Palaeogeography, Palaeoclimatology, Palaeoecology 587 (2022) 110793

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Change from shallow to deep-water environment on an isolated carbonate platform in the Middle Triassic of the Transdanubian Range (Hungary)

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ARTICLE INFO

Editor: Isabel Montanez

Keywords:
Anisian
Ladinian
Ammonoids
Conodonts
Ostracods
U-Pb geochronology

ABSTRACT

The stratigraphic and paleoecologic investigations of the Middle Triassic Kádárta section of the western part of the Transdanubian Range (Hungary) let an insight to the drowning of an isolated carbonate platform and the deposition of the following pelagic successions in deep neritic and bathyal environment. The biostratigraphic and radiometric ages revealed the presence of a gap between the Pelsonian (Middle Anisian) shallow-marine carbonates and the overlying deep-water succession, since the onset of pelagic sedimentation was dated as late Illyrian (latest Anisian). This suggests that the study area was located on a relatively high paleotopographic position after the break-up of the Neotethys in the late Pelsonian. Correlation with other localities of the western Neotethys indicates that some sections were located either on rapidly subsiding blocks (e.g., Klisura – Dinarides, Schreierkogel – Northern Calcareous Alps, Baradla Cave – Aggtelek-Rudabánya Unit) or on more emerged highs (Rid – Dinarides). The integrated ammonoid and conodont biostratigraphy accompanied by U—Pb ages provided a good opportunity for correlations with Ladinian key sections (Bagolino, Monte San Giorgio, Rio Nigra) from the Southern Alps.

1. Introduction

During the Middle Anisian the passive margin of the western Neotethys was affected by extensional tectonic activity due to the westward opening of the ocean (Bertotti et al., 1993; Gaetani, 2010; Gawlick et al., 2012, 2021 and further references therein). The previously existed carbonate ramp disintegrated along normal faults and a horst-and-graben topography was formed in the late Pelsonian (late Middle Anisian) in the Balaton Highland area (Budai and Vörös, 1993, 2006 and further references therein). The rapidly subsiding basins were flooded ("Reifling Event"; Schlager and Schöllnberger, 1974) whereas the shallow-marine carbonate factories still survived for a short period on the elevated blocks as isolated carbonate platforms. With the overall flooding of these horsts in the middle-late Illyrian (Late Anisian) (Gawlick et al., 2021) deep-marine depositional environment dominated in large part of the Alpine region of the western Tethys shelf during the Ladinian.

A segment of this shelf is represented by the Transdanubian Range Unit (TR; Fig. 1) where the Middle Triassic evolution of the western Neotethys can be traced in several successions (Budai and Vörös, 2006). The aim of the present study is to investigate the development of the depositional regime of an emerged horst from the middle Anisian to the late Ladinian based on the recently exposed section in the Kádárta quarry. A recently introduced change in the Anisian ammonoid zonation (Monnet et al., 2008; Balini et al., 2010; Ogg, 2012; Jenks et al., 2015; Vörös, 2018) is discussed, since it deeply affects the chronostratigraphic assignment and consequently the precise dating of events in the western Neotethys Realm. Accurate correlations of the Kádárta section with other successions from various regions of the western Neotethys are performed through ammonoid and conodont biostratigraphy supplemented with zircon U—Pb geochronology, and ostracod paleoecology is used for comparison of the depositional environments of different

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https://doi.org/10.1016/j.palaeo.2021.110793
Received 16 March 2021; Received in revised form 12 November 2021; Accepted 9 December 2021
Available online 14 December 2021

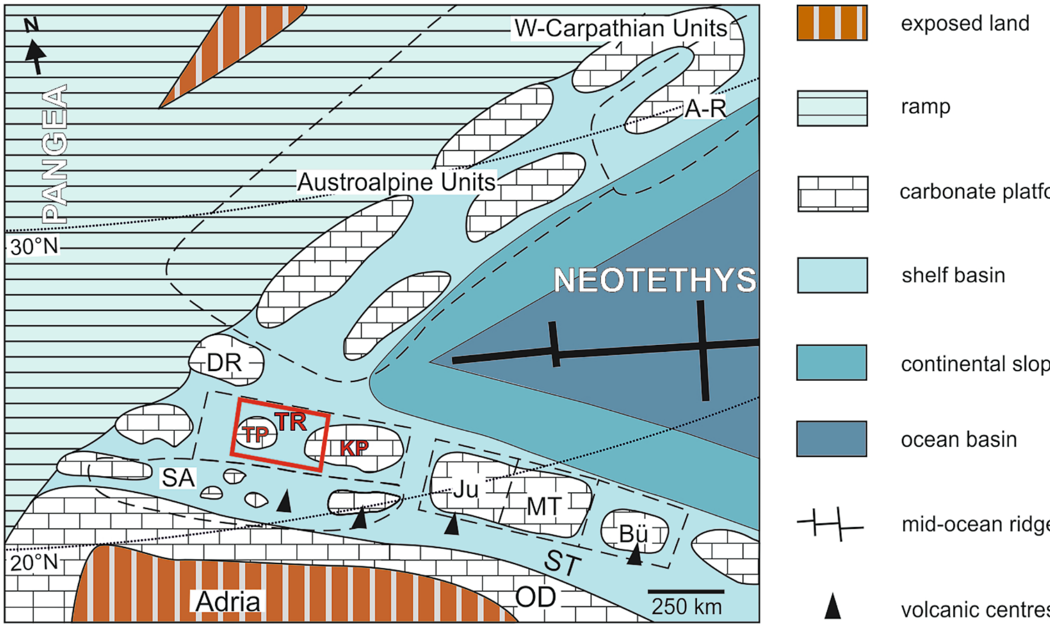

Fig. 1. Palaeogeographic reconstruction for the Middle Triassic of the western part of the Neotethys with the position of the Transdanubian Range Unit (TR) (after Budai et al., 2017, modified). The red rectangle marks the area shown in detail in Fig. 2B. Abbreviations: A-R – Aggtelek–Rudabánya Units; Bü – Bükk Unit; DR – Drau Range; Ju – Julian Unit; KP – Kádárta Platform (TR); SA – South-Alpine Units; MT – Mid-Transdanubian Unit; OD – Outer Dinarides; ST – Slovenian Trough; TP – Tagyon Platform (TR). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

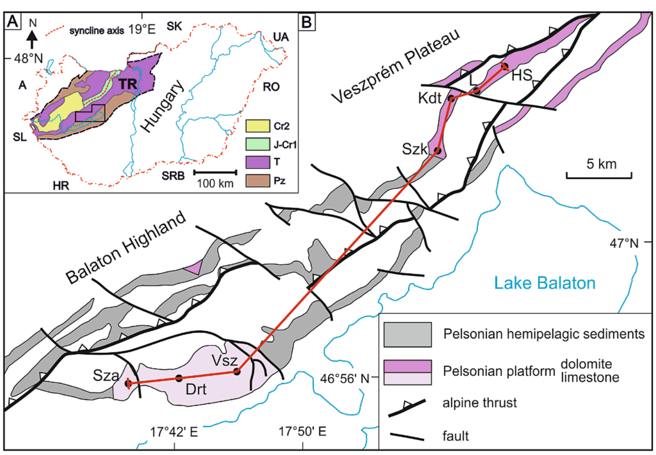

Fig. 2. A) Simplified pre-Cenozoic geological map of the Transdanubian Range Unit (TR). Legend: Pz – Paleozoic formations; T – Triassic formations; J-Cr1 – Jurassic–Lower Cretaceous formations; Cr2 – Upper Cretaceous formations; B) Surface extension of middle Anisian formations of the Balaton Highland and the Veszprém Plateau with colours referring to the Pelsonian facies (after Budai and Vörös, 2006, modified). Red line shows the location of the cross-section presented in Fig. 3. Abbreviations: Drt – Dörgicse Drt-1 borehole, HS – Hajmáskér–Sóly; Kdt – Kádárta; L – Litér; Sza – Szentantalfa; Szk – Szentkirályszabadja; Vsz – Vászoly. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

localities in the area.

2. Geological setting

The Balaton Highland is located in the southwestern part of the Transdanubian Range Unit (TR) in the western part of Hungary (Fig. 2A). Forming the southeastern limb of the SW–NE directed syncline structure of the TR, the Balaton Highland is made up of Lower Paleozoic and Upper Permian to Triassic formations. The Alpine compression events led to folding and significant southeast vergent overthrusting of the Paleozoic–Triassic rock units (Fig. 2B). The lateral relations of different Middle Triassic facies can be traced through numerous localities along a more or less SW-NE directed cross section (Fig. 2B, Fig. 3).

The studied section (Fig. 4) is exposed in an active quarry south of Kádárta (47°6′32.07″N, 17°57′50.44″E) near Veszprém on the Veszprém Plateau (Fig. 2B). The lowermost 10 m thick interval of the section is characterized by a cyclic alternation of thick bedded and medium to thin bedded–laminated dolomite of the Tagyon Fm (Fig. 5A). This platform carbonate succession is directly overlain along a sharp contact by the lower part of the basinal Vászoly Fm, comprising volcanic tuffs, and tuffites with dolomite interbeds (Fig. 5B). The tuffaceous dolomite is followed by a thick bedded, matrix-supported dolomite breccia-conglomerate unit of toe of slope facies (Figs. 5B, 6). Upsection the thickness of the beds decreases, and marl intercalations appear. Slump folds were observed in the upper part of this unit. The sedimentary breccia–conglomerate bed-set has a tectonically disturbed contact with the upper part of the Vászoly Fm that is made up of bedded dolomite and volcanic tuff (Fig. 7A). The Vászoly Fm is overlain by a well-bedded, nodular, siliceous limestone succession of the deep-marine Buchenstein Fm, containing thin tuff or tuffitic clay intercalations (Fig. 7B).

