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ORIGINAL ARTICLE

Sedimentary aspects of the onset of Middle Triassic continental rifting in the western end of Neotethys; inferences from the Silica and Torna Nappes, NE Hungary: a review

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Abstract

The initiation of continental rifting from the latest Early Triassic was reconstructed by correlation of sedimentary formations deposited in the western end of Neotethys (in the Dinaric–Alpine oceanic branch). The shallow-marine and basinal strata of the Silica Nappes and the Bódvarákó Series from the Torna Nappe (located in the southern part of the Inner Western Carpathians) were studied and compared to sedimentary successions described from the Alps, the Carpathians and the Dinarides. The depositional zonation, developed on the shelf during the Late Permian─Early Triassic transgression, was dissected and rearranged from the latest Early Triassic. The facies pattern and the differential sedimentary evolution of the shelf domains suggest that the accelerated subsidence began in the latest Early Triassic, and was connected to the onset of continental rifting. Three stages are reconstructed in the studied time-frame. (1) Dark grey carbonates, very poor in fossils, were deposited in restricted and hypersaline intraplatform basins in many shelf domains. In the external domains, shallow-marine carbonates, depositional gaps and terrestrial deposits are typical (formations in the Southern Alps, the External Dinarides and the Serbian–Macedonian Massif). From the latest Early Triassic, this latter shelf segment formed a threshold that restricted water circulation from the intraplatform basins. (2) Shallowing-up carbonate successions mark the next stage that implies a period of tectonic quiescence on the shelf from the late Early Anisian to late Middle Anisian. A peculiar change in biota occurring in previously restricted domains was coeval in shallow-marine and deep-marine settings. The biotic change is revealed by observations that dark grey carbonates, which are very poor in fossils, are overlain by carbonate successions rich in fossils typical for normal-marine water. The biota and environmental changes indicate the opening of a passage which allowed the circulation of well-oxygenated and normal-salinity marine water towards the previously restricted depositional areas. The geodynamic setting switching from continental rifting to spreading in the southern sector of the Dinaric–Alpine oceanic branch (Hellenides and Albanides), triggered the opening of the gateway between the future continental margins, i.e., between the External Dinaridic domain (Adria) and Serbian–Macedonian Massif (Eurasia). (3) Following the biotic event in the northern sector of the shelf, subsidence accelerated and additional intraplatform basins opened from the latest Pelsonian.

Keywords Biotic changes · Carbonates · Microbialites · Extensional setting · Facies correlation · Geodynamic evolution

Introduction

In the Alpine–Carpathian–Dinaridic region, the Alpine plate tectonic cycle, leading to the opening of the Neotethys Ocean (namely the Dinaric–Alpine branch, Kovács 1992, or the Meliata branch, Stampfli et al. 2001; Fig. 1), was initiated by Permian continental rifting, which was accompanied by volcanism (Ziegler 1988; Stampfli et al. 2001). In the Dinaridic and South Alpine domains, the marine sedimentary cycle began via Middle and Late Permian transgression (Tollmann 1976; Kovács 1992; Scotese and Golonka 1992; Dercourt et al. 1993). In the Western Carpathian and Northern Calcareous Alpine domains, a significant expansion of the shallow sea started only at the beginning of the Triassic when broad, formerly continental areas became inundated (Tollmann 1989). The Middle Triassic opening

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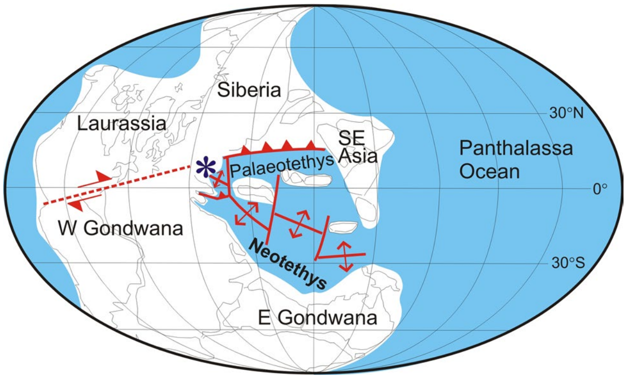


Fig. 1 Middle Triassic (Anisian) palaeographic reconstruction showing the Tethys Ocean, Pangea (continental area is white), the oceanic basin (blue) (after Tollmann and Kristan-Tollmann 1985; Dercourt et al. 1993; Muttoni et al. 2009). The purple star marks the study area

of the Dinaric–Alpine branch as a back-arc basin behind the Early to Middle Triassic volcanic arc is considered as a response to subduction in the Aegean–Sicilian branch (Palaeotethys; summary in Kovács 1992). The remnants of the Dinaric–Alpine oceanic branch, containing very low-grade metamorphic serpentinite, Triassic radiolarite and Jurassic flysch-type deposits, are preserved as olistoliths in Jurassic mélange formations (e.g., Plasienka et al. 1997; Pamić, 2002; Schmid et al. 2004).

Triassic formations in the Alpine−Carpathian−Dinaridic region have been the subject of stratigraphic and sedimentological investigations for a long time. Stratigraphic correlation of the formations made possible the reconstruction of the geodynamic evolution of the region (Csontos and Vörös 2004; Kovács et al. 2011). In connection with the oceanic spreading of the Dinaric–Alpine branch, an extensional tectonic regime was established on the continental margin in the Middle Triassic. Ziegler (1988) applied the Wernicke crustal extension model (Wernicke and Burchfiel 1982; Wernicke 1985) for this region. Accelerated block faulting and rapid subsidence of basinal areas were preceded by differential subsidence of the shallow shelf area (Kovács 1984; Lein et al. 2012). In this review paper, (1) a summary of published data on Lower and Middle Triassic formations from the Silica Nappes and Bódvarákó Series (Torna Nappe) is presented, (2) the formations are correlated to Alpine, Carpathian and Dinaridic formations and thus, (3) the characteristics of the incipient stage of facies differentiation is evaluated from the geodynamic aspect. In addition, (4) the first description of a Pelsonian microbial and *Tubiphytes*–microbial reef facies from the Steinalm Formation is presented and (5) the lateral transitions of shallow-marine and basinal formations are reviewed.

Geological setting

The Aggtelek Karst and Rudabánya Hills are parts of the Inner Western Carpathians (Fig. 2a). They are made of a nappe stack of Upper Permian–Jurassic rocks which are locally covered by Cenozoic formations (Less et al. 1988, 2006; Less 2000; Fig. 2b). Six Triassic facies areas (namely Aggtelek, Szőlősardó, Bódva, Bódvarákó, Martonyi, Torna) were defined by their typical sedimentary series (Kovács et al. 1989, 2011). Rocks of facies areas were organised into non-metamorphic and metamorphic nappes (Kovács 1984; Fodor and Koroknai 2000; Lexa et al. 2003; Kövér et al. 2009; Kövér 2012). The Silica Nappe system (including the Aggtelek, Szőlősardó and Bódva Nappes) represents the highest tectonic unit of the Aggtelek Karst and Rudabánya Hills, similarly as in Slovakia (Kovács et al. 1989; Less 2000; Lexa et al. 2003). The Meliata Nappe system (s.l.) was defined in Slovakia and it is considered to be the remnant of an accretionary wedge, containing remnants of oceanic crust and related sedimentary rocks. It was formed in the course of closure of the Triassic–Jurassic Neotethys Ocean (Mock et al. 1998). The Torna (Turňa) Nappe includes anchi- to epi-metamorphic Triassic rocks, which were deposited on thinned continental crust (e.g., Mello and Mock 1977; Kovács et al. 1989). The Bódvarákó Series consists of a reduced, tectonically truncated Middle Triassic sedimentary succession. Based on lithological features and the metamorphic grade of the rocks it can be assigned to the Torna Nappe (Fodor and Koroknai 2000).

Stratigraphy and sedimentary features

The studied Triassic successions are composed of mixed siliciclastic–carbonate and carbonate rocks (Fig. 3). Descriptions of the formations are based on stratigraphy and sedimentology. The data were compiled from publications of mapping programmes and sedimentary studies. In the studied area, the rocks are mainly covered by soil and vegetation; surface exposures are sporadic; rock cliffs, roadcuts, quarries, cave sections and borehole cores provide opportunities for studies.

