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Dolomitization of Late Norian carbonate deposits of restricted basin facies in the Keszthely Mts., Transdanubian Range, Hungary

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Abstract
In the Transdanubian Range (Hungary), a wide spectrum of Triassic dolomites is known. Mechanism of dolomitization of the platform carbonate successions was subject of a number of studies but the study of dolomitization of basinal carbonates is very limited. Petrographical and isotope–geochemical characteristics of the Upper Triassic dolomitized carbonate deposits, formed in a fault-controlled intraplate basin, and interpretation of the dolomite-forming processes are presented in the current paper. From the latest Carnian to Middle Norian under semi-arid climatic conditions density-driven flux of seawater derived from nearshore mesohaline fluids was the dominant mechanism of the near-surface pervasive dolomitization of the thick platform carbonate succession. In the late Middle Norian incipient rifting of the Alpine Tethys led to establishment of an extensional structural regime and onset of the formation of the Kössen Basin. In the study area, above the dolomitized platform carbonate succession, platform-derived carbonate sediments were accumulated in a fault-bounded, semi-restricted sub-basin of the Kössen Basin, whereas talus breccias and debrites were deposited near a basin-bounding master fault. The basin deposits (lower and upper members of the Rezi Dolomite Formation) were subject of early diagenetic dolomitization in shallow burial setting. Enhanced salinity seawater was the dolomitizing fluid; the synsedimentary fracturing may have promoted the fluid flow and thereby the dolomitization. Thick-bedded carbonates (middle member of the Rezi Dolomite Formation) representing a progradational tongue of the ambient platform are intercalated between the basin deposits. The dolomitization of this unit can be explained by the reflux model.

Keywords Dolomitization · Reflux · Extensional basin · Triassic · Transdanubian range

Introduction

In spite of more than 200 year research activity of generations of earth scientists, many aspects of the dolomite genesis are still rather enigmatic. There is no doubt, that most dolomites were formed via replacement of calcareous sediments/limestones during diagenesis. However, dolomitization is commonly the result of multiple processes and the reconstruction of the complex history of dolomitization from the end products requires an integrated approach based on results from multidisciplinary methods. Understanding of the syndepositional/penecontemporaneous dolomite forming processes is strongly hampered by the facts that there are only a few examples for dolomite formation in recent/sub-recent deposits and the laboratory experiments for the reconstruction of dolomite formation under surface conditions have not yielded unambiguous results (McKenzie 1991; Purser et al. 1994; Land 1998; Machel 2004; Gregg et al. 2015). Due to these aspects, the case studies are still
important tools for understanding the dolomite forming processes, and in many cases, these studies are indispensable for the correlation of the rock bodies and, therefore, the correct lithostratigraphic assignment of many dolomitized carbonate rocks.

The 3–3.5-km-thick Triassic succession of the Transdanubian Range (TR), in NW Hungary, is made up mostly of carbonate rocks and a wide variety of dolomites and partially dolomitized limestones evolved in this domain (Haas et al. 2017). The Keszthely Mountains, forming the westernmost part of TR, consists predominantly of Upper Triassic dolomites representing platform, slope and semi-restricted basin facies. Interpretation of the main controlling factors and reconstruction of dolomite-forming processes of the thick Upper Triassic platform carbonate successions was subject of several studies (Haas et al. 2014a, b, 2015, 2017) but no detailed study of dolomitization of basinal carbonates has been presented so far. That is why the presentation of petrographical and geochemical characteristics of the dolomitized slope and basin dolomites and interpretation of the dolomite-forming processes are placed into the focus of the current paper.

Geological setting

The study area is in the Keszthely Mts., located at the south-western end of the TR, west Hungary (Fig. 1). The TR belongs to the Transdanubian Range Unit (TRU) that is considered as the eastern continuation of the Upper Austroalpine nappes (Fodor et al. 2003; Tari and Horváth 2010). In the early period of the Alpine plate-tectonic cycle, this unit was located between the South Alpine and Upper Austroalpine realm, as a segment of the Adriatic margin of the Neotethys Ocean (Fig. 2; Haas et al. 1995; Mandl 2000; Gawlick 2000; Csontos and Vörös 2004). Lateral extrusion led to its large-scale eastward displacement during the postcollisional deformation stages of the Alps (Schmid et al. 1989; Ratschbacher et al. 1991; Frisch et al. 1998; Haas

Fig. 1 Simplified pre-Cenozoic geological map a of the Transdanubian Range Unit (TRU); the framed area shows the position of the Keszthely Mts. (modified after Haas and Budai 2004). The inset map b shows the structural setting of the TRU in the Alpine–Carpathic–Dinaric region (after Haas et al. 2010). Abbreviations: (A) cov covered; (B) D–I Drina–Ivanjica; DOB Dinaridic Ophiolite Belt; MH MU Mid-Hungarian Megaunit; P Penninic Unit

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et al. 2014a, b). The TRU forms an arcuated mega-syncline structure. This mega-syncline is NE–SW directed in the central part of the TRU (Bakony Mts.), whereas it becomes gradually N–S trending in the southwestern part of the TRU (Keszthely Mts., Zala Basin; Fodor et al. 2013). The related folds and thrusts came into existence in the mid-Cretaceous. The investigated area belongs to the south-eastern limb of this mega-syncline, and accordingly, the major folds of the Keszthely Mts. are N–S trending (Budai et al. 1999a, b).

