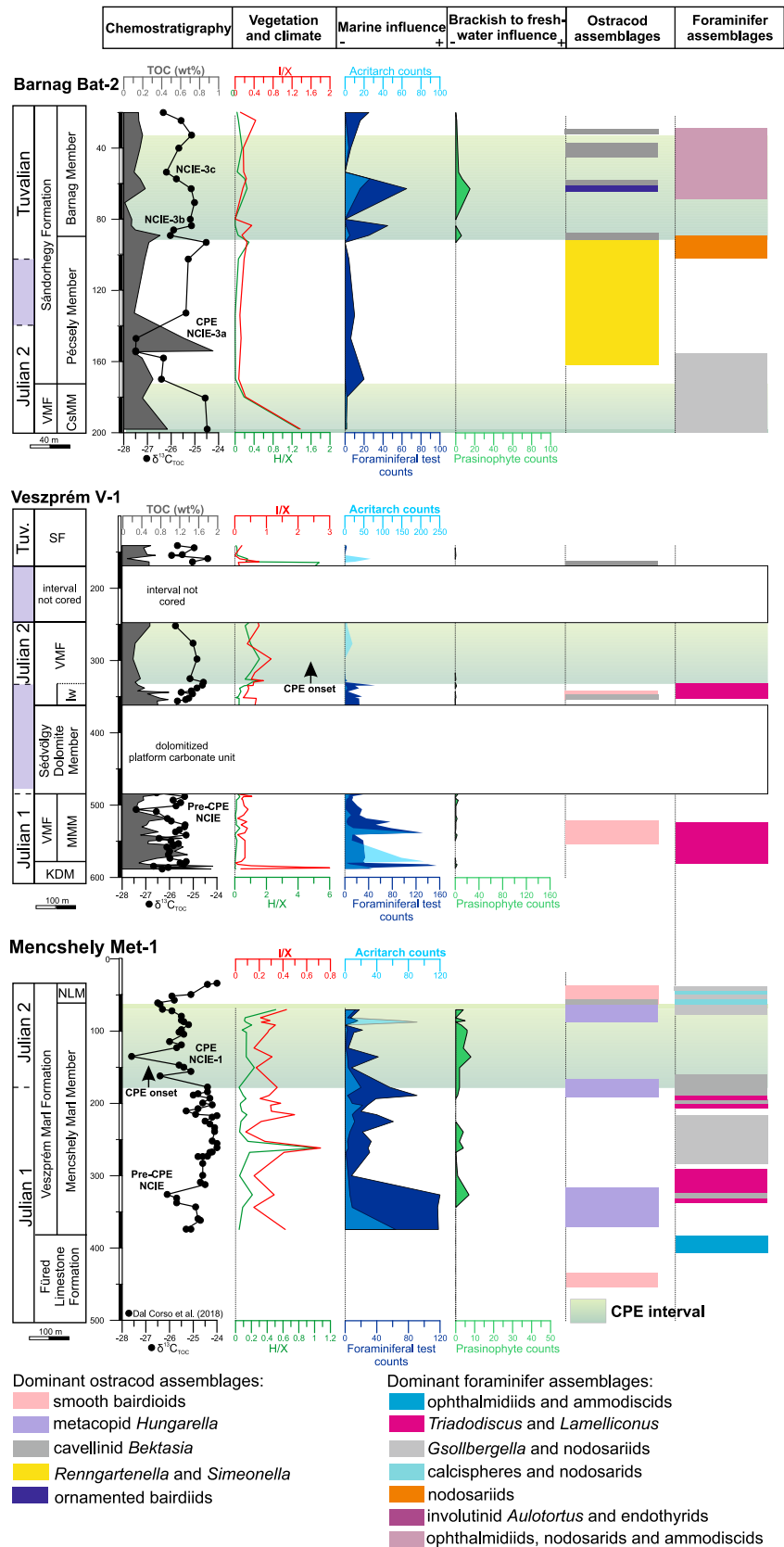


Fig. 9. Summary of the biotic changes in three selected borehole successions from the Balaton Highland (Transdanubian Range) prior to and during the CPE. Ostracod and palynological data are obtained from Baranyi et al. (2019b, 2025), Tóth et al. (2024). Abbreviations: KDM = Kádárta Dolomite Member; VMF=Veszprém Marl Formation; MMM = Mencshely Marl Member; NLM = Nosztor Limestone Member; CsMM = Csicsó Marl Member; SF=Sándorhegy Formation. H/X and I/X = ratio of hygrophyte to xerophyte and intermediate to xerophyte palynomorphs (from Baranyi et al., 2025).

presence of background volcanic activity during this period.