3. Material and methods

Algae fragments were observed in the middle part of the Tagyon Fm (Kd-5; Fig. 4). A 5 × 5 cm thin section was prepared, in which remains of dasycladalean algae were found.

A total of five samples were collected for conodont biostratigraphic investigations from the carbonate interbeds of the Vászoly Fm and from the nodular limestone of the Buchenstein Fm (K; Fig. 4). The weight of each sample was between two and three kg. Samples were processed in the laboratory of the Department of Palaeontology of the Eötvös Loránd University in Budapest using acetic acid diluted to 10%, and washed twice a week. Washing residue was collected on a 125 μm mesh size sieve. Conodont elements were found in all samples and ostracods were recovered from four of the conodont samples (K-3, K-14, K-2, K-1). Conodont and ostracod specimens were coated with ~5 nm of gold-palladium sputter to avoid charging of sample surface and scanning electron micrographs of the specimens were taken with a Hitachi S-

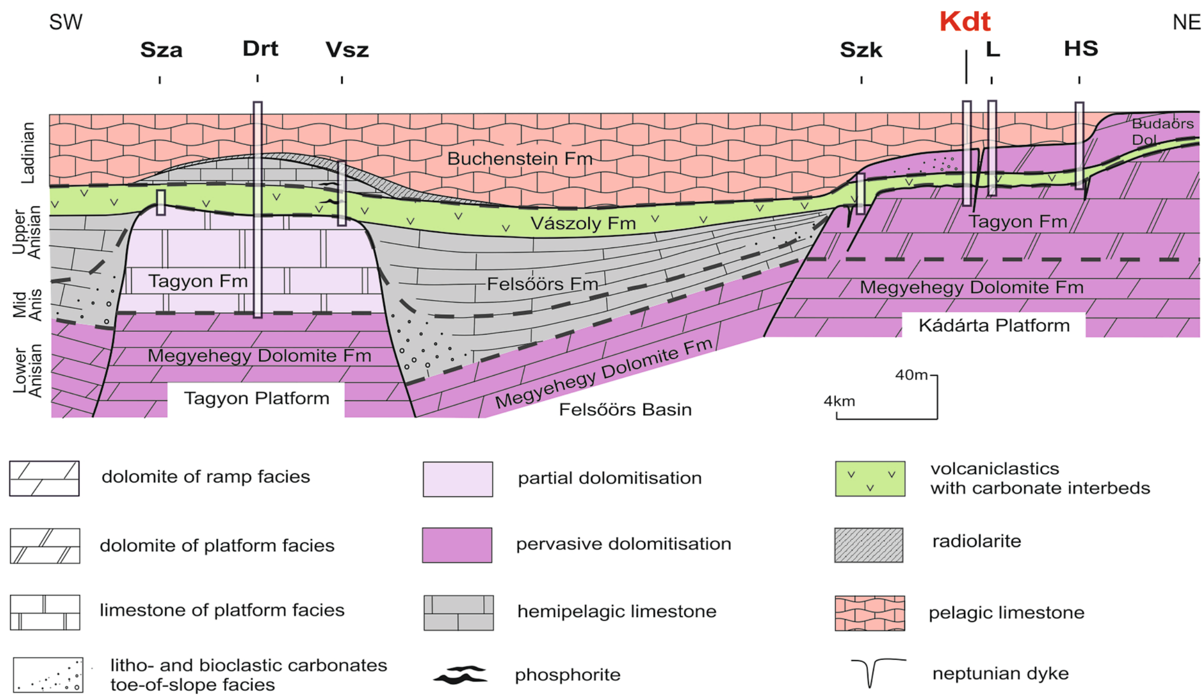

Fig. 3. Geological profile of the Anisian-Ladinian formations of the Balaton Highland and the Veszrém Plateau showing the development history of the area. Lower Anisian: shallow-water sedimentation (Megyehegy Dolomite Fm) on a uniform carbonate ramp. Middle Anisian: formation of a horst-and-graben morphology, deposition of deeper-water sediments (Felsőörs Fm) in the subsided Felsőörs Basin, continuous shallow-water sedimentation (Tagyon Fm) on the isolated horsts (Tagyon Platform and Kádárta Platform), downfaulting of a marginal block of the Kádárta Platform. Upper Anisian: continuous hemipelagic sedimentation in the Felsőörs Basin, flooding of the isolated platforms and deposition of volcaniclastics with deeper-water carbonate interbeds (Vászoly Fm) in the whole area. Ladinian: prograding shallow-water carbonates (Budaörs Dolomite Fm) above the former Kádárta Platform, widespread deep-marine sedimentation above the former basin and isolated highs (Buchenstein Fm). Transparent rectangles mark the stratigraphic position of the studied Kádárta section and other sections discussed in the text and shown in Fig. 13 (after Budai and Vörös, 2006; Haas et al., 2014, modified). For abbreviations see Fig. 2.

2600 N SEM at the Department of Botany of the Hungarian Natural History Museum. All specimens are deposited at the Department of Palaeontology of the Eötvös Loránd University in Budapest.

Bed-by-bed ammonite collection could not be carried out in the active Kádárta quarry, however, one ammonite specimen was found in the basal layer of the dolomite breccia unit (Fig. 4), right above the conodont sample K-13.

Two tuff samples were taken for isotope geochronology, one from a coarse-grained lapilli tuff in the lowermost part of the Vászoly Formation and another from the biotite-bearing tuff in the upper part of the Vászoly Formation (Kz; Fig. 4). The in-situ zircon U—Pb dating was performed by laser-ablation single-collector sector-field inductively coupled plasma mass spectrometry (LA-SF-ICP-MS). The method employed for analysis is described in details by Frei and Gerdes (2009) and Dunkl et al. (2019). The number of single-grain ages per sample ranges between 40 and 49. The concordia plots and age spectra were constructed by the help of Isoplot/Ex 3.0 (Ludwig, 2012) and Isoplot R (Vermeesch, 2018). The dated zircon crystals have lower radiation damage density, than the zircon reference materials used for correction of the fractionation. The increasing radiation damage density has an impact on the ablation rate of zircons (Marillo-Sialer et al., 2014) and it needs a correction that is based on the offset between the TIMS ages and laser ablation ages detected on a series of reference material having different degree of metamictization (Sliwinski et al., 2017). These radiation damage corrected ages can be considered as the most reliable approximation of the crystallization age of zircons.

4. Results

4.1. Floral and faunal content

The dasycladalean algae specimen from sample Kd-5 of the Tagyon Fm was determined as *Physoporella* sp. (Fig. 8A).

The lower part of the Vászoly Fm (sample K–13) yielded the conodonts *Paragondolella excelsa* Mosher, 1968, *P. fueloepi* (Kovács, 1994), *P. trammeri* (Kozur in Kozur and Mock, 1972), *Neogondolella cornuta* Budurov and Stefanov, 1972, *N. pseudolonga* (Kovács et al., 1980), *N. transita* (Kozur and Mostler, 1971) and *Gladigondolella* sp. (Fig. 9). The conodont species *Sephardiella mungoensis* (Diebel, 1956), *S. diebeli* (Kozur and Mostler, 1971), *P. inclinata* (Kovács, 1983), *P. foliata* Budurov, 1975 and *Gl. tethydis* (Huckriede, 1958) were found in the samples from the Buchenstein Fm (K-3, K-14, K-2, K-1).

The ammonite specimen encountered in the basal layer of the dolomite breccia could be classified as *Eoprotrachyceras* cf. *gervasuttii* Fantini Sestini, 1994 (Fig. 10).

Ostracods are represented by both single valves and carapaces. Specimens are mostly delicate single valves with fine details preserved due to the partial silicification of the carbonate skeletons and host limestone. The good preservation allowed in most cases the identification of diagnostic morphological characters and the classification of the specimens in species level. Diverse benthic ostracod faunas were identified from the samples (K-3, K-14, K-2, K-1) of the Buchenstein Fm (Fig. 11, Table S1). The assemblages are composed of 18 taxa belonging