Lower Triassic ramp carbonates and mixed siliciclastic–carbonate rocks (Szin Marl Formation)

The Szin Marl Formation consists predominantly of alternating beds of grey silty limestone and beige marl; otherwise, red or varicoloured oolite, cross-bedded, cross-laminated and graded, grey crinoidal limestone, clay-rich marl and red sandstone, siltstone and shale occur in certain intervals

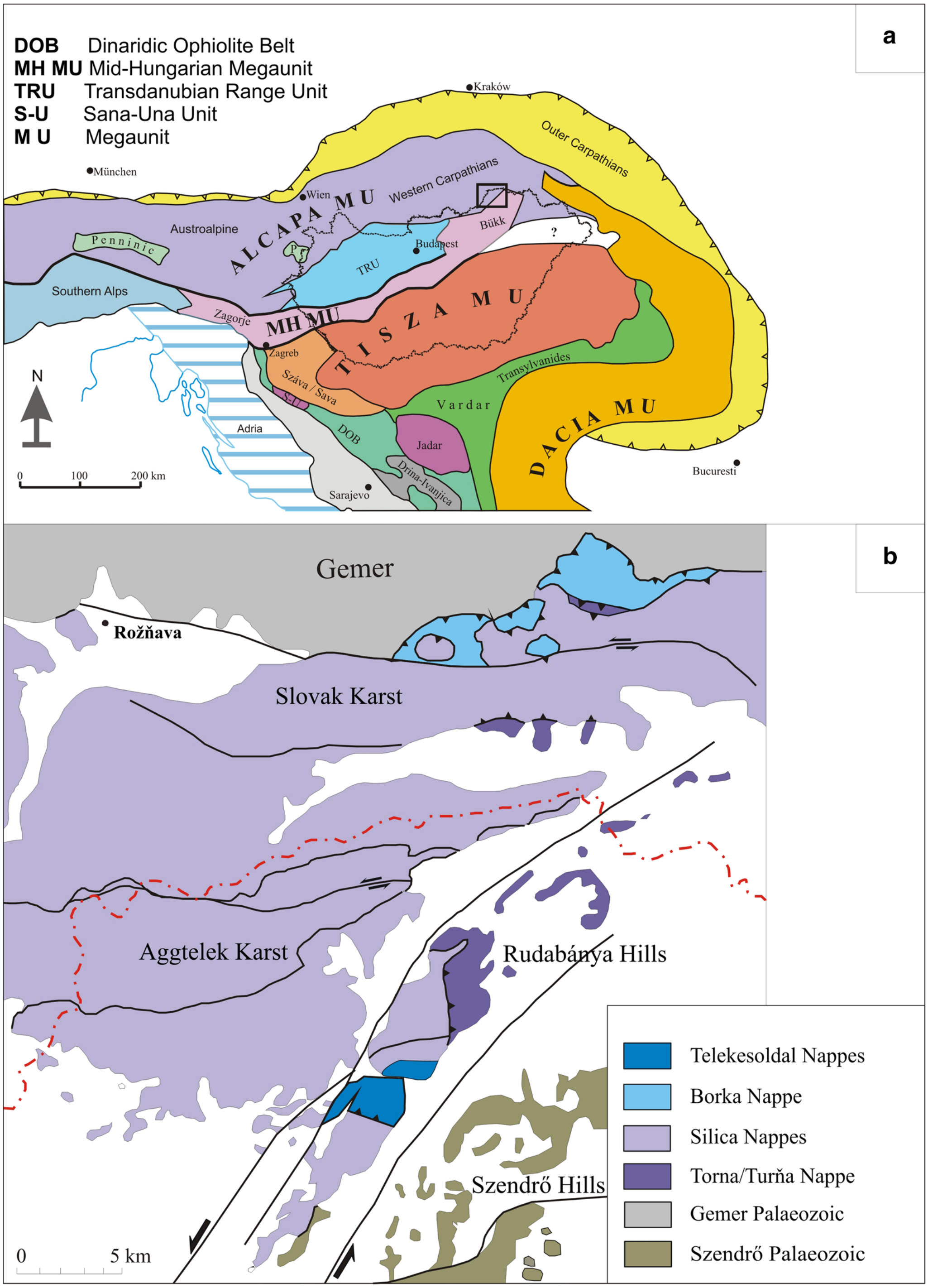
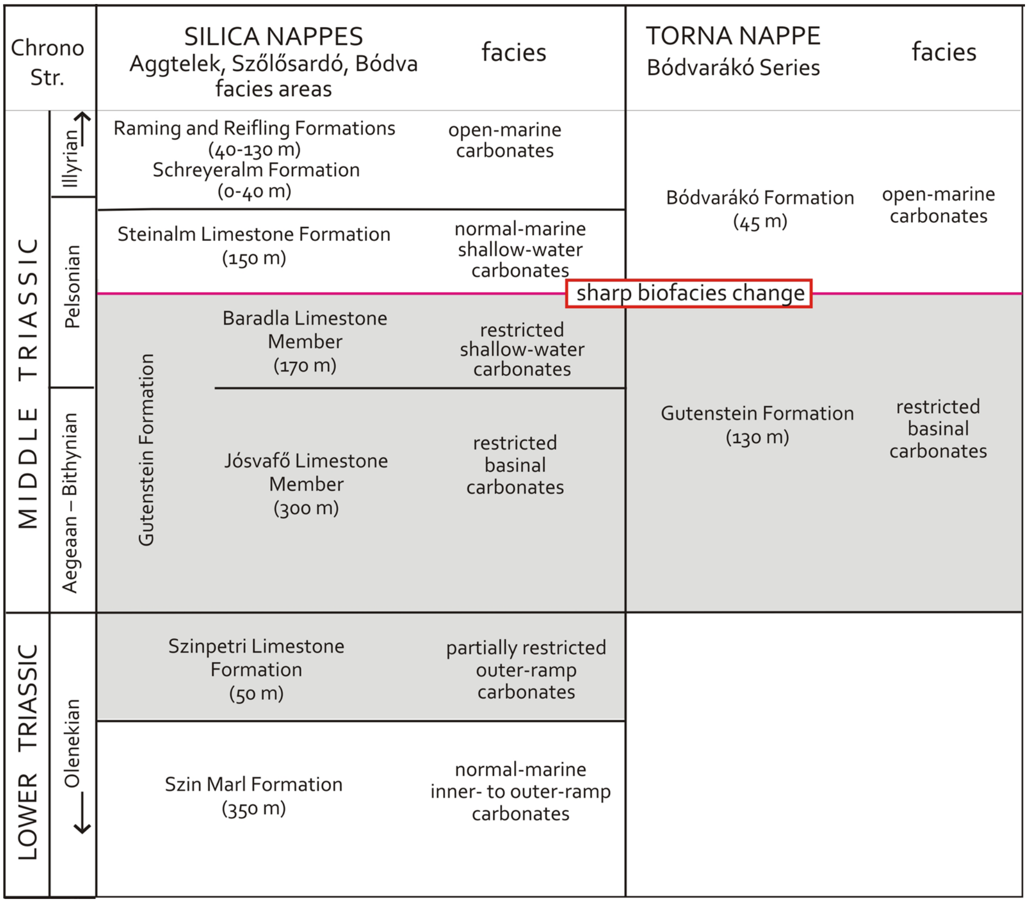


Fig. 2 Structural units of the Pannonian basin. **a** Structural units of the Pannonian basin and related areas (Kovács et al. 2011). Location of the study area is indicated by the rectangle. **b** Simplified tectonic map of the Aggtelek Karst and the Rudabánya Hills (Less et al. 1988; Kövér 2012)

(Fig. 4). The thickness of the formation is *ca* 350 m. Late Olenekian (Spathian) age is proved by *Tirolites cassianus* and *T.* gr. *carniolicus* (Hips 1996). Foraminifers, gastropods, bivalves, ammonites, crinoid fragments, ostracods and conodonts are encountered (Hips 1996). The Szin Marl Formation is underlain by red siliciclastic rocks (Bódvaszilas Formation). The lower boundary of the formations is conformable but the change in the lithology is rather sharp. The transition to the overlying Szinpetri Formation is gradual. The sedimentary succession consists of metre-scale,



Chrono Str.		SILICA NAPPES Aggtelek, Szőlősardó, Bódva facies areas		facies	TORNA NAPPE Bódvarákó Series	facies
MIDDLE TRIASSIC	Illyrian		Raming and Reifling Formations (40-130 m) Schreyeralm Formation (0-40 m)	open-marine carbonates	Bódvarákó Formation (45 m)	open-marine carbonates
	Pelsonian		Steinalm Limestone Formation (150 m)	normal-marine shallow-water carbonates		
sharp biofacies change						
		Gutenstein Formation	Baradla Limestone Member (170 m)	restricted shallow-water carbonates	Gutenstein Formation (130 m)	restricted basinal carbonates
	Aegeaan – Bithynian		Jósvafő Limestone Member (300 m)	restricted basinal carbonates		
LOWER TRIASSIC	Olenekian		Szinpetri Limestone Formation (50 m)	partially restricted outer-ramp carbonates		
			Szin Marl Formation (350 m)	normal-marine inner- to outer-ramp carbonates		

Fig. 3 Stratigraphic setting of the studied Lower and Middle Triassic sedimentary successions in the Silica Nappes and Bódvarákó Series (based on Hips 1996; Kovács et al. 2004; Péró et al. 2015; not to scale)

deepening- and shallowing-upward cycles in which the beds were deposited in tidal-flat, storm-dominated middle-ramp and outer-ramp environments (Hips 1998). As a result of increasing differences in the accumulation rates between the low-energy outer-ramp and the high-energy and coarser-grained inner- to middle-ramp, the carbonate ramp morphology likely evolved to a distally steepened one.

