AKADÉMIAI KIADÓ

Development and dolomitization of Anisian isolated carbonate platforms in the Transdanubian Range, Hungary

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RESEARCH ARTICLE

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ABSTRACT

In the Middle Anisian, extensional tectonic movements led to the development of isolated carbonate platforms in the area of the southwestern part of the Transdanubian Range. The platforms are made up of meter-scale peritidal–lagoonal cycles bounded by subaerial exposure surfaces. One of the platform successions (Tagyon Platform) consists predominantly of limestone that contains partially and completely dolomitized intervals, whereas the other one (Kádárta Platform) is completely dolomitized. Drowning of the platforms took place in the latest Pelsonian to the early Illyrian interval when submarine highs came into existence and then condensed pelagic carbonate successions with volcanic tuff interbeds were deposited on the top of the drowned platforms from the late Illyrian up to the late Ladinian. The comparative study of dolomitization of the coeval platforms, affected by different diagenetic histories, is discussed in the current paper. Traces of probably microbially-mediated early dolomitization were preserved in the slightly dolomitized successions of the Tagyon Platform. This might also have been present in the successions of the Kádárta Platform, but was overprinted by geothermal dolomitization along the basinward platform margin and by pervasive reflux dolomitization in the internal parts of the platform. The Carnian evolution of the two submarine highs was different, and this may have significantly influenced the grade of the shallow to deeper burial dolomitization.

KEYWORDS

carbonate platform, dolomitization, Middle Triassic, Transdanubian Range

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INTRODUCTION

In spite of the efforts of generations of researchers, the main controlling factors and the mechanism of dolomite-forming processes are still rather enigmatic. Petrographic features and geochemical characteristics of a predominant part of the dolomite rocks suggest that they were formed via the replacement of precursor carbonates during various diagenetic settings (e.g., Tucker & Wright, 1990; Budd, 1997; Machel, 2004; Pearce et al., 2013). However, there is no general model for the explanation of the large-scale dolomitization of marine carbonate rocks. Although laboratory experiments yielded valuable results on dolomite-forming processes (e.g., Bontognali et al., 2008; Kaczmarek & Sibley, 2014; Zhang et al., 2012; Roberts et al., 2013; Xu et al., 2013; Kaczmarek et al., 2017), case studies on various dolomite formations are indispensable to understand the usually complex dolomitization history (e.g., Budd, 1997;

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Nader et al., 2004; Di Cuia et al., 2011; Fu & Quing, 2011; Meister et al., 2013; Haas et al., 2017). A prominent problem of the interpretation of the complete series of dolomite-forming processes is rooted in the later diagenetic alterations (recrystallization, dissolution and reprecipitation, fracturation, etc.) which commonly destroy the sedimentary characteristics of the precursor carbonates and the earlier dolomite phases. Fortunately, in the Triassic succession of the Transdanubian Range (TR), detailed geologic mapping revealed that in several cases, the carbonate formations were completely dolomitized, while certain parts of the unit were affected only by partial dolomitization or remained undolomitzed in other parts. The Middle Anisian Tagyon Formation is the best example of this phenomenon. This platform carbonate succession is generally subjected to complete dolomitization but in a smaller area of the Balaton Highland, the formation is made up predominantly of limestone, although it contains partially or completely dolomitized intervals. In our previous studies, a section exposed in the Szentkirályszabadja Quarry was investigated for the characterization of the totally dolomitized successions, and the core section Dörgicse (Drt)-1 for demonstration of the partially dolomitized Tagyon Formation (Haas et al., 2014, 2017). In the past years, a more complete Middle Triassic section was exposed in a large active quarry at Kádárta, near Veszprém. The study of this section revealed that, although the sedimentological characteristics of the exposed upper part of the completely dolomitized Tagyon Formations are similar to that of the Szentkirályszabadja Quarry, the stable O and C isotope values are remarkably different. This means that a reconsideration and modification of the previous dolomitization are necessary; the story is probably more complex than was previously supposed. These results inspired the compilation of the current paper containing the results of our petrographic and isotope-geochemical studies of the recently exposed section of the Kádárta Quarry. The new data were compared to and combined with the results of the previous studies, providing the basis for the reconstruction of the history of platform evolution and for the evaluation of controlling factors and processes of dolomitization of the platform carbonates.

GEOLOGIC SETTING

The Balaton Highland is located in the southwestern part of the Transdanubian Range Unit (TR) in the western part of Hungary. Forming the southeastern limb of the SW–NE-directed syncline structure of the TR, the Balaton Highland is made up of low-grade metamorphosed Lower Paleozoic and unmetamorphosed Permian to Triassic formations. The Alpine compressions led to folding and significant southeast-vergent overthrusting of the Paleozoic–Triassic rock units (Fig. 1).

In the Middle Triassic, the TR was a segment of the passive margin of the western Neotethys Ocean (Fig. 2). Westward

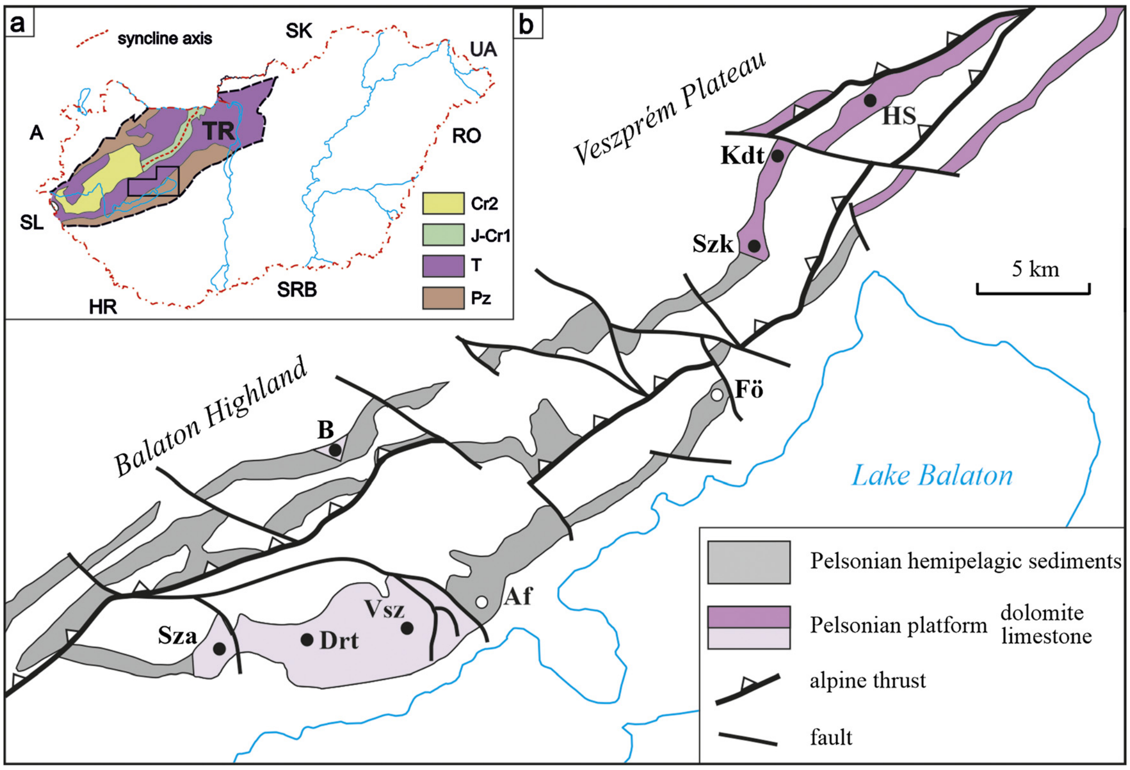

Fig. 1. a – Simplified pre-Cenozoic geologic map of the Transdanubian Range Unit (TR). Legend: Pz – Paleozoic formations; T – Triassic formations; J–Cr1 – Jurassic–Lower Cretaceous formations; Cr2 – Upper Cretaceous formations; b – Surface extension of Middle Anisian–Ladinian formations of the Balaton Highland and the Veszprém Plateau (after Budai & Vörös, 2006, modified) showing the locations of the studied sections (colors refer to the Pelsonian facies). For abbreviations see Fig. 3