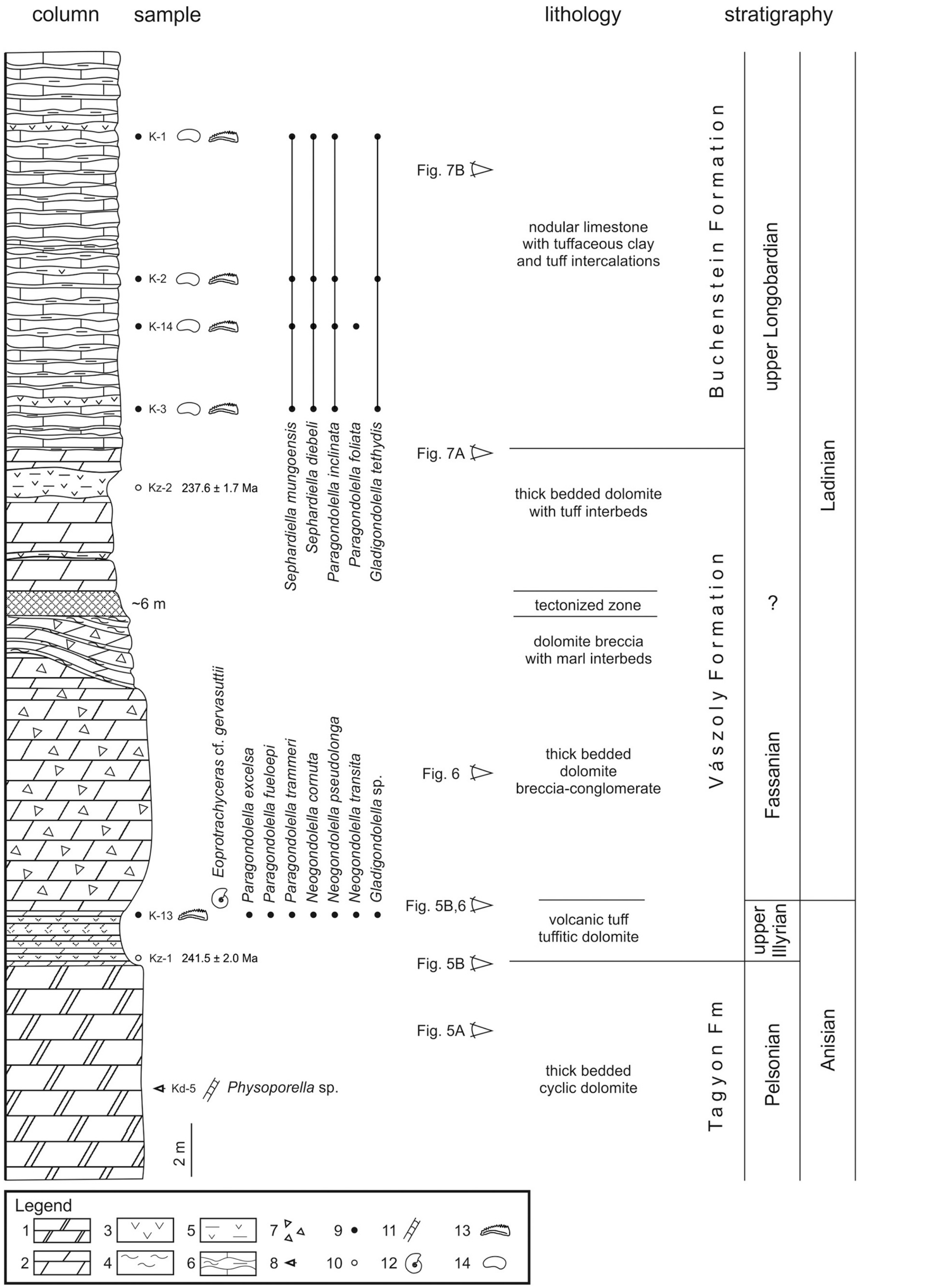

Fig. 4. Stratigraphic log of the studied section of the Kádárta quarry (Veszprém Plateau) showing the sites of the taken samples and the distribution of the dasycladalean algae, ammonoid and conodont taxa. Legend: 1 – bedded dolomite, 2 – dolomite, 3 – tuff, tuffite, 4 – marl, 5 – weathered tuff, 6 – nodular, siliceous limestone with marl intercalations, 7 – breccia, 8 – sample for carbonate microfacies, 9 – sample for micropaleontology, 10 – sample for zircon, 11 – dasycladalean algae, 12 – ammonite, 13 – conodont, 14 – ostracod.

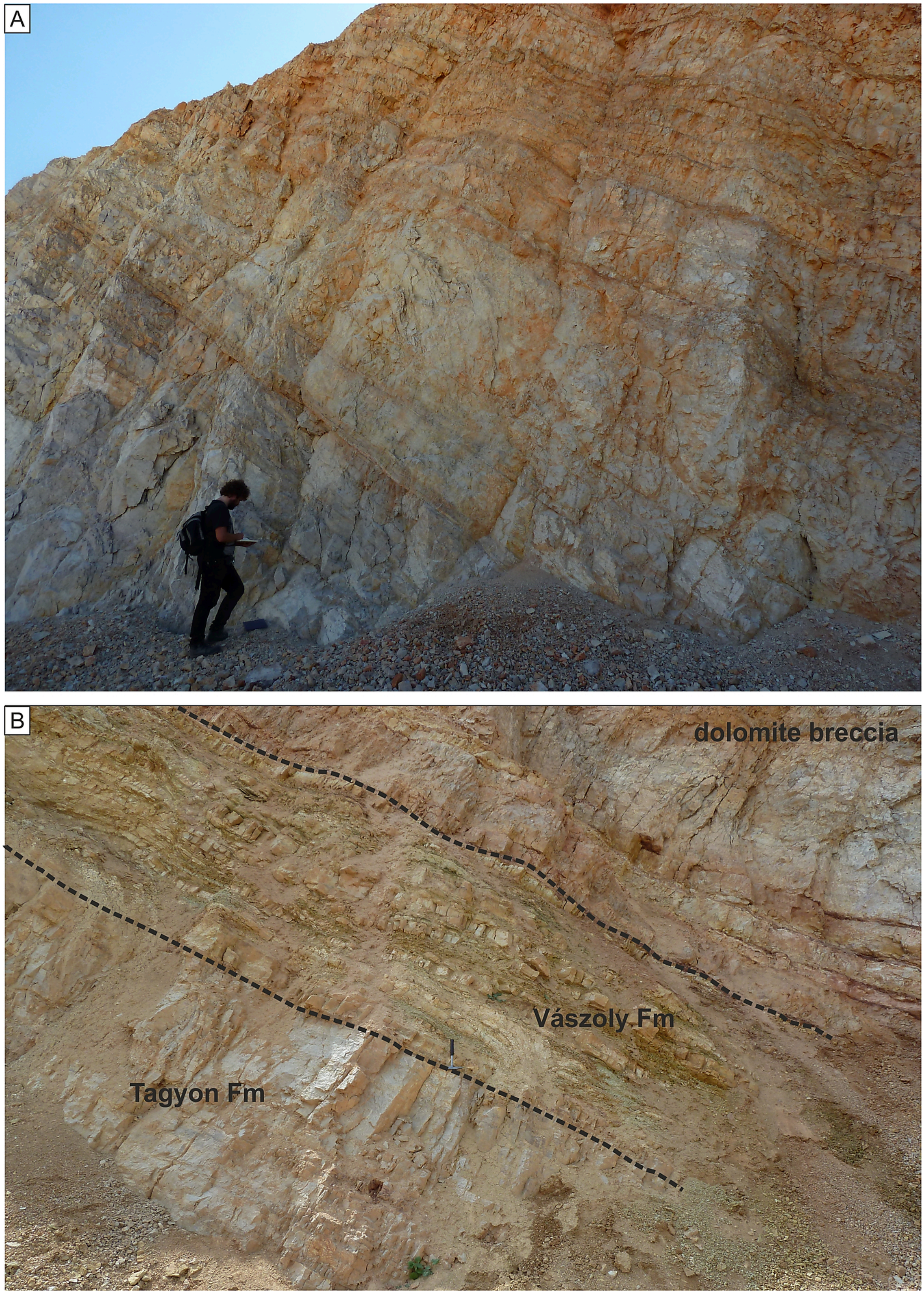

Fig. 5. A) Middle Anisian cyclic platform carbonate of the Tagyon Fm in the Kádárta quarry; B) sharp contact (hammer) between the Tagyon Fm and the overlying tuffitic Vászoly Fm.

Fig. 6. Thick bedded dolomite breccia–conglomerate above the lower part of the Vászoly Fm.

to eight genera and six families (Polycopidae, Healdiidae, Bairdiidae, Beecherellidae, Tricorninidae and Macrocyprididae). All samples provided similar assemblages; there is no trend in the ratio of different taxa. The fauna is dominated by species of the smooth healdioid genus *Hungarella*, which represent 48% of the total number of specimens. The proportion of the genera *Acanthoscapha, Nagyella* and *Praemacrocypris* is 5%, and that of the smooth bairdioids is 33%. The remaining 14% is given by opportunistic nektobenthic polycopids. (See Table S1 for the list of species.)

4.2. U—Pb dating

Zircon crystals gave an age of 241.5 ± 2.0 Ma for the lower sample (Kz-1; Fig. 4) and an age of 237.6 ± 1.7 Ma for the upper sample (Kz-2; Fig. 4; Table S2; Fig. S1).

5. Discussion

5.1. Remarks on the ammonoid and conodont zonal schemes

The Triassic was primarily subdivided on the base of ammonoids, and in former times, before the discovery of various microfossil groups, ammonoid zonation was the most reliable tool in the biostratigraphy of open-marine successions. More and more frequent investigations on pelagic microfossils (e.g., conodonts) and cross correlations in ammonoid-bearing localities during the 20th century allowed the accurate biostratigraphic dating of sections that are poor in or lack ammonoids. Intentions for the establishment of a conodont zonation similar to the ammonoid zonation had formed among conodont specialists, however, such a zonal scheme has never been standardized. The Middle Triassic integrated ammonoid and conodont zonation presented herein (Fig. 12) is a combination of the zonations by Krystyn (1983), Kovács et al. (1994), Kozur (2003), Vörös et al. (2003) and Vörös (2018). Due to the slightly different timing of turnovers in the evolution of ammonoids and conodonts, the boundaries of ammonoid and conodont biozones are often not concurrent (Krystyn, 1983; Kozur, 2003). This problem became the subject of scientific discussions particularly in the case of the definition of the Anisian-Ladinian boundary, before the base of the Curionii Zone was chosen to mark the base of the Ladinian (Fig. 12). This definition makes it quite hard to catch the Anisian-Ladinian boundary by conodonts, because most of the late Anisian conodont species either disappear before the boundary or range up in the Ladinian (e.g., Brack et al., 2005).

