Microfacies associations of Middle and Upper Triassic slope and basin carbonates deposited along the Neo-Tethyan margin, NE Hungary

DOI: 10.17738/ajes.2015.0003

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KEYWORDS

Middle Triassic
Upper Triassic
clotted micrite
carbonate
slope

Abstract

Microfacies types presented here are based on thin section analysis of more than 1.500 samples from drilling cores, surface sections and several outcrops from Middle and Upper Triassic slope and basin carbonates in the Aggtelek–Rudabánya Hills (Hungary). The observed compositional and textural types were grouped into five microfacies associations which are characteristic for slope and basin environments. The clotted micrite "boundstone" typically contains bioclasts, peloids and stromatactis structures. The inhomogeneous clotted micrite-rich groundmass suggests that the sediment originated from mats or mounds enriched in organic matter. Bioclastic wackestone with radiolarians, pelagic bivalve shells and signs of bioturbation was likely deposited in deep-water basinal environment. Bioclastic grainstone–packstone and bivalve–crinoid packstone deposited from turbidity currents which often occurred along the slope. The mudstones can be found after events of sudden deepening, mostly related to the drowning of the Steinalm platform. Data based on comparison of stratigraphical logs show that the Middle Triassic was characterised by rapid deepening followed by the formation and expansion of a carbonate slope. During the Late Triassic, the breakup of the Wetterstein platform had an effect on slope environment as well.

Die hier präsentierten Mikrofazies-Typen basieren auf der Analyse von mehr als 1500 Proben der Region Aggtelek-Rudabanya (Ungarn). Die Proben entstammen entweder aus Bohrungen oder Oberflächenaufschlüssen, z.T. künstlicher Natur. Die beobachteten Mikrofazies-Typen wurden in fünf verschiedene Mikrofaziesassoziationen untergliedert, die typisch für Abhang- bzw. Beckenablagerungen sind. Der „clotted micritic boundstone" führt Bioklasten, Peloide und Stromatactis-Strukturen. Der nicht homogene „clotted micrite" erlaubt eine Interpretation, dass das Sediment von Matten bzw. Mounds, die reich an organischer Substanz sind, herzuleiten ist. Bioklastische Wackestones mit Radiolarien, offen marinen Muschelschalen und Bioturbation werden einem Tiefwasserablagerungsraum zugeordnet. Bioklastische Grainstones bzw. Packstones und Krinoiden-Muschel Packstones werden als turbiditische Ablagerungen interpretiert, wie das häufig an Abhängen zu beobachten ist. Die Mudstones treten nach Ereignissen mit abrupter Vertiefung auf und sind meist mit dem Ertrinken der Steinalm Karbonatrampe in Verbindung stehend. Basierend auf den Vergleichen verschiedener Profile kann konstatiert werden, dass die Mittel-Trias charakterisiert war durch ein rasches Vertiefen des Ablagerungsraumes, gefolgt von der Entstehung und folgender Ausdehnung von karbonatischen Abhängen. Während der Späten Trias zeigt auch das Zerbrechen der Wetterstein-Karbonatplattform einen Einfluss auf die Hangsedimentation.

1. Introduction

The paper focuses on the sedimentological evaluation of the Middle and Upper Triassic slope and basin carbonates of the Aggtelek–Rudabánya Hills in Hungary. In order to characterise the depositional environments, the rock-forming components and their interrelationships were analysed in thin sections. The vertical stratigraphic position and lateral distribution were documented and compared in several boreholes and surface profiles. A specific microfacies type was described

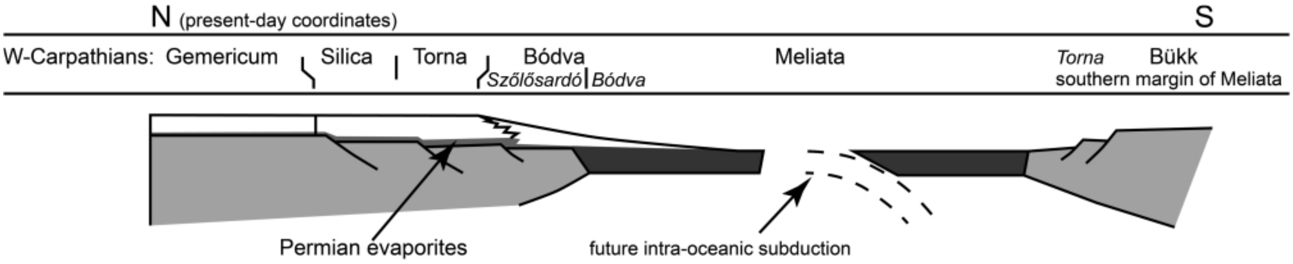

Figure 1: Supposed palaeogeographic relationships of the various domains and tectonic units as used in the Western Carpathians according to the model of Schmid et al., 2008. Different interpretations of the previous model proposed by Kovács (1989) regarding the location of the Torna unit and the Szőlősardó facies of the Bódva unit are indicated in italic.

that is the clotted micrite "boundstone". As a result, a number of modifications on the evolutionary palaeoenvironmental model of the Middle and Late Triassic carbonate environments (Kovács et al., 1989) can be suggested. Boundstone consisting of clotted micrite was previously reported as a microfacies characteristic for platform slopes from Carboniferous carbonates in the Cantabrian Mountains (Della Porta et al., 2002, 2003; Kenter et al., 2005) and Triassic carbonates in the Dolomite Alps (Blendinger, 1994; Keim and Schlager, 1999, 2001; Marangon et al., 2011; Preto, 2012). The clotted micrite "boundstone" was described neither from the Aggtelek–Rudabánya Hills nor from the Northern Calcareous Alps. According to terrane reconstructions these units were situated close to each other during the Triassic (Haas et al., 1995). The evolutionary development of these two units shows many common characteristics, such as similar lithological composition in a well correlating stratigraphic framework. The aim of the microfacies study is to understand better sediment formation of the Middle and Late Triassic slope and basin environments.

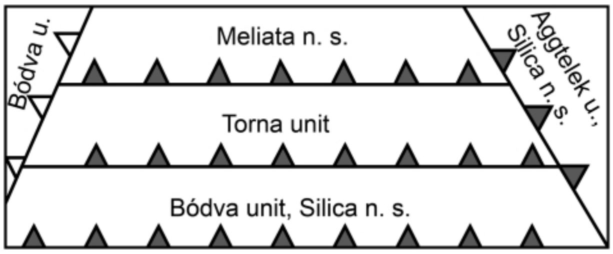

Figure 2: Schematic block section showing the nappe structure of the Aggtelek–Rudabánya Hills, Hungary (Deák-Kövér, 2012). This complex structural geologic build-up was created by the successive deformation phases D4 (dark grey) and D5 (white).

The results likely will provide new interpretational aspects on the similar formations and depositional environments along the Neo-Tethyan margin.

2. Geological settings

The Inner Western Carpathians are the southern segment of the Western Carpathians, in which the remnants of the oceanic

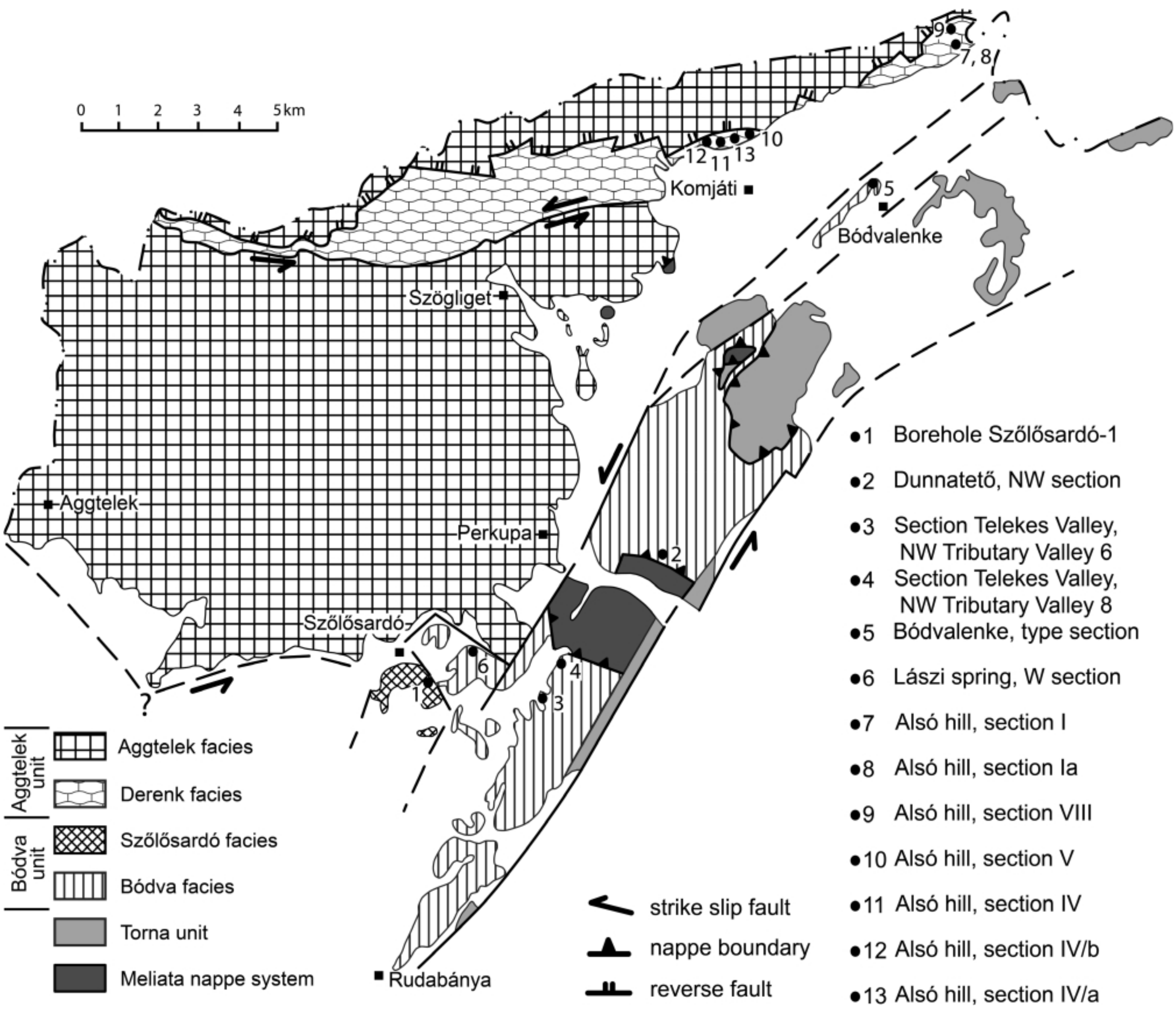

Figure 3: Simplified covered geologic map showing the units and facies areas of the Aggtelek–Rudabánya Hills and locations of the featured boreholes and sections (Haas, 2004 modified after Less et al., 2006 and Deák-Kövér, 2012).