Data from the upper part of the Mencshely Marl Member in the Met-1 reveal an additional NCIE (around 60 m) that may correspond to the NCIE-2 of the CPE (Fig. 7). However, this excursion is only weakly expressed in the age-equivalent Csukrét Ravine outcrop where it is represented by a minor negative shift at the base of the Nosztor Limestone Member followed by a positive trend through the Csicsó Marl Member (Fig. 7). Likewise, our record could not reproduce the previously reported NCIE-1 in the V-1 core. Interpretation of this interval is also hindered by limited availability of the core material: only six samples were available from the ~80 m interval between 335 and 255 m, where NCIE-1 would be expected based on biotic changes (Fig. 9). Alternatively, the signal may have been obscured by mixing of platform-derived carbonate material with clastic, terrestrial-derived organic matter.

Across the Western Tethys, the late Julian 2 is characterized by a pronounced positive carbon isotope rebound following the NCIEs at the onset of the CPE (Fig. 1A), commonly attributed to declining atmospheric CO₂ due to intensified hydrological cycle, weathering, burial of isotopically light organic matter (Dal Corso et al., 2018; Pecorari et al., 2023), or possibly increased delivery of isotopically heavier refractory terrestrial organic matter to marine basins (Ruebsam et al., 2020; Schobben et al., 2019). A comparable positive trend is observed in the limited data from the Veszprém V-1 core (~334–255 m, Fig. 7), although no distinct excursions are evident within the sparsely sampled interval (Fig. 7). Even though the upper part of the Csicsó Marl Member could not be sampled in the V-1, but the lower part of the Barnag Bat-2 core recorded similarly more positive values from the Csicsó Marl Member (Fig. 7). Both core segments are dominated by hygrophytic palynomorph assemblages with many pteridophytes, lycopsid spores, and cycad pollen (Baranyi et al., 2025), indicating humid climatic conditions, expansion of wetland habitats, and intensified terrestrial organic matter input that likely influenced the bulk organic carbon isotope record.

5.3. Biotic stress prior to and during the CPE carbon cycle perturbation

Dating and correlating the onset of the increased terrestrial input is critical for understanding the biotic impact of the CPE. The revised biostratigraphic framework of the Füred-Veszprém Formation transition and the lower Mencshely Marl Member suggests that siliciclastic input began already during the early Julian. The decrease in the number of conodonts in the upper part of the Füred Limestone Formation also implies that the environmental perturbation preceded the Julian 1–2 boundary and the pronounced lithological transition between the Füred and Veszprém Formation (Fig. 9). The immediate decrease in the conodont abundance highlights the high sensitivity of this group to terrigenous input and environmental stress during the Carnian (e.g., Kolar-Jurkovšek et al., 2005; Kolar-Jurkovšek and Jurkovšek, 2010; Zhang et al., 2018). Ostracod assemblages record a similar ecological response, with a marked decline in diversity across the Füred–Veszprém Formation transition (Tóth et al., 2024). In the Mencshely Marl, metacopid *Hungarella* formed monogeneric assemblages in the marly strata of Met-1 well (at 325.9 to 260 m and 150 to 69 m, Fig. 9) suggesting stressed environment and reduced bottom-water oxygenation (Tóth et al., 2024). However, this increase in clastic influx was not necessarily driven solely by climate change. Instead, a more plausible explanation is the coupling between relative sea-level fluctuations and the sedimentary dynamics of intra-platform basins, alongside a concurrent decrease in platform-derived carbonate mud production and transport (Bechstädt and Schweizer, 1991; Rostási et al., 2011). Although kaolinite content increases and becomes more variable in the lower Mencshely Marl Member relative to the Füred Formation, suggesting a transition from arid to more seasonal, monsoonal conditions, the dominance of illite and chlorite indicates enhanced erosion of a moderately weathered continental source rather than intense chemical