The Keszthely Mts. are made up mainly by Upper Triassic formations (Figs. 3, 4). A significant fault system divides the mountain into two parts (Budai et al. 1999a, b). The northern segment of this fault system is the N–S striking Szent Miklós fault. The southern continuation of this fault is the NW–SE striking Ederics fault (Héja et al. 2018). In the eastern part of this fault system, completely or partially dolomitized or non-dolomitized Carnian platform carbonates (Ederics Limestone) and basinal marl and limestone (Veszprém Marl, Sándorhegy Formation) crop out (Csillag et al. 1995; Budai et al. 1999a, b; Haas et al. 2014a, b). The western side of the mountain comprises mostly Upper Carnian to Lower–Middle Norian platform dolomite (Fődolomit Formation; equivalent with the Hauptdolomit in the Eastern Alps and the Dolomia Principale in the Southern Alps). This internal platform carbonate succession that is made up of cyclic alternation of completely dolomitized subtidal and peritidal beds is widely extended in the TR. East to the Keszthely Mts., in the area of the Bakony Mts., the Fődolomit Formation progresses upward into the Dachstein Limestone through a transitional interval (Fenyőfő Member; upper Middle Norian—lower Upper Norian) that is characterised by entirely dolomitized, partially dolomitized and non-dolomitized segments (Fig. 4, Haas et al. 2015). In the southern part of the Keszthely Mts., the typical cyclic development of the Fődolomit Formation can also be observed, but darker grey, thick-bedded dolomite (dolomitized subtidal facies) occurs directly below the basinal Rezi Dolomite Formation (Budai and Koloszár 1987; Budai et al. 1999b).
From the end of Middle Norian fault-bounded basins began to develop, where the Rezi Dolomite and then the Kössen Marl were formed during the Late Norian and Rhaetian. These formations are preserved mostly in the central part of Cretaceous synclines of the Keszthely Mts.

The Upper Norian Rezi Dolomite consists of grey, thin-bedded and laminated, locally cherty dolomite of semi-restricted basinal facies (Fig. 5). The rocks are relatively rich in organic matter. Based on measurements of cores from Rezi Rzt-1 well and Zalaszentlászló Zl-1 well (Figs. 3, 4) representing the uppermost part of the Rezi Dolomite, the TOC ranges from 0.7 to 6.8%. The organic matter is predominantly of marine origin (unicellular planktonic algae) and immature ($R_o$ 0.32–0.34%; Vető et al. 2000; Hetényi et al. 2002). Ostracodes occur in some layers in rock-forming quantity (Budai et al. 1999b). The presence of a monospecific conodont-assemblage (*Metapolygnathus slovakensis*) was also reported in the lower member (Budai and Kovács 1986). According to a recent comparative study (Du et al. 2021) the time range of this species (its present-day name *Mockina slovakensis*) is latest Aluanian to late Sevatian. Thick-bedded to massive dolomite (middle member), rich in bioclasts (dasyycladalean algae, gastropods and bivalves) is intercalated into the basinal succession which were interpreted as a dolomitized progradation tongue of the neighbouring carbonate platform (Csillag et al. 1995; Budai et al. 1999b). The thin-bedded, laminated dolomite in the upper part of the Rezi Dolomite is overlain by Upper Norian to Rhaetian dark grey to black marl of the Kössen Formation (Fig. 5). A 10-m-thick transitional interval, made up of alternation of dolomite, dolomarl and limestone, occurs in the basal part of the Kössen Formation (Haas 1993).

Due to multistage denudation from the mid-Cretaceous onward, Mesozoic formations younger than Rhaetian are not known in the area of the Keszthely Mts. However, the younger Mesozoic to Cenozoic formations have been preserved in other parts of the TR, north-east to the Keszthely Mts., allowing the reconstruction of the evolutionary history for the missing parts (Vörös and Galácz 1998; Haas et al. 1985; Horváth and Cloething 1996; Budai et al. 1999b; Magyar et al. 1999; Haas 2012).

### Materials and methods

The basic concept of the sampling was to represent the lithofacies types of the Upper Triassic succession from the upper part of the Fődolomit Formation through the transitional interval and the Rezi Dolomite Formation to the basal part of the Kössen Formation. A series of abandoned quarries along the western belt of the Keszthely Mts. (Fig. 3) provided a good opportunity for sampling of suitable sections from the upper part of the Fődolomit Formation up to the middle member of the Rezi Dolomite. Since no suitable surface exposures were available for the upper part of the Rezi Dolomite, well Rzt-1 (Figs. 3, 4) was sampled for representation of this member.
From the above outcrops and cores, 45 samples were taken, and 58 thin sections were made for petrographic studies. The thin sections were stained by Alizarin red-S and potassium ferricyanide to determine the carbonate phases in the samples (Dickson 1966). For description of the dolomite texture the classification proposed by Sibley and Gregg (1987) was applied. Folk’s classification (1962) was applied for description of the crystal size.

Stable carbon and oxygen isotope analyses of the dolomite samples (in total 86 samples, Table 1, Online Resource)
were carried out using the continuous flow technique (Spötl and Vennemann 2003), and dolomite reaction conditions and fractionation factors described by Rosenbaum and Sheppard (1986). The samples for stable isotope analyses were prepared using an electric microdrill with a bit diameter of 0.6 mm. The obtained powders (150–200 μg) were dissolved by carbonate-orthophosphoric acid reaction at 72 °C (Spötl and Vennemann 2003). The $^{13}$C/$^{12}$C and $^{18}$O/$^{16}$O ratios were determined in CO$_2$ gases liberated by phosphoric acid using an automated GASBENCH II sample preparation bench attached to a Thermo Finnigan Delta Plus XP Isotope Ratio Mass Spectrometer (Thermo Fisher Scientific, Bath, UK) at the Institute for Geological and Geochemical Research, Research Centre for Astronomy and Earth Sciences, (IGGR, RCAES) Budapest, Hungary. Standardization was conducted using laboratory standards calibrated against the NBS 18 and NBS 19 standards. During the measurement of the dolomite samples, a laboratory dolomite standard (DST; calibrated to NBS-19) was used. 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 δ13C and ±0.1 ‰ for δ18O.