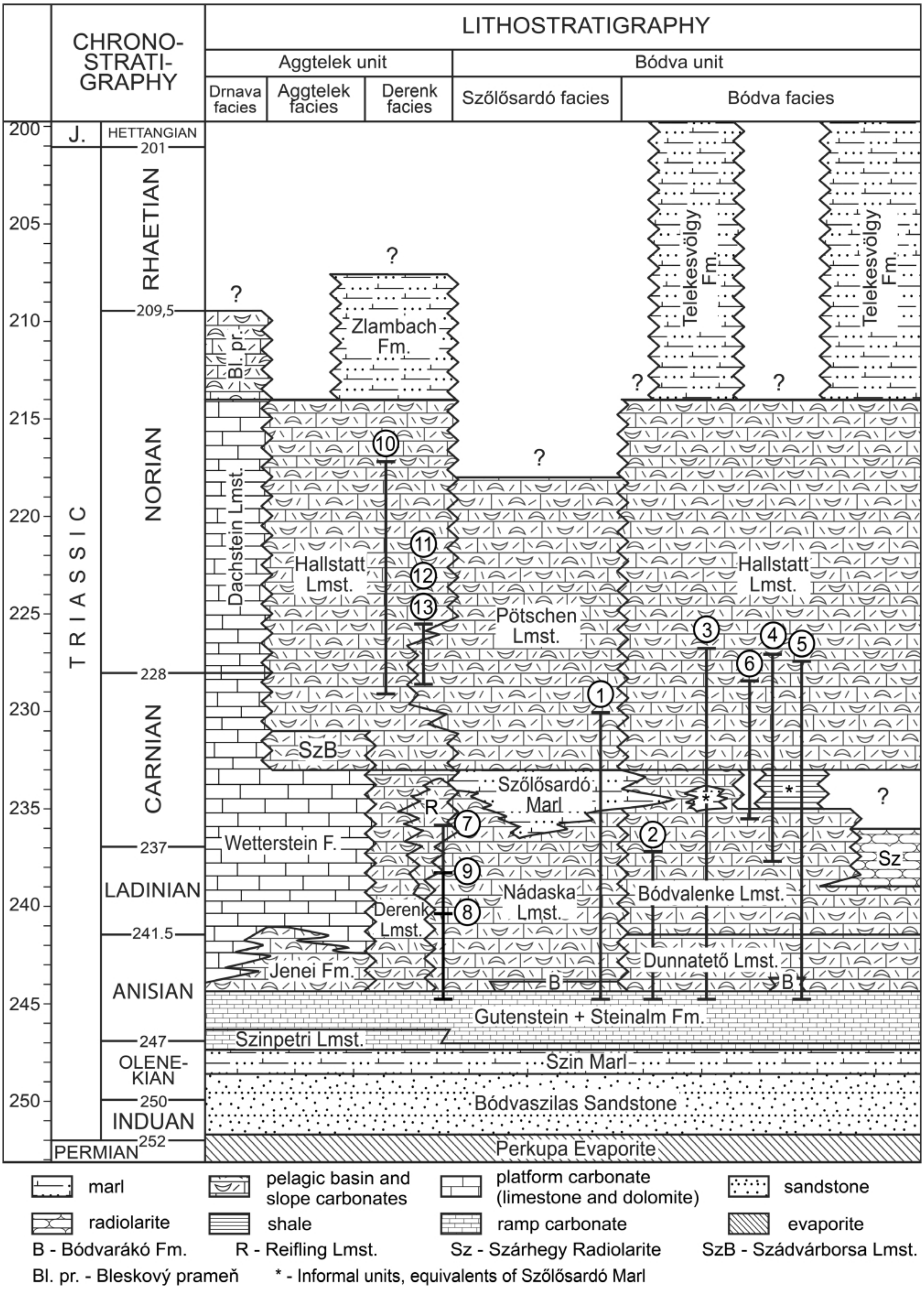

FIGURE 4: Lithostratigraphic subdivision in the units of the Aggtelek–Rudabánya Hills (Haas, 2013 modified after Less, 2000; Less et al., 2006; Velledits et al., 2011; Deák-Kövér, 2012). Jenei Formation is the equivalent of Raming Limestone. The Drnava facies is only known from Slovakia. The numbered vertical lines represent the age range of sections 1–13. Geochronology is based on Ogg et al., 2014.

zone (Meliata nappe system), the adjacent continental slope (Gemeric and Torna units) and the shelf (Silica nappe system) are preserved (Mello et al., 1998; Kovács et al., 2011) (Fig. 1). As part of the Inner Western Carpathians the Aggtelek–Rudabánya Hills are built up by a threefold nappe structure (Grill et al., 1984; Grill, 1989). Members of the non-metamorphosed Silica nappe system (Aggtelek unit and Bódva unit) are in the highest position. They are underlain by the metamorphic rocks of the Meliata nappe system and the Torna unit. The non-metamorphosed Bódva unit of Silica nappe system appears again in the lowermost position (Kövér et al., 2009; Deák-Kövér, 2012) (Fig. 2).This was caused by several successive phases of nappe stacking and thrusting (Deák-Kövér, 2012).

Since this study focuses on the formations of the Silica nappe system only that unit will be discussed in detail in the following. The Silica nappe system contains non-metamorphosed Late Permian–Jurassic formations deposited on the partly thinned continental crust (passive margin) of the Neotethys Ocean (Mello, 1974; Mello, 1975; Mello et al., 1996; Less et al., 1988; Kovács et al., 1989; Less et al., 2006; Kovács et al., 2011) including the formations discussed in the present study. The evolution of this area started with the pre-rift stage, when Neotethyan transgression began and formed a sabkha environment in the Late Permian under arid climatic conditions. The evaporite and associated siliciclastic deposits served as detachment surfaces for the Silica nappes during the tectonic processes which removed them from their pre-Permian basement (Grill et al., 1984; Less et al., 2006). By the Early Triassic normal marine conditions have been established and the continuous deepening led to the deposition of Lower Triassic sandstone, marl and limestone followed by Anisian ramp carbonates (Gutenstein and Steinalm Formations) (Mello, 1974; Less et al., 1988; Kovács et al., 1989; Hips, 2001; Less et al., 2006). Due to the onset of the Neotethyan rifting, the Steinalm carbonate ramp began to get disrupted in the Middle Anisian (Pelsonian–Illyrian) (synrift stage). This

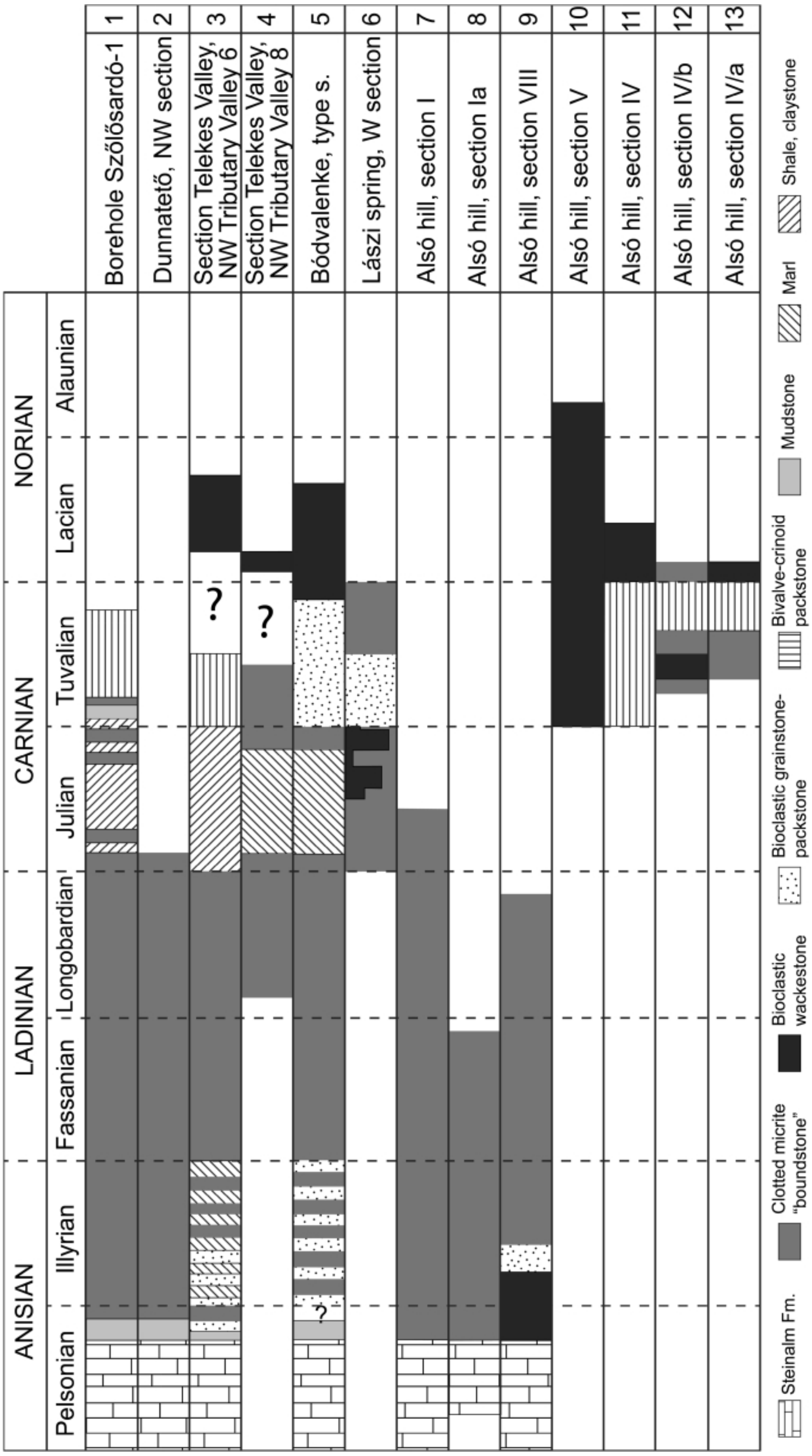

Figure 5: Stratigraphical logs of the 13 chosen sections from the studied area. The logs indicate the described carbonate microfacies associations and other lithologies present in significant amounts. The table covers only the time period represented by the logs (Pelsonian–Alaunian). The question marks represent hiatus in the record caused by tectonic processes and lack of outcrops. Geographical location of these logs is marked on Figure 3. Geochronology is based on Ogg et al., 2014.

ended the hitherto uniform evolution of the area and led to the differentiation of the facies units (Kovács et al., 1989; Less et al., 2006). Each later-formed tectonic unit included a different palaeoenvironment: the Aggtelek unit contained the area where the building of the carbonate platform continued (Aggtelek facies) whereas the Bódva unit was supposed to represent the slope (Szőlősardó facies) and deep-water pelagic (Bódva facies) domains (Kovács, 1989; Kovács et al., 1989). The Aggtelek facies was further subdivided into the Aggtelek (platform) and Derenk (platform slope) facies (Less, 2000; Less et al., 2006) (Fig. 3).