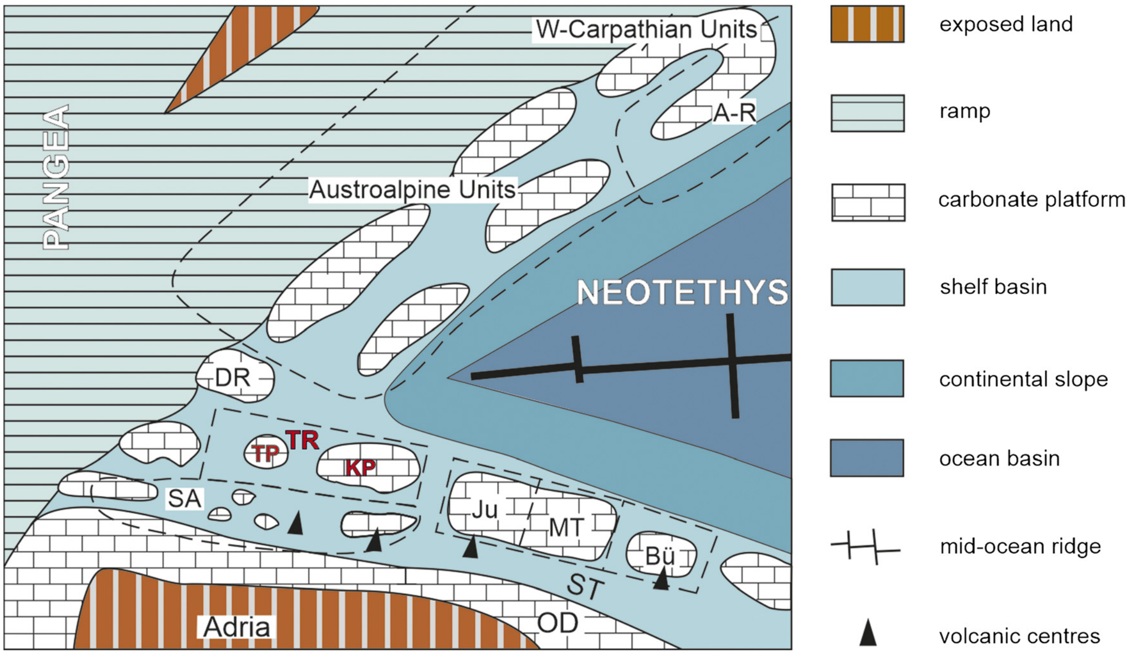

Fig. 2. Paleogeographic reconstruction for the Middle Triassic of the western part of the Neotethys with the position of the Transdanubian Range Unit (TR, more details in Fig. 3) (after Budai et al., 2017, modified). Abbreviations: A-R – Aggtelek–Rudabánya Units; Bü – Bükk Unit; DR – Drau Range; Ju – Julian Unit; KP – Kádárta Platform (TR); MT – Mid-Transdanubian Unit; OD – Outer Dinarids; SA – South-Alpine Units; ST – Slovenian Trough; TP – Tagyon Platform (TR)

opening of the ocean reached this region in the middle Anisian and led to the disintegration of the previously existing carbonate ramp along normal faults (Budai & Vörös, 1992, 1993).

At the beginning of the Pelsonian, halfgraben-type basins developed on the downfaulted blocks, whereas the shallow-marine carbonate factories survived on the relatively elevated ones. As a result, smaller and larger isolated carbonate platforms came into existence (Fig. 3). Acceleration of the relative sea-level rise may have resulted in the drowning of the small Tagyon Platform and parts of the

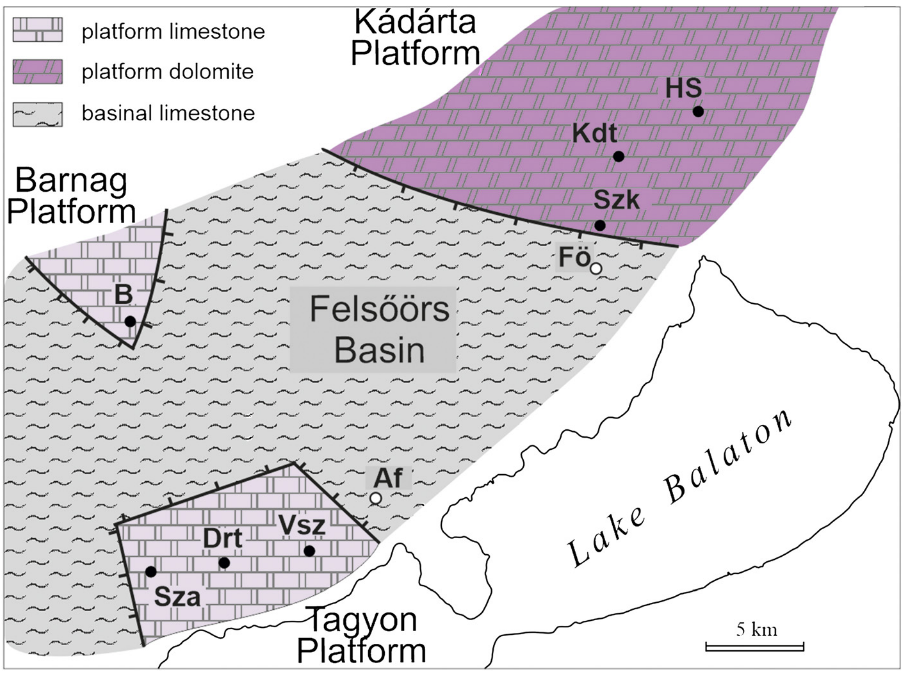

Fig. 3. Middle Anisian paleogeographic map of the Balaton Highland and the Veszprém Plateau showing the extension of the Pelsonian platforms and the Felsőörs Basin (after Budai & Vörös, 2006, modified). Abbreviations: Af – Aszófő; B – Barnag; Drt – Dörgicse; Fö – Felsőörs, HS – Hajmáskér–Sóly; Kdt – Kádárta; Sza – Szentantalfa; Szk – Szentkirályszabadja; Vsz – Vászoly

larger Kádárta Platform in the late Illyrian (Budai & Haas, 1997; Budai & Vörös, 2006).

Reflecting the paleogeographic setting and the structural evolution (onset of extensional tectonics) of the study area, remarkable lateral facies changes were pointed out in the middle Anisian (Pelsonian) interval (Fig. 4). In most of the area this is represented by a hemipelagic basinal sequence (Felsőörs Formation) that is made up of medium to thin-bedded and locally laminated limestones containing characteristic ammonite and pelagic bivalve assemblages. This formation continues in the Upper Anisian and is covered by the uppermost Anisian Vászoly Formation that is characterized by the appearance of volcanic tuff interlayers. In contrast, in the middle part of the Balaton Highland and on the eastward located Veszprém Plateau, the Pelsonian substage is represented by shallow marine platform carbonates (Tagyon Formation) that are characterized by a cyclic alternation of shallow subtidal and peritidal bed-sets (stromatolites and vadose calcretes). Above a sharp surface (drowning unconformity), this platform carbonate succession is directly overlain by basinal carbonate beds of the uppermost Anisian Vászoly Formation. The lack of four ammonite subzones indicates the duration of the gap at the drowning unconformity (Vörös et al., 1997; Budai & Haas, 1997). The Pelsonian platform carbonates have been subjected to various degrees of dolomitization (Fig. 4).

Basinal successions were formed in the late Illyrian to Ladinian interval in the area of the Balaton Highland, although the lateral differences in the facies pattern did not disappear completely (Fig. 4). Northeast of the Balaton Highland, in the central and northeastern part of the TR, thick platform carbonates (Budaörs Dolomite) were formed during the late Anisian and the Ladinian. The facies differences between the two areas are even more definite in the Carnian. In the area of the Balaton Highland, hemipelagic limestones (Füred Fm) occur in the basal part of the Carnian succession, overlain by a hundreds of meters-thick basinal marl unit (Veszprém Formation), whereas in the area of the Veszprém Plateau this time range is represented by shallow marine carbonates (Sédvölgy Dolomite) formed on the Sédvölgy Platform (Budai & Haas, 1997; Haas & Budai, 1999). Near the Ladinian–Carnian boundary the westward progradation of the Sédvölgy Platform led to a remarkable increase in the extension of the carbonate platform (Fig. 4). Carbonate turbidites were deposited along the toe of the platform foreslope (Berekhegy Limestone). Increasing humidity in the Early Carnian led to an enhanced influx of fine-grained siliciclasts, which resulted in the gradual upfilling of the basin of the Balaton Highland by the Late Carnian, whereas the evolution of the coeval Sédvölgy Platform continued. From the Late Carnian up to the Middle Norian extremely shallow marine conditions became prevailing over a predominant part of the area of the Transdanubian Range, leading to the deposition and early diagenetic dolomitization of a more than 1 km-thick platform carbonate succession defined as the Fődolomit Formation.