Lower Triassic outer-ramp carbonates (Szinpetri Limestone Formation)

The Szinpetri Limestone Formation is composed of a monotonous series of dark grey, platy–nodular limestone beds and clayey marl laminae, in which graded bioclastic limestone beds locally occur (Figs. 5a, 6). In the Aggtelek facies area, the nodular limestone is typical, whereas in the Bódva facies area, the platy limestone is predominant. The thickness of the formation is *ca* 50 m. Based on *Stacheites* sp., it can be assigned to the latest Olenekian (late Spathian; Hips 1996). Bioclasts are rare and include foraminifers, bivalves, ammonites, crinoid fragments and ostracods. The transition to the overlying Gutenstein Formation is gradual. The succession was deposited in a low-energy outer-ramp environment below storm-wave base, where the crinoidal limestone represents the distal storm deposits (Hips 1998).

Middle Triassic dark grey carbonates of the intraplatform basin and overlying shallow-ramp carbonates (Gutenstein Formation)

The Gutenstein Formation is characterised by dark grey limestone (Fig. 5b–d). In the Aggtelek facies area, the succession can be subdivided into two members (Hips 2003, 2007). The lower Jósvafő Member is a *ca* 250–300-m-thick succession, typified by monotonous mudstone, which is punctuated by detrital carbonate silt laminae. Fossils are extremely rare; bivalves, echinoderm fragments, ostracods and a few foraminifers were found in its lower part. The uppermost beds of the member contain the foraminifer *Glomospira densa* (det. Bérczіné Makk, in Kovács et al. 2004) constraining a late Early Anisian age. Accordingly, the Jósvafő Member is assigned to the Aegean and Bithynian.

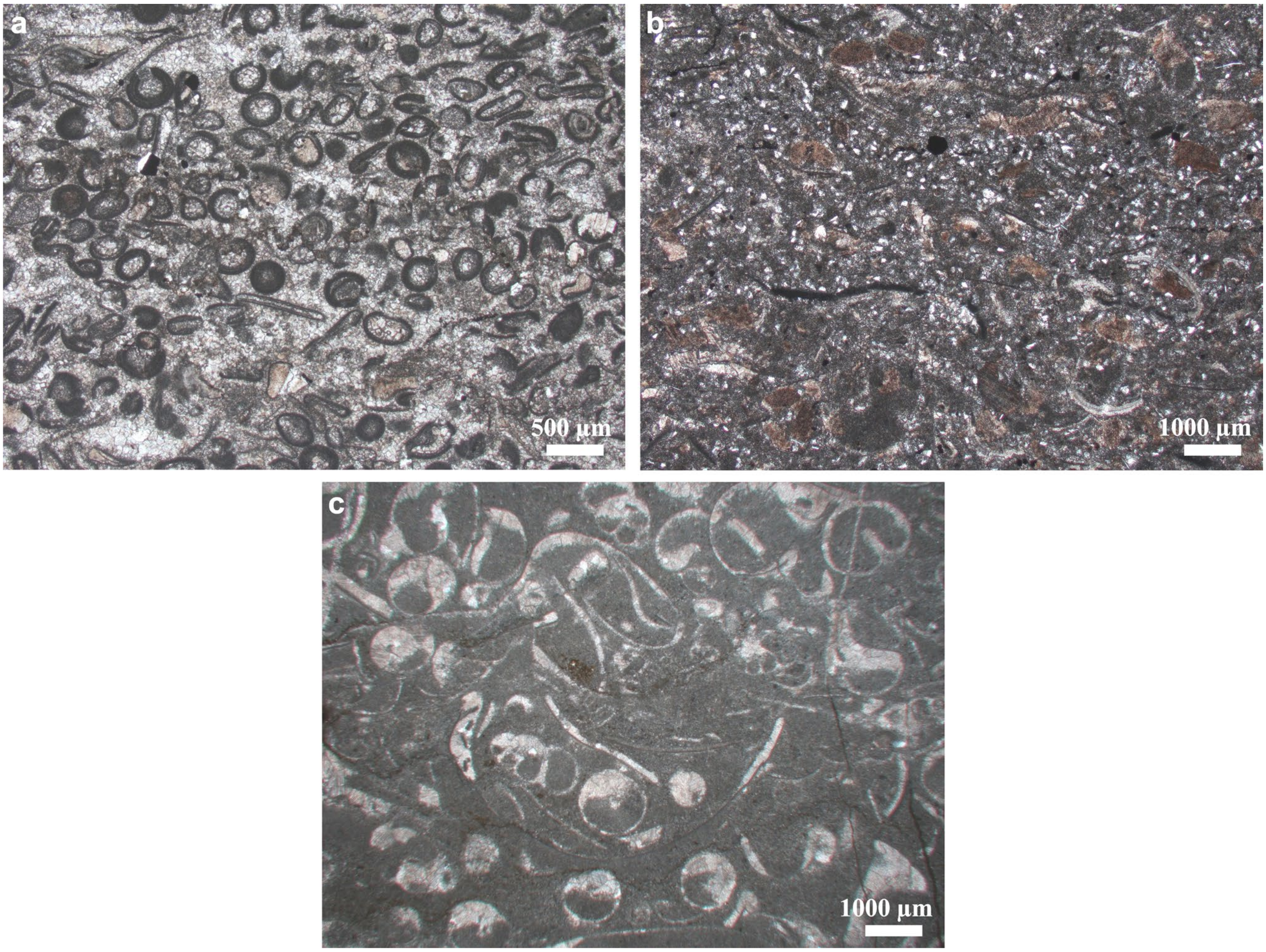


Fig. 4 Photomicrographs of the Lower Triassic Szin Marl showing some typical microfacies. **a** Ooidal grainstone with bioclasts in ooidal shoal facies (east of Szin, Aggtelek facies area). **b** Bioclastic wackestone–packstone with abundant detrital quartz grains, crinoid fragments and ostracods in distal middle-ramp facies (south of Jósvafő, Aggtelek facies area). **c** Bioclastic wackestone with gastropods in middle-ramp facies (Rudabánya Hills, Bódva facies area)

The lowermost part of this member consists of an alternation of laminated and burrow-mottled beds, where bivalve coquina layers with *Costatoria costata* and crinoidal tempestite layers locally occur (Fig. 7a). Slump structures are ubiquitous all over the Jósvafő Member (Fig. 5c). The transitional interval between the two members is characterised by increasing frequency of thin to thick, intraclastic−bioclastic packstone beds (Figs. 5b, 7b). The upper Baradla Member is a *ca* 170-m-thick succession. It is heterogeneous and consists of biogenic and bioclastic limestone and dolomite. The foraminiferal association (*Pilammina densa*, *Trochammina almtalensis*, *Endothyranella wirzi*, *Haplophragmella inflata*, *Agathamnia* sp., *Aulotortus* sp., *Diplotremina* sp., det. Bérziné Makk, in Kovács et al. 2004) indicates Early Anisian to early Middle Anisian (Bithynian and early Pelsonian) age (cf. Rettori 1995). The Baradla Member is typified by thick beds of sponge–microbial boundstone (Figs. 5d, 8a). In addition, cross-bedded and cross-laminated bioclastic, peloidal packstone–grainstone, thin-bedded bioclastic wackestone, laminated and brecciated dolomite with calcite pseudomorphs after gypsum, and dolocrete containing pisoids occur in the cyclic succession (Fig. 8b). Bioclasts include foraminifers, gastropods, bivalves and ostracods.

In the Szőlősardó facies area, massive finely crystalline dolomite occurs, where the upper part of the formation is characterised by dolomitized microbial boundstone. The thickness of the formation is estimated as a few 100 m, which is comparable to that in the Aggtelek facies area. In the Bódva facies area, a relatively thick section of the formation was drilled (Szalonna-4 core section) that is represented by dark grey, finely crystalline limestone and dolomite characterised by slump structures and a breccia fabric. In the uppermost part of the succession, finely crystalline dolomite beds alternate with finely crystalline dolomitic limestone,