The Total Organic Carbon (TOC) percentage of the dolomite samples (5 samples, Table 2, Online Resource) was determined at IGGR. The dolomite samples were treated by hydrochloric acid (10%) and the remaining fraction (between 0.3 and 2.5 mg) was wrapped in a tin capsule. Triple aliquots of 0.3–2.5 mg samples were weighed and wrapped into Sn capsules (IVA Analysentechnik e.K. Meerbusch, Germany) for the measurements of C elemental percentage (Karlik et al. 2018). The element specific peak area was detected by the internal TCD detector of the Flash 2000 Elemental Analyzer (Thermo Scientific, Rhodano, Italy). The element percentage was calculated according to Hedges and Stern (1984) as

$$C\% = \frac{A_{\text{spl}}^C - A_{\text{blk}}^C}{W_{\text{spl}}} / K,$$

where $A_{\text{spl}}$ and $A_{\text{blk}}$ stand for the peak area of the sample and the blank, respectively; and $K$ is the average $K$-Factor determined by a 6-point calibration curve fitted with the $K$-factor function in the mass range of 0.3–2.5 mg. Applied standard material was N-phenylacetamide (Acetanilide, Thermo Scientific, Cambridge, UK). Reproducibility of the analyses is estimated by the standard deviation of the Acetanilide standards ($n=6$) which was 0.5% for C%, respectively.

The carbon isotope composition of Total Organic Carbon ($^\delta^{13}$C$_{\text{TOC}}$) was measured by a Thermo Scientific Delta V Advantage Isotope Ratio Mass Spectrometer in continuous flow mode, coupled with a Flash 2000 Elemental Analyzer and a ConFlo III interface at IGGR. The dolomite samples were treated by hydrochloric acid (10%) and the remained fraction (between 0.3 and 2.5 mg) was wrapped in a tin Sn capsule and fed to the Elemental Analyzer; the resulting CO$_2$ gas was analysed by Mass Spectrometer following the method presented by Karlik et al. (2018). The isotopic compositions were calibrated against repeated analyses of two international standards (IAEA-CH6, −10.449‰, and IAEA-CH7, −32.151‰). The long-term reproducibility is estimated to be better than 0.1‰.

Strontium isotope composition of dolomites (7 samples, Table 3, Online Resource) was determined at the Institute for Nuclear Research (ICER) in Debrecen. All sample preparation was done in a Class 1000 cleanroom. For strontium isotope analyses, 10–15 mg samples were drilled using an electric microdrill with a bit diameter of 0.6 mm. Then, ultrapure water (UPW; Merck, 18 MΩ·cm) and doubly distilled 14 mol l$^{-1}$ nitric acid were used for sample digestion, resin cleaning and elutions. The powdered dolomite samples were dissolved in 1 M acetic acid (Rieder et al. 2019) solution in PTFE vessels. Crown ether-based Sr-Spec Resin (100–150 mm particle size) (Triskem International, France) was pre-cleaned prior to use with 8 M HNO$_3$ and UPW. Sr was isolated from the matrix components and Rb (isobaric overlap $^{87}$Sr$^+$ and $^{86}$Rb$^+$). After the separation, the solution was evaporated to dryness and 1 ml of 14 mol l$^{-1}$ nitric acid was added and evaporated again. The residue was taken up in 4 ml 3% HNO$_3$ solution. Standard solutions were prepared from the NBS987 SrCO$_3$ (National Institute of Standards and Technology). Strontium isotope ratios were measured using a Neptune Plus MC–ICP–MS (Thermo Fisher Scientific) equipped with an Aridus-3 (CETAC) desolvation system. The $^{87}$Sr/$^{86}$Sr ratio was corrected for instrumental mass discrimination using ($^{88}$Sr/$^{86}$Sr) = 8.375209, as well applying an interference correction for $^{87}$Rb$^+$ and $^{86}$Kr$^+$. Reproducibility of the standard NBS987 during analysis of samples was 0.710257 ± 0.000018 (1σ, $n=6$). All values have been normalised to the accepted value of 0.710240 for NBS987.

**Results**

**Lithological and petrographic characteristics**

The typical cyclic peritidal development of the Fődolomit Formation is exposed in small quarries in the southern part of the Keszthely Mts. near Balatongyörök. From among them, the Szépkilátó Quarry was studied (Fig. 3). The exposed succession is made up of cyclic alternation of 2–5-m-thick beds of beige or light (rarely dark) grey finely crystalline dolomite and 0.1–1.0-m-thick fenestral laminated microbial boundstone (stromatolite) layers (Fig. 6a, b). The cycles exhibit the characteristics of Lofer cycles (Fischer
Fig. 6 Depositional structures and petrographic features of the Fődolomit Formation in the Szépkilátó Quarry. a Thick finely crystalline dolomite beds alternate with thinner stromatolite beds. b Thin, parallel laminated stromatolite interbeds between two thick beds. c Very finely to finely crystalline dolomite with poorly preserved fabric; thin-shelled ostracodes are recognisable (sample 249). d Well-preserved microbial structures in a stromatolite bed (sample 251). f Well-preserved microbial fabric; peloidal dolo-microsparite with bedding parallel sheet cracks and fenestral pores, which are filled by finely crystalline dolomite cement
The stromatolite layers correspond with the peritidal B member, and the thick beds with the subtidal C member of the Lofer cycle.