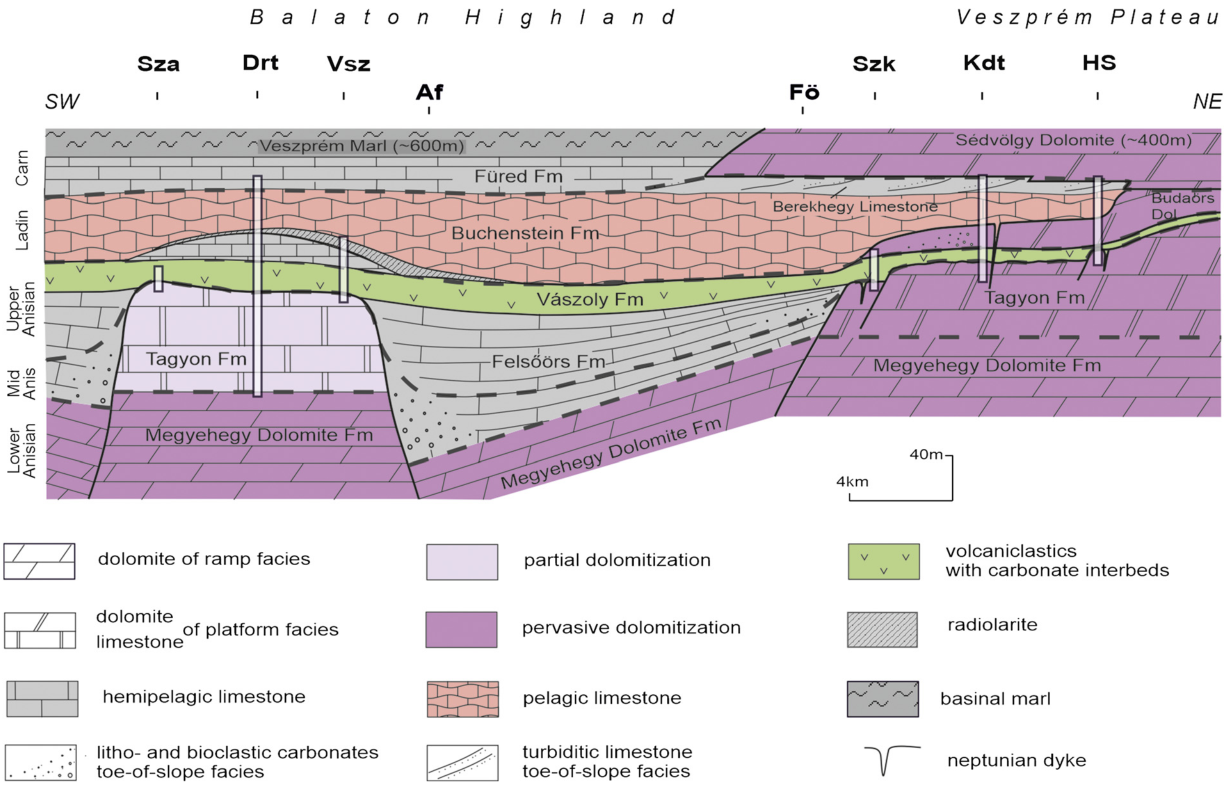

Fig. 4. Geologic profile of the Anisian–lowermost Carnian formations of the Balaton Highland and the Veszprém Plateau, showing the stratigraphic position of the studied sections (after Budai & Vörös, 2006; Haas et al., 2014, modified). For abbreviations see Figs 1 and 3

MATERIALS AND METHODS

An active quarry exposed the Middle Anisian–Ladinian succession of the Veszprém Plateau south of Kádárta (Kd), near Veszprém. Along the wall of the quarry a continuous section was documented and sampled (Fig. 5). The samples that were taken for microfacies studies and stable isotope analyzes from the Tagyon Formation and the overlying dolomite breccia beds are presented in Fig. 5.

Stable carbon and oxygen isotope analyses were performed at the Institute for Geological and Geochemical Research (Budapest, Hungary) using a Finnigan delta plus XP mass spectrometer (Thermo Fisher Scientific, Bath, UK). The dolomite samples were prepared by a hand-held dental drill. The stable carbon and oxygen isotope compositions of micro-drilled powders of dolomite samples were determined using a continuous flow technique (Spötl & Vennemann, 2003), and dolomite reaction conditions described by Rosenbaum & Sheppard (1986). All samples were measured at least in duplicate, and the mean values are in the traditional δ notation in parts per thousand (‰) relative to Vienna Pee Dee Belemnite (VPDB). Reproducibility is better than ±0.1 ‰ for $\delta^{13}C$ and ±0.1 ‰ for $\delta^{18}O$. More details of sample measurements can be found in Győri et al. (2020).

RESULTS

Petrography

The studied uppermost 10 m-thick interval of the Tagyon Formation is made up of a cyclic alternation of thick-bedded subtidal and medium to thin-bedded–laminated dolomite (Figs 5 and 6a). The thick beds consist of fabric destructive or poorly fabric-retentive, very finely crystalline dolomite. In contrast, well preserved sedimentary fabric was found in some thin interbeds between the thick beds.

In the 5 to 15 cm-thick basal part of a thick bed (Kd-2 sample on Figs 5 and 6b) excellently preserved oncoidal bindstone fabric was encountered (Fig. 7a). The 1 to 5 mm-sized oncoids (Fig. 7b) are surrounded by microbial micrite-microsparite (Fig. 7c). Five to eight mm-sized bedding-parallel elongated cavities and tiny fenestral pores occur among the grains. A complex infilling could be observed in the cavities (Fig. 7a). They are lined by very finely crystalline, inclusion-rich dolomite. This is overlain by brownish, fibrous dolomite cement crust but only along the upper cavity wall, whereas the central part of the cavity is occluded by coarsely crystalline dolomite cement. Above a few mm-thick stromatolitic crust an inversely graded oncoidal grainstone microlayer was found (Fig. 7d).

Below another thick bed (Kd-3 sample on Fig. 5) bioclastic, peloidal bindstone fabric was observed in a 10 cm-thick darker grey layer. Along with fine calcarenite grains, fragments of relatively well-preserved dasycladalean algae (Fig. 8a) and bivalves were recognized. The biomoulds and vugs are filled with fine to medium crystalline dolomite. Stromatactoid cavities with basal dolomitized intrasediment, finely crystalline lining, and medium crystalline dolosparite cement were also encountered. In a dm-thick interbed (Kd-4 sample on Fig. 5) found between two thick beds, bioclastic grainstone with mm-sized fragments of dasycladalean algae was observed (Fig. 8b).

In the uppermost thick bed of the Tagyon Formation (Kd-8 sample on Figs 5 and 9a) cm-sized oncoids could be

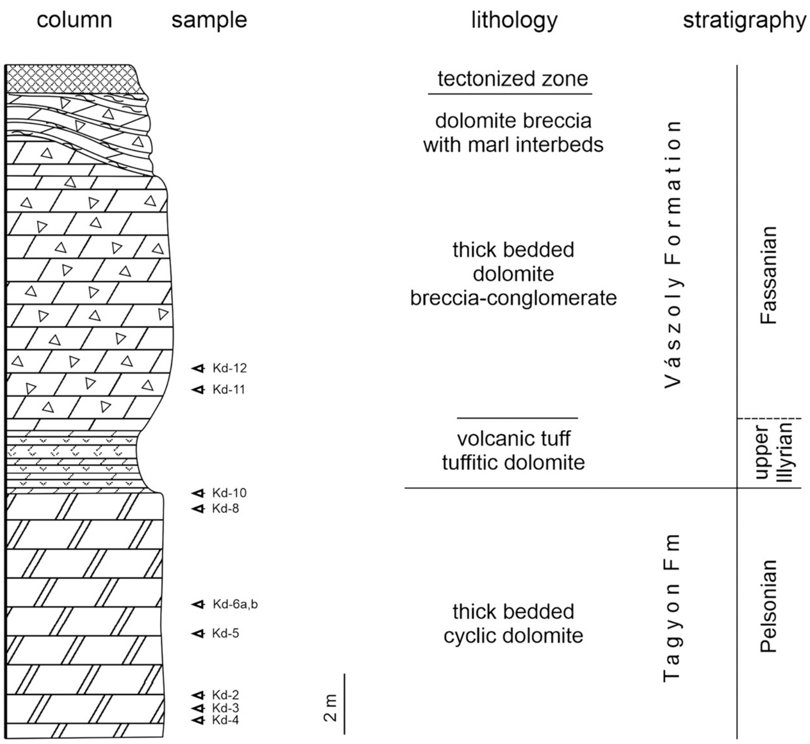

Fig. 5. Middle Anisian–Lower Ladinian sequence of the Kádárta Quarry (near Veszprém) showing the sites of the taken samples