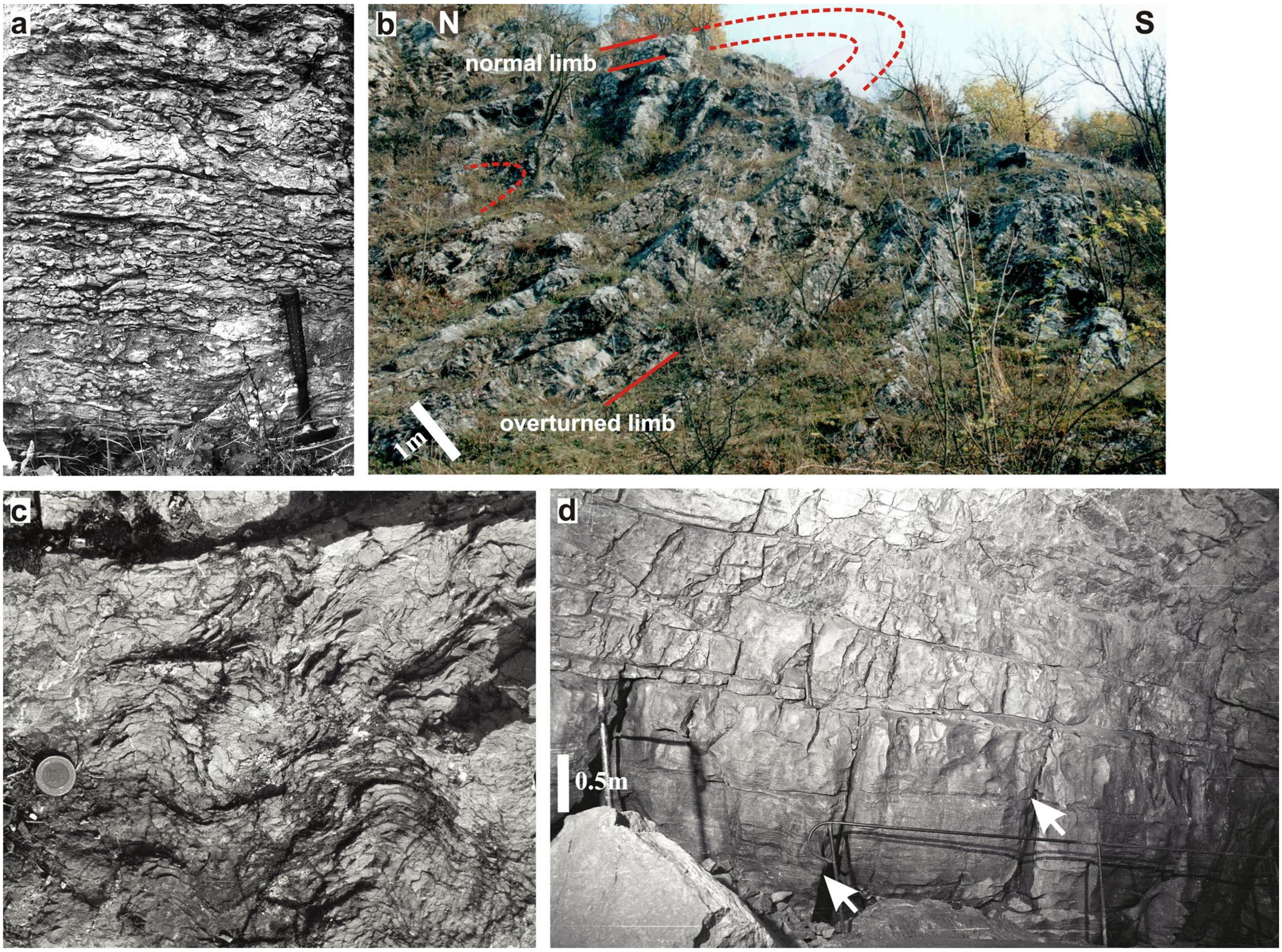


Fig. 5 Bedsets of dark grey limestones in the Aggtelek facies area. **a** Thin-bedded and nodular limestone, Szinpetri Formation (roadcut west of Szinpetri village, hammer for scale). **b** Thick-bedded bioclastic limestone and thin-bedded finely crystalline limestone alternate in the overturned limb of a fold, Gutenstein Formation, transitional interval of the Jósvafő Member and the Baradla Member (north of Jósvafő; north–south section). **c** Slump structure in thin-bedded limestone, Gutenstein Formation, Jósvafő Member (roadcut east of Jósvafő village, coin for scale). **d** Cross-laminated limestone bank (lower arrow) and overlying massive limestone banks of stratiform microbial–sponge reef (upper arrow at the base of bedset), Gutenstein Formation, Baradla Member (Baradla Cave)

bioclastic limestone, oncoidal and peloidal dolomite and microbial boundstone beds. The thickness of the formation is several hundred metres; however, the studied section is cut by a number of fault breccia zones. In the metamorphosed Bódvarákó Series, massive, locally laminated, finely to coarsely crystalline dolomite, clayey dolomite and dolomitic limestone represent this formation (Less 2000). The thickness is *ca* 120 m.

In the Aggtelek facies area, the thin-bedded succession of the finely crystalline limestone was deposited below storm wave base in a low-energy, relatively deep basin. The relatively large thickness of the monotonous deposits suggests gradual deepening of the environment. The general poverty of both benthic and nektonic fossils indicates a restricted environment with hypersaline and oxygen-depleted conditions (Hips 2007). The slump structures indicate post-depositional sliding likely triggered by relatively overpressured pore-fluid within the buried deposit as a consequence of sea-level fall or synsedimentary tectonic activity. In the Szőlősardó and Bódva facies areas, similar sedimentary features also imply restricted basinal deposition. In these settings, pervasive dolomitization of the deposits took place in intermediate and deep burial realms by hydrothermal fluids which were channelled along fault zones (Csalagovits 1973; Hofstra et al. 1999). The transitional beds to the upper part of the Gutenstein Formation are characterised by resedimented grains of shallow-platform origin that formed bioclastic sand shoals in the proximal middle-ramp area. Sponge–microbe reefs played a crucial role in the shallow-ramp area. The reef facies and the related deposits are thicker in the Aggtelek and Szőlősardó facies areas and rather thin in the Bódva facies area. A lack of

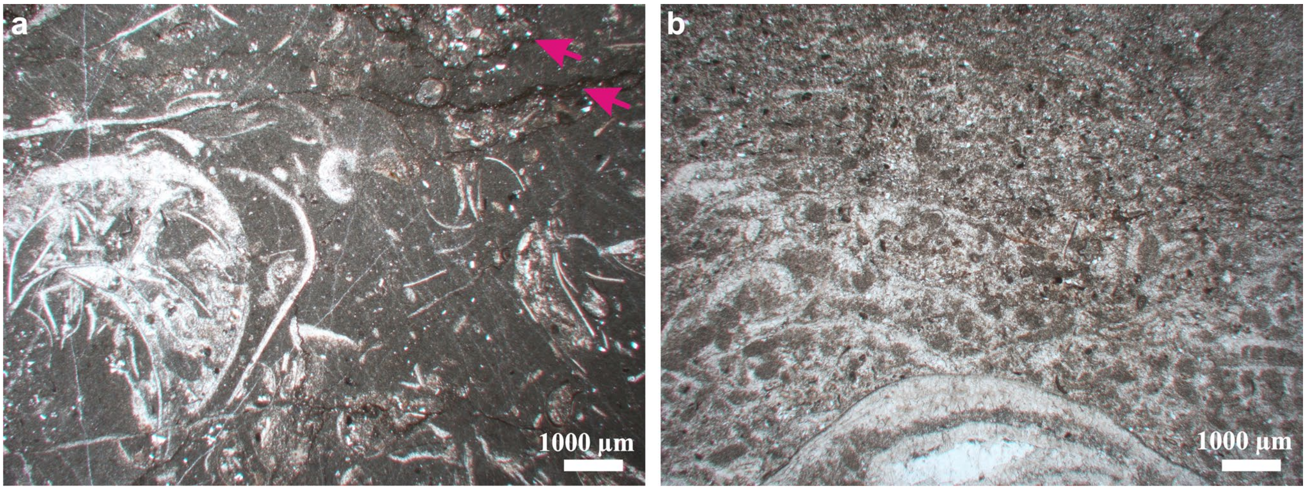


Fig. 6 Photomicrographs of the Lower Triassic Szinpetri Limestone. **a** Bioturbation mottles with abundant shell fragments in bioclastic wackestone in outer-ramp facies. Bed-parallel dissolution seams and stylolite are shown by arrows (east of Varbóc, Aggtelek facies area). **b** Graded tempestite layer is characterized by bioclastic–peloidal grainstone and packstone in outer-ramp facies (east of Varbóc, Aggtelek facies area)