weathering (Rostási et al., 2011). Thus, the increased fine-grained siliciclastic input into the lower Veszprém Formation reflects a climatic shift but not yet to the extent that generally characterizes the CPE (e.g., Pecorari et al., 2023). Palynomorph assemblages from the lower Mencshely Marl Member also contain a mixed xerophytic–hygrophytic flora, indicative of a strongly seasonal monsoonal climate with episodic, potentially intense precipitation events (Baranyi et al., 2025). There are, however, early signs for environmental and C-cycle instability, including the Pre-CPE-NCIE, accompanied by the transient increase in hygrophytic palynomorphs, and the proliferation of stress-tolerant prasinophytes (Fig. 9). Yet, according to the microfacies and foraminifer data, this “event” was not followed by the shutdown of the shallow-water carbonate production or the demise of the Wetterstein type reefs. Moreover, the amount of hygrophytic palynomorphs increased episodically even in intervals lacking carbon isotope excursions (e.g., Met-1, 261 m, Fig. 9) suggesting that the depositional style and terrestrial flux were controlled not only by climate but also by local to regional factors, including relative sea-level fluctuations and tectonic activity (Rostási et al., 2011; Haas et al., 2012).

Platform-derived calcarenite intercalations and rich marine biota occur regularly in the lower part of the Mencshely Marl Member (until ~260 m in Met-1) and, although less abundant, they persist up to ~190 m in the Met-1 (Figs. 9 and S1), indicating the presence of an active carbonate factory. By contrast, the NCIE in the upper part of the Mencshely Marl Member represents the clear tipping point in the demise of marine microbiota inferred from a sharp decline in acritarchs and foraminiferal test linings, accompanied by a marked increase in clastic detrital material (180–120 m Met-1, Fig. 9). Elevated prasinophyte abundances in the phytoplankton spectrum in the same interval suggest increased freshwater or brackish influence and stressed marine conditions (Tyson, 1995). Foraminiferal assemblages shift to low-diversity communities dominated by the small miliolid *Gsollbergella spiroloculiformis* (Figs. 9, S1–S2), consistent with increased terrigenous input and possible bottom-water oxygen depletion (Oravecz-Scheffer, 1987). At the same time, hygrophytic to intermediate palynotaxa increase in abundance (Fig. 9) hinting at changes in the vegetation cover and climate. However, these taxa still achieve much lower abundance values than xerophytes, usually conifer pollen, as the abundance of some thick-walled and/or ornamented spores and pollen is influenced by taphonomical and transport bias due to their preferential settling in more proximal waters due to their high density (Baranyi et al., 2025). Together, these synchronous changes in carbon isotopes, microfacies, marine microfossils, and terrestrial palynomorph assemblages indicate that the NCIE in the upper Mencshely Marl Member records a critical ecological turnover and most likely represents the true onset of the Carnian Pluvial Episode in the Transdanubian Range (Fig. 9).

Although we do not have direct evidence for ocean acidification, it is a common phenomenon during past carbon cycle perturbations (e.g., Rigo et al., 2007; Hermoso et al., 2009). The abrupt proliferation of calcispheres (microfacies MF 5), most likely representing *Orthopithonella*, in the Nosztor Limestone Member (Dal Corso et al., 2021) may therefore represent a calcification overshoot (Kump et al., 2009) following a carbonate production crisis, driven by the short-lived recovery of ocean alkalinity (Trecalli et al., 2012; Jin et al., 2022). Across the wider Western Tethys realm, vegetation turnovers and the expansion of wetland habitats with lush lowland forests with enhanced photosynthetic activity (e.g., Roghi et al., 2010; Mueller et al., 2016; Baranyi et al., 2019b, 2025), together with intensified silicate weathering, likely enhanced atmospheric CO₂ drawdown (Zhang et al., 2024). At the same time, increased runoff supplied nutrients and dissolved carbonate to marine basins, promoting carbonate oversaturation and temporarily benefitting the radiation of pelagic calcifiers (Erba, 2004; Ridgwell, 2005). The recovery of carbonate precipitation was however, short-lived, restricted to the deposition of the Nosztor Member, as the subsequent clastic influx drove the complete demise of marine microbiotas as the CPE unfolded. This deterioration is reflected by the temporary