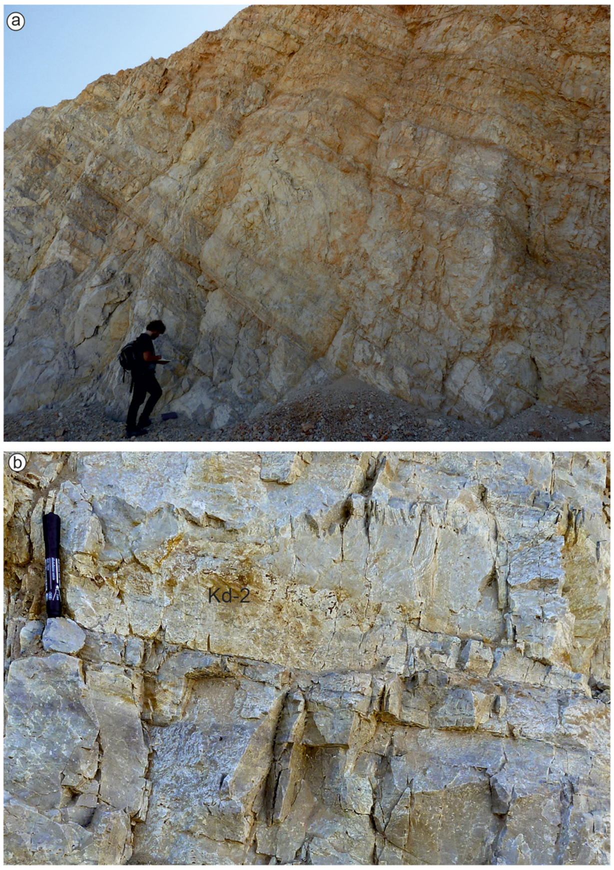

Fig. 6. a – Middle Anisian cyclic platform carbonate succession of the Tagyon Formation in the Kádárta Quarry; b – A lenticular oncoidal bindstone body (sample Kd-2) at the base of a thick bed

macroscopically observed. This bed is characterized by a medium to poorly preserved oncoidal grainstone texture. Only ghosts of globular grains are visible in the finely to medium crystalline dolomite. In the uppermost few dm-thick parts of the bed (Kd-10 sample on Fig 5) a fenestral laminated stromatolite crust was observed, which is overlain by a few mm-thick oncoidal grainstone (Fig. 9b) lamina just below the slightly uneven drowning unconformity surface.

The basal volcanic tuff and tuffaceous dolomite beds of the Vászoly Formation are overlain by thick beds of matrix-supported dolomite breccia–conglomerate (Figs. 10a and 10b); darker grey clasts are visible in a light beige matrix (Kd-11 and Kd-12 samples in Fig. 5). In the lower part of the succession a Lower Ladinian ammonite (*Eoprotrachyceras* cf. *gervasuttii*, Fig. 10c) was found (Vörös A. pers. com.). The microscopic investigation revealed that the cm-sized clasts (intraclasts, Fig. 10b) consist of aphanocrystalline to very finely crystalline (1–10 μm) dolomite while the matrix is finely crystalline and both are rich in 100–200 μm-sized peloids. The boundary between them is typically definite but locally rather faint (Fig. 10d). Centimeter-sized dissolution cavities and mm-sized biomouldic and vug pores are also common. The beds are intersected by a fracture network. Two fracture generations could be distinguished. The older fractures are filled by very finely crystalline dolomite cement, whereas the younger fractures that commonly crosscut the former ones are filled by medium crystalline dolomite cement. 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 slightly disturbed contact with the upper part of the Vászoly Formation that is made up of bedded dolomite and volcanic tuff (Fig. 5).

Isotope geochemistry

Stable C and O isotope analyses were carried out on samples from the studied interval of the Tagyon Formation and the breccia–conglomerate bed-set. The results are presented in Fig. 11 and Suppl. Table 1 together with relevant petrographic data. As for the Tagyon Formation, the $\delta^{13}C$ values vary in a narrow range from 2.6 to 3.1‰. The range of $\delta^{18}O$ is between −0.6 and 1.8‰. No significant relationship was found between the petrographic features and the isotope values. Very similar values were measured on the samples taken from the dolomite breccia-conglomerate bed-set ($\delta^{13}C$ 2.4–2.6‰; $\delta^{18}O$ −1.2 to 0.6‰).

DISCUSSION

Petrographic features of the Pelsonian platform carbonate successions were studied in several sections in the area of the Balaton Highland (Budai et al., 1993; Budai & Haas, 1997; Vörös et al., 1997, 2003; Haas et al., 2014). However, the investigation of the recently exposed Kádárta section yielded remarkable new data and provided a good opportunity to correlate and compare them with those of the previously documented sections. In addition to understanding the controlling factors of the drowning, this comparative analysis may also serve as a basis for deciphering the complex history of the multi-stage dolomitization of these platform carbonates.

In the area of the central part of the Balaton Highland, representing the internal part of the small Tagyon Platform, the Tagyon Formation is made up predominantly of limestone or partially dolomitized limestone (see Figs 2 and 4). It was intersected by the well Dörgicse Drt-1, exposing a cyclic succession of alternating thick subtidal beds and thin peritidal interbeds of stromatolite and/or pizolitic calcrete facies (Budai et al., 1993, 1999; Haas et al., 2014). In the succession, various fabric selective dolomite types were encountered. In the pizolitic pedogenic crusts nodules, glaebules and coated grains occur, which are composed of very finely to finely crystalline dolomite, although their micropores are occluded by very finely crystalline calcite, and rarely dolomite. Clotted micrite fabric characterizes the dolomitic stromatolites. Irregular aggregates of very finely crystalline dolomite and individual dolomite crystals or crystal clusters (15–200 μm-sized) occur in the micritic components (peloids, nodules, cortex of oncoids) in the subtidal beds. Mostly in the upper part of the formation, there are completely dolomitized intervals where the sedimentary fabric is usually totally