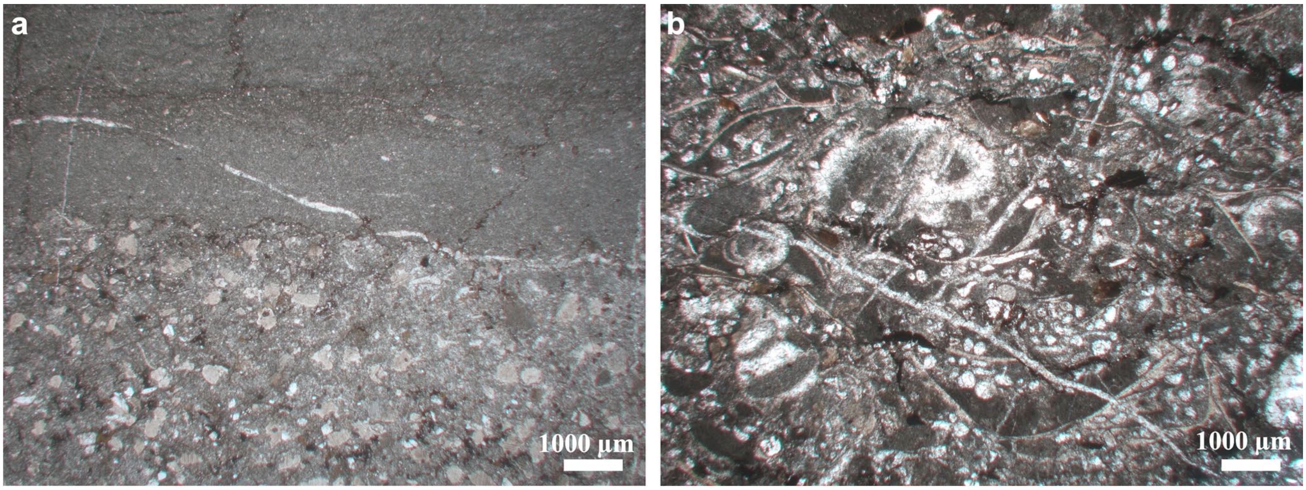


Fig. 7 Photomicrographs of the Middle Triassic (Aegean–Bythinian) Jósvafő Member of the Gutenstein Formation. **a** Thin-bedded tempestite (crinoidal packstone) and laminated calcisiltite in restricted outer-ramp facies (east of Jósvafő, Aggtelek facies area). **b** Intraclastic–bioclastic packstone in bioclastic shoal facies (transitional interval to Baradla Member; north of Jósvafő, Aggtelek facies area)

debris of shallow-platform origin in the succession of the formation in the Bódvarákó Series indicates a low-energy basinal depositional area located relatively far from the shallow-marine carbonate factories.

Middle Triassic light grey, shallow-ramp carbonates (Steinalm Formation)

The Steinalm Formation, *ca* 150 m in thickness, consists predominantly of light grey dasycladalean packstone−grainstone and microbial boundstone. The microbialite is mainly light grey stromatolite in the Aggtelek facies area, light grey thrombolite in Szőlősardó facies area and heterogeneous light and dark grey thrombolite in the Bódva facies area. In addition, oncoidal dolomite and coarse crystalline dolomite occur in the Aggtelek facies area (Piros 2002; Fig. 9a). In the Szőlősardó and Bódva facies areas, the thickness of the succession is reduced (Less 2000; Kovács et al. 2004). Based on the dasycladalean alga–foraminifer association, the formation is assigned to Middle Anisian, Pelsonian (Piros 2002; Velledits et al. 2011). Bioclasts include foraminifers, calcareous algae, gastropods, bivalves, crinoid fragments and ostracods. The rocks are dissected by neptunian dykes, which are filled by bioclastic wackestone–packstone and/or

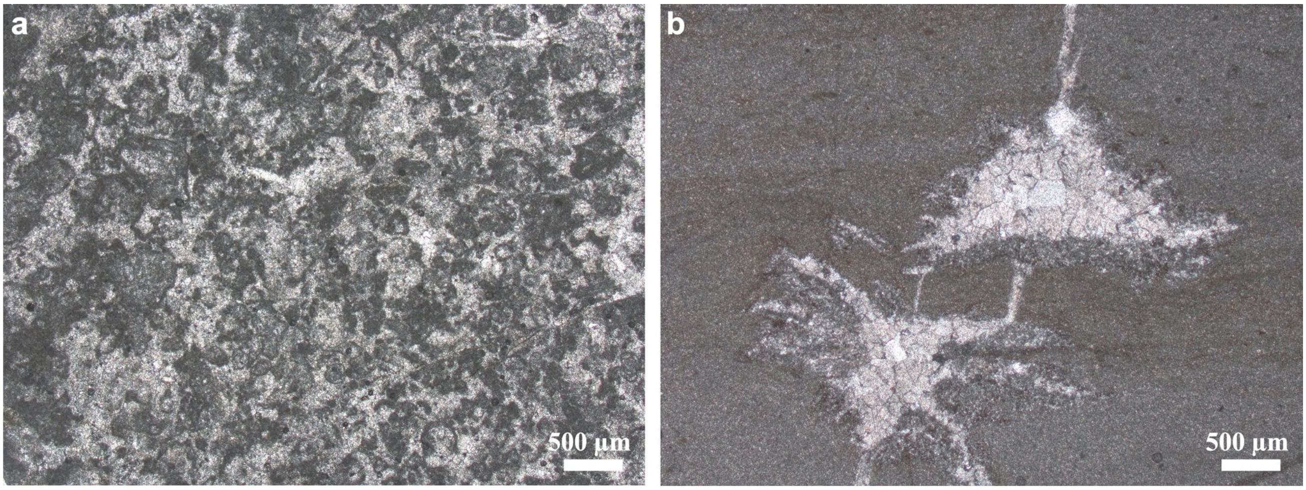


Fig. 8 Photomicrographs of the Middle Triassic (Pelsonian) Baradla Member of the Gutenstein Formation. **a** Dolomitized microbial boundstone from reef facies from the uppermost part of the succession (transition to the overlying formation; southwest of Jósvafő, Aggtelek facies area). **b** Dolomitized laminated mudstone with mosaic calcite cement in pores left after dissolution of evaporite crystals, a sample from supratidal facies (Baradla Cave, Aggtelek facies area)

radiaxial fibrous calcite cement (Péró et al. 2015; Fig. 9b). The conodont association indicates late Pelsonian to middle Illyrian age (Velledits et al. 2011). The Steinalm Formation occurs in the Silica Nappes.

A thrombolite facies is first described in this paper. Microscopic components are characterized by clotted micrite clusters and fenestral pores occluded by radiaxial fibrous calcite (Fig. 9b–d). The microbialite was studied in the Szőlősardó-1 (Szől-1) core section (Szőlősardó facies area) and the Szalonna-4 (Sza-4) core section and a surface exposure in Csipkés Hill (Bódva facies area). Three fabric types of boundstone are distinguished. (1) Upward-expanding bushy aggregates of micrite clots and the fenestral framework pores, occluded by radiaxial fibrous calcite cement, are equally typical (Fig. 9c). It occurs in the Bódva facies area, in the lower part of the microbial reef facies (Sza-4, in samples between 99 and 70 m) and in samples collected from Csipkés Hill. The underlying beds are characterised by dasycladalean grainstone (Sza-4, in samples between 124 and 99 m). (2) Abundant clotted micrite involves bioclasts, predominantly dasycladalean algal fragments (Fig. 9b). It occurs in the Szől-1 section (deposited on dasycladalean grainstone beds) and in the middle part of the microbial reef facies in the Sza-4 section (in samples between 66 and 39 m). (3) Tufted aggregates of micrite clots occur together with *Tubiphytes* sp. (Fig. 9d). Additional components are foraminifers (*Meandrospira dinarica*) and ostracods. This fabric type alternates with thin grainstone beds, which contain *Tubiphytes* sp. fragments (Fig. 9e). It was observed in the upper part of the microbial reef facies in the Sza-4 section (in samples between 39 and 25 m), in the Bódva facies area. Bioclastic grainstone–boundstone beds, with dasycladalean alga (*Teutloporella peniculiformis*; det. O. Piros) and *Tubiphytes* sp. fragments, are associated with microbialite reef facies in the Csipkés Hill section. The overlying beds in the core sections are characterised by bioclastic wackestone, including thin-shell bivalves, ostracods and fine sand-sized biodetritus (Reifling Formation). Although the drilled interval of the microbial reef facies is relatively thick in the Sza-4, the depositional thickness of the facies is likely less than that. Not only because the drilling direction likely deviated from the depositional direction, but also because a number of faults cut across the interval.

A transitional section, exhibiting gradual changes in sedimentary features of the microbialite boundstone, is observed from the underlying Gutenstein Formation (Hips 2007). Appearance of dasycladalean algal fragments in the succession of the Steinalm Formation indicates a significant change in shallow-marine conditions (Piros 2002). The cyclic alternation of subtidal bioclastic limestone, stromatolite and peritidal dolomite is typical in the Aggtelek facies area. The sediments were deposited on a tidal flat and in well-oxygenated, moderately agitated, wide inner-ramp environments, which were characterised by normal-marine water. In the Szőlősardó and Bódva facies areas, fabric features of the bioclastic limestone and the thrombolite indicate permanent subtidal deposition. The vertical depositional trend from bioclastic grainstone to microbialite indicates a shift of the depositional area from an inner-ramp to a middle-ramp one, where the microbial and *Tubiphytes*–microbial reefs thrived.