As to the position of the Pelsonian-Illyrian boundary (middle-late Anisian) similar problem raises, since a profound change was proposed lately in the ammonoid zonation of this interval. The base of the Illyrian, which was marked for a long time by the upper boundary of the Binodosus Zone/Subzone (e.g., Kovács et al., 1994; Kozur, 2003; Vörös et al., 2003), was suggested to be placed on the upper boundary of the preceding Balatonicus Zone (dashed line in Fig. 12) due to correlative reasons in ammonoid biostratigraphy (Monnet et al., 2008; Balini et al., 2010; Ogg, 2012; Jenks et al., 2015; Vörös, 2018). The upper boundary of the Binodosus Zone/Subzone is an important level in conodont evolution, since it coincides with the disappearance of the typical middle Anisian species *Paragondolella bulgarica* and *Nicoraella kockeli* (Germani, 2000; Kozur, 2003; Kovács and Rálisch-Felgenhauer, 2005). These conodont species are used in many sections to confirm that the drowning of the Steinalm Carbonate Ramp and equivalents ("Reifling Event") occurred not later than the late Pelsonian (e.g., Sudar et al., 2013; Velledits et al., 2017; Gawlick et al., 2021). Moving the Pelsonian-

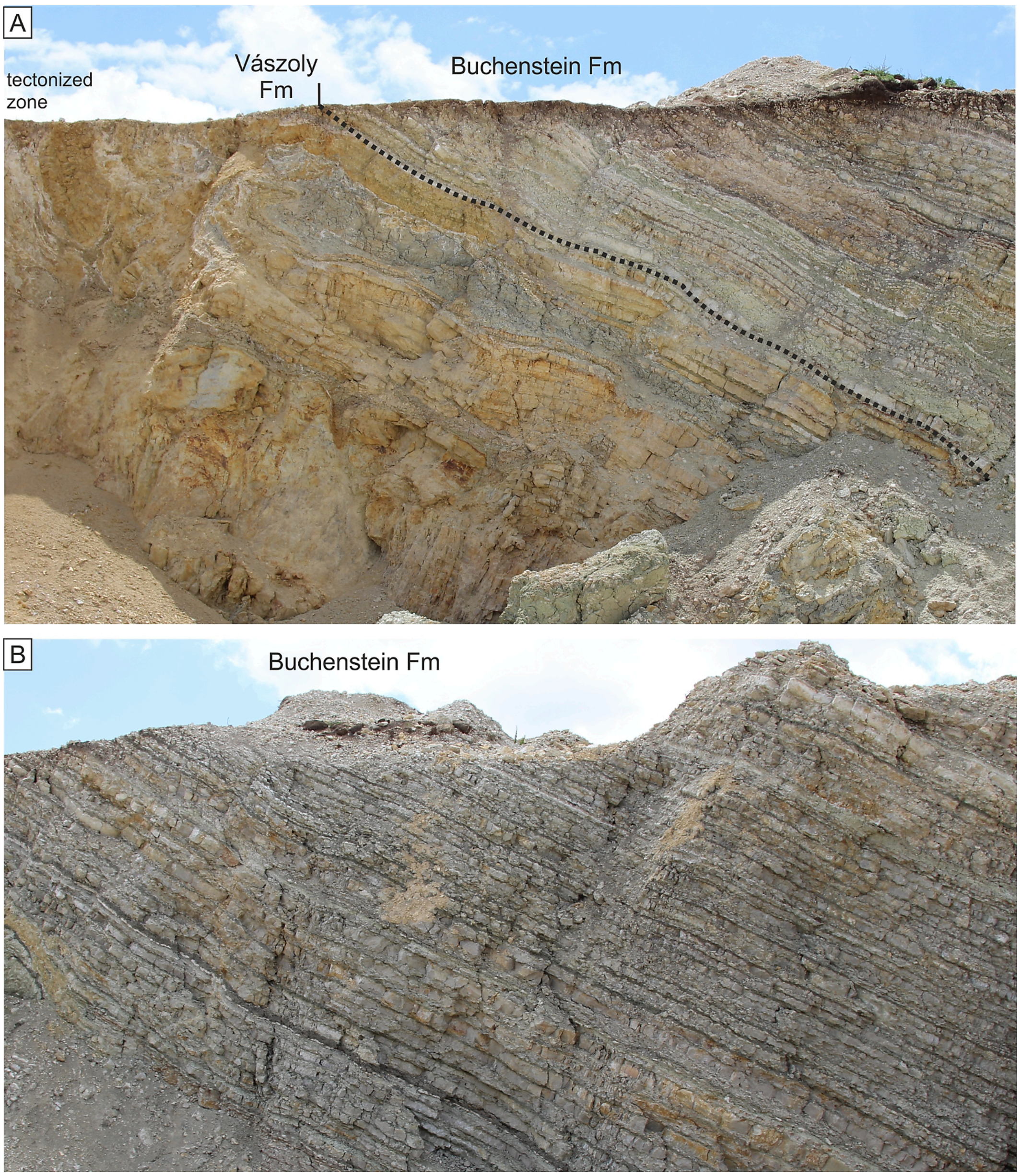

Fig. 7. The Ladinian sequence of the Kádárta quarry: A) the upper part of the Vászoly Fm and the overlying Buchenstein Fm; B) the upper part of the Buchenstein Fm.

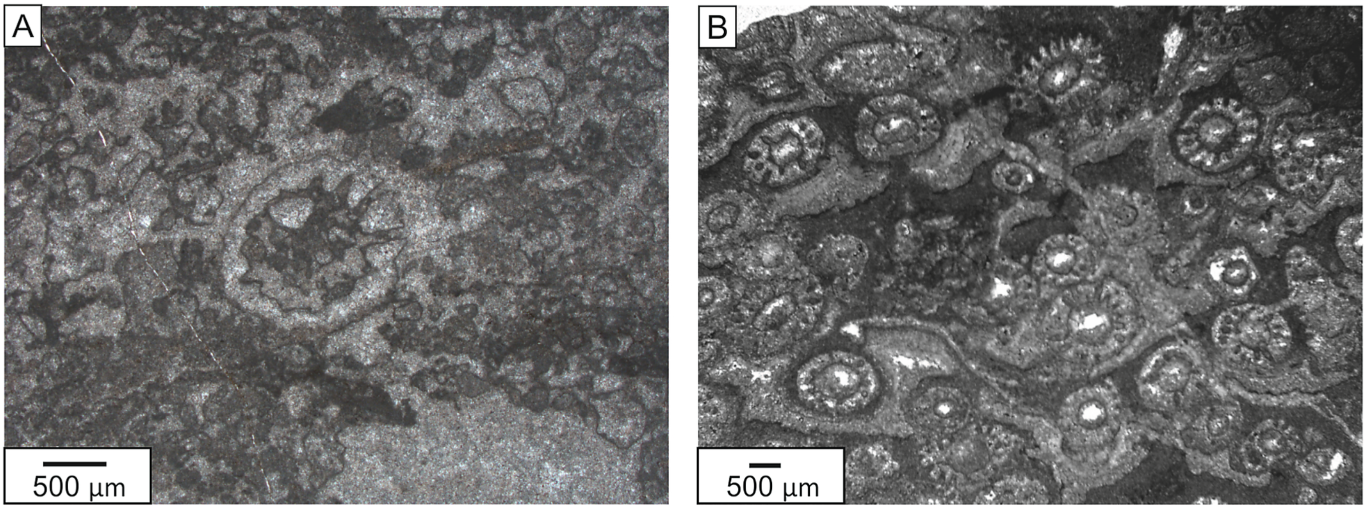

Fig. 8. Dasycladalean algae from the Tagyon Fm: A) *Physoporella* sp., Kádárta quarry; B) *Physoporella pauciforata*, Szentkirályszabadja section (Budai and Vörös, 2006).

Illyrian boundary to the base of the Binodosus Zone/Subzone places the conodont faunal turnover in the early Illyrian. Consequently, it will be impossible to determine whether deep-marine sediments started to accumulate already in the late Pelsonian or only in the Illyrian in sections where ammonoids are absent. Moreover, this act would affect the stratigraphic ranges of shallow-water organisms (e.g., algae and foraminifera) as well, which are calibrated with pelagic microfossils in most cases (e.g., Gawlick et al., 2021). Considering the above mentioned facts and the aim for accurate correlation, the Pelsonian-Illyrian boundary is kept in this study as it was before, i.e. at the upper boundary of the Binodosus Zone/Subzone.

5.2. Age assignment

Based on the *Physoporella* dasycladalean algae from sample Kd-5, this level of the Tagyon Fm can be assigned to the Pelsonian Substage of the Anisian (Budai and Haas, 1997; Vörös et al., 2003). The conodont assemblage from the lower part of the Vászoly Fm indicates the upper Illyrian – lower Fassanian interval (upper *Paragondolella trammeri* Zone to lower *Neogondolella praehungarica* Zone; Figs. 4, 12) based on similar faunas of Kovács et al. (1980), Kovács (1993, 1994, 2011) and Brack et al. (2005), although the zonal marker species *N. praehungarica* is absent in the sample. The ammonite *Eoprotrachyceras* cf. *gervasuttii* at the base of the dolomite breccia-conglomerate is characteristic of the lower Fassanian Curionii Zone (Vörös, 1998). The biostratigraphic dataset is in agreement with the U—Pb age (241.5 ± 2.0 Ma) from below, since the Anisian-Ladinian boundary falls in the 240–242 Ma interval (Brack et al., 2005). The newly gained age data most likely indicate a gap between the shallow water carbonate succession and the overlying basinal sequence; however, the exact range of this gap is not quite clear.