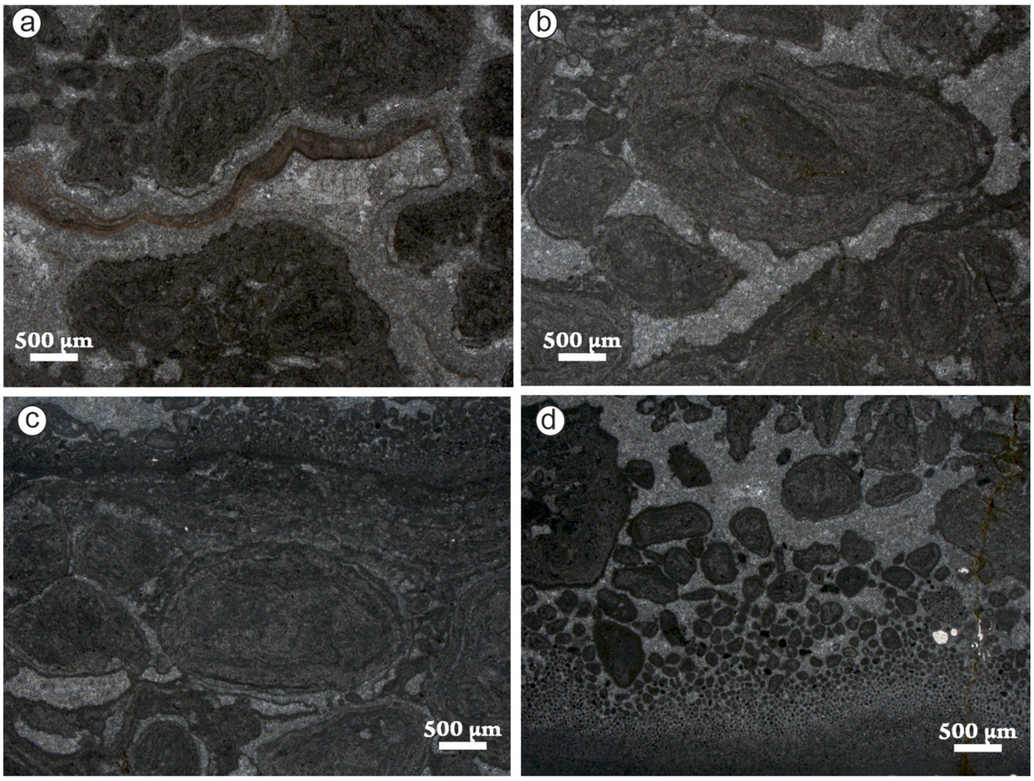

Fig. 7. a – Oncoidal bindstone; an elongated cavity with multiple dolomite cement filling is visible in the central part of the photo. The wall of the cavity is lined by very finely crystalline cement. It is covered by a fibrous cement layer along the upper wall, and coarsely crystalline blocky cement occurs in the central part of the cavity (sample Kd-2); b – Cm-sized oncoid embedded in a microbial bindstone fabric (sample Kd-2); c – Microbial mat containing oncoids, small microbial nodules and mm-sized fenestral pores occluded by fine to medium crystalline cement (sample Kd-2); d – Inversely graded oncoid grains in a grainstone microlayer (sample Kd-2)

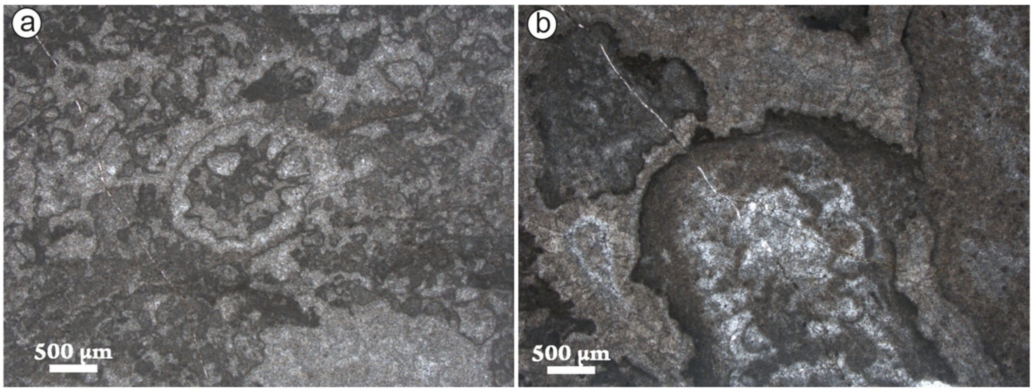

Fig. 8. a – Middle Anisian dasycladalean alga (*Physoporella* sp. – det. O. Piros) in the Tagyon Formation (sample Kd-3); b – Ghost of a dasycladalean alga; distribution pattern of inclusion-rich parts of the fine to medium-sized crystals preserved the internal structure of the fossil (sample Kd-4)

destroyed, although ghosts of some grains are locally recognizable in the fine-to-medium crystalline rock (Haas et al., 2014, 2017). Above the drowning unconformity surface, the basal layers of the overlying Vászoly Formation consist of reddish-brown crinoidal limestone (Vörös, 1998, 2018).

Both the Kádárta (Kd) section and the previously investigated Szentkirályszabadja (Szk) section belong to the Kádárta Platform, but as far as their paleogeographic setting is concerned, the latter was located in the basinward marginal zone of this large carbonate platform (Figs 3 and 4). In the abandoned Szk quarry the uppermost 20 m of the entirely dolomitized Tagyon Formation is exposed. The rich calcareous algae flora and the presence of the ammonite *Balatonites balatonicus* prove the Pelsonian age of the succession (Budai & Haas, 1997; Vörös et al., 1997, 2003). In the thicker beds of the cyclic succession, as a rule the dolomitization did not destroy the sedimentary fabric and the

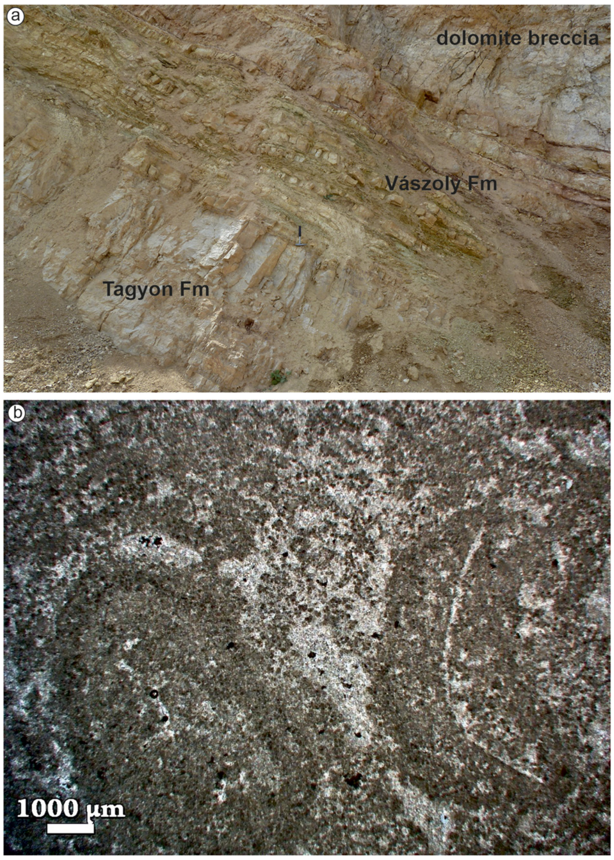

Fig. 9. a – Sharp drowning unconformity surface (hammer) between the Tagyon Fm (below) and the overlying tuffitic Vászoly Formation; b – cm-sized oncoid grains in the topmost bed of the Tagyon Formation (sample Kd-10)

crystal morphology of the precursor early diagenetic cement, although in many cases, only ghosts of the grains are visible. In some beds, dolomite cement-filled biomoulds after dasycladalean algae are abundant. The pedogenic and microbial fabric in the topmost part of the cycles is well-preserved (Haas et al., 2014). Above a sharp boundary, the platform carbonate succession is overlain by brownish-grey dolomite representing the base of the Vászoly Formation (Budai & Haas, 1997; Budai et al., 1999, 2001).

The basic lithologic features of the upper part of the Tagyon Formation are similar in the Szk and Kd sections; they are made up of thick-bedded dolomite showing excellent or relatively good fabric preservation. However, there is a remarkable difference between the two successions. In the Szk section pedogenic crusts or stromatolitic horizons (akin to those in the core Drt-1) occur between the thick beds, which contain a rich shallow marine fossil assemblage. Accordingly, this succession reflects periodically-changing depositional conditions. The shallow marine conditions were interrupted by peritidal, and occasionally subaerial exposure episodes as a consequence of the high-frequency sea-level oscillation (Haas et al., 2014). In contrast, in the Kd section, the peritidal horizons are missing, suggesting permanency of the subtidal depositional setting even in the periods of the lowest sea-level. According to biostratigraphic constraints the age of the basal part of the post-drowning succession is late Illyrian in both sections; however, this does not mean that the drowning took place at the same time. It is more probable that due to downfaulting of the platform margin zone the drowning occurred earlier in the Szk area, although the intense winnowing did not allow for sediment deposition. However, in the internal part of the platform, the shallow subtidal conditions were prolonged during the early Illyrian. This means that the different paleogeographic settings of the two studied sections is manifested in the observed lithological differences.

Based on previous and recent studies we conclude that platform carbonates of the Tagyon Formation were commonly subject to multistage dolomitization. The Tagyon Platform (Drt-1) was not affected by pervasive dolomitization either before drowning or after it in shallow to deep burial settings. That is why traces of penecontemporaneous fabric-selective partial dolomitization were preserved and could be locally recognized in the rocks (Haas et al., 2014). The pedogenic cap in the topmost part of the cycles, the peritidal stromatolite bed and the micritic fabric elements (micritic nodules, coatings, cortex of oncoids) of the subtidal beds were typically affected by dolomitization, which can be bound to the earliest, probably microbially-mediated dolomitization phase (for the pedogenic crusts: Wright, 2007; Alonso-Zarza et al., 2010; for the peritidal settings: Wright, 2000; Wright & Wacey, 2005; Bontognali et al., 2008; Spadafora et al., 2010). Unfortunately, only a few stable isotope data are available from separated dolomite samples of the partially dolomitized limestone, due to the very small size of the crystals. The majority of the samples were taken from slightly to moderately dolomitized limestone and fabric-retentive dolomite and calcite and dolomite cement. The negative $\delta^{18}O$ values (down to -7.4‰; Fig. 11) clearly indicate higher temperature recrystallization of the selectively dolomitized limestone succession which likely, therefore, took place in an intermediate to deep burial diagenetic setting. This higher temperature recrystallization was accompanied by precipitation of calcite and dolomite cement in the fractures and pores.