The C members consist of replacive, fabric-destructive, finely to medium crystalline (20–80 µm), planar-s dolomite with solid inclusion-rich cores and limpid rims. However, poorly to moderately preserved sedimentary texture (bioclastic, lithoclastic, peloidal wackestone) was also observed (Fig. 6c). The sedimentary structure of the B members is perfectly preserved. Slightly undulating very finely crystalline microbial boundstone laminae with fenestral pores are visible (Fig. 6d,e). The fenestral pores are filled by finely and medium crystalline dolomite (dolomitized calcite cement), and coarsely crystalline dolomite cement (Online Resource 1). The finely crystalline replacive dolomite is non-luminescent (Fig. 7a,b). The fenestral pores (many of them are enlarged by dissolution) are occluded or partially filled by a non-luminescent blocky cement phase. The second generation of cement has rhombohedral form and exhibits dull red CL zonation (Fig. 7a,b). This latter cement phase also appears in fracture pores that interconnect the larger fenestral pores.

The medium to dark grey, thick-bedded dolomite unit (upper part of the Fődolomit Fm), that will be referred in this paper as “Keszthely-type dolomite” was studied in the middle yard of the Gyenesdiás Quarry (Figs. 3, 8). The exposed succession is made up of alternating thick and very thick (1.0–1.5 m), medium (20–40 cm) and thin (8–15 cm) beds (Fig. 9a, b). In the lower part of the investigated interval, relatively well preserved peloidal, intraclastic wackestone sedimentary fabric was observed. Favreina-type faecal pellets were recognised in the finely crystalline dolomite matrix (Fig. 9c). The millimetre-sized grains, exhibiting various fabric (mudstone, bioclastic, peloidal wackestone and peloidal packstone) are probably intraclasts. Aphanocrystalline and very finely to finely crystalline dolomite laminae alternate in the overlying thin bed, where synsedimentary microfaults and brecciation were encountered (Fig. 9d). Above it, brecciated fabric was observed in a thick bed. The millimetre-to-centimetre-sized, unrounded clasts consist of very finely crystalline dolomite, whereas the matrix is finely to medium crystalline (Fig. 9e).

The lower member of the Rezi Dolomite is exposed in the western yard of the Gyenesdiás Quarry (Fig. 8). The succession is made up of alternating thick-bedded (0.5–1.0 m) medium grey and thin-bedded (2–15 cm) and laminated dark grey dolomite (Fig. 10a). The dolomite is unimodal, finely crystalline (10–50 µm), planar-s; the sedimentary fabric was completely destroyed (Online Resource 1; Fig. 10b). The fractures are occluded by medium to coarsely crystalline (50–500 µm) dolomite cement (Fig. 10c).

The lower member of the Rezi Dolomite succession is exposed also in the eastern yard of the Gyenesdiás Quarry (Fig. 8). The studied section comprises medium to thick-bedded (bed thickness is 10–40 cm) brownish grey and dark grey dolomite. Within the beds, parallel lamination is common (Fig. 11a). Slump folds were encountered in some beds and lateral outpinching of some layers was also observed.

![Fig. 7](image-url) Photomicrograph (a) and cathode-luminescence image (b) of a fenestral pore. The pore is lined by a non-luminescent blocky cement phase, whereas its central part is occluded by coarse rhombohedral crystals exhibiting dull red CL zonation (sample 250)

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Well-preserved sedimentary fabric, bioclastic wackestone/packstone was found in some layers (Online Resource 1). In the very finely crystalline dolomite ghosts of ostracods and fragments of thin-shelled bivalves are common; ostracod coquina laminae occur, locally (Fig. 11b). Finely crystalline dolomite of poorly preserved sedimentary fabric with ghosts of bioclasts and peloids (Fig. 11c), furthermore, completely fabric-destructive finely crystalline (50–150 µm) dolomite was also found in other beds. This thin-to-medium-bedded interval is overlain by thick-bedded to massive dolomite that forms a progradational tongue containing platform-derived components (middle member of the Rezi Dolomite).

The lower member of the Rezi Dolomite is exposed also in the Pilikán Quarry (Fig. 3). The dolomite is very thick, thick- and medium-bedded, beige, light grey and dark grey, and finely crystalline. Intertonguing into the bedded succession, metre-sized, matrix-supported breccia bodies occur. In certain parts of the quarry, the rocks are fractured, and the pore network is occluded by dolomite cement. In the lower part of the studied section 3–1.5-m-thick beds occur. These beds consist of aphanocrystalline to finely crystalline (max. 50 µm), fabric-destructive dolomite (Online Resource 1). They are cut through by thin fractures with medium to coarsely crystalline (max. 800 µm) dolomite cement.