The conodont association of the four samples from the Buchenstein Fm represents the upper Longobardian *Sephardiella diebeli* Zone (Figs. 4, 12) based on the comparison with the faunas of Brack and Nicora (1998), Balini et al. (2000), di Stefano et al. (2014) and Maron et al. (2019). This conodont zone corresponds to the upper Archelaus to Regoledanus Ammonoid Zones (Krystyn, 1983). The radiometric age (237.6 ± 1.7 Ma) from below the conodont samples fits well the conodont-based age assignment.

5.3. Paleoecology and paleoenvironment

The composition of the ostracod fauna from the upper Longobardian layers of the Kádárta section can be described as a mixture of taxa from deep-marine and open-marine shelf habitats. The species assigned to the genus *Hungarella* occur in all water depth below 30–50 m in the Tethys (Kozur, 1991). *Acanthoscapha, Nagyella* and *Praemacrocypris* are typical 'palaeopsychrospheric' (sensu Kozur, 1991) or Thuringian-type (sensu Bandel and Becker, 1975) ostracod genera. Such thin-shelled, often smooth podocopids possessing long spines and lacking eye-tubercles are known from the Silurian to the Triassic, and inhabited deep-marine environments characterized by water depths between 200 and 2000 m and connections with the open ocean (Kozur, 1972, 1991). The relatively high proportion of the nektobenthic polycopids in the studied ostracod fauna has no special palaeoecological value, however, they are commonly associated with Middle Triassic deep-marine assemblages (e.g., Kozur, 1991; Crasquin-Soleau and Grădinaru, 1996; Sebe et al., 2013). Recent representatives occur from abyssal ocean depths (Karanovic and Brandão, 2012, 2016) to less saline estuarine environments (Tanaka and Tsukagoshi, 2010).

The relatively low abundance of archaic elements such as *Nagyella* and *Acanthoscapha*, and the absence of neritic, shallow-water forms suggest an open-marine depositional environment below the storm-wave base, most probably in the deep neritic to upper bathyal region with water depth between 200 and 500 m. Similar Triassic faunas are known in the Balaton Highland (Hungary) from the Illyrian (Trinodosus Zone) basinal sediments of the Felsőörs section (Kozur, 1970; Kozur, 1971a, 1971b, 1971c; Bunza and Kozur, 1971; Monostori, 1995) and the Fassanian to Longobardian part of the Buchenstein Fm of the Litér and Nemesvámos sections (Monostori and Tóth, 2013). Moreover, Tethyan 'palaeopsychrosphaeric' ostracod faunas were recognized in Aegean to lower Pelsonian strata of North Dobrogea, Romania (Crasquin-Soleau and Grădinaru, 1996; Sebe et al., 2013) and upper Pelsonian beds in the Northern Calcareous Alps, Austria (Reifling Fm; Mette et al., 2015). However, the former fauna suggests deeper, the latter one somewhat shallower open-marine environment than the depositional environment of the studied strata in the Kádárta quarry.

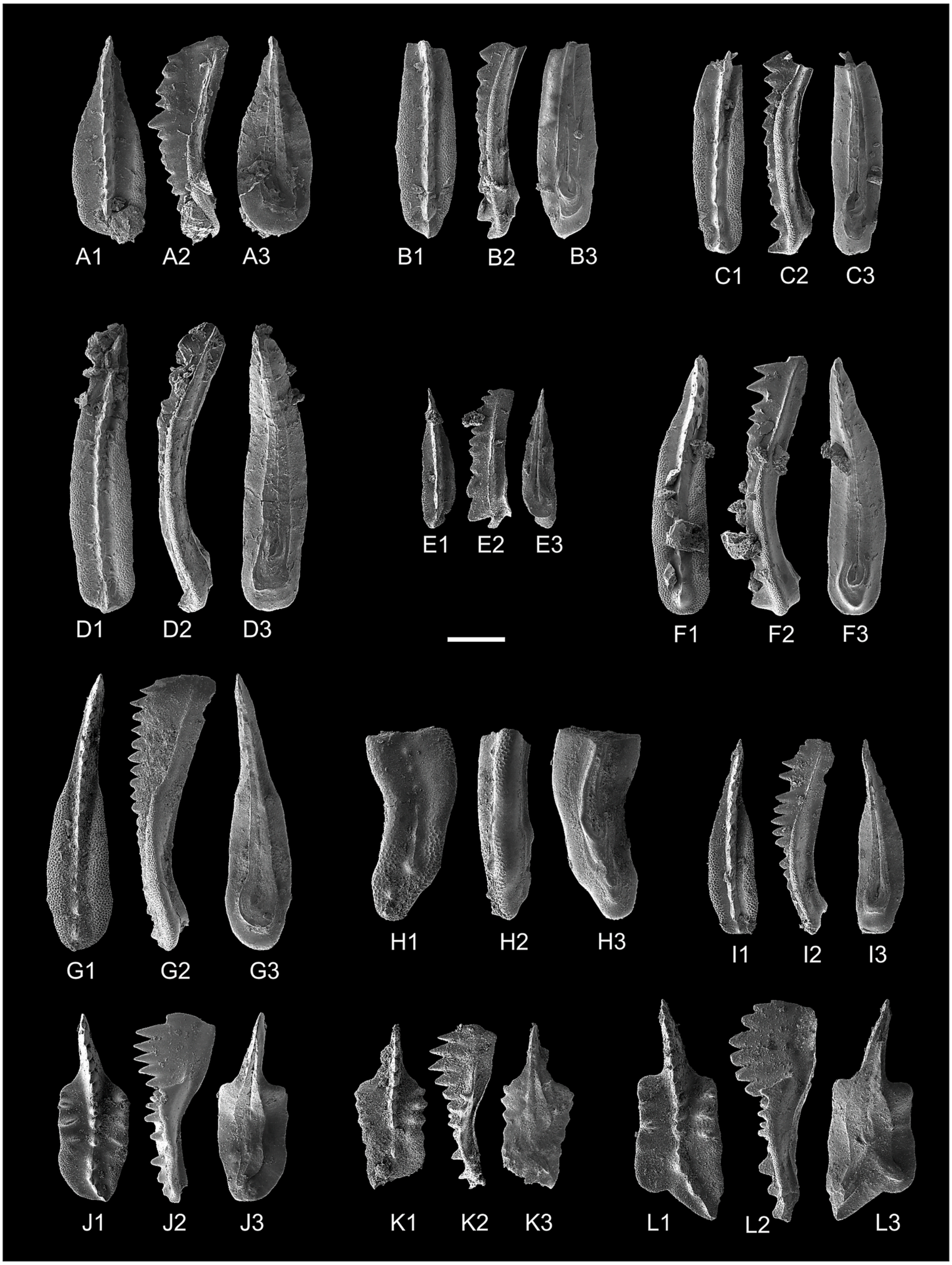

Fig. 9. Conodonts of the Kádárta section. A) *Paragondolella excelsa*, sample K-13; B) *Neogondolella transita*, sample K-13; C) *Neogondolella pseudolonga*, sample K-13; D) *Neogondolella cornuta*, sample K-13; E) *Paragondolella trammeri*, juvenile growth stage, sample K-13; F) *Paragondolella trammeri*, sample K-13; G) *Paragondolella inclinata*, sample K-1; H) *Gladigondolella tethydis*, sample K-1; I) *Paragondolella foliata*, sample K-1; J, K) *Sephardiella mungoensis*, sample K-1; L) *Sephardiella diebeli*, sample K-14. 1: upper view, 2: lateral view, 3: lower view. Scale bar: 200 μm.

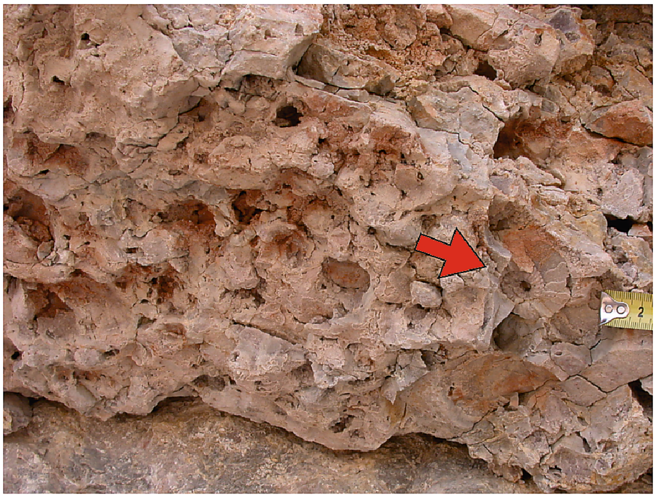

Fig. 10. Ammonite *Eoprotrachyceras* cf. *gervasuttii* (red arrow) in the lowermost bed of the breccia-conglomerate unit in the Kádárta section. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.4. Local correlation

Beside the emerged block (Kádárta Platform) documented in the Kádára quarry, another Pelsonian high is known from the central part of the Balaton Highland (Tagyon Platform) (Fig. 3; Budai and Vörös, 2006). The drowning of both isolated carbonate platforms can be detected in several sections in the area, which provides a good opportunity for comparison of the timing of flooding through biostratigraphic correlation (Fig. 13).

Likewise in the Kádárta section (Kdt), rich dasycladalean algae flora confirms the Pelsonian age of the cyclic, shallow-marine platform carbonates (Tagyon Fm) in the Dörgicse Drt-1 borehole (Drt, Tagyon Platform), the Szentkirályszabadja section (Szk, Kádárta Platform; Fig. 8B) and the Hajmáskér-Sóly area (HS, Kádárta Platform). At Szentkirályszabadja even the Balatonicus Subzone was documented based on the presence of the ammonite *Balatonites balatonicus* in the cyclic platform dolomite (Vörös et al., 2003; Budai and Vörös, 2006). The most part of the Pelsonian was still the interval of shallow-marine sedimentation on the isolated platforms (Fig. 3).