disappearance of foraminifers, the appearance of the stress resistant cavellinid *Bektasia* in the ostracod fauna (Tóth et al., 2024), and the dominance of hygrophytic and intermediate palynotaxa, typical of the *Aulisporites-Aratisporites* assemblage of the CPE (Baranyi et al., 2019b, 2025), and the temporary absence of phytoplankton and foraminiferal tests, as shown by the palynological assemblages in V-1 above 334 m (Fig. 9).

5.4. Julian-Tuvalian boundary environmental and C-cycle perturbation

In the Western as well as in the Eastern Tethys, the Julian–Tuvalian boundary (JTB) is marked by a prominent negative carbon isotope excursion (NCIE-3 of Dal Corso et al., 2018, Fig. 1A) and is accompanied by major biotic turnovers (Chen et al., 2016; Dal Corso et al., 2020). In the Transdanubian Range, the late Julian 2–early Tuvalian strata, contains one pronounced negative carbon isotope excursion, which has been recorded in all three successions, together with several minor negative swings (Fig. 7). However, the precise regional to global correlation of these curves is complicated despite the plethora of paleontological and palynological data, as robust age-markers, ammonoids or conodonts are absent in the Sándorhegy Formation.

In the palynological assemblages, characteristic Tuvalian taxa first appear at ~100 m in the Bat-2 core and at ~50–60 m in the Bht-6 core, the latter offset caused by the presence of the thick dolomitized unit of the Henye Member (Baranyi et al., 2025). In the Nosztor Valley section, a mass occurrence of *Cornucardia hornigii*, 23 m above the base of the Pécsely Member correlates with the megalodontid-bearing horizon at ~141 m in the Bat-2 core (Nagy, 1999; Nagy and Csillag, 2002). This characteristic bed, overlying the bituminous laminites of the Pécsely Member is traceable throughout the entire TR (Végh-Neubrandt, 1982; Budai et al., 1999), and in the Alpine region these fossils were traditionally regarded to indicate the Tuvalian age (Zapfe, 1972). Although this bivalve-based age constraint is not well calibrated, the lower NCIE labelled here as NCIE-3a within similar stratigraphical position both in the Nosztor Valley outcrop and Bat-2 core successions, is clearly located below what could be considered as the JTB. Based on the first occurrence of diagnostic Tuvalian palynomorphs (Baranyi et al., 2025), it seems more likely that the second NCIE (here NCIE-3b) correlates with the NCIE-3 of Dal Corso et al. (2018).

In the Bat-2, Bht-6, and Nosztor Valley isotope records also contain numerous smaller positive and negative shifts, which may reflect additional minor carbon cycle perturbations during the latest Julian 2 and earliest Tuvalian (Figs. 8–9). However, this interval, in particular the upper part of the Bat-2 succession is again characterized by pronounced variations in the amount of terrestrial vs marine organic matter (see e.g., acritarch, foraminiferal test, and prasinophyte abundance variations, Fig. 9). Consequently, the smaller isotope swings might represent only a local signal rather than reflecting global carbon cycle events.

The NCIE-3a excursion is of a much larger magnitude compared to the other smaller shifts from the early Tuvalian (Fig. 7). Nevertheless, its interpretation requires caution because it coincides with elevated TOC values and occurs within the bituminous, algal-laminated interval of the Pécsely Member (Nagy, 1999), where increased contributions of algal and bacterial organic matter may have shifted bulk organic carbon isotope values towards more negative compositions (Meyers, 1994).