The demise of the Steinalm ramp was followed by the deposition of slope carbonates, such as Jenei Formation (equivalent of Raming Limestone), Nádaska and Reifling Limestone in both facies of the Aggtelek unit (Kovács, 1987, 1991; Kovács et al., 1989; Velledits et al., 2011). Small-sized sponge reefs appeared in the Aggtelek facies in the Late Anisian (Wetterstein Formation) which developed into platform margin reefs during the Ladinian and Early Carnian (Kovács, 1979; Velledits et al., 2011). Meanwhile in the Derenk facies a characteristic slope facies developed simultaneously in front of the carbonate platform (Derenk Limestone). In the Late Carnian (Tuvalian), the drowning of the shallow platform led to the formation of the Szádvárborsa Limestone and the overlying pelagic Hallstatt Limestone (Mišík and Borza, 1976; Kovács et al., 1989; Less et al., 2006; Diviki, 2013). The onset of the Zlambach Marl in the Late Norian was associated with increased input of terrigenous grains (Less, 1987) (Fig. 4).

In the Szőlősardó and Bódva facies, no shallow water carbonates were formed after the Middle Anisian; instead, slope and basin formations were deposited throughout the Late Anisian, Ladinian and Early Carnian (Bódvarákó Formation, Nádaska Limestone, Dunnatető Limestone, Szárhegy Radiolarite, Bódvalenke Limestone). Carbonate production was interrupted by the Carnian event during the Middle Carnian (Julian) which is marked by marl (Szőlősardó Marl) and shale deposition (Balogh and Kovács, 1981; Kovács et al., 1989; Kovács, 2010). After the breakdown of the Aggtelek shelf margin (Tu-

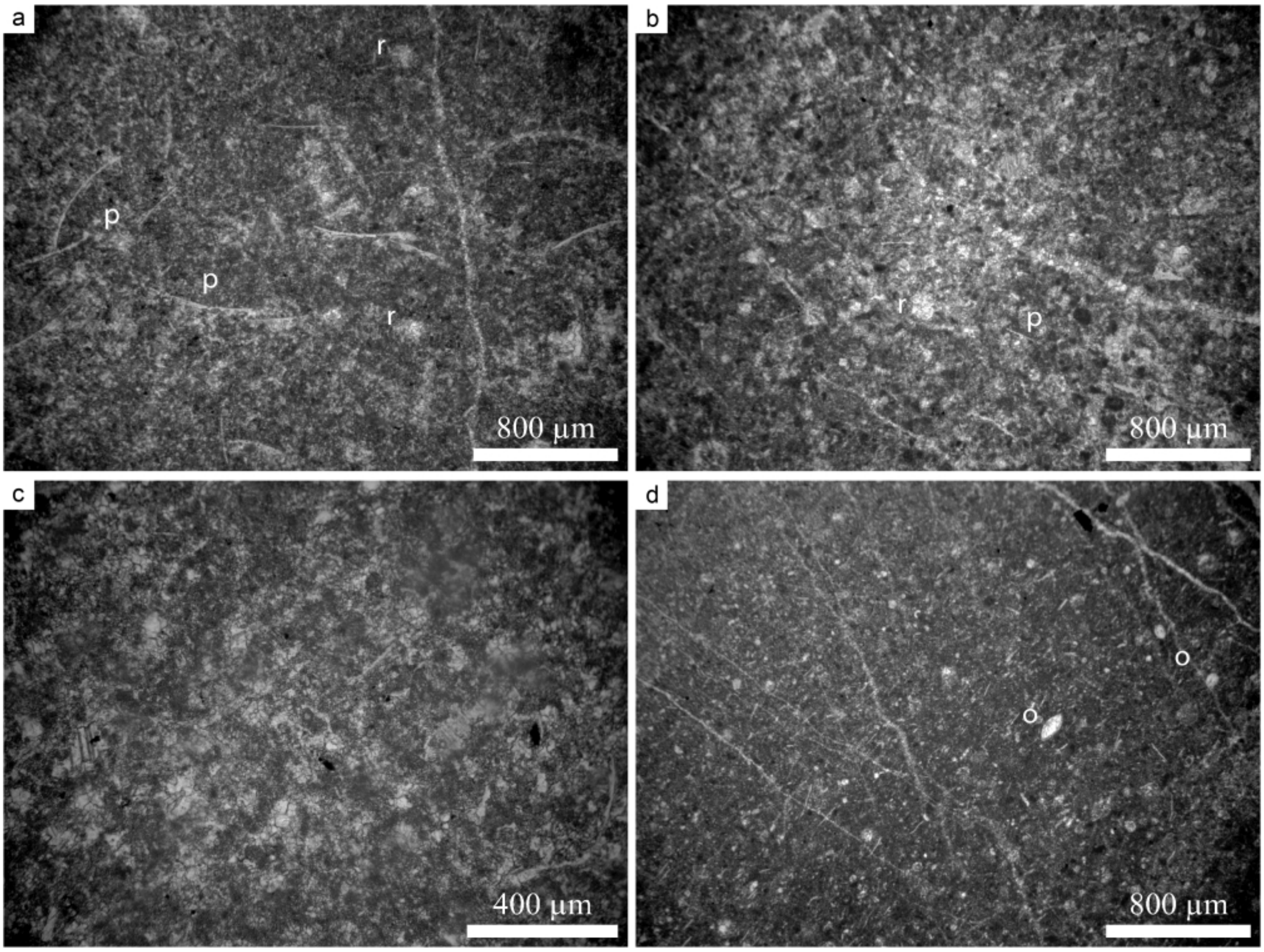

Figure 6: a-c) Photomicrographs showing clotted micrite “boundstone”. The pelagic bivalve shells (p) and radiolarians (r) are embedded into the groundmass of clots, micrite and microspars. The darker spots indicate a higher ratio of micrite, the lighter ones a higher ratio of microspar in the groundmass. a) Borehole Szőlősardó-1, 340.0–340.2 m, Ladinian/Fassanian (*Gondolella excelsa*, *G. cf. balcanica*, *G. constricta*, *G. trammeri*, *G. balcanica*, *Gladigondolella tethydis* - Balogh and Kovács, 1981). b) Alsó hill, section I, 53.17–53.34 m, Carnian/Julian (*Gondolella polygnathiformis* - Kovács, unpublished). c) Borehole Szőlősardó-1, 19.8–20.0 m, Carnian/Tuvalian (*Gondolella polygnathiformis*, *Metapolygnathus communisti*, *M. primitus* - Balogh and Kovács, 1981). d) Photomicrograph showing clotted micrite “boundstone” with almost exclusively micrite in its groundmass. Radiolarians are rare but ostracods (o) are common. Alsó hill, section I, 50.0–50.9 m, Ladinian/Longobardian (*Metapolygnathus mostleri* - Kovács, unpublished).

valian), pelagic sediments were deposited in both the Szőlősardó (Pötschen Limestone) and the Bódva facies (Hallstatt Limestone, Telekesvölgy Formation; Kovács et al., 1989; Less et al., 2006; Deák-Kövér, 2012) (Figure 4).

3. Methods

Geological mapping and sampling of the Middle and Upper Triassic carbonates was carried out focusing on the selected Middle and Upper Triassic formations in the Szőlősardó facies. More than 1.500 thin sections were studied according to the conventional microfacies and textural analyses from 6 drilling cores and 23 surface sections. The sites were systematically studied and 13 of these 29 successions were selected for detailed analyses. They were chosen because of the high number of samples available from previous mappings, small sampling spacing, good accessibility, suitable outcropping conditions, detailed lithological documentation and availability of conodont ages. Accordingly, these 13 successions are presented in this paper for the demonstration of basic microfacies associations (Fig. 3, Fig. 5). The data from the other 16 sections was used for correlation and comparison with the selected ones because they are located close to these successions. They did not give additional information compared to the selected ones.

4. Lithology

The studied Middle and Upper Triassic successions were formed on top of the drowned Steinalm platform. They predominantly consist of thin to thick bedded, finely crystalline limestone in which only very small, mostly microscopic-sized bioclasts occur. The bioclast content comprises of foraminifers, radiolarians, bivalves, ammonites, crinoids and brachiopods (Kovács et al., 1989; Less et al., 2006). There is also a coquina limestone in which coarser-sized skeletal grains, such as pelagic bivalves, crinoids and brachiopods, appear in a vast amount. Although this type is also present in most of the