The very early selective dolomitization and the precipitation of early diagenetic marine and meteoric cement may have also taken place on the Kádárta Platform. However, in this area, it was followed by pervasive dolomitization in near-surface shallow burial settings, as the $\delta^{18}O$ values (majority of the data range between –2 and 0‰) do not indicate the condition of elevated temperature which would imply greater depth. Moreover, the current investigation revealed some differences in the $\delta^{18}O$ values between the samples of the Kádárta and those of the Szentkirályszabadja sections (Fig. 11). The values of the former locality (−0.6 to +1.8‰) suggest dolomitization via reflux of mesohaline fluids produced by evaporation of sea-water in tidal flat pools (Meister et al., 2013; Gabelon & Withaker, 2015). The values of the latter section show a wider range (−2.0 to +1.4‰) but a dominant part of the values is in the negative field (between −1.7 and −0.4‰), suggesting dolomitization via marine water circulation driven by thermal convection

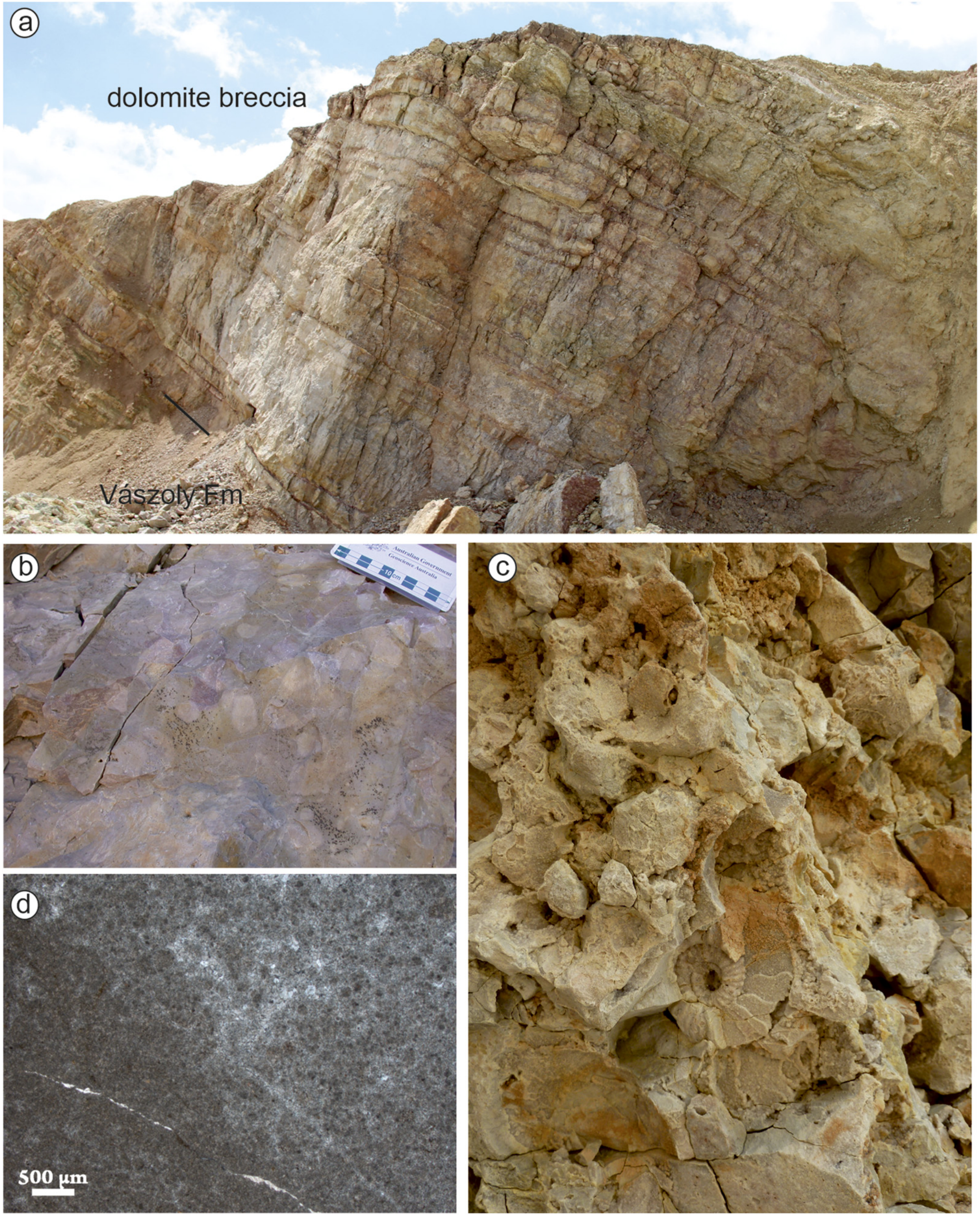

Fig. 10. a – Thick-bedded dolomite breccia–conglomerate above the lower part of the Vászoly Fm; b – rounded cm-sized clasts; c – ammonite (*Eoprotrachyceras* cf. *gervasuttii*) in the lowermost bed of the breccia–conglomerate (det. A. Vörös); d – photomicrograph showing the transition between a very finely crystalline clast and the finely crystalline matrix; peloids are abundant both in the clast and the matrix

(Kohout et al., 1977; Withaker at al., 1994; Machel, 2004; Hughes et al., 2007).

The significant differences in the grade and mechanism of dolomitization can be attributed to differences in the paleogeographic setting of the localities. The early diagenetic processes of the isolated carbonate platforms/islands are mostly governed by the climatic conditions and the related effective recharge (precipitation/evaporation), and also determined by the size and the shape of the platforms/islands and the permeability of the carbonate deposits (Allen & Matthews, 1982; Vacher, 1988; Budd, 1988; Christ et al., 2012). On the small Tagyon Platform, the extension of the tidal flat pools may have been rather limited and this resulted in the absence of the pervasive reflux dolomitization. In addition to this, the post-drowning burial of the platform carbonates by a tuffaceous and cherty pelagic limestone succession, and a thick argillaceous sequence (Veszprém Marl; Fig. 4) also hampered the extensive dolomitization in the course of the deeper burial setting. As far as the Kádárta Platform is concerned, in the internal part of this large platform intense reflux dolomitization may have taken place during the subaerial exposure