Above an uneven surface, the thick-bedded interval is overlain by a peculiar rock body that is made up of finely crystalline dolomite containing 1–10-cm-sized clasts and irregular mottles (Fig. 12a). The matrix is light beige,
Fig. 9 Petrographic characteristics of the Keszthely-type dolomite exposed in the middle yard of the Gyenesdías Quarry. **a** Succession of alternating darker and lighter grey and light brownish grey dolomite beds. **b** Upper part of a thick light brownish grey bed, containing cm-sized dark grey dolomite clasts (C). **c** Favreina-type pellets (p) in very finely crystalline matrix (sample 218). **d** Synsedimentary micro-fault (f) in laminated fabric (sample 217). **e** Aphanocrystalline intra-clasts (c) in very finely crystalline matrix (sample 216).
whereas the clasts/mottles are darker. In some cases, the crystal size exhibits a gradual change from the matrix to the mottles, whereas in other cases, there is an abrupt crystal size change along a sharp boundary. In most cases, both the matrix and the clasts/mottles are very finely to finely crystalline (20–60 µm) fabric-destructive, planar-s dolomite (Online Resource 1). In other cases, the matrix is aphanocrystalline, the clasts/mottles are very finely crystalline (Fig. 12b), and in those cases, where the matrix is finely to medium crystalline (max. 100 µm), finely crystalline (max. 50 µm) clasts/mottles occasionally occur (Online Resource 1; Fig. 12c). The entire fabric exhibits blotchy dull red luminescence (Fig. 12d), where the coarser crystals are brighter (Fig. 12e).

The non-brecciated bed found directly above the above-described rock body exhibits the same features as those below the breccia and no significant difference was found in the fabric and textural characteristics of the medium grey and dark grey, thin-bedded dolomite sampled in other parts of this quarry. From samples taken from the Pilikán Quarry, in the biomouldic pore- and fracture-filling medium crystalline dolomite cement, less than 3 µm-sized, irregularly shaped, single-phase, all-liquid fluid inclusions were found (Fig. 13a). The inclusions are arranged in the core of the crystal pointing to primary origin (Fig. 13b).

Above the Fődolomit Formation, with a brecciated tectonic contact, a cc. 20-m-thick part of the Rezi Dolomite is exposed in the Molnárkő Quarry (Fig. 3). Light grey, thin-bedded (2–5 cm) and laminated dolomite alternates (Fig. 14a). Parallel lamination is prevailing but small-scale slump folds also occur, locally. The thin beds consist of aphanocrystalline to very finely crystalline dolomite. The laminated rocks are made up of alternation of thicker (3–4 mm) finely crystalline laminae with large amount of micritic intraclasts and thinner (0.2–0.5 mm) very finely crystalline laminae (Fig. 14b,c). Synsedimentary micro-faults were encountered in the laminated rock type.

The large active Csőkakő Quarry is located in the neighbourhood of the Cserszegtomaj Fault (Fig. 3). This structural setting determines the structure of the exposed rock that is

Fig. 10 Depositional structures and petrographic features of the Rezi Dolomite in the western yard of the Gyenesdiás Quarry. a Thick-bedded medium grey dolomite is overlain by thin-bedded dark grey dolomite. b Unimodal, finely crystalline dolomite; in which a narrow fracture is filled by medium crystalline cement (sample 213). c Wider fracture is filled by medium to coarsely crystalline dolomite cement (sample 214)
made up predominantly of brecciated dolomite of various clast sizes from large blocks to cm-sized clasts (scarp breccia; Fig. 15a–c). The rockfall clasts derived from the footwall block and accumulated along the basin margin. Along with lithoclasts, empty or partly cement-filled mouldic pores of cm-to-mm-sized bioclasts (fragments of dasycladalean algae and molluscs) can be observed in these rock bodies (Fig. 15c–e). Intercalating with the breccia bodies, medium to dark grey, thin-bedded, and commonly laminated finely crystalline dolomite bed-sets also occur (Fig. 15a,b,f,g).

Well Rezi Rzt-1 (Fig. 3) intersected the middle and upper members of the Rezi Dolomite and the lower part of the overlying Kössen Formation. The light grey and brownish grey thick-bedded, commonly porous dolomite exposed by core samples from the basal part of the well (288–324.4 m) is assigned to the middle member. Breccia fabric characterizes the uppermost 10 m of this interval, similar to that exposed in the Csókakő Quarry. Centimetre-sized lithoclasts of various fabric, bioclasts (fragments of foraminifera, calcareous sponges, molluscs), micritic nodules, and encrusted bioclasts occur in a finely crystalline matrix (Fig. 16a–d). The dolomite is typified by fine and medium crystals, where the medium crystals have undulose extinction under cross-polars. Many finely crystalline breccia clasts are stained to brown.

The upper member of the Rezi Dolomite (288–265 m) is characterised by dark grey, brownish grey thin-bedded and commonly laminated dolomite. The dolomite is very finely
Fig. 12 Petrographic features of the Rezi Dolomite in the Pilíkán Quarry. a Matrix supported breccia bed (sample 237). b Matrix supported breccia; the matrix (m) is finely to medium crystalline, the clast (c) is finely crystalline dolomite (sample 238). c Coarsely crystalline fracture-filling cement in aphanocrystalline and finely crystalline fabric destructive dolomite (sample 245). d Cathode-luminescence image of the finely crystalline matrix showing blotchy dull red luminescence (sample 247T). e Cathode-luminescence image of coarser crystalline cement exhibiting bright red luminescence.
crystalline, the sedimentary fabric is well-preserved, usually mudstone with scattered peloids and foraminifera. Coalified plant fragments are common. The quantity of bioclasts significantly increases in the upper part of this member. Argillaceous dolomite with lithoclastic dolomite interbeds occurs in the uppermost part of the formation that is overlain by dark grey marl belonging to the overlying Kössen Formation.