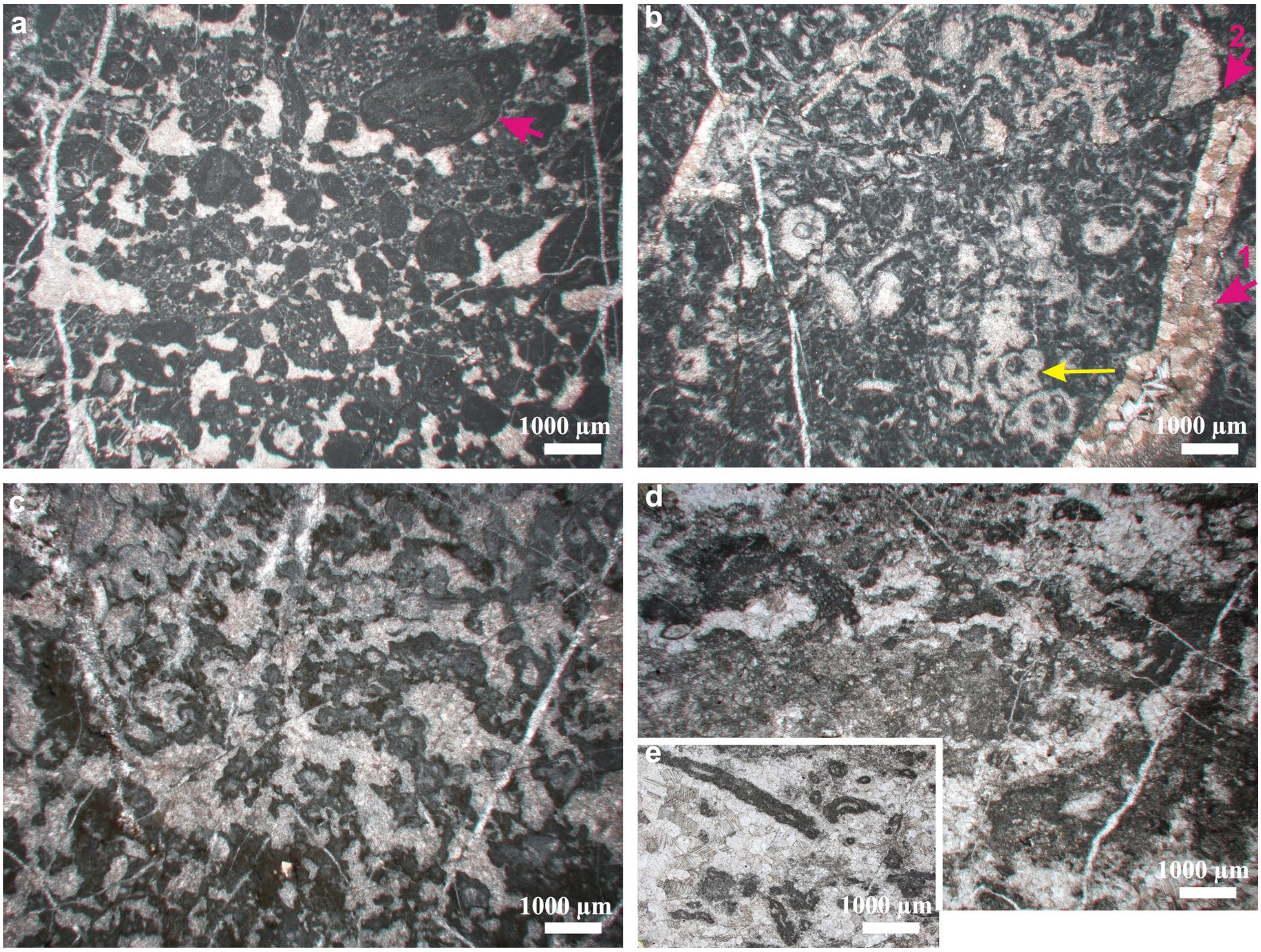


Fig. 9 Photomicrographs of the Middle Triassic (Pelsonian) Steinalm Formation. **a** Oncoidal boundstone, in which oncoids are attached by microbial clotted micrite (arrow) containing fenestral pores. Pore space is occluded by radiaxial fibrous calcite cement. This facies is one of the microbialite types of the formation, formed in a subtidal environment (Kecső valley, Aggtelek facies area). **b** Microbial boundstone from subtidal microbial reef facies with abundant clotted micrite and dasycladalean algae (thin, yellow arrow; *Physoporella* sp. fragments, det. O. Piros). Vertical fracture is occluded by radiaxial fibrous calcite (RFC) and dolomite cement (short, red arrow number 1) and cut across by a bed-parallel stylolite (short, red arrow number 2). RFC cement indicates precipitation from marine pore-water. Cement type and cross-cutting stylolite indicate early formation of fracture during burial, which suggest this element is a part of neptunian dyke system (Szőlősardó-1 core section 502.9 m, Szőlősardó facies area). **c** Microbial boundstone with abundant clotted micrite in dark grey limestone which is typical for subtidal microbial reef (Csipkés tető, Bódva facies area). **d** *Tubiphytes*–microbial boundstone (Szalonna-4 core section 38.9 m, Bódva facies area). **e** *Tubiphytes* sp. fragments in grainstone (Szalonna-4 core section 39.0 m, Bódva facies area)

Middle Triassic cherty basinal carbonates (Bódvarákó Formation)

The Bódvarákó Formation is characterised by dark grey, cherty dolomite, cherty limestone containing radiolarians and thin-shelled bivalves, and clayey, dolomitic limestone, siltstone and shale (Less 2000; Fig. 10). It occurs in the metamorphosed Bódvarákó Series (Torna Nappe), where it overlies the Gutenstein Formation. Its thickness is estimated as 40–45 m. Conodonts (*Gondolella* cf. *bulgarica*, *G. constricta*, *Gladigondolella tethydis*, *Gondolella foliate inclinata*) constrain a Middle Anisian–Late Ladinian, such as Pelsonian to Longobardian, age (Kovács 2011). The biotic components, preserved despite the significant diagenetic and metamorphic alteration, suggest deposition in a basinal environment.

Middle Triassic slope and basinal carbonates (Schreyeralm, Raming and Reifling Formations)

In the Silica Nappes, the Steinalm Limestone is overlain by the Schreyeralm Formation, which is covered by the Raming Formation (Aggtelek facies area), the Reifling Formation (Szőlősardó facies area) and basinal carbonates (Bódva

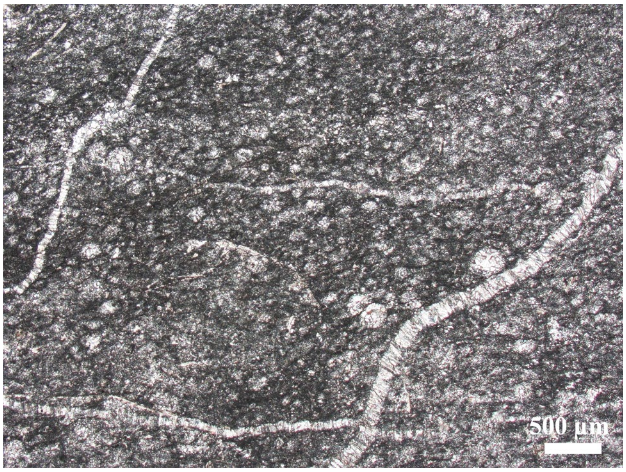


Fig. 10 Photomicrograph of Middle Triassic Bódvarákó Formation. Bioclastic packstone with abundant radiolarians and some thin-shelled bivalves (Nyúlkertlápa, Bódvarákó Series)

facies area; Balogh and Kovács 1981; Kovács et al. 1989; Péró et al. 2015).

The Schreyeralm Formation, 20–40 m in thickness, is characterised by pink and red micritic limestone which contains foraminifers, radiolarians, bivalves, ammonites, brachiopods, crinoid fragments and ostracods (Fig. 11a). It was referred to as the Dunnatető Formation in the earlier literature (Szőlősardó and Bódva facies areas; Balogh and Kovács 1981; Kovács et al. 1989). The formation is thinner in the Aggtelek facies area and thicker in the Szőlősardó and Bódva facies areas (Kovács et al. 2004). The conodont assemblage constrains the Middle Anisian age in the Aggtelek facies area and the Middle–Late Anisian age in the Szőlősardó and Bódva facies areas (Kovács 2011; Péró et al. 2015). The beds were deposited in distal toe-of-slope and basinal environments. Relatively thick successions of crinoidal limestone occur locally and likely were developed on a proximal slope of rotating blocks, which were formed by normal faults.

The Raming Formation (Aggtelek facies area), *ca* 40–130 m in thickness, consists of a thin-bedded alternation of grey and varicoloured reddish packstone–grainstone, with foraminifers, *Tubiphytes* sp., dasycladales, calcareous sponge, bryozoans, crinoid fragments, ostracods and lithoclasts, and wackestone with fragments of thin-shelled bivalves. In the upper part of the succession, redeposited reef detritus within the packstone–grainstone beds occurs abundantly, overlain by thin tuffite beds and radiolarite. Conodonts constrain a latest Middle Anisian and Late Anisian age, such as latest Pelsonian and Illyrian (Kovács et al. 2004; Péró et al. 2015). Cyclicity is characterised by an upward-thickening bedding pattern associated with upward-coarsening detritus. These features reflect highstand shedding, i.e., coarser detritus transported during a highstand of sea-level. Sediments were deposited in the toe-of-slope and fore-reef slope environments. Occurrence of reef detritus defines large-scale progradation of the reefs (Velledits et al. 2011).