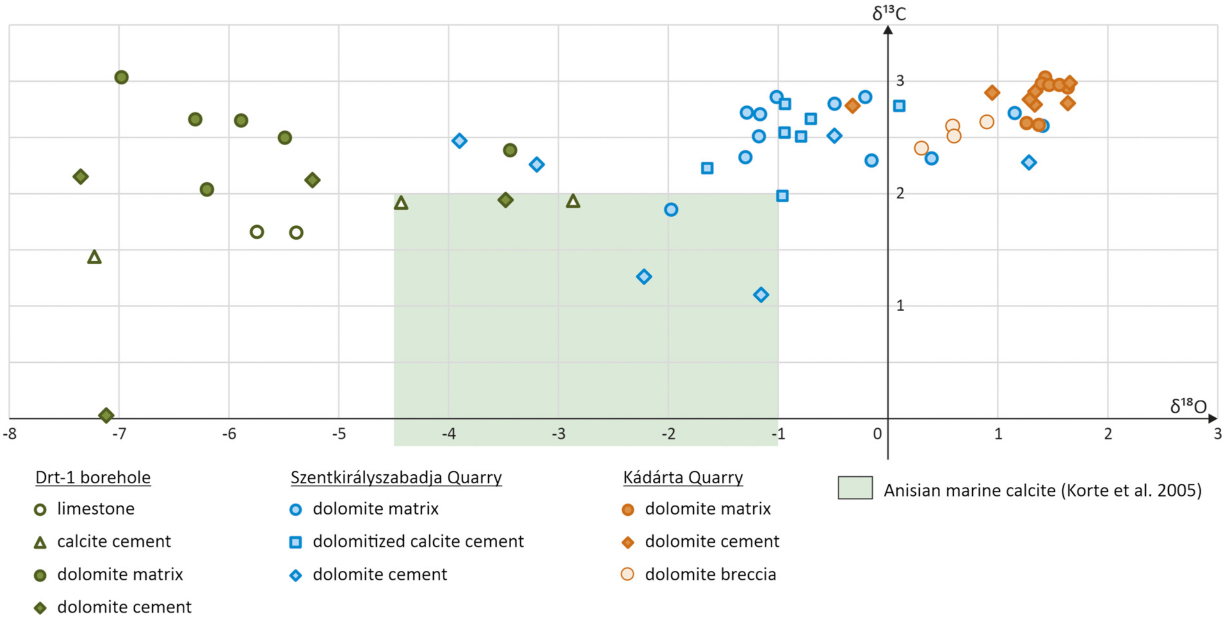

Fig. 11. Stable isotope chart showing values measured on samples taken from the Tagyon Formation in the area of the Tagyon Platform (Drt-1) and in the area of the Kádárta Platform (Szentkirályszabadja and Kádárta Quarries). Data from the Drt-1 borehole and the Szentkirályszabadja quarry are from Haas et al. (2014). The database is presented in Suppl Table 1. The isotopic values are expressed in ‰ relative to Vienna Pee Dee Belemnite (VPDB).

episodes, leading to high-grade dolomitization of the previously-deposited and still unconsolidated deposits. Near-surface very early dolomitization may explain the excellent to relatively good fabric preservation found in the oncoid-rich and locally stromatolitic bindstone interbeds between the thick beds of poorly-preserved depositional fabric. However, in this area, the deep reflux-related dolomitization may have continued later when the thin post-drowning deep marine succession was covered by the prograding Budaörs Platform (Fig. 4). The succession exposed in the Szentkirályszabadja Quarry was formed near the tectonically-controlled basin-ward slope of the platform; taking into account the relatively low δ^{18}O values (Fig. 11), thermal convection of the sea-water may have been the dolomitizing agent in this case (Kohout et al., 1977; Withaker at al., 1994; Hughes et al., 2007).

The dolomite conglomerate-breccia bed-set encountered in the Kádárta section within the Vászoly Formation can be interpreted as a proximal gravity mass flow deposit accumulated at the toe of the foreslope of the prograding Budaörs Platform. A similar interfingering dolomite breccia body in the basinal succession was also documented in the Litér Quarry and the surroundings of Sóly and Hajmáskér in the area of the Veszprém Plateau (Budai et al., 2001; Budai & Vörös, 2006). This early Ladinian progradation episode of the Budaörs Platform (Budai & Haas, 1997; Budai & 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). Since the δ^{13}C and δ^{18}O values measured in the dolomite conglomerate-breccia bed-set of the Kádárta section do not show a significant difference from those of the samples of the Tagyon Formation in the same section, the dolomitization of these beds can also be attributed to deep reflux, i.e., the same process that led to pervasive dolomitization of the underlying platform carbonate succession.

CONCLUSIONS

In a predominant part of the southwestern part of the Transdanubian Range, platform carbonates of the Tagyon Formation were subjected to complete pervasive dolomitization, whereas in a smaller area it was affected only low-grade and commonly partial dolomitization. The grade of dolomitization and the characteristics of the partially or completely dolomitized successions are mostly controlled by the paleogeographic conditions that prevailed during the deposition and in the course of burial.

Traces of probably microbially-mediated syndiagenetic dolomitization were encountered in the slightly dolomitized successions of the Tagyon Platform. Similar dolomitization processes may have also taken place in the successions of the Kádárta Platform, but it was overprinted and usually totally destroyed by the subsequent shallow burial pervasive dolomitization.

On the small Tagyon Platform the syndiagenetic and low-intensity shallow reflux dolomitization resulted only in low-grade and fabric-selective partial dolomitization prior to drowning. After the drowning, the lithological properties of the overlying tuffaceous and cherty pelagic limestone and thick argillaceous sequences hampered extensive dolomitization in a deeper burial diagenetic setting.

Reflux of sea-water-derived mesohaline fluids already led to high-grade dolomitization during the early diagenesis in the internal part of the large Kádárta Platform, whereas near the margin of the basinward foreslope of the platform, thermal convection of the sea-water may have been the prominent dolomitizing agent.

In the studied area of the Kádárta Platform, dolomitization may have resumed during the next platform progradation after the incipient drowning episode via deep reflux. The dolomitization of the conglomerate-breccia bedset occurring above the drowning surface in the basal part of the overlying Vászoly Formation can also be attributed to the same process.

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SUPPLEMENTARY MATERIAL

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REFERENCES

Allan, J.R. and Matthews, R.K. (1982). Isotopes signatures associated with early meteoric diagenesis. *Sedimentology*, 29: 797–817.

Alonso-Zarza, A.M. and Wright, V.P. (2010). Calcretes. In: Alonso-Zarza, Am. and Tanner, L.H. (Eds.), *Carbonates in continental settings, developments in sedimentology 61*. Elsevier, Amsterdam, Oxford, pp. 225–267.

Bontognali, T.R.R., Vasconcelos, C., Warthmann, R.J., Dupraz, C., Bernasconi, S., and McKenzie, J.A. (2008). Microbes produce nanobacteria-like structures, avoiding cell entombment. *Geology*, 36: 663–666.

Budai, T. and Haas, J. (1997). Triassic sequence stratigraphy of the Balaton Highland (Hungary). *Acta Geologica Hungarica*, 40(3); 307–335.

Budai, T. and Vörös, A. (1992). Middle Triassic history of the Balaton Highland: extensional tectonics and basin evolution. *Acta Geologica Hungarica*, 35(3): 237–250.

Budai, T. and Vörös, A. (1993). The Middle Triassic events of the Transdanubian Central Range in the frame of the Alpine evolution. *Acta Geologica Hungarica*, 36(1): 3–13.

Budai, T. and Vörös, A. (2006). Middle Triassic platform and basin evolution of the Southern Bakony Mountains (Transdanubian Range, Hungary). *Rivista Italiana di Paleontologia e Stratigrafia*, 112(3): 359–371, https://doi.org/10.13130/2039-4942/6346.

Budai, T., Lelkes, Gy., and Piros, O. (1993). Evolution of Middle Triassic shallow marine carbonates in the Balaton Highland (Hungary). *Acta Geologica Hungarica*, 36(1): 145–165.

Budai, T., Császár, G., Csillag, G., Dudko, A., Koloszár, L., and Majoros, Gy. (1999). Geology of the Balaton Highland. Explanation to the Geological Map of the Balaton Highland, 1:50 000. *Occasional Papers of the Geological Institute of Hungary*, 197: 1–257.

Budai, T., Csillag, G., Vörös, A., and Dosztály, L. (2001). Middle to Late Triassic platform and basin facies of the Veszprém Plateau (Transdanubian Range, Hungary). *Bulletin of the Hungarian Geological Society*, 131(1–2): 37–70, (in Hungarian with English abstract).

Budai, T., Haas, J., Vörös, A., and Molnár, Zs. (2017). Influence of upwelling on the sedimentation and biota of the segmented margin of the western Neotethys: a case study from the Middle Triassic of the Balaton Highland (Hungary). *Facies*, 63(4): 22, https://doi.org/10.1007/s10347-017-0504-1.

Budd, D.A. (1988). Aragonite-to-calcite transformation during fresh-water diagenesis of carbonates: insights from pore-water chemistry. *Geological Society of America Bulletin*, 100: 1260–1270.

Budd, D.A. (1997). Cenozoic dolomites of carbonate islands: their attributes and origin. *Earth-Science Reviews*, 42: 1–47.

Christ, N., Immerhauser, A., Amour, F., Mutti, M., Preston, R., Withaker, F.F., Peterhänsel, A., Egenhoff, S.O., Dunn, P.A., and Agar, S.M. (2012). Triassic Latemar cycle tops — Subaerial exposure of platform carbonates under tropical arid climate. *Sedim Geol*, 265–266: 1–29.

De Zanche, V., Gianolla, P., Mietto, P., Siorpaes, Ch., and Vail, P.R. (2003). Triassic sequence stratigraphy in the Dolomites. *Mem. Sci. Geol.*, 45: 1–27.

Di Cuia, R., Riva, A., Scifoni, A., Moretti, A., Spötl, Ch., and Caline, B. (2011). Dolomite characteristics and diagenetic model of the Calcari Grigi Group (Asiago Plateau, Southern Alps – Italy): an example of multiphase dolomitisation. *Sedimentology*, 58: 1347–1369.