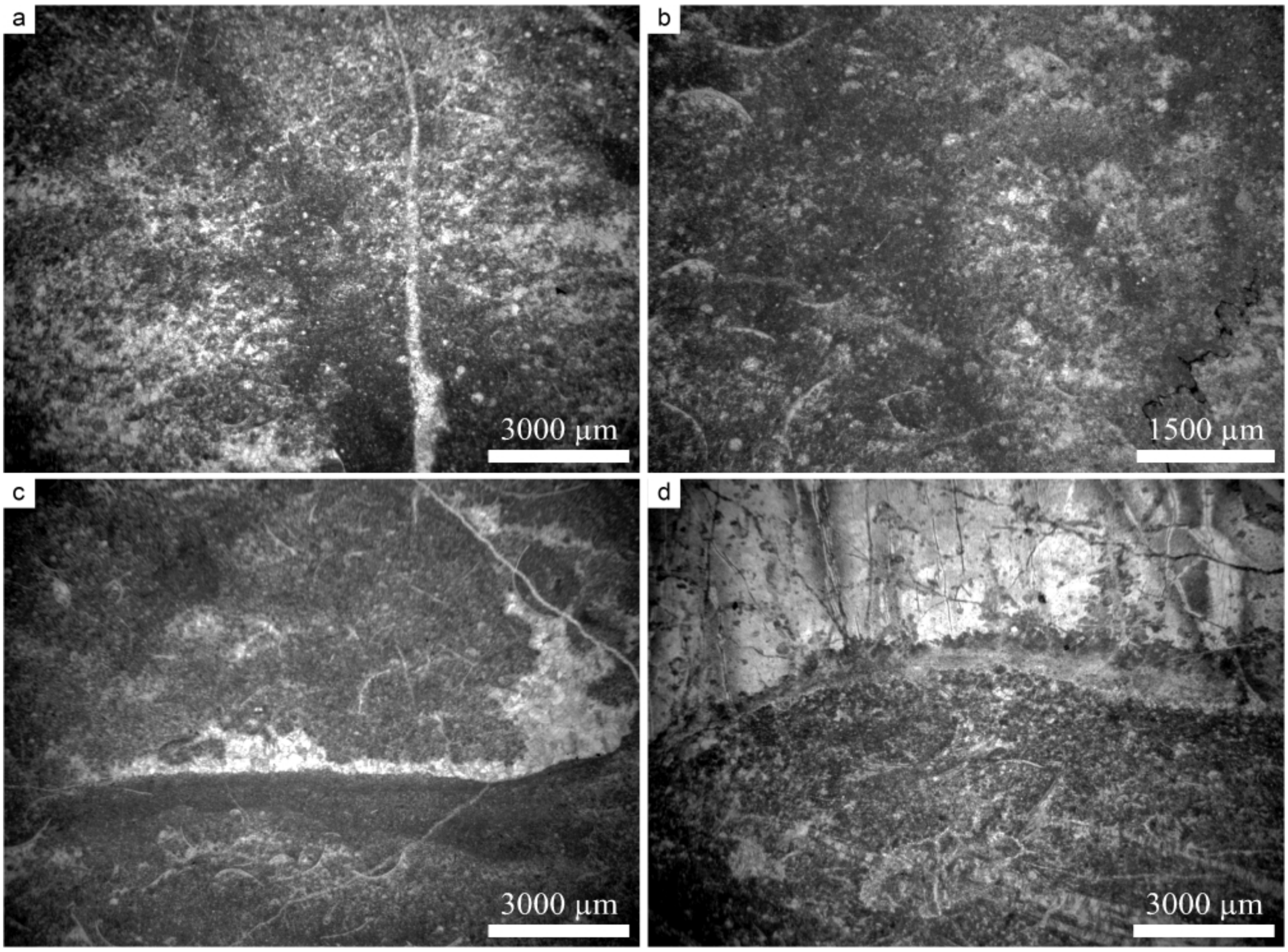

Figure 7: a–b) Photomicrographs showing possible microbial structures inside the clotted micrite “boundstone”. The white, microspar zones supposedly represent the growth pattern of the microbial mat whereas the darker areas are rich in detrital micritic sediment that presumably accumulated in the intermediate space of the mat. a) Section Telekes Valley, NW Tributary Valley 6, 56.11–56.23 m, Carnian/Tuvalian (no Conodont data available). b) Section Telekes Valley, NW Tributary Valley 8, 21.7-21.9 m, Carnian/Tuvalian (*Gondolella polygnathiformis* - Kovács, 1991). c) Photomicrograph showing a horizontally elongated pore with flat base and fractal top in the clotted micrite boundstone. It is filled by micrite at the bottom and calcite spars on the top. Borehole Szőlősardó-1, 299.9–300.1 m, Ladinian/Fassanian (*Gondolella excelsa*, *G. trammeri*, *G. transita*, *Gondolella sp.*, *Metapolygnathus hungaricus*, *M. cf. truempyi*, *Gladigondolella tethydis* - Balogh and Kovács, 1981). d) Photomicrograph showing chert nodule inside clotted micirite “boundstone”. The silicification removed most of the original fabric features. Bódvalenke, type section, sample L-28, Anisian/Illyrian (*Gondolella excelsa*, *G. constricta cornuta*, *G. constricta balkanica* - Kovács, 2010).

successions its amount is subordinate compared to the finely crystalline ones. These two types, finely crystalline and bioclastic, alternate in thin beds (e.g. Bódvalenke type section), or 1–5-m-thick intervals of the coquina-bearing one occur within 20–120-m-thick series of finely crystalline limestone (e.g. borehole Szőlősardó-1). Both limestone types may gradually develop into cherty limestone that contains purplish red or brownish grey chert lenses, nodules or even beds. The thickness of these intervals varies between 20 and 150 m.

The colour of these limestones has a great variety as follows: orange, grey, dark grey, light grey, brown, green, red, beige and white. These colours are not related to any fabric feature. They might mix in any form, size and combination and might also gradually transform into each other.

The studied Middle and Upper Triassic formations do not comprise solely of limestones (Fig. 4, Fig. 5). Thin-bedded, purplish red or brown shale and claystone occur between cherty carbonate beds. In three surface profiles, it is represented by a 2–5-m-thick purplish red coloured interval (stratigraphical logs no. 3, 4 & 5 in Fig. 5; hereinafter referred to as no. 3, 4 & 5). Marl forms an approximately 100-m-thick succession which mostly comprises of 1–5-m-thick dark grey coloured beds (no. 1). The bottom 20 m and top 30 m of the succession contains 0.1–0.5-m-thick dark grey and black limestone layers which alternate with 0.3–0.5 thick marl layers. Dark grey and greenish brown dolomite was found in one borehole (no. 1). Radiolarite is rare; only 5 greenish yellow and dark grey striped layers of it are known. Quartz-biotite tuffite is typically present as green or red coloured, 0.1–2 mm large lenses, <1-mm-thick thin seams or 30–40 mm wide fissure fillings inside the limestones.

5. Microfacies associations

Five basic microfacies associations appear in the Middle and

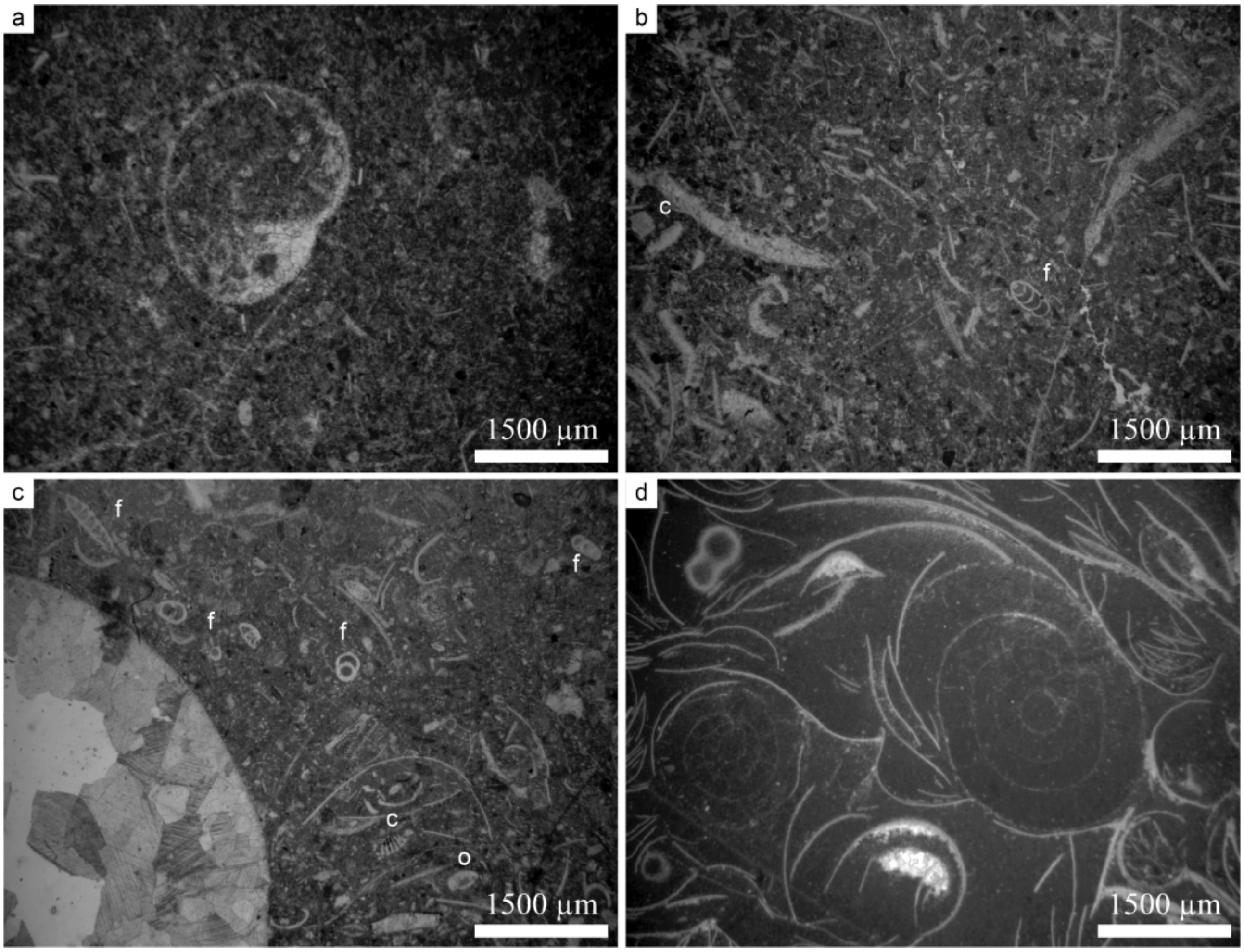

Figure 8: a) Photomicrograph showing a badly preserved ammonite in a clotted micrite "boundstone". Borehole Szőlősardó-1, 219.9–220.1 m, Ladinian/Fassanian (*Gondolella foliata foliata*, *G foliata n. subsp.*, *Metapolygnathus mungoensis*, *M. mostleri*, *Gladigondella tethydis* - Balogh and Kovács, 1981). b) Photomicrograph showing a foraminifer (f) and crinoid skeletal particles (c) in clotted micrite "boundstone". Alsó hill, section VIII, 11.8–12.5 m, Anisian/Illyrian (*Gladigondolella tethydis*, *Gondolella cornuta*, *G. excelsa*, *G. cf. praetrammeri*, *G. aff. szabói* - Kovács, 1987). c) Photomicrograph showing bioclastic wackestone rich in skeletal grains such as a large ammonite on the left surrounded by foraminifers (f), crinoid skeletal particles (c), ostracod shell (o). Alsó hill, section VIII, 6.3–6.5 m, Anisian/Illyrian (*Gladigondolella malayensis budurovi*, *Gladigondolella tethydis*, *Gondolella bifurcata*, *Gondolella excelsa*, *Gondolella hanbulogi*, *Gondolella aff. szabói*, *Gondolella n. sp* - Kovács, 1987). d) Photomicrograph showing two ammonites among pelagic bivalve shells in a dense pack of skeletal grains in a bioclastic wackestone. Lászi spring, W section, 4.4–4.6 m, Carnian/Tuvalian (*Gondolella polygnathiformis*, Holothuria: *Calclamna regularis*, *Irinella canalifera* - Kovács, unpublished).