The interval with NCIE-3a is, however, consistently associated in all three studied successions (Nosztor Valley, Bat-2, and Bht-6) with a distinctive low-diversity but extremely abundant ostracod fauna with *Simeonella* and *Renngartenella* (Figs. 7 and 9, Tóth et al., 2024). This characteristic fauna is widespread throughout the entire Western Tethys region and extends as far as the northern shelf of Gondwana (e.g., Gerry et al., 1990). Although its precise age is not uniformly constrained, generally spanning the Julian–Tuvalian boundary interval, its broad geographic distribution and apparently synchronous appearance calls for a regional trigger for the pandemic occurrence of this ostracod fauna. The ecological interpretation of the *Simeonella-Renngartenella*

assemblage is still highly uncertain but it most likely indicates brackish to freshwater influence and oscillating salinity (Keim et al., 2001, 2006; Forel et al., 2020). During the CPE, an intensified hydrological cycle likely increased freshwater runoff into shallow-marine settings, promoting water-column stratification, bottom-water oxygen depletion, and enhanced preservation of organic matter, as reflected by the bituminous facies of the Nosztor Valley, Bat-2, and Bht-6 successions (Tóth et al., 2024). This interpretation is consistent with findings indicating that the accelerated hydrological cycle and subsequent halocline stratification during the CPE may have served as a primary driver for the development of low oxygenation in marine basins (Lukeneder and Lukeneder, 2021). Besides global trends, the intraplatform basins in the Balaton Highland were continuously filling since the early Julian establishing a shallow ramp environment for the Sándorhegy Formation (Nagy, 1999). This unit is characterized by varied depositional settings and some of them were likely more susceptible to restriction due to sea-level fluctuations and an inherited dissected bottom topography (Nagy, 1999). Such local restriction may have enhanced organic matter preservation and influenced the magnitude of NCIE-3a, superimposing regional sedimentological controls on the global carbon cycle signal.

Carbon cycle instability likely persisted in the early Tuvalian represented by further NCIEs (NCIE-3b, 3c) and episodic revival of clastic influx. These intervals are accompanied by the recurrence of the stress-tolerant ostracod *Bektasia*, which constituted the only ostracod taxon in the Csicsó Marl Member during phases of maximum terrestrial influx (Tóth et al., 2024, Figs. 7 and 9). However, the simultaneous reappearance of rich shallow water biota including ornamented shallow-water ostracods (Tóth et al., 2024) and rich skeletal components in the microfacies (MF 8), does not point to severe environmental stress in the early Tuvalian (Fig. 9). Similarly, increasing ratios of xerophytic palynomorphs in the palynological assemblages (i.e., low H/X, I/X) even in marly clastic-rich intervals in the uppermost part of the Bat-2 core (Fig. 9), points to a progressive return to more arid conditions in the early Tuvalian and the waning of the humid episode (Baranyi et al., 2025).

Nevertheless, foraminiferal assemblages underwent some changes during the Julian–Tuvalian transition in the TR, reflecting a combination of increased terrigenous input and broader evolutionary turnover among reef-associated microfaunas (Bernecker, 2005; Martindale et al., 2019). Only ca. 52% of foraminifer taxa return in the early Tuvalian Sándorhegy Formation as the typical “Wetterstein-type” reef dweller involutinids of Triadodiscidae (*Triadodiscus* and *Lamelliconus*) with *Tubiphytes* disappeared in the Julian (Fig. 9). In contrast, the lower Tuvalian platform facies (e.g., Henye Dolomite Member, in Bht-6), likely equivalent of the Waxeneck Kalk of the Northern Calcareous Alps, upper member of the Heiligkreuz Formation in the Dolomites, and the upper part of the Raibl Group of the Karavanke Mts., is dominated by autotortids like *Aulotortus sinuosus* (Figs. 9 and S3, Bosellini and Broglio Loriga, 1965; Riedel, 1990; Dullo and Lein, 1982; Zaninetti et al., 1987; Kolar-Jurkovšek et al., 2005). Despite these compositional changes, according to the globally available Carnian records, foraminifers likely did not experience significant extinctions during the CPE and were likely able to migrate to refuge areas away from enhanced clastic influence to maintain some community structure (Gale et al., 2012; Li et al., 2025). Consequently, the reduced diversity of foraminiferal assemblages in the early Tuvalian Sándorhegy Formation is more plausibly interpreted as reflecting a protracted recovery of the carbonate factory during the waning phase of the CPE, when episodic siliciclastic influx continued to inhibit the re-establishment of diverse reef-associated communities.