Fu, Q. and Quing, H. (2011). Medium and coarsely crystalline dolomites in the Middle Devonian Ratner Formation, southern Saskatchewan, Canada: origin and pore evolution. *Carbonates Evaporites*, 26: 111–125.

Gabellone, T. and Whitaker, F. (2015). Secular variations in seawater chemistry controlling dolomitization in shallow reflux systems: insights from reactive transport modelling. *Sedimentology*, 63(5): 1233–1259, https://doi.org/10.1111/sed.12259.

Gianolla, P., De Zanche, V., and Mietto, P. (1998). Triassic sequence stratigraphy in the Southern Alps (Northern Italy): definition of sequences and basin evolution. In: Gracianscky, P.C., Hardenbol, J., Jacquin, T., Vail, P.R., and Ulmer-Scholle, D. (Eds.), *Mesozoic–Cenozoic sequence stratigraphy of European basins*, Vol. 60. SEPM Special Publication, pp. 719–747.

Győri, O., Haas, J., Hips, K., Lukoczki, G., Budai, T., Demény, A., and Szőcs, E. (2020). Dolomitization of shallow-water, mixed

siliciclastic-carbonate sequences: The Lower Triassic ramp succession of the Transdanubian Range, Hungary. *Sedimentary Geology*, 395: 105549.
Haas, J. and Budai, T. (1999). Triassic sequence stratigraphy of the Transdanubian Range, Hungary. *Geologica Carpathica*, 50(6): 459–475.
Haas, J., Budai, T., Győri, O., and Kele, S. (2014). Similarities and differences in the dolomitization history of two coeval Middle Triassic carbonate platforms, Balaton Highland, Hungary. *Facies*, 60(2): 581–602, https://doi.org/10.1007/s10347-014-0397-1.
Haas, J., Hips, K., Budai, T., Győri, O., Lukoczki, G., Kele, S., Demény, A., and Poros, Zs. (2017). Processes and controlling factors of polygenetic dolomite formation in the Transdanubian Range: a synopsis. *International Journal of Earth Sciences*, 106(3): 991–1021.
Hughes, J.D., Vacher, H.L., and Sanford, W.E. (2007). Three-dimensional flow in the Florida platform: Theoretical analysis of Kohout convection at its type locality. *Geology*, 35(7): 663–666, https://doi.org/10.1130/G23374A.1.
Kaczmarek, S.E. and Sibley, D.F. (2014). Direct physical evidence of dolomite recrystallization. *Sedimentology*, 61: 1862–1882.
Kaczmarek, S.E., Gregg, J.M., Bish, D.L., Machel, H.G., and Fouke, B.F. (2017). Dolomite, very-high magnesium calcite, and microbes: implications for the microbial model of dolomitization. In: *Characterization and Modeling of Carbonates–Mountjoy Symposium 1*, Vol. 109. SEPM Special Publication, http://doi.org/10.2110/sepmsp.109.01.
Kohout, F.A., Henry, H.R., and Banks, J.E. (1977). Hydrogeology related to geothermal conditions of the Floridan Plateau. In: Smith, K.L. and Griffin, G.M. (szerk.), *The geothermal nature of the Floridan Plateau*, Vol. 21. Florida Department of Natural Resources Bureau, Geology Special Publications, pp. 1–34.
Machel, H.G. (2004). Concepts and models of dolomitization: a critical reappraisal. In: Braithwaite, C., Rizzi, G., and Darke, G. (szerk.), *The geometry and petrogenesis of Dolomite Hydrocarbon Reservoirs*. Geological Society, London, Special Publication, pp. 7–63.
Meister, P., McKenzie, J.A., Bernasconi, S.M., and Brack, P. (2013). Dolomite formation in the shallow seas of the Alpine Triassic. *Sedimentology*, 60: 270–291.
Nader, F.H., Swennen, R., and Ellam, R. (2004). Reflux stratabound dolostone and hydrothermal volcanism-associated dolostone: a two-stage dolomitization model (Jurassic, Lebanon). *Sedimentology*, 51: 339–360, http://doi.org/10.1111/j.1365-3091.2004.00629.x.
Pearce, M.A., Timms, N.E., Hough, R.M., and Cleverley, J.S. (2013). Reaction mechanism for the replacement of calcite by dolomite and siderite: implications for geochemistry, microstructure and porosity evolution during hydrothermal mineralisation. *Contributions to Mineralogy and Petrology*, 166: 995–1009, http://doi.org/10.1007/s00410-013-0905-2.
Roberts, J.A., Kenward, P.A., Fowle, D.A., Goldstein, R.H., González, L.A., and Moore, D.S. (2013). Surface chemistry allows for abiotic precipitation of dolomite at low temperature. *Proceedings of the National Academy of Sciences of the United States of America*, 110(36): 14540–14545.
Rosenbaum, J. and Sheppard, S.M.F. (1986). An isotopic study of siderites, dolomites and ankerites at high temperatures. *Geochimica et Cosmochemica Acta*, 50: 1147–1150.
Spadafora, A., Perri, E., McKenzie, J.A., and Vasconcelos, C. (2010). Microbial biomineralization processes forming modern Ca:Mg carbonate stromatolites. *Sedimentology*, 57: 27–40.
Spötl, C. and Vennemann, T.W. (2003). Continuous-flow isotope ratio mass spectrometric analysis of carbonate minerals. *Rapid Communications in Mass Spectrometry*, 17: 1004–1006.
Tucker, M.E. and Wright, V.P. (1990). *Carbonate sedimentology*. Blackwell Science, Oxford, p. 482.
Vacher, H.L. (1988). Dupuit–Ghyben–Herzberg analysis of strip-island lenses. *Geological Society of America Bulletin*, 100: 580–591.
Vörös, A. (1998). Triassic ammonoids and biostratigraphy of the Balaton Highland. *Studia Naturalia*, 12: 1–104.
Vörös, A. (2018). The Upper Anisian ammonoids of the Balaton Highland (Middle Triassic, Hungary). *Geologica Hungarica series Palaeontologica*, 60: 1–241.
Vörös, A., Budai, T., Lelkes, Gy., Monostori, M., and Pálfy, J. (1997). A Balaton-felvidéki középső-triász medencefejlődés rekonstrukciója üledékföldtani és paleoöklógiai vizsgálatok alapján. *Földtani Közlöny*, 127(1–2): 145–177.
Vörös, A., Budai, T., Lelkes, Gy., Kovács, S., Pálfy, J., Piros, O., Szabó, I., and Szente, I. (2003). The Pelsonian Substage at the Balaton Highland (Middle Triassic, Hungary). *Geologica Hungarica series Palaeontologica*, 55: 1–195.
Whitaker, F., Smart, P.L., Vahrenkamp, V.C., Nicholson, H., and Wogelius, R.A. (1994). Dolomitization by near-normal seawater? Field evidence from the Bahamas. In: Purser, B.H., Tucker, M.E., and Zenger, D.H. (szerk.), *Dolomites*, Vol. 21. International Association of Sedimentologists Special Publication, pp. 111–132.
Wright, V.P. (2007). Calcrete. In: Nash, D.J. and McLaren, S.J. (Eds.), *Geochemical sediments and landscapes*. Blackwell Publishing Ltd, Oxford, pp. 10–47.
Wright, D.T. (2000). Benthic microbial communities and dolomite formation in marine and lacustrine environments - new dolomite model. In: Glenn, C.R., Prévôt-Lucas, L., and Lucas, J. (szerk.), *Marine Authigenesis: from global to microbial*, vol. 66. SEPM Special Publication, 7–20.
Wright, D.T. and Wacey, D. (2005). Precipitation of dolomite using sulphate-reducing bacteria from the Coorong Region, South Australia: significance and implication. *Sedimentology*, 52: 987–1008.
Xu, J., Yan, C., Zhang, F., Konishi, H., Xu, H., and Teng, H.H. (2013). Testing the cation-hydration effect on the crystallization of Ca–Mg–CO3 systems. *Proceedings of the National Academy of Sciences of the United States of America*, 110(44): 17750–17755.
Zhang, F., Xu, H., Konishi, H., Shelobolina, E.S., and Roden, E.E. (2012). Polysaccharide-catalyzed nucleation and growth of disordered dolomite: a potential precursor of sedimentary dolomite. *American Mineralogist*, 97: 556–567.