The basal part of the deeper-marine Vászoly Fm of the Kádárta section could not be assigned to an ammonoid zone in the lack of ammonoids. However, the upper Illyrian Reitzi Zone (Reitzi and Avisianum Subzones) recorded in the nearby Litér section (L, Kádárta Platform) and the Hajmáskér-Sóly area (Vörös, 1998; Budai et al., 2001; Vörös, 2018) suggests that the tuffaceous dolomite beds below the dolomite breccia in the Kádárta quarry might also represent the upper Illyrian (upper Reitzi Zone). The presence of beds assignable to the uppermost Illyrian Secedensis Zone remains uncertain, because the base of the dolomite breccia is already Fassanian in age (Curionii Zone) and the conodonts recovered from this interval may indicate either the uppermost Illyrian or the lowermost Fassanian (upper *Paragondolella trammeri* Zone or lower *Neogondolella praehungarica* Zone).

Unlike the previous localities, the base of the Vászoly Fm was assigned to the Camunum Subzone of the lower Illyrian Trinodosus Zone in the Szentkirályszabadja section of the Kádárta Platform, as well as in the Vászoly (Vsz) and Szentantalfa (Sza) sections and the Dörgicse Drt-1 borehole of the Tagyon Platform (Vörös, 1998, 2018). This clearly indicates that accumulation of pelagic sediments on the Tagyon Platform and at Szentkirályszabadja started in the late part of the early Illyrian, whereas on the inner part of the Kádárta Platform only later, i.e. in the late Illyrian (Fig. 3). Since the shallow-marine platform carbonates were dated as lower Pelsonian (Balatonicus Subzone) based on *Balatonites balatonicus* as mentioned before, the range of the gap between the Tagyon Fm and the overlying Vászoly Fm seems to attain four ammonoid subzones in Szentkirályszabadja and maximum four ammonoid subzones in the area of the Tagyon Platform. In the Hajmáskér-Sóly area, the Litér section and supposedly also in the Kádárta section the range of the gap can represent maximum eight ammonoid subzones, although it cannot be excluded that the shallow-marine sedimentation continued also in the Illyrian. Szentkirályszabadja might have been a downfaulted block at the margin of the Kádárta Platform. The faulting and subsidence of this marginal block might have been related to the final break-up of the Neotethys in the late Pelsonian (as proven by Gawlick et al. (2021) in several sections) and from that time onwards it was most probably situated more or less at the same paleotopographic level as the Tagyon Platform.

The progressive sea-level rise in the Ladinian resulted in widespread deep-marine sedimentation in the former Anisian basins and also above the submarine highs (Fig. 3). Ammonoids were not found in the Buchenstein Fm of the Kádárta quarry, but the conodonts of the *Sephardiella diebeli* Zone suggest that the Buchenstein Fm of the studied section can be assigned to the upper Archelaus Ammonoid Zone and thus cannot be older than upper Longobardian (Fig. 12). As a consequence, the dolomite breccia and the overlying thick bedded dolomite should represent the whole Fassanian and early Longobardian. This dolomite conglomerate-breccia within the Vászoly Formation (Fig. 4) can be interpreted as a proximal gravity mass flow deposit accumulated at the toe of the foreslope of the prograding Budaörs Platform (Fig. 3). This early Ladinian progradation episode of the Budaörs Platform (Budai and Haas, 1997; Budai and Vörös, 2006) can be correlated with the first progradation of the Sciliar (Schlern) Platforms pointed out in the Southern Alps (De Zanche et al., 1993, Gianolla et al., 1998). Taking into account the tectonized zone at the middle of the section (Fig. 4), it cannot be excluded that some part of the Ladinian is missing. The Archelaus Zone and the preceding Gredleri Zone are documented in the Litér section and in the Hajmáskér-Sóly area (Fig. 13; Budai et al., 2001; Budai and Vörös, 2006), but the absence of an exact marker for the base of the Archelaus Zone in the Kádárta quarry and the lack of conodont data from the other sections hamper the precise correlation.

5.5. Regional correlation

Many other units of the western Neotethys margin show similar middle to late Anisian evolution, and four sections were chosen for comparison regarding the onset of deep-marine sediment accumulation (Fig. 14). The flooding of the Ravni Fm (equivalent of the Tagyon Fm) in the Rid section of the Dinarides was dated as middle/late Illyrian (Sudar et al., 2013). The conodont assemblage containing *Paragondolella excelsa* and *Neogondolella pseudolonga*, reported by Sudar et al. (2013) from the basal part of the deep-water Rid Fm directly above the shallow water limestones, is very similar to the fauna of the lower conodont sample (K-13; Fig. 4) in the Kádárta quarry approximately 2 m above the base of the deep-marine Vászoly Fm. The Rid section seems to have been situated on a somewhat higher paleotopographic level than the Kádárta section, due to the slight difference in the timing of the flooding. The signs of karstification described from the Ravni Fm suggest that the elevated block where the Rid succession deposited was even exposed for

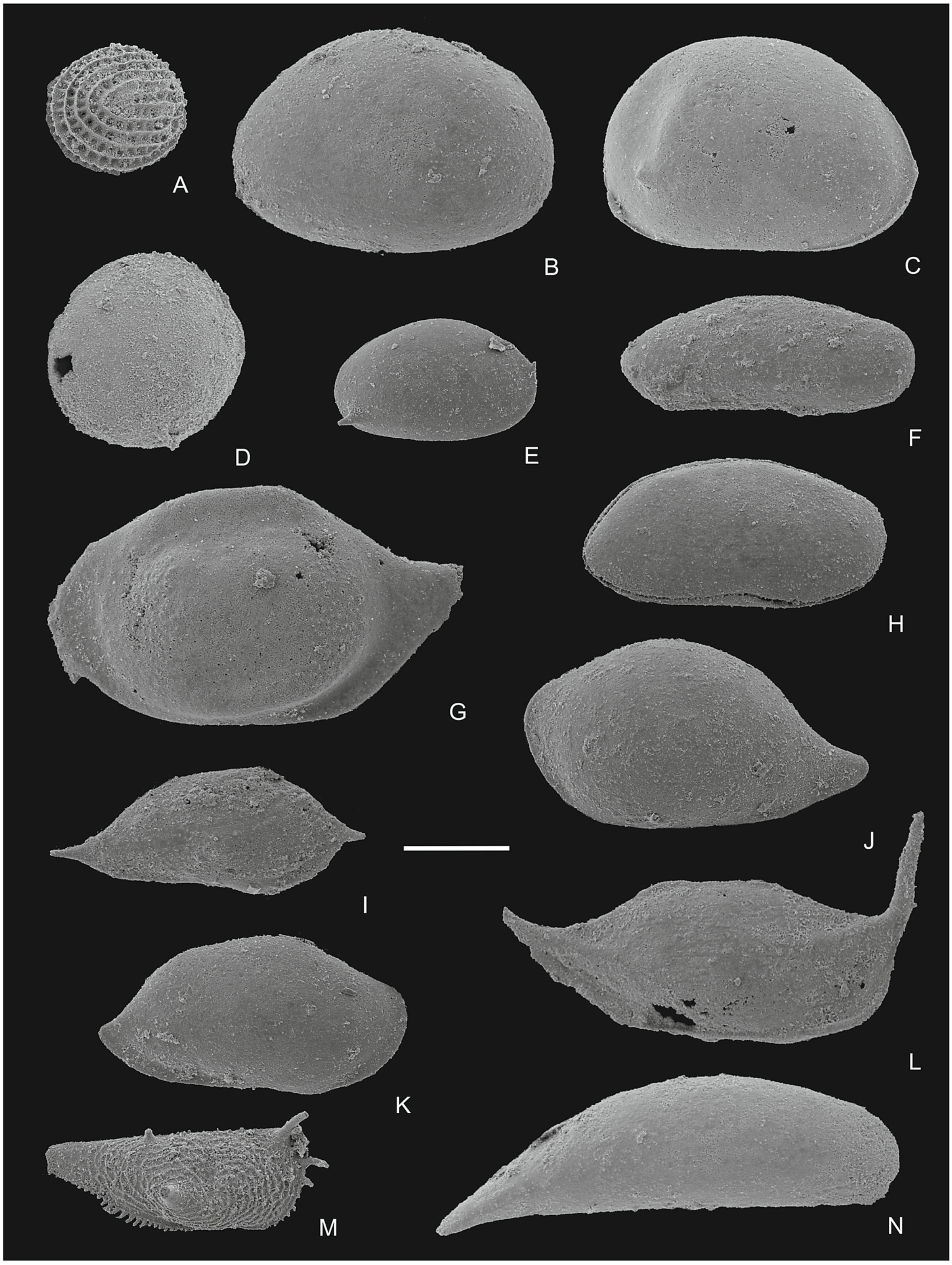

Fig. 11. Ostracods of the Kádárta section. A) *Polycope cincinnata*, LV in lateral view, sample K-14; B, C, E) *Hungarella problematica*, B: RV in lateral view, sample K-2; C: LV in lateral view, sample K-14; E: RV in lateral view, sample K-1; D) *Polycope pelta,* LV in lateral view, sample K-3; F) *Bairdiacypris anisica,* RV in lateral view, sample K-1; G) *Bairdia (Urobairdia) austriaca*, LV in lateral view, sample K-14; H) *Bairdiacypris triassica,* C in right view, sample K-3; I) *Acanthoscapha veghae*, RV in lateral view, sample K-1; J) *Bairdia (Urobairdia) angusta*, LV in lateral view, sample K-3; K) *Bairdia cassiana,* RV in lateral view, sample K-1; L) *Acanthoscapha bogschi,* RV in lateral view, sample K-2; M) *Nagyella longispinosa*, RV in lateral view, sample K-1; N) *Praemacrocypris mocki*, RV in lateral view, sample K-1. Abbreviations: C – carapace, RV – right valve, LV – left valve. Scale bar: 250 μm.