Stable carbon and oxygen isotopes

The results of the stable isotope analyses are presented in Online Resource (Tables 1 and 2) and Fig. 17. Separate measurement of the matrix, certain fabric elements and the cement was carried out where possible. The samples taken from the Lofer cyclic Fődolomit Formation in the Szépkilátó Quarry yielded δ^{18}O values between +0.2 and +0.5‰ and δ^{13}C values between +3.2 and +3.8‰. There is no significant difference between the values of the B and C members of the Lofer cycle. Values of δ^{18}O −0.7 to +0.7‰ and δ^{13}C +2.9 to +3.6‰ were measured on samples taken from the"Keszthely-type dolomite” unit of the Gyenesdiás Quarry. The separately sampled fracture-filling cement yielded values δ^{18}O −1.8‰ and δ^{13}C +2.9‰.

The samples taken in the Gyenesdiás Quarry from the lower part of the Rezi Dolomite yielded δ^{18}O values between +0.1 and +1.7‰ and δ^{13}C values between +1.8 and +3.3‰. Carbon elemental percentage and isotope values of bulk organic matter (Total Organic Carbon, TOC) were determined on five samples. The amount of TOC varies between 0.035 and 0.256%. The δ^{13}C_{TOC} values ranges from −25.0 to −28.1‰. The fracture filling cement from here yielded values δ^{18}O−3.7‰ and δ^{13}C +1.8‰. The values for the samples taken from the Pilikán Quarry are as follows: δ^{18}O −0.1 to +0.8‰ and δ^{13}C +1.7 to +2.8‰. The range of the values for the fracture filling cement: δ^{18}O −3.7 to −7.6‰ and δ^{13}C +1.5 to +2.0‰. Values of δ^{18}O +0.3 to +1.5‰ and δ^{13}C +0.9 to +2.3‰ were measured on samples taken in the Molnárkő Quarry from the Rezi Dolomite.

Strontium isotope ratios

^{87}Sr/^{86}Sr ratios were measured on selected samples (Online Resource, Table 3) to determine the origin and age of the dolomitizing fluids. For this aim 1 sample was taken from the Lofer-cyclic facies of the Fődolomit Formation derived from the Szépkilátó Quarry, 4 samples from various texture types of the “Keszthely-type dolomite” unit of the Gyenesdiás Quarry, one sample from the laminated version of the Rezi Dolomite exposed in the Molnárkő Quarry, and one sample from the thick-bedded, brecciated facies of the Rezi Dolomite of the Pilikán Quarry. The measured ^{87}Sr/^{86}Sr ratios are within a range of 0.707738 and 0.708128 (Table 3 Online Resource 1 and Fig. 18).

Interpretation and discussion

Our petrographic and geochemical investigations suggest that in the cases of all of the studied rock bodies (the Lofer-cyclic and the “Keszthely-type” Fődolomit Formation and the Rezi Dolomite Formation) the pervasive dolomitization of the precursor carbonate sediments took place during the early diagenesis, and seawater of more or less modified chemical composition was the dolomitizing fluid. During the investigated time range from the Middle to Late Norian the study area was located far from the open ocean, in the continent-ward belt of a wide carbonate platform which transformed to a back-platform basin system (Haas and Budai 1995; Haas 2002), and during this time interval the climatic conditions gradually changed from semi-arid to semi-humid (Haas et al. 2012, 2017). These paleogeographic conditions...
must be taken into consideration for the evaluation of the dolomitization processes.

The δ18O values measured on the samples of the Fődolomit Formation (+0.2 to +0.5‰) are slightly less positive than those measured on the samples taken from the same formation in other parts of the TR (Bakony and Vértes Mts.). However, similar values were measured on the dolomite samples of the Fenyőfő Member that is a transitional unit between the Fődolomit Formation and the Dachstein Limestone, made up of alternation of dolomitized, partially dolomitized and non-dolomitized beds (Haas et al. 2015). The δ13C values (+3.2 and +3.8‰) fit to the range of those of the Fődolomit Formation in other part of the TR (Haas et al. 2017).

The δ18O range suggests near-surface dolomitization. The δ13C values are within the range of the Norian seawater determined by Korte et al. (2005). δ13C values between +3.0 and 0‰ were measured on the samples taken from the Middle Norian pelagic limestones in the Western Neotethys key-section Pizzo Mondello, Sicily (Muttoni et al. 2014). Although the values measured for the roughly coeval Fődolomit Formation in the Keszthely Mts. are slightly more positive, the difference is not significant and seems

![Fig. 14 Depositional structures and petrographic features of the Rezi Dolomite in the Molnárkő Quarry.](image)

**a** Thinly bedded dolomite with laminated intervals. **b** Alternating thicker finely crystalline and thinner very finely crystalline laminae (sample 224). **c** Thicker laminae consist of silt-sized carbonate grains and fine sand-sized micritic intraclasts (sample 224).
Precipitated pore-lining calcite cement. Coarser crystalline affected the carbonate sediments, and also the previously near-surface early replacive dolomitization may have taken place on the wide and levelled internal belt of the Neotethys Ocean. The high-frequency sea-level oscillation led to alternation of subtidal and peritidal depositional conditions which were periodically interrupted by subaerial exposures. Shallow marine calcareous sediments were deposited during the high sea-level phase of the cycles. In the low sea-level phase fenestral laminated microbial boundstone (stromatolite) beds were formed. Precipitation of Mg–Ca carbonates (very-high magnesium calcite—VHMC) might have initiated already in the Bohemian Carbonate Platform developed along the passive margin of the Fődolomit Formation, the carbonate succession of the “Keszthely-type dolomite”. The δ18O isotope geochemical data seems to support this interpretation. The observed slight negative shift in the δ18O values in the samples of the “Keszthely-type dolomite” unit might be explained by periodically changing influence of meteoric water. The synsedimentary fracturing may have promoted the flux of the dolomitizing fluid.