Upper Triassic carbonates. These are the following:

1. *Clotted micrite "boundstone"*. The most characteristic feature of this type is the clotted micrite content. Clots consist of microcrystalline calcite. They have round shape with vague outlines and grade into the surrounding microspars. The clots, micrite and microspars form a groundmass into which grains are embedded (Figs. 6, 7a–b). The texture is usually rich in skeletal grains which predominantly consist of pelagic bivalves with the addition of a few foraminifers, radiolarians, brachiopods, crinoids and ammonites (Fig. 8a-b). Some of the shells are well preserved while overall grade of fragmentation is 80%. Peloids are abundant. Horizontally elongated occluded pores are common (Fig. 7c). Their size varies widely: 1–20 mm in thin sections but macroscopically it might reach up to 150 mm as well. They are totally filled by micrite, calcite spars, or both. The pores have flat base, fractal top and are often large enough to be visible even by the naked eye. They tend to be arranged into horizons where they occur in large numbers. Otherwise, between these horizons, they are rarely present. Pores of two or even three horizons might be connected vertically through calcite veins.
2. *Bioclastic wackestone.* Among the skeletal grains, radiolarians are predominant (Fig. 9). Sponge spicules, pelagic bivalves, crinoids and brachiopods can be usually found in a slightly lower proportion whereas ammonites and ostracods are present in a noticeably smaller quantity (Fig. 8c-d). The grains are sparsely distributed although there are bioturbational mottles which consist of densely packed skeletal grains (Fig. 9).
3. *Bioclastic grainstone–packstone.* Based on the bioclast content and the presence of micrite matrix three subtypes can be assigned: bivalve grainstone, bivalve packstone and crinoid–brachiopod packstone. In the bivalve grainstone, the grains are almost exclusively disarticulated pelagic bivalve shells (Fig. 10). They show orientation parallel or sub parallel to bedding. The intergranular pores are filled by calcite spar cement. The proportion of the micrite matrix is

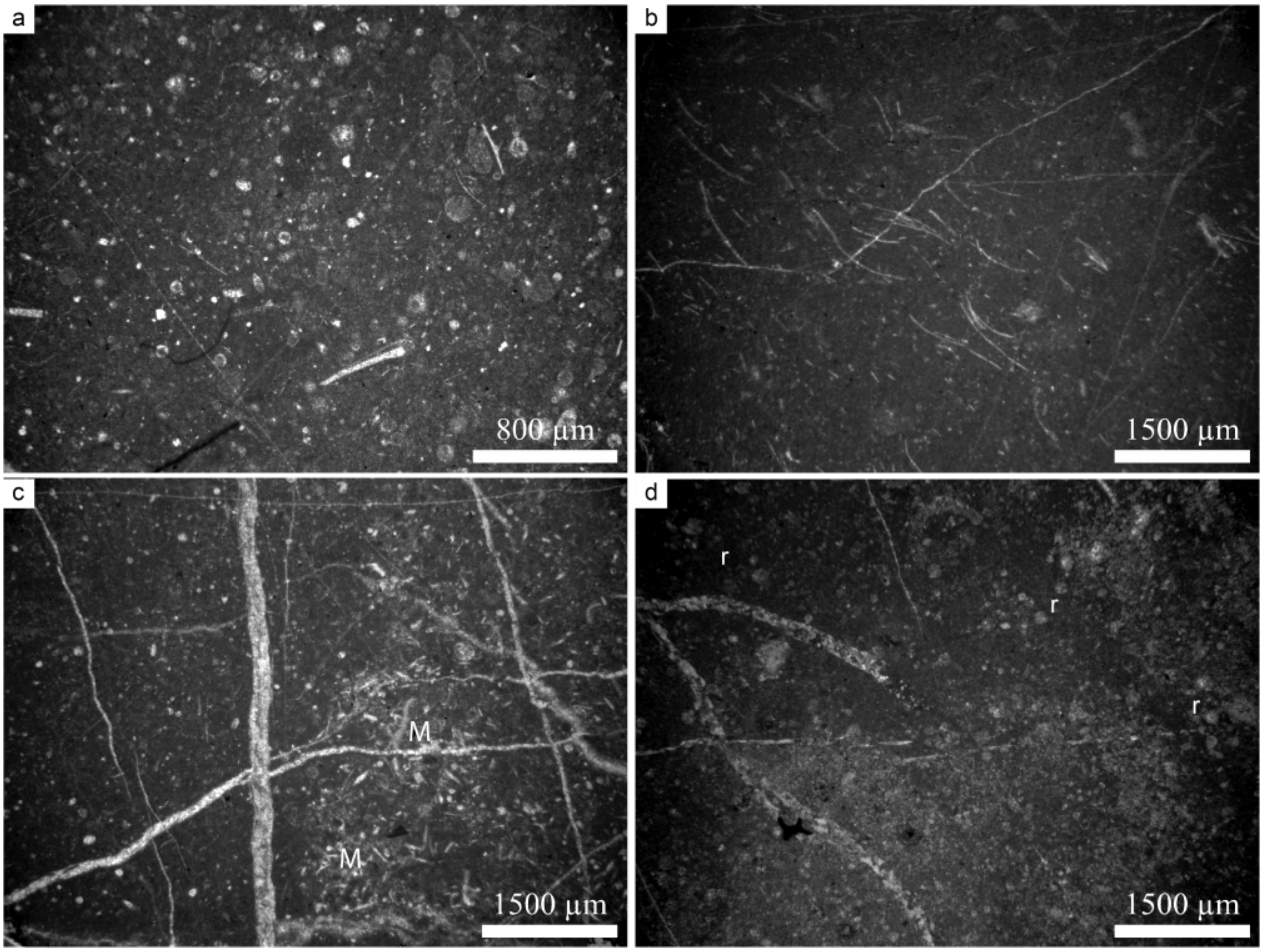

Figure 9: a-b) Photomicrographs showing bioclastic wackestone. a) Section Telekes Valley, NW Tributary Valley 6, 74.4 m, Norian/Lacian (no Conodont data available). b) Dunnatető, NW section, 4.4–4.6 m, Anisian/Illyrian (*Gondolella constricta*, *G. excelsa*, *Gladigondolella malayensis budurovi* - Kovács, unpublished). c) Photomicrograph showing wackestone with skeletal grains, i.e. radiolarians, sponge spicules and shell debris. It often contains bioturbational mottles consisting of denser pack of grains (right) (M). Alsó hill, section IV/c, sample KI-85, Norian/Lacian (no Conodont data available). d) Photomicrograph showing silicified bioclastic wackestone (XN). The silicification process removed most of the original fabric features, only a few radiolarians (r) were preserved. Szőlősardó, Pötschen Limestone key section, 1.55 m, Norian/Lacian (*Gondolella navicula*, *Metapolygnathus abneptis abneptis*, *M. abneptis spatulatus* - Kovács, unpublished).

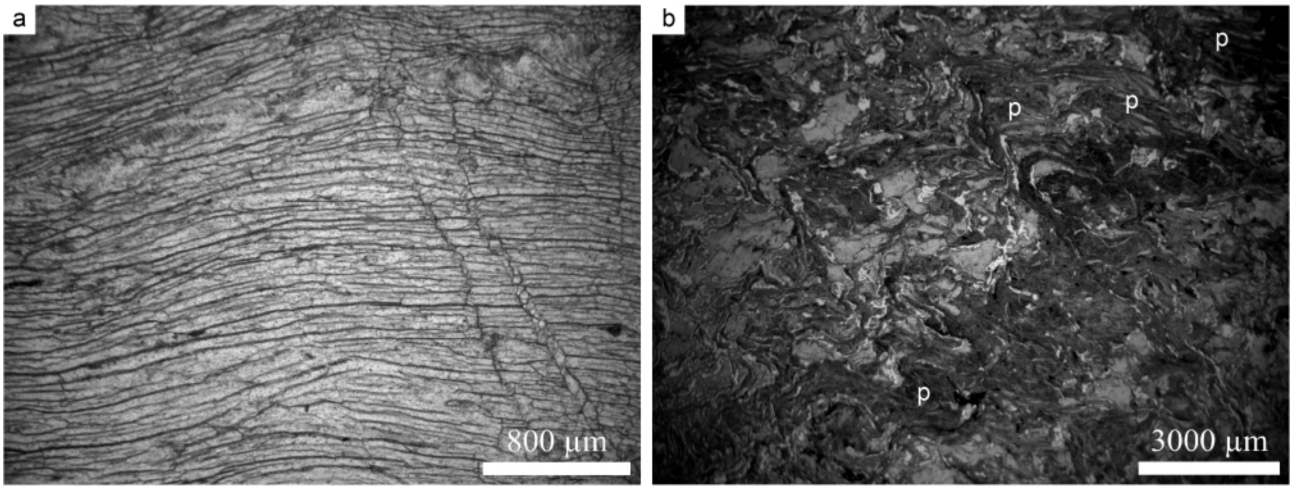

Figure 10: a) Photomicrograph showing bivalve grainstone. The striped appearance is created by thin micrite bands (dark) alternating with parallel oriented bivalve shells and calcite spar cement (light). Bódvalenke, type section, sample 62B, Carnian/Tuvalian (*Gondolella polygnathiformis* - Kovács, 2010). b) Photomicrograph showing silicified bivalve packstone–grainstone. The silicification process created thin, irregular bands of silica (white) surrounded by patches of altered (light grey) and unaltered limestone (dark grey) rich in pelagic bivalve shells (p). Notice the lesser extent of silicification in the grainstone (top right) compared to the packstone (left). Bódvalenke, type section, sample 49, Carnian/Tuvalian (*Gondolella polygnathiformis* - Kovács, 2010).