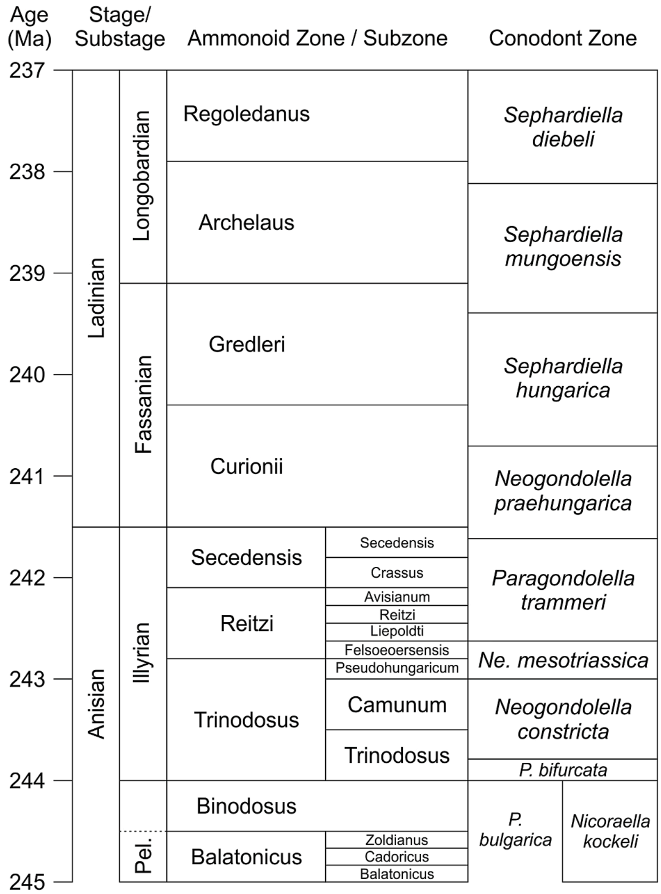

Fig. 12. Integrated ammonoid and conodont zonation of the Middle and Upper Anisian and Ladinian. Ammonoid zonation is based on Krystyn (1983), Kozur (2003) Vörös et al. (2003), Brack et al. (2005) and Vörös (2018). Conodont zonation is compiled from Krystyn (1983), Kozur (2003) and Kovács (2011). Ages are after Ogg (2012). Dashed line marks the alternative option for the place of the Pelsonian-Illyrian boundary as suggested by Monnet et al. (2008). Abbreviations: *P* – *Paragondolella*, Pel. – Pelsonian, *Ne* – *Neogondolella*.

a short time (Sudar et al., 2013). Karstic features were not observed in the Kádárta section.

The Klisura section of the Dinarides (Sudar et al., 2013) and the Schreierkogel section of the Northern Calcareous Alps (Velledits et al., 2017; Gawlick et al., 2021) show a different drowning sequence from that of the Kádárta and the Rid sections (Fig. 14). In Klisura and in Schreierkogel the carbonate ramp succession contains multiple fissures and neptunian dykes, which are absent in the other two localities. The conodonts from the first generation fissures are characteristic for the *Paragondolella bulgarica* Zone and indicate late Pelsonian age. The pelagic limestones of the Klisura section contain several condensed horizons (Sudar et al., 2013), and in the Schreierkogel section a gap is documented over the shallow-water carbonates (Velledits et al., 2017; Gawlick et al., 2021). These depositional environments might have been in lower position compared to the section in Kádárta, since deep-marine sedimentation started already in the late Pelsonian. The gap and the condensed intervals mentioned above might be the results of starvation in the depositional realm as noted also by Sudar et al. (2013).

The section of the Baradla Cave in the Aggtelek-Rudabánya Unit of northeastern Hungary has a complete sedimentary record of the drowning phase (Fig. 14; Velledits et al., 2017). The shallow-marine Steinalm Limestone is directly overlain by the pelagic Schreyeralm Limestone containing a conodont assemblage assignable to the late Pelsonian *Paragondolella bulgarica* Zone, which suggest that the section represented a subsiding block during the Reifling Event.

The Ladinian part of the Kádárta section can be correlated with deep-marine successions of the Southern Alps, such as Bagolino (Brack et al., 2005), Monte San Giorgio (Stockar et al., 2012) and Rio Nigra (Maron et al., 2019) (Fig. 14). The large number of ammonoids in the lower part of the Bagolino section (GSSP of the base of the Ladinian) enabled to establish a continuous ammonoid zonation through the Anisian-Ladinian boundary interval (Brack et al., 2005). Correlation can be made by the base of the Curionii Zone (i.e. the base of the Ladinian) between Bagolino and Kádárta (Fig. 14). The radiometric ages from Kádárta (241.5 Ma), Bagolino (241.2 Ma; Mundil et al., 1996; Brack et al., 2005) and Monte San Giorgio (242.1 Ma; Mundil et al., 2010) also support this interpretation.

Ammonoids are absent in several intervals in the Ladinian of Bagolino, thus the lower and upper boundaries of the Ladinian ammonoid zones are approximate (Brack et al., 2005). On the other hand, the radiometric ages (237.9, 238 Ma) near the base and within the Archelaus Zone in the Bagolino section (Mundil et al., 1996; Brack et al., 2005) are in correspondence with the new U—Pb age (~237.6 Ma) from below the *Sephardiella diebeli* Conodont Zone (= upper Archelaus to Regoledanus Ammonoid Zones; Fig. 12) of the Kádárta section. Especially, because a very similar U—Pb age (237.773 ± 0.052 Ma) and a conodont fauna, almost identical to the assemblage from Kádárta, was reported from the Rio Nigra section close to the boundary of the Naumayri Subzone (= upper Archelaus Zone) and the successive Regoledanus Zone (Fig. 14; Mietto et al., 2012; Maron et al., 2019). The radiometric age of 239.51 Ma measured from an ash bed of the Archelaus Zone in Monte San Giorgio (Stockar et al., 2012) seems to be too old, compared to the data from Kádárta, Bagolino and Rio Nigra. The same stands for the other two U—Pb ages (241.07 and 240.63 Ma) of Stockar et al. (2012) reported from and slightly above the Gredleri Zone of Monte San Giorgio. These ages should rather fall within the Curionii Zone based on the radiometric dating in the Bagolino (Mundil et al., 1996; Brack et al., 2005) and the Kádárta sections. The interpretations made by the correlation of the Kádárta section with the South Alpine successions suggest that the radiometric ages of Stockar et al. (2012) might be inaccurate and have to be treated carefully.

6. Conclusions

The current study of the Middle Triassic succession of the Kádárta quarry and the extensive correlation and comparison with other sections of the western Neotethys revealed that accurate dating of the drowning of distinct blocks can be a proxy for estimating the paleotopographic differences in the late Pelsonian and Illyrian caused by the horst-and-graben morphology. Moving the Pelsonian-Illyrian boundary from the top of the Binodosus Zone/Subzone to the top of the preceding Balatonicus Zone would hamper biostratigraphy in several sections where ammonoids are not available. Even if this act seems reasonable due to the change in the ammonoid faunas at that level, it would have many negative effects on the precise dating of important geological events, and thus it should be reconsidered.

The gap between the Pelsonian shallow-marine carbonates and the late Illyrian pelagic successions of the Kádárta quarry indicates that the study area was situated on an elevated block in a slightly higher paleotopographic position than the nearby Tagyon Platform. From the Anisian-Ladinian boundary onwards the sedimentation continued in deep neritic and bathyal environment.

The calibration of newly gained U—Pb ages from the Kádárta section with integrated ammonoid and conodont biostratigraphy allows a good correlation with radiometric data from the Southern Alps, and can support geochronologic investigations and the framework of the Triassic timescale.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2021.110793.