During the Late Norian the development of the extensional basin (Kössen Basin) accelerated in the continentward belt of the huge Late Triassic carbonate platform system. Listric fault-controlled half grabens (sub-basins) came into existence (Haas et al. 2003; Kustatscher et al. 2017) that can be correlated with semi-arid and semi-humid periods (Haas et al. 2012). In the platform, surviving north–east from our study area, this is reflected in ephemeral and commonly partial dolomitization of the platform carbonate successions (Fenyőfő Member). As a consequence of the basin evolution the direction of the flux of platform-derived slightly evaporated seawater turned towards the newly formed back-platform basin at least in its neighbourhood. It means that the reflux model can be applied also for the dolomitization of the shallow subtidal carbonate succession of the “Keszthely-type dolomite”. The isotope geochemical data seems to support this interpretation. The observed slight negative shift in the δ18O values in the samples of the “Keszthely-type dolomite” unit might be explained by periodically changing influence of meteoric water. The synsedimentary fracturing may have promoted the flux of the dolomitizing fluid.

The precursor lime mud of the “Keszthely-type dolomite” unit may have been deposited permanently in the deeper part of the subtidal zone although probably still within the euphotic zone. Accordingly, the sea bottom remained below the intertidal zone even during the periods of the low sea levels (Fig. 19). This deepening trend can be interpreted as an indicator of an increase in the subsidence rate that is accompanied with synsedimentary faulting, i.e., incipient phase of the basin evolution. Roughly contemporaneously with this, during the latest Middle Norian to early Late Norian changes commenced also in the climate; the long-lasting, semi-arid regime was followed by changing semi-arid and semi-humid periods (Haas et al. 2012). In the platform, surviving north–east from our study area, this is reflected in ephemeral and commonly partial dolomitization of the platform carbonate successions (Fenyőfő Member). As a consequence of the basin evolution the direction of the flux of platform-derived slightly evaporated seawater turned towards the newly formed back-platform basin at least in its neighbourhood. It means that the reflux model can be applied also for the dolomitization of the shallow subtidal carbonate succession of the “Keszthely-type dolomite”. The isotope geochemical data seems to support this interpretation. The observed slight negative shift in the δ18O values in the samples of the “Keszthely-type dolomite” unit might be explained by periodically changing influence of meteoric water. The synsedimentary fracturing may have promoted the flux of the dolomitizing fluid.

Further sea-level lowering led to the establishment of supratidal conditions over large parts of the area. Under semi-arid climate this environmental setting may have been favourable for reflux of seawater-derived mesohaline fluids (37–48%), which resulted in pervasive dolomitization (Haas et al. 2015, 2017). Based on the results of transport modeling slight increase in salinity can drive fluids through underlying sediments and may cause pervasive reflux dolomitization (Jones and Xiao 2005; Manche and Kaczmarek 2019). The near-surface early replacive dolomitization may have affected the carbonate sediments, and also the previously precipitated pore-lining calcite cement. Coarser crystalline dolomite cement occluded the larger fenestral pores and fractures later, in the course of burial.
with the lower member of the Rezi Dolomite. The Seefeld Formation was covered by the upper unit of the Hauptdolomit Group which may correspond with the middle member of the Rezi Dolomite. It was followed by the deposition of the Plattenkalk (Donofrio et al. 2003) formed in basin setting, akin to that of the upper member of the Rezi Formation prior to the onset of the deposition of the Kössen Formation.

The Cserszegtomaj Fault was the western boundary of the sub-basin developed in the Keszthely Mts. It was an asymmetric basin with a steep erosional slope along the western master fault, and a wide low-angle slope on the northeastern side of the sub-basin towards the large Dachstein Platform (Fig. 19). Redeposited shallow marine gastropods and bivalves reported from the Csókakő Quarry (Budai and Koloszár 1987) indicate the prolongation of shallow marine conditions on the western, footwall side of the Cserszegtomaj Fault. Unsorted breccia exposed in the Csókakő Quarry is interpreted to be debris-flow and hyper-concentrated flow. These gravity mass transport deposits were accumulated along the toe of the steep slope. The deposition of the breccia body intersected in core Rzt-1 below the thin-bedded dolomite succession (upper member of the Rezi Dolomite) may also be related to the vicinity of the basin-bounding fault zone. The relatively deep internal part of the sub-basin was the site of the deposition of the precursor carbonate sediments of the lower and upper members of the Rezi Dolomite (Fig. 19). The ambient carbonate platforms (mostly the large Dachstein Platform) may have been the source of a predominant part of the fine-grained carbonate sediment. The thin-shelled bivalves and ostracods may have thrived on the gently sloping bottom of the basin. The relatively high total organic carbon (TOC) content and millimetre scale lamina-tion in some beds indicate the establishment of dysoxic to anoxic conditions in the lower stagnant water layer that may have got enhanced salinity during the more restricted periods of the basin. On the other hand, the conodonts found in some