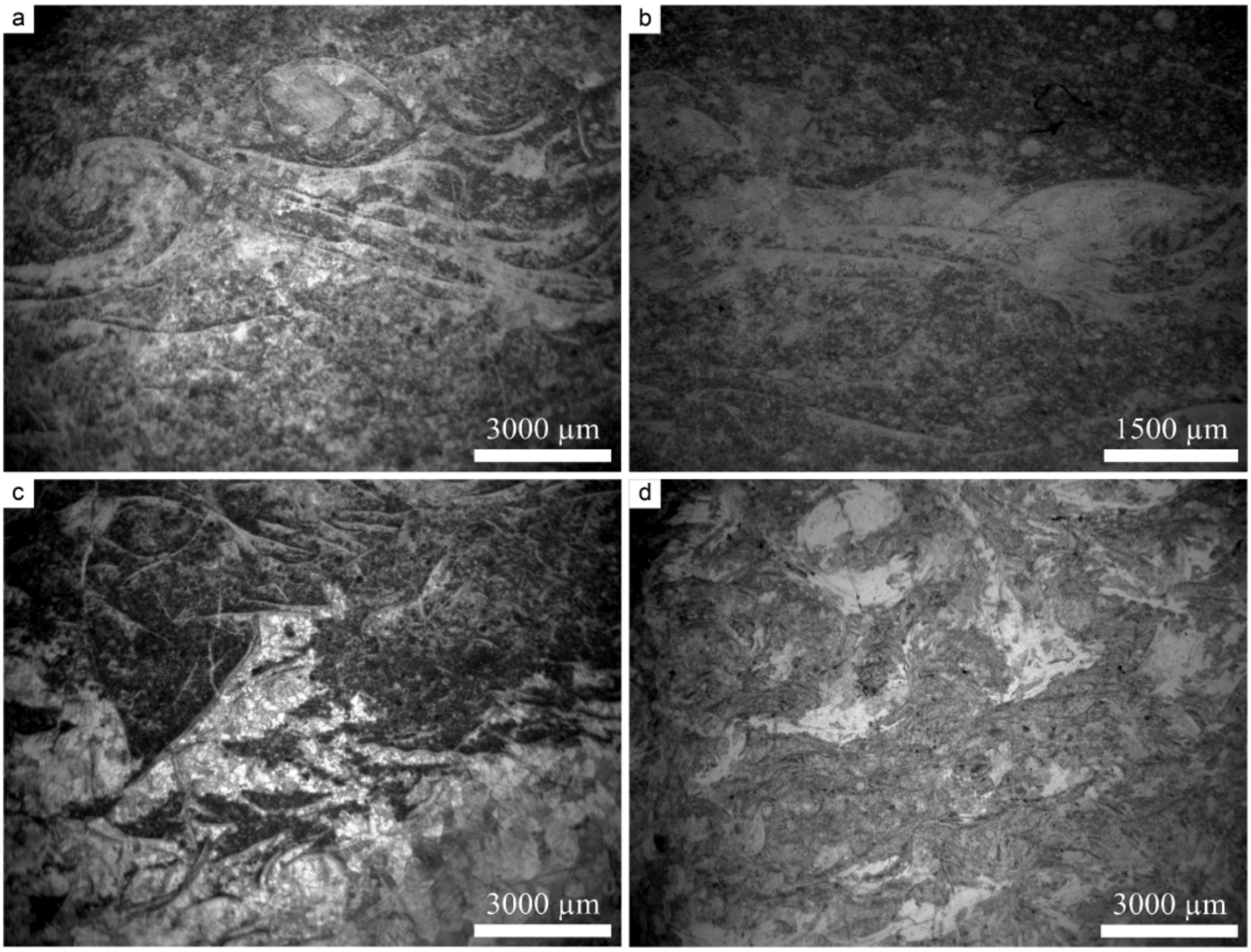

Figure 11: a–b) Photomicrographs showing lenses and patches of bivalve packstone inside clotted micrite "boundstone". a) Dunnatető NW section, 18.15–18.45 m, Ladinian/Fassanian (*Gondolella foliata inclinata*, *Gondolella n. sp.* - Kovács, unpublished). b) Dunnatető NW section, 23.0 m, Ladinian/Fassanian (*Gondolella excelsa*, *Gondolella cf. n. sp.*, *Gladigondolella tethydis* - Kovács, unpublished). c) Photomicrograph showing the borderline of a clotted micrite "boundstone" (up) and a bivalve packstone interbedding (down). Borehole Szőlősardó-1, 191.9–192.2 m, Ladinian/Longobardian (*Gondolella foliata foliata*, *G foliata n. subsp.*, *Metapolygnathus mungoensis*, *M. mostleri*, *Gladigondella tethydis* - Balogh and Kovács, 1981). d) Photomicrograph showing silicified bivalve packstone. The silicification was restricted to the micrite matrix, the shells are mostly intact. Section Telekes Valley, NW Tributary Valley 6, 6.4 m, Pelsonian/Illyrian (no Conodont data available).

less than 5% that appears as thin bands of micrite along the upper surface of the shells. In a few cases, normal gradation can be observed. In the bivalve packstone, disarticulated pelagic bivalve shells are still the predominant grains (Fig. 11). However, the majority of them is fragmented (80–90%). Parallel orientation is not characteristic of them; it only occurs in some parts of the fabric. The micrite matrix contains large amounts of clotted micrite. The crinoid–brachiopod packstone contains coarse (0.6–2 mm) crinoid skeletal particles and brachiopod shells (Fig. 12). Although overall fragmentation is around 80%, a few of the skeletal grains appear well preserved. They occur chaotically, no orientation was observed. Round peloids are abundant, too. Elongated mottles in 1–3 mm size consisting of micrite, microspars and calcite spars are randomly distributed within the texture.

4. *Bivalve–crinoid packstone.* The fabric consists predominantly of disarticulated pelagic bivalve shells and crinoid fragments (columnals, stems and arm plates) (Fig. 13). The rest of the fabric comprises of clotted micrite, calcite spar cement and micrite matrix, rarely a few foraminifers, ostracods and peloids. About 90% of the bivalve shells are fragmented. They are usually oriented parallel to each other although short fragments tend to occur chaotically. Normal gradation is common. Most of the larger-sized matrix patches have rich clotted micrite content.
5. *Mudstone.* Grains occur very rarely and are represented by very small calcitic debris. Their origin is indeterminable. Elongated, channel- or lobe-like structures with circular cross-section are often present (Fig. 14). These structures are filled by micrite, microspars, calcite spars and rectangular micritic grains. They also contain fragments of foraminifers, bivalve shells and ostracods which are usually arranged in bundles.

Chert might occur in every fabric type except mudstone and crinoid–brachiopod packstone (Fig. 7d, Fig. 9d, Fig. 10b, Fig. 11d, Fig. 13d). The silicification is non-fabric selective. Minor silicification occurs in irregularly shaped spots or along solution seams. Major silicification, however, creates “hollow” chert nodules that preserve the original carbonate fabric in their

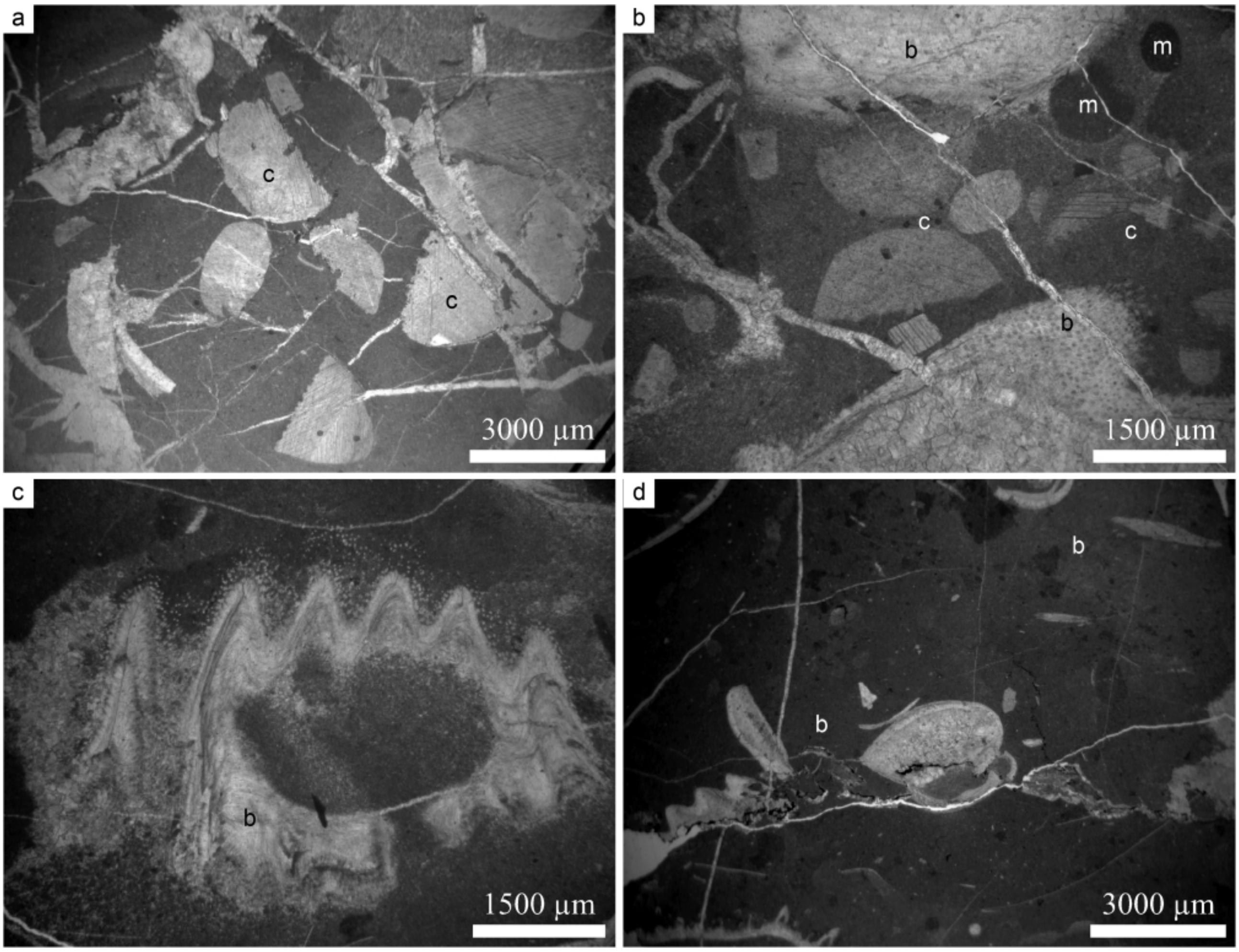

Figure 12: a–d) Photomicrographs showing crinoid–brachiopod packstone in a micrite matrix with crinoid skeletal particles (c) and brachiopod valves (b). Rounded micritic grains (m) which can be either mudstone clasts or large peloids occur among the skeletal grains. a) Section Telekes Valley, NW Tributary Valley 6, 2.9–3.0 m, Anisian/Pelsonian (no Conodont data available). b) Section Telekes Valley, NW Tributary Valley 6, 3.8 m, Anisian/Pelsonian (no Conodont data available). c) Section Telekes Valley, NW Tributary Valley 6, 9.6 m, Anisian/Pelsonian (no Conodont data available). d) Section Telekes Valley, NW Tributary Valley 6, 13.2 m, Anisian/Pelsonian (no Conodont data available).

cores (Fig. 15a–b) as well as nodules and layers that are characterised by the total loss of the original fabric features (Fig. 7d, Fig. 9d). The boundary of the carbonate and chert consists of a stylolite surface or a thick calcite spar zone. The colour of the chert is either brownish grey or purplish red.