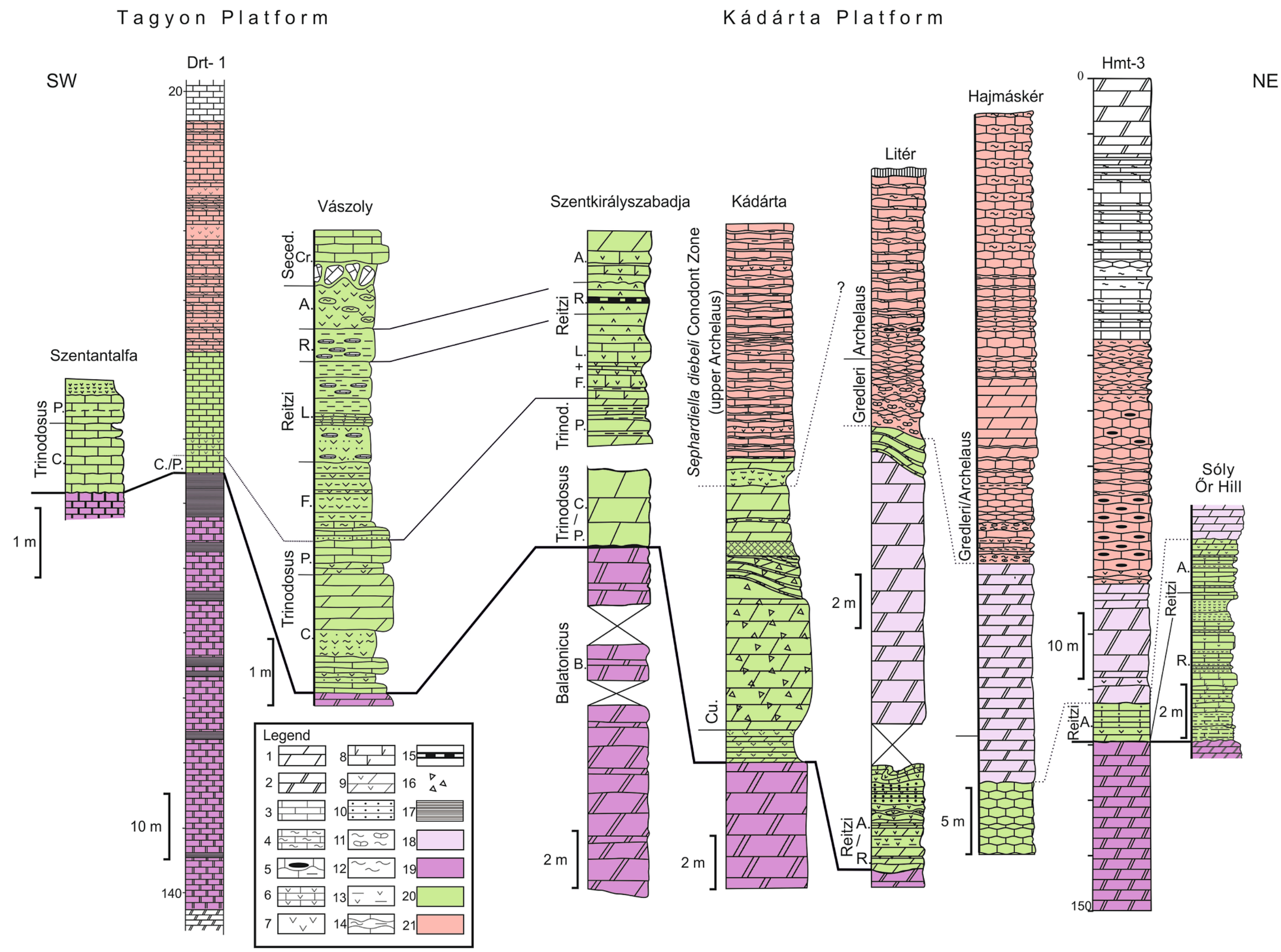

Fig. 13. Correlation of the Middle Triassic successions of the Tagyon Platform and the Kádárta Platform. Dotted lines mark uncertainty. Geographic location of the sections is shown in Fig. 2B. Sections are modified after Vörös and Pálfy (1989), Budai et al. (1993, 2001) and Vörös (1993, 1998). Abbreviations: A – Avisianum, B – Balatonicus, C – Camunum, Cr – Crassus, Cu – Curionii, Drt-1 – Dörgicse Drt-1 borehole, F – Felsoeoersensis, Hmt-3 – Hajmáskér Hmt-3 borehole, L – Liepoldti, P – Pseudohungaricum, R – Reitzi, Trinod. – Trinodosus, Seced. – Secedensis. Legend: 1 – dolomite, 2 – bedded dolomite, 3 – limestone, 4 – calcareous marl, 5 – nodular limestone with chert, 6 – tuffitic limestone, 7 – tuff, tuffite, 8 – dolomitic limestone, 9 – tuffitic dolomite, 10 – calcareous tuff sandstone, 11 – marl with limestone nodules, 12 – marl, 13 – weathered tuff, 14 – nodular, siliceous limestone with marl intercalations, 15 – siliceous laminite, 16 – breccia, 17 – Lofer-cyclic platform limestone, 18 – Budaörs Dolomite Fm, 19 – Tagyon Fm., 20 – Vászoly Fm., 21 – Buchenstein Fm.

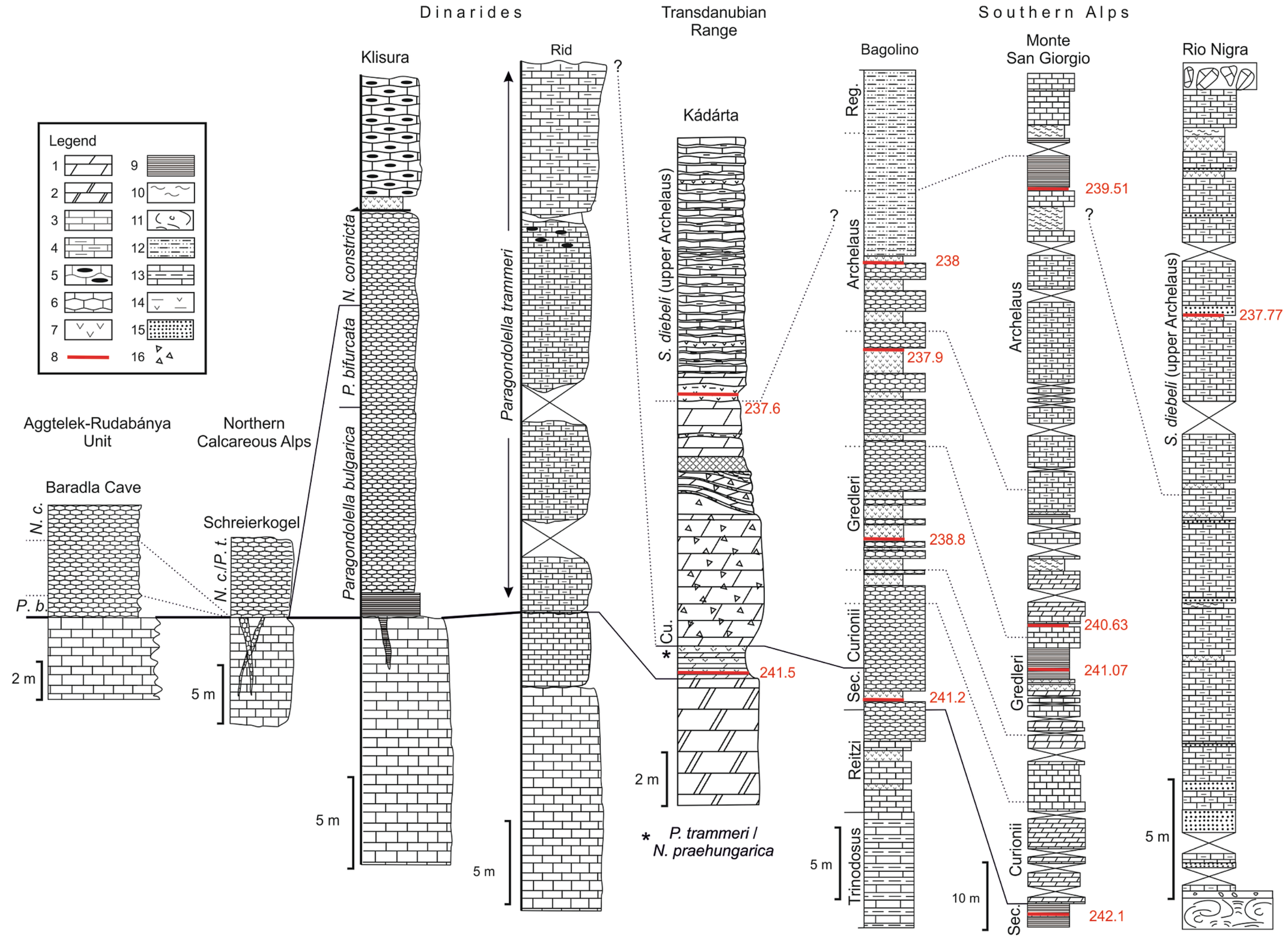

Fig. 14. Correlation of the Middle Triassic successions of the western Neotethys. Dotted lines mark uncertainty. Sections are modified after Brack et al. (2005), Stockar et al. (2012), Sudar et al. (2013), Velledits et al. (2017), Maron et al. (2019) and Gawlick et al. (2021). Abbreviations: Cu – Curionii, *N. c.* – *Neogondolella constricta*, *P. b.* – *Paragondolella bulgarica*, *P. t.* – *Paragondolella trammeri*, Reg. – Regoledanus, *S.* – *Sephardiella*, Sec. – Secedensis. Legend: 1 – dolomite, 2 – bedded dolomite, 3 – limestone, 4 – micritic limestone and calcareous marl, 5 – nodular limestone with chert, 6 – nodular limestone, 7 – tuff, tuffite, 8 – samples for U—Pb ages, 9 – laminated limestone, 10 – marl, 11 – lava, pillow lava and pillow breccia, 12 – siliciclastic storm/turbiditic beds, 13 – limestone with marl intercalations, 14 – weathered tuff, 15 – volcaniclastic sandstone, 16 – breccia.

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.

Acknowledgments

Authors are grateful to Lajos Katona (Bakony Museum, Zirc) for providing field photographs. Special thanks is given to Krisztina Buckó for her assistance in taking the SEM photos of the microfossils. Two anonymous reviewers and A. Pérez-López (University of Granada) are acknowledged for improving the manuscript with their useful comments and suggestions. The research was partly supported by the National Research, Development and Innovation Office (NKFIH K 124313 and NKFIH FK 134229 grants). Our paper corresponds to IGCP-710 Project.

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