The Reifling Formation (Szőlősardó facies area) is characterised by dark grey, finely crystalline locally nodular limestone (Kovács 1997). Its thickness cannot be determined due to a lack of a complete section; based on geological mapping it is estimated as 50 m. The stratigraphic setting of the formation suggests an Anisian−Early Carnian age, whereas Middle Anisian, Late Ladinian−Early Carnian age was proved by conodonts (Kovács et al. 1989). Two facies variants can be distinguished in the Hungarian part of the Silica Nappe system (Kovács 1997). One of them (Reifling facies-1) is characterised by thin- to thick-bedded cherty limestone. Grey and brown chert forms nodules and layers. Radiolarians, thin-shelled bivalves and ostracods commonly occur; crinoid fragments are encountered in some sections. The beds were deposited in basinal and distal toe-of-slope environments. The other facies (Reifling facies-2) is thick-bedded and contains peloids and bioclasts of shallow-platform origin; in addition, radiolarians, brachiopods, crinoid fragments and ostracods occur in variable quantity. Platform-derived lithoclasts commonly contain dasycladalean algae and *Tubiphytes* sp. A variation of facies-2 can be distinguished, in which stromatactis structures (relatively large irregular pores filled by internal sediment and radiaxial fibrous calcite cement) occur. The thickness of this facies is changing between 50 and 120 m. It was referred to as the Nádaska Formation in the earlier literature (Kovács et al. 1989; Fig. 11b, c). The beds were deposited in toe-of-slope and fore-reef slope environments. The source of the shallow-marine components was the *Tubiphytes*–microbial reefs (in the Anisian), which likely evolved in a proximal slope environment of rotating blocks defined by normal faults, and sponge reefs (in Ladinian and Early Carnian). Dolomitized rocks of the Reifling Formation occur for example in the Szőlősardó-1 core section (Balogh and Kovács 1981; Kovács et al. 1989; Fig. 11d). The conodont *Gondolella* cf. *bulgarica* (det. by Kozur, in Kovács et al. 2004) found in the dolomitized limestone constrains a Middle Anisian (Pelsonian) age.

Palaeogeographic setting and geodynamic interpretation of the facies successions

In the course of the Late Permian and Early Triassic, regional transgression created shallow-marine environments with widely extended and rather uniform zonation on the continental shelf at the western end of the Neotethys (Tollmann 1976, 1987; Kovács 1992; Haas et al. 1995). An increase in facies variability in the uppermost

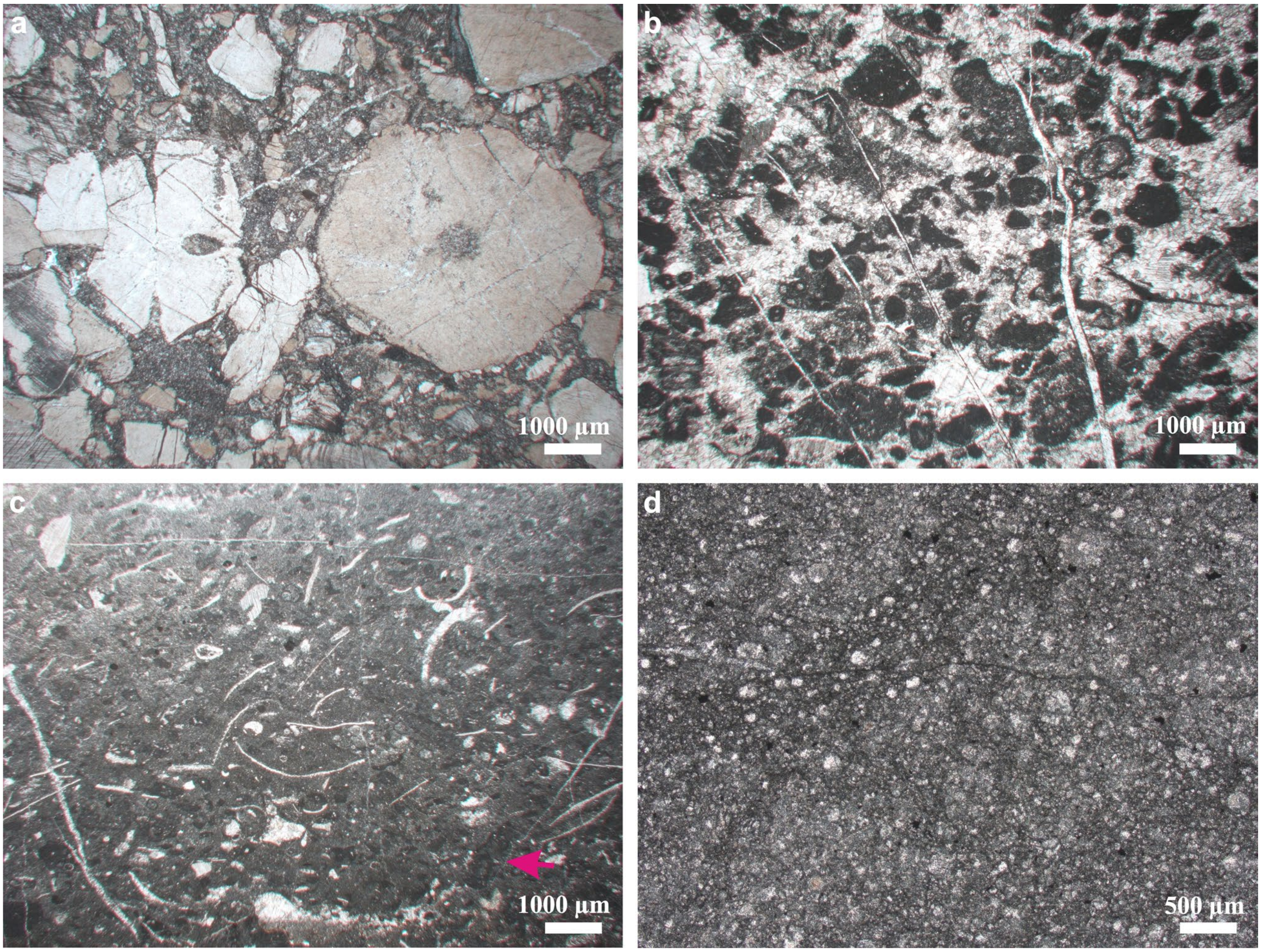


Fig. 11 Photomicrographs of Middle Triassic slope and basinal facies (Szőlősardó facies area). **a** Highly tectonized crinoidal packstone (Varbóc-4 core section 146.9 m, Schreyeralm Formation). **b** Lithoclastic–bioclastic grainstone with detritus of shallow-platform origin (Varbóc-4 core section 79.9 m, Reifling Formation, facies-2). **c** Filamentous wackestone with *Tubiphytes* sp. fragments (arrow), bivalves, brachiopods, crinoidal fragments and ostracods (Varbóc-4 core section 71.8 m, Reifling Formation, facies-2). **d** Dolomitized radiolarian packstone (Szőlősardó-1 core Sect. 435.8 m, Reifling Formation, facies-1)

Lower Triassic formations reported from the Dinarides, Alps and Carpathians implies differentiation of the shelf segment (Kovács et al. 2011). Deep basins were formed from the latest Early Triassic and widely developed in the Aegean–Bithynian (Gutenstein Formation; Fig. 12). The Lower and Middle Triassic sedimentary successions considered in the recent reconstruction are the following. (1) Formations in the Inner Western Carpathians, Eastern and Southern Carpathians, Northern Calcareous Alps, which were deposited on the shelf domains that established the future European margin. (2) Formations in the Southern Alps, Transdanubian Range, Dinarides and Bükk Mountains, which were deposited on the shelf domains that established the future Adriatic margin (Schmid et al. 2004; Kovács et al. 2011; Porkoláb et al. 2019).