6. Occurrence and relation of the microfacies associations

Based on the microfacies data set, vertical patterns were compared and correlated in 29 sections.

The clotted micrite "boundstone" typically forms 20–100-m-thick succession but it might also reach 250 m. This rock is not bedded. In the Anisian (Pelsonian–Illyrian) formations, it develops gradually from mudstone (no. 1 & 3), from bivalve grainstone (no. 9) or appears directly on top of the Steinalm Formation (no. 2, 7 & 8). In the Upper Triassic formations, it alternates with bioclastic wackestone (no. 6 & 12) or grades upwards into bivalve–crinoid packstone (no. 1, 12 & 13).

The bioclastic wackestone rarely occurs in the Middle Triassic deposits. It is present only in one section (no. 9) as 5-m-thick beds. However, in the Upper Triassic successions, especially from the Norian (Lacian), it gets predominant over the clotted micrite "boundstone" and forms 30–150-m-thick non-bedded series. It develops gradually from bivalve packstone (no. 5 & 9) or bivalve–crinoid packstone (no. 11 & 13).

The bivalve grainstone forms 5–15-cm-thick layers and occurs throughout all the studied formations. In the Middle Triassic successions, it typically alternates with 2–8-cm-thick layers of clotted micrite "boundstone" and 0.1–1-cm (no. 5) or 1–10-cm-thick (no. 3) shale and claystone. In one section, however, it is present as a 1-m-thick interval between bioclastic wackestone and clotted micrite "boundstone" (no. 9). In the Upper Triassic deposits, it gradually develops from and into clotted micrite "boundstone" and bioclastic wackestone in 5–20 m thickness (no. 5 & 6).

The bivalve packstone does not form macroscopic layers; it occurs as 0.5–2 mm large lenses, patches inside the clotted micrite "boundstone" or as 0.2–1-mm-thick laminae alternating with it. They are commonly deposited on a sharp surface and they exhibit gradational transition into the "boundstone" upwards.

Crinoid–brachiopod packstone was found in only one sequence (no. 3). It forms 10-m-thick bundle of beds between

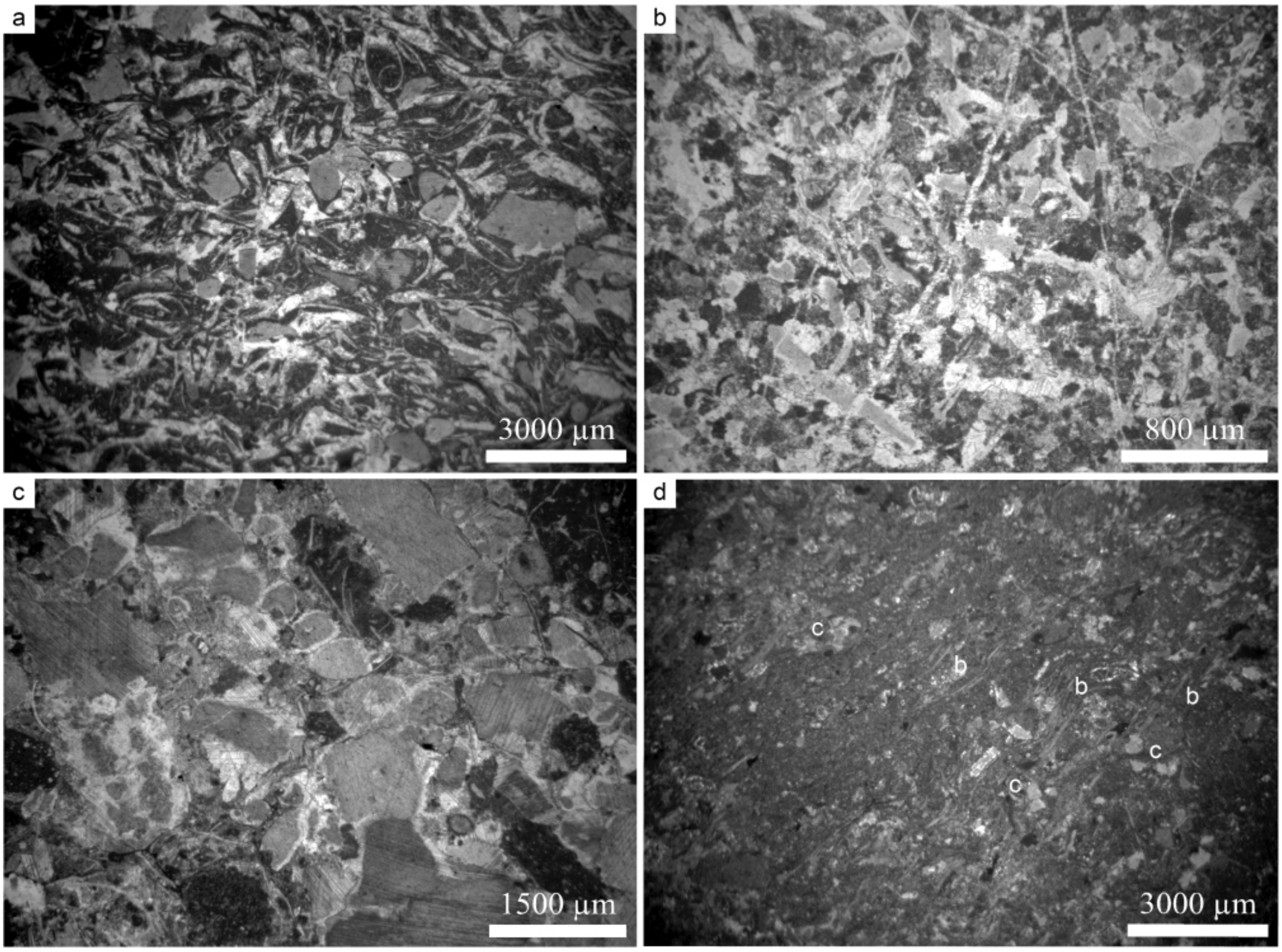

Figure 13: a–c) Photomicrographs showing bivalve–crinoid packstone. a) Borehole Szőlősardó-1, 153.9–154.1 m, Carnian/Julian (*Gondolella polygnathiformis*, *G. tadpole* - Balogh and Kovács, 1981). b) Alsó hill, section IV, 37 m, Carnian/Tuvalian (no Conodont data available). c) Section Szőlősardó II, 3.8–4.0 m, Norian/Lacian (*Gondolella navicula*, *Metapolygnathus abneptis abneptis*, *M. abneptis spatulatus* - Kovács, unpublished). d) Photomicrograph showing silicified bivalve–crinoid packstone (XN). The silicification affected only the micrite matrix, the bivalve shells (b) and crinoid fragments (c) can still be recognised. Section Telekes Valley, NW Tributary Valley 6, 51.25–51.45 m, Carnian/Tuvalian (no Conodont data available).

0.2 and 1-m-thick sections of limestone with mudstone fabric in the Anisian (Pelsonian) succession just above the Steinalm Formation. It has no continuous transition from or into the mudstone.

The bivalve–crinoid packstone composes 25–80-m-thick series of cherty and coquina limestone. It is remarkable, that it occurs only in the Upper Triassic above the Carnian siliciclastic beds. It gradually develops from clotted micrite "boundstone" and grades either into it (no. 12) or into bioclastic wackestone (no. 11 & 13).

Mudstone represents short time intervals and its total thickness varies widely (0.6–16 m). It can be found right after the drowning of the Steinalm ramp in the Anisian (Pelsonian) successions in form of neptunian dykes penetrating the top 5–10 m of the Steinalm Formation (no 1, 2 & 5) and as layers on top of it (no 1 & 3). The siliciclastic formations of the Carnian (Julian) event are also followed by rocks with mudstone microfacies (no 1). Both the Anisian (Pelsonian) and Carnian (Julian) mudstone appears suddenly, without any transition from its underlying rocks and changes gradually into clotted micrite "boundstone" upwards (no 1, 2 & 3).

and Schlager, 2001; Della Porta et al., 2002; Della Porta et al., 2003; Marangon et al., 2011; Preto, 2012). Slope facies with clotted micrite deposits fits into the carbonate shelf model of the Silica nappe (Kovács et al., 1989). Although the common associated bivalve packstone and grainstone beds also suggest reworking along a slope, the depositional morphology and environments where the clotted micrite "boundstone" accumulated requires further research.

The horizontally elongated pores filled by calcite spar cement were referred to as stromatactis structures in the previous literature (Balogh and Kovács, 1981; Kovács et al., 1989). According to Bathurst (1982) and Bourque and Boulvain (1993), stromatactis structures are special pore types which have four basic attributes: 1) a relatively flat base and a domical, fractal-shaped upper part; 2) infill that consists of geopetal sediment and isopachous, fibrous or bladed calcite cements of shallow burial, marine cementation stages; 3) they are interconnected and have a network-like appearance; 4) they appear in finely crystalline, mostly red coloured limestones. In the studied samples, however, they do not always show all of these four attributes.

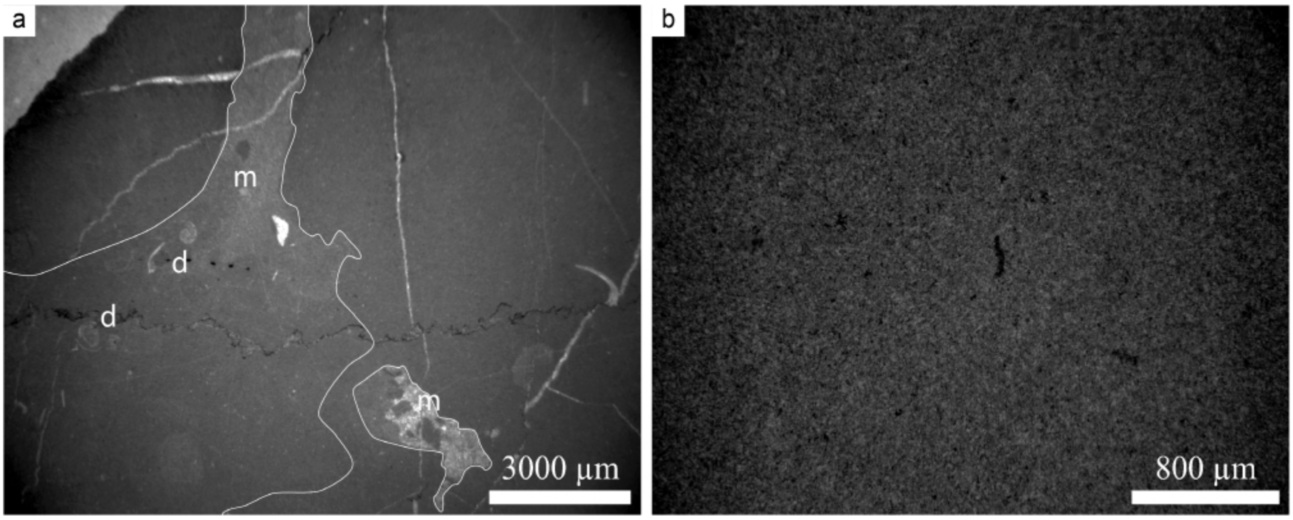

Figure 14: a) Photomicrograph showing mudstone with two bioturbational mottles (outlined). Note the micritic grains (m) which are probably mudstone clasts or peloids. The skeletal grain debris (d) comprises of foraminifers and bivalve shells. Section Telekes valley, NW tributary valley 4, sample TV3D, Anisian/Pelsonian (no Conodont data available). b) Photomicrograph showing homogenous mudstone. Borehole Szőlősardó-1, 56.6–56.7 m, Carnian/Julian (no Conodont data available).