Fig. 16 Petrographic features of a breccia body intersected in core Rezi-1. a Centimetre-sized dolomite lithoclast in aphanocrystalline dolomite matrix with mm-sized lithoclasts and biomolds occluded by very finely crystalline cement. The larger clast consists of very finely crystalline dolomite exhibiting poorly preserved sedimentary fabric (303 m). b Centimetre-sized fragment of a well-preserved calcareous sponge, microbial micritic nodule and small micritic clasts. Intergranular pores are lined by very finely crystalline dolomite and partially filled by medium crystalline dolomite cement (288 m). c Dolomite lithoclasts of various sizes, exhibiting poorly preserved sedimentary fabric. Finely crystalline cement occurs in the intergranular pores. (288 m). d Very finely crystalline breccia clasts of various sizes, which are surrounded by finely to medium crystalline dolomite cement. The dissolution seam (S) is visible in one of the clasts, which does not extend beyond the clasts (297 m)
beds (Budai and Kovács 1986) indicate oxic normal marine conditions in the upper water layer at least during periods of high sea level. However, according to recent comparative Conodont studies performed in various facies areas of the western Neotethys (Du et al. 2021), the *Mockina slovakensis* may have been a surface dweller species living in different

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**Fig. 17** $\delta^{13}$C and $\delta^{18}$O values measured on dolomite samples taken from the studied sections. Lithostratigraphic assignment and petrographic features of the measured samples are presented in Online Resource 1

**Fig. 18** Comparison of $^{87}$Sr/$^{86}$Sr values presented by Korte et al. (2003) from Triassic brachiopods and conodonts of the Tethyan and Germanic Basin realms and those that were measured on selected samples taken from the studied Upper Norian succession (yellow dots). Phanerozoic reference curve of secular changes in marine $^{87}$Sr/$^{86}$Sr isotope ratio (Nebel and Stammeier 2018; based on Veizer et al. 1999) is presented on the inset diagram.
larger dolomite crystals were formed than in the previous dolomitization. Along the synsedimentary fracture network of seawater and whereby the continuation of the replacive fracture network came into being, which promoted the flux of slightly enhanced salinity) was the dolomitizing fluid. (Fig. 19). The early diagenetic fabric-retentive dolomitization of the Kössen Basin during the Late Norian semi-restricted sub-basins in the advanced phase of the range of the upper Middle Norian to Upper Norian values of the measured δ13C values, the organogenic dolomitization might have taken place in the uppermost part of the zone of bacterial methanogenesis. However, for the evaluation of the δ13C values we must keep in mind that +0.5 to +2.0‰ were measured on the samples taken from the Upper Norian part of the pelagic limestone in the Western Neotethys key-section Pizzo Mondello, Sicily (Muttoni et al. 2014) which do not differ significantly from those of the Rezi Dolomite. Therefore, in our opinion it is more probable that the measured values reflect the dominance of platform derived precursor carbonate fraction.

As to the dolomitization of the fault-bounded debris flow deposits, based on data of core Rzt-1, it can be supposed that the redeposited clasts of various origin and preceding diagenetic history were subject of dolomitization near the boundary of shallow and deep burial diagenetic settings (100–200 m) parallel with onset of chemical compaction.

The lithologic features of the upper member of the Rezi Dolomite are similar to those of the lower member although the poor exposure conditions did not allow the detailed study of this interval. Based on studies on cores (e.g., Rzt-1), there is a continuous transition between the Rezi Dolomite and the Kössen Formation. The lithological change from the carbonate-dominated to the clay-dominated deposits likely reflects a significant climatic change at the end of Norian. Increased influx of terrestrial clay and organic matter can be related to enhanced seasonality and humidity which resulted in increased erosion on the continental hinterland (Bonis et al. 2010; Haas et al. 2012).

Conclusions

1. In the area of the Keszthely Mts., the pervasive dolomitization of the Norian carbonate sediments was the result of near-surface early diagenetic processes that were controlled mainly by the paleogeographic setting, the climatic conditions, and the structural evolution of the region.

2. In the latest Carnian a widely extended carbonate platform system came into being in the area of the TRU that was a sector of the passive margin of the western Neotethys Ocean. From the latest Carnian to Middle Norian under semi-arid climatic conditions huge amount of dolomites were formed in the peritidal to shallow subtidal internal parts of the carbonate platform (Fődolomit Formation). The density-driven flux of seawater derived mesohaline fluids may have been the dominant mechanism of the near-surface early diagenetic pervasive dolomitization.

3. In the late Middle Norian incipient rifting of the Alpine Tethys led to an extensional structural regime in the south-western continent-ward part of the area of the TRU, and onset of the formation of a basin system (Kös-
In the Late Norian, during the advanced phase of the technical contributions. The authors thank the reviewers Prof. Patrick (OTKA 124313). The authors are indebted to Zsanett Szilágyi for her Union and the State of Hungary, co-financed by the European Regional The research was supported by the European Acknowledgements

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4. In the Late Norian, during the advanced phase of the development of the Kössen Basin predominantly platform-derived carbonate sediments were accumulated in the internal part of the fault-bounded semi-restricted sub-basins, whereas talus breccias and debrisites were deposited near the basin-bounded faults. In the case of the lower and upper members of the Rezi Dolomite Formation the early diagenetic dolomitization may have taken place in shallow burial setting. Seawater, probably of slightly enhanced salinity, was the dolomitizing fluid, although the contribution of organogenic dolomitization cannot be excluded either. The extensional structural regime may have promoted the flux of seawater in the upper semi-consolidated part of the sediment column.

5. The finely to medium crystalline dolomite cement observed in the fenestral and biomouldic pores and syn-sedimentary fractures may have formed contemporaneously with the pervasive replacement dolomitization of the precursor carbonate sediments and the occasionally occurring pore-lining meteoric calcite cement. The medium to very coarse crystalline dolomite cement commonly occurs in the central part of wider fractures and also appears as lining in larger secondary pores. This cement phase was formed in deeper burial setting during the post-Triassic extensional structural regimes prevailed in the region from the Early Jurassic to the Early Cretaceous.

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