6. Conclusions

Chemostratigraphical correlation across the Western Tethys shows four sharp negative carbon-isotope excursions (NCIEs) across the Carnian Pluvial Episode (CPE) that have been crucial in establishing the

timing and correlation of biotic events. Yet the lack of proper calibration of isotope curves can lead to erroneous correlation of the negative carbon isotope excursions. The Carnian successions of the Transdanubian Range (TR) represent a key CPE area in the Western Tethys where the event is marked by a pronounced shift from carbonate-dominated to mixed clastic-carbonate sedimentation. However, new conodont, microfacies, and foraminifer data from six successions in the TR together with the revision of previous biostratigraphic anchors required the recalibration of the previously published carbon isotope curves and Carnian stratigraphic correlations. The revised biostratigraphy demonstrates that the lower part of the Veszprém Formation, including the previously recorded CPE NCIE-1, is still Julian 1 (early Carnian), likely correlated to the *Aonoides* Zone. New microfacies and foraminifer data further indicate an active shallow-water microbial-skeletal carbonate factory associated with the Wetterstein reef facies from the Mencshely Marl Member, even after the presumed onset of the CPE, previously marked by NCIE-1. These findings suggest that the previously recorded NCIE-1 predates the CPE and is therefore reinterpreted as a Pre-CPE NCIE. Although this interval in the early Julian was already characterized by elevated terrestrial influx and ecosystem disturbances, its biotic impact was limited, as the carbonate factory survived the Pre-CPE NCIE. By contrast, the onset of the CPE is now placed in a higher stratigraphic position and is marked by the pronounced NCIE in the upper Mencshely Marl Member (formerly CPE NCIE-2) across multiple successions. This NCIE also coincides with major ecological reorganization among foraminifers, ostracods, phytoplankton, and the final demise of the carbonate platform. A short-lived proliferation of pelagic calcifiers, calcispheres, in the TR shortly after the onset of the CPE can be linked to a calcification overshoot after a carbonate production crisis. Peak environmental perturbation, indicated by the predominance of hygrophytic terrestrial palynomorphs, temporary collapse of marine microbiota or the occurrence of low-diversity stress faunas in ostracods, is restricted to the late Julian 2. This interval was followed by the waning of the CPE and the recovery of the shallow water carbonate factory in the early Tuvallian, despite continued minor carbon cycle perturbations. Overall, the Carnian of the TR records a prolonged interval of environmental instability beginning in the early Julian, indicated by smaller fluctuations in clastic influx, and changes in conodont or hygrophytic palynomorph abundance. However, most pronounced environmental stress and biotic turnovers were concentrated in two discrete phases: the onset of the CPE and the end of Julian 2, both associated with marked negative carbon isotope excursions (NCIEs). Recovery, characterized by reduced siliciclastic input and the re-establishment of marine microbiotas, already commenced in the early Tuvallian.

CRediT authorship contribution statement

Viktória Baranyi: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Viktor Karádi:** Writing – original draft, Visualization, Investigation, Formal analysis. **Dominik Telek:** Writing – review & editing, Investigation. **Tamás Budai:** Writing – review & editing. **Xin Jin:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Béla Raucsik:** Writing – review & editing. **György Czuppon:** Methodology. **Biao Chang:** Methodology. **Emőke Tóth:** Writing – original draft, Visualization, Investigation, Funding acquisition, Formal analysis.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT and DeepL in order to improve the language and readability of the text. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.sedgeo.2026.107184>.

Data availability

Data will be made available on request.

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