7. Interpretation and discussion on depositional environments

Based on the microfacies associations following conclusions can be drawn about their depositional environments – since they are genetically determined – but more details can be expected by further systematic analyses.

The clotted micrite was documented as *in situ* precipitated finely crystalline carbonate being produced by microbially mediated biochemical processes (e.g. Reitner and Neuweiler, 1995; Keim and Schlager, 1999). Several authors described limestone having clotted micrite microfacies as typical deposits of platform margins and slopes (Blendinger, 1994; Keim

This implies that at least some of them are inhibited or aborted stromatactis structures that failed to develop properly (cf. Neuweiler et al., 2001). On the basis of co-occurrence of clotted micrite and stromatactis structures, it has been clearly established that these structures indicate presence of organic matter in increased amount e.g. decayed sponges or microbial activity (Aubrecht et al., 2002; Hladil, 2005; Neuweiler and Bernoulli, 2005). Sponge spicules and skeletons are rare elements in the analysed thin sections. That is why further and more detailed study is needed to better understand the origin and creating mechanism of these structures in the studied setting.

The bioclastic wackestone with radiolarians which was observed in the studied carbonates is an indicator of a basinal deep-water environment. The pelagic microfossils which form mottles in the wackestone probably came from periodically deposited thin layers with increased skeletal grain content. The lack of bedding implies homogenisation after the deposition through active bioturbation which created the mottles.

The bivalve grainstone microfacies was interpreted as deposit of turbidity currents that is related to deep-water environments, probably deep slope or basinal areas (Kovács, 2010). The orientation of the shells and lack of mud could indicate a moderate to high energy environment where mud was winnowed away by currents.

The occurrence of the bivalve packstone is linked to that of the clotted micrite "boundstone". The large number of bivalve shells might have been accumulated through currents, probably mass-gravity flows and turbidity currents (Balogh and Kovács, 1981). This is supported by the common erosional features which appear as sharp surfaces. The non-parallel orientation of the shells as well as the frequent occurrence of the microfacies in pockets implies that these shells were trapped in depressions of the microbial mat. The frequency of these intercalations implies that the carbonate slopes were quite unstable.

The rare occurrence of the crinoid–brachiopod packstone suggests that its formation took place in a limited area under special circumstances which were strongly related to the drowning of the Steinalm platform. Considering the factors above the most probable source area of this sediment was a short-lived shallow water high which favoured the establishment of crinoid gardens. The skeletal grain fragments might have been accumulated at the foot of this elevation. The elongated mottles are signs of bioturbation.

Bioclastic packstone that predominantly consists of crinoids and pelagic bivalve shells can be associated with open marine deep slope or basinal environments. This microfabric has been interpreted as allochthonous limestone deposited by turbidity currents (Balogh and Kovács, 1981).

The mudstone was likely formed via pelagic sedimentation which took place in the absence of both shallow-water and pelagic skeletal organisms that characterise the previous deposits. The bioturbational mottles point to an active benthic life. Its composition and location in the sequences suggests that this microfacies represents deposits of the post-drowning phase of the Steinalm platform in the Anisian (Pelsonian). It is obvious to assume that it is related to similar processes in case of its Carnian (Tuvalian) occurrence as well.

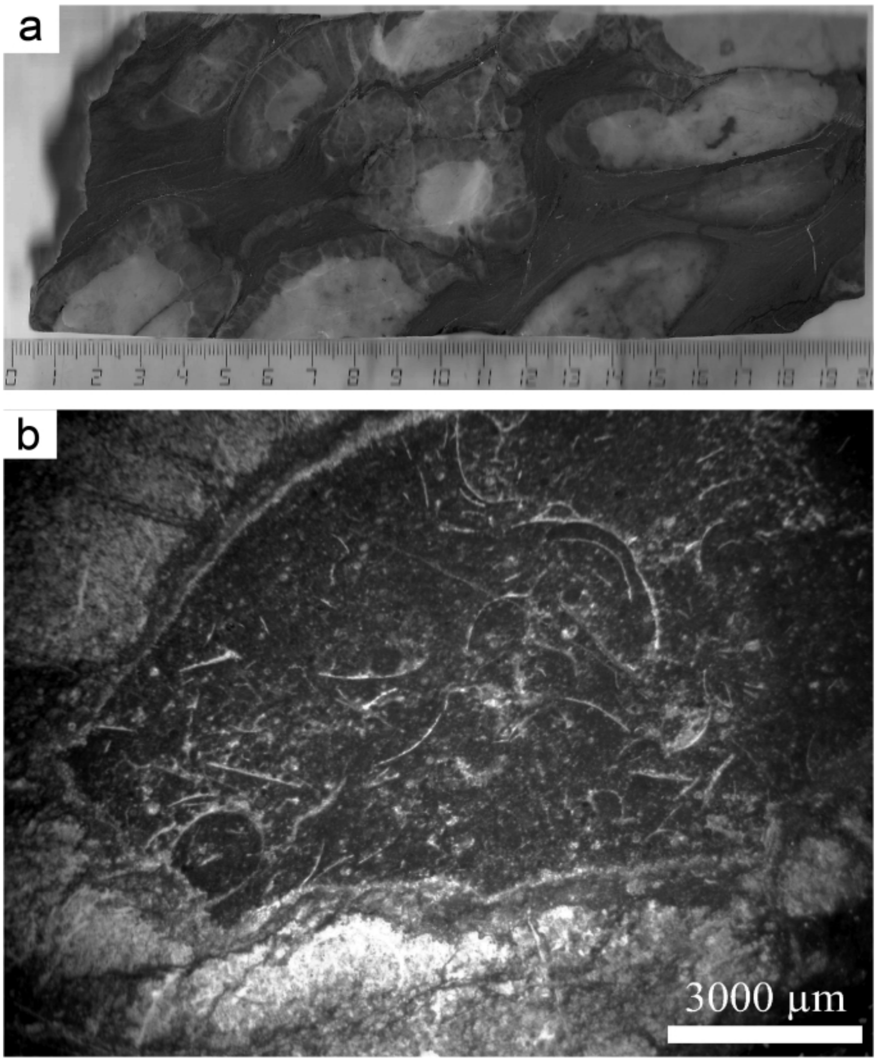

Figure 15: a) Red coloured "hollow" chert nodules with orange coloured fine crystalline limestone in their cores inside a red marl matrix. These nodules likely formed by selective silicification of the carbonate nodules along the limestone/marl surface. The scale is in cm. Halved drilling core from Borehole Varbóc-4, 24.15–24.45 m. Age unknown. b) Photomicrograph showing a sample from the same core. Note the clotted micrite "boundstone" in the centre of the chert nodule.

8. Implications on the evolution of the depositional area

Although the aim of this paper was to define and present the microfacies associations found in the studied rocks there are observations regarding the history of the area. In most of the sections, the Steinalm Formation is directly overlain by post-drowning beds but there are also sections where these beds are absent (no 7, 8 & 9). This is probably the effect of the diverse bottom created by the extensional fault-block tectonics responsible for the drowning of the Steinalm platform at the end of the Middle Anisian (Pelsonian) (Less et al., 2006; Kovács et al., 2011). The first deep-water carbonates appeared at the end of the Pelsonian and by the end of the Anisian (Illyrian) the entire study area was characterised by the formation of clotted micrite “boundstone”. This indicates the accretion and expansion of the supposed carbonate slope over the deeper areas. Contrary to the previous model (Kovács et al., 1989; Less et al., 2006) very few sedimentary features of a basinal environment were found in the Middle Triassic rocks. In fact, even the few sections which begin with deeper slope (no 3 & 5) or basin deposits (no 9) in the Pelsonian show upwards shallowing. This means that the Middle Triassic basinal palaeoenvironment assigned to the Bódva unit (Kovács, 1989; Kovács et al., 1989) is not supported by this model. Furthermore, the necessity of separation of the Bódva and Szőlősardó units––which was based on the assumption that the former represents basinal formations whereas the latter is built up by slope deposits––is questionable as well. The slope environment continued to exist throughout the Ladinian up to the Carnian (Julian) siliciclastic event. During the Late Carnian (Tuvalian), the slope deposits were replaced by rocks with microfabrics indicating toe-of-slope and basin environments. This deepening took place parallel to the demise of the Wetterstein platform in the Aggtelek facies, which implies that the process responsible for the event affected both the platform and the slope areas.

9. Conclusions

1. The studied Middle and Upper Triassic rocks consist of 5 different microfacies associations. These are clotted micrite “boundstone”, bioclastic wackestone, bioclastic grainstone–packstone, bivalve–crinoid packstone and mudstone. These specific microfabrics were associated with slope, deep slope and basin environments.
2. During the Middle Triassic an expanding carbonate slope, typified by in situ precipitated clotted micrite, was formed on top of the drowned Steinalm platform. The presence of basin environment during the Middle Triassic was not verified by the thin section analysis.
3. According to the similarities in the microfacies associations and evolution of the rocks the separation of the Szőlősardó and Bódva units is questionable both in the Middle and Upper Triassic record.
4. The relations of the microfacies associations confirm the two stages of subsidence in the studied area (Kovács et al., 1989; Less et al., 2006). The first stage occurred in the Anisian (Pelsonian) and caused a sudden and rapid deepening that was later followed by the accretion of the slope. The second stage took place in the Late Carnian (Tuvalian) parallel to the breakdown of the shelf margin which changed the possible area of deposition from slope to toe-of-slope and basin.

Acknowledgements

This work is part of the PhD thesis research conducted at the Eötvös Loránd University. Constructive comments of journal reviewers, Géza Császár and an anonymous reviewer are highly appreciated. I am also grateful to the MTA–ELTE Geological, Geophysical and Space Science Research Group (Hungarian Academy of Sciences) for ist support.

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Received: 28 March 2014
Accepted: 12 October 2014

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