Latest Early Triassic and Early Anisian

In the latest Early Triassic, the rate of subsidence gradually increased in many shelf domains which led to the formation of an intraplatform basin system (e.g., Michalík 1993). This trend is reflected in striking lithofacies changes. The basinal facies is characterized by dark grey finely crystalline limestone, in which only a few types of fossil occur. The oolite and peritidal dolomite, which is common in underlying formations and indicates an inner-ramp setting, is missing from these uppermost Lower Triassic carbonates. According to Rychliński and Jaglarz (2017), seismite, described from a dark grey, finely crystalline carbonate succession in the Western Carpathian Križna Nappe, confirms tectonic activity in the late Olenekian. Sedimentary

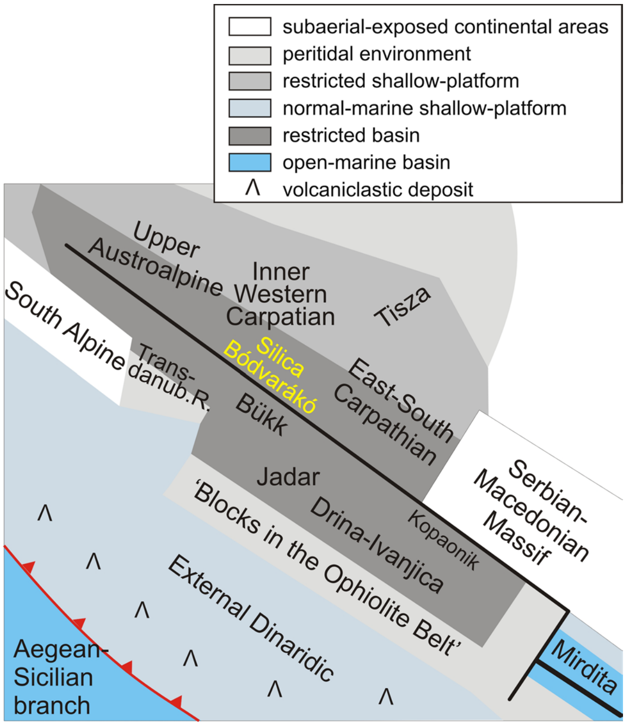


Fig. 12 Sketch map of the Early Anisian palaeogeographic reconstruction showing shelf domains of the Dinaric–Alpine branch, north of the Aegean–Sicilian branch in the western end of the Neotethys Ocean (based on Kovács 1992; Csontos and Vörös 2004; not to scale). *Transdanub.R* Transdanubian Range Unit. The black line indicates the location of the future Triassic ocean

features of thin-bedded and nodular limestone in the Silica Nappes suggest deposition in an outer-ramp environment, where oxygen-depleted bottom conditions evolved. A similar outer-ramp facies was documented from the Inner Western Carpathians (Werfen Group, Šuňava Formation), the Northern Calcareous Alps (Werfen Formation), the Bükk Mts (Ablakoskővölgy Formation, Újmassa Member), the Inner Dinarides (Bioturbate Formation), the Bihor Mtns (Werfen Formation) and the Eastern and Southern Carpathians (Werfen Formation; Kovács et al. 2011).

During the Early Anisian, gradual changes took place in the sedimentary features of mud-dominated deposits that are attributed to gradually increasing oxygen depletion. It was most likely the result of density stratification of hypersaline seawater in a deep intraplatform basin (Gutenstein Formation, Silica Nappes). Coeval sedimentary successions are also characterized by dark grey limestone, such as the Gutenstein Formation in the Northern Calcareous Alps (NCA), the Inner Western (IWC), the Eastern–Southern Carpathians and the Bihor Mtns; Hámor Dolomite Formation in the Bükk Mtns; Jablanica and Ravni Formation in the Inner Dinarides (e.g., Brandner 1984; Lein 1987; Dimitrijević and Dimitrijević 1991; Mello et al. 1997; Filipović et al. 2003; Piller et al. 2004). The sedimentary features in these formations likely reflect restricted, hypersaline conditions and a stratified water column in deep intraplatform basins (Bechtel et al. 2005). In the inner-ramp settings connected to the intraplatform basins, dark grey, finely crystalline limestone–dolomite and peritidal evaporite–dolomite successions indicate a hypersaline setting (Reichenhall Formation in the NCA, Vysoká Formation in the IWC, Sohodol Formation in the Bihor Mts; Spötl and Burns 1991; Michalík et al. 1992; Kovács et al. 2011; Čerňanský et al. 2018).

During the latest Early Triassic, as far as the future Adriatic margin is concerned, a progressive shallowing from outer-ramp to inner-ramp oolite shoals and dolomitic tidal flats took place (e.g., in the Southern Alps, Cencenighe and S. Lucano Members; Broglio Loriga et al. 1983; Radoičić 1989, 1990; Haas et al. 1995). From the earliest Anisian, in the South Alpine domain, repetitive tectonic uplift formed regional horst blocks that resulted in long-term erosional gaps (Bertotti et al. 1993). The subsidence exhibits large lateral variations that are explained as strike-slip tectonics by Doglioni (1984) and Feist-Burkhardt et al. (2008). Between the tectonically active intervals, fine-grained carbonates were deposited in the peritidal zone and on the oxygenated shallow shelf (De Zanche et al. 1993; Rüffer and Zühlke 1995). In the depositional area of the External Dinarides (ED) and 'blocks in the Ophiolite Belt' (in the Inner Dinarides), the Anisian succession is rather uniform, represented mostly by bedded dolomite exhibiting features of peritidal sedimentation (Grad and Ogorelec 1980; Radoičić 1989, 1990). Finely crystalline bioclastic limestone subordinately also occurs, which contains the foraminifers *Pilammina densa* and *M. dinarica*. In the western zone of the ED, volcaniclastic and flysch deposits are documented, in which formations are genetically related to the Aegean–Sicilian oceanic branch (Kovács et al. 2011). In the Transdanubian Range, the lowermost Anisian peritidal dolomite is overlain by dark grey, finely crystalline limestone (Iszkahegy Formation). This latter one exhibits features of restricted intraplatform basins (cf. Kovács et al. 2011). The basinal facies indicates that the initiation of accelerated subsidence began during the Aegean–Bithynian in this shelf domain. The External Albanides domain formed an elevated block until the Middle Anisian (Pelsonian). In the Albian Alps, the Lower Triassic conglomerate is overlain by Anisian marginal marine marl, shale and limestone (Plan Formation; Gaetani et al. 2015).

The above-described features imply that a large shelf segment of the future Adriatic margin was in a relatively elevated setting throughout the Early Anisian. Accordingly, this, together with the Serbian–Macedonian Massif (SMM), formed a threshold for water-circulation that restricted the intraplatform basins from the open-marine basin, situated farther southwards. In the Albanides, the initiation of open-marine, deep basinal sedimentation in late Early Triassic was represented by red nodular limestone (Korabi Unit, Mirdita Zone; Krystyn 1974; Muttoni et al. 1996; Gawlick et al. 2008; Fig. 12).

Summarizing, the facies pattern and the differential sedimentary evolution suggest that the accelerated subsidence (1) began in the latest Early Triassic and (2) was connected to the onset of continental rifting due to the northward propagation of the Dinaric–Alpine oceanic branch.

Middle Anisian (Pelsonian)

The appearance of a large amount of sand-sized bioclasts and non-skeletal carbonate grains in the successions of the Gutenstein Formation in the Silica Nappes, following long-term, monotonous lime-mud deposition, indicates significant changes in sedimentary conditions (Hips 2007). This change was associated with shallowing of the depositional area during latest Early Anisian. In the Pelsonian in this area, sponge–microbe reefs were the centres of high carbonate production and a complex mosaic of environments was related to them. Sedimentary features imply a shallow subtidal, moderate-energy, inner-ramp and middle-ramp setting in the Aggtelek and Szőlősardó facies areas, respectively. The total absence of dasycladaleans and prevalence of microbes and sponges were likely controlled by extreme environmental conditions, such as elevated water salinity. The cyclical occurrence of evaporite-rich peritidal dolomite and dolocrete in the upper part of the Gutenstein Formation in the Aggtelek facies area indicates periodic subaerial exposure as a consequence of sea-level falls (Hips 2007). The coarse detrital grains are absent from the finely crystalline carbonate succession in the Bódvarákó Series. The significant facies differentiation between the formations in the Silica Nappes and Bódvarákó Series indicates differences in the subsidence rates within the former intraplatform basin. The differential subsidence led to the development of submarine relief.

The Gutenstein Formation is overlain by either shallow-marine carbonate (in the Silica Nappes) or basinal formations (in the Bódvarákó Series), respectively. The features of these overlying units indicate crucial changes in the biota both in shallow-marine and basinal settings (Fig. 3). In the shallow-marine setting, dasycladalean algae thrived under moderately agitated, well-oxygenated and normal-marine conditions (Steinalm Formation). In the basinal setting, radiolarians, thin-shelled bivalves and conodonts also indicate normal-marine salinity (Bódvarákó Formation). The presence of the conodont *Gondolella* cf. *bulgarica* constrains this peculiar biofacies change, which indicates a severe change in environmental conditions, to the Pelsonian (Kovács 2011).

Coeval shallow-marine and basinal carbonate successions were also reported from NCA sections (e.g., Lein et al. 2012; Velledits et al. 2017). The Gutenstein Formation is overlain either by the shallow-marine Steinalm Formation or the basinal Reifling Formation (Lein 1987; Gawlick et al. 2021). A thick succession of coarse-grained packstone–grainstone beds represents the lateral transition between these two overlying formations. Dasycladales and conodonts occur in the transitional interval and indicate early Pelsonian age (Lein et al. 2010; Gawlick et al. 2021). In those sections, where the Gutenstein Formation is overlain by radiolarian-rich basinal facies, the Reifling Formation (NCA) can be correlated with the Bódvarákó Formation (Rudabánya Hills). Limestone of open-marine facies overlying the Gutenstein Formation is linked to a gradual thinning of the continental crust (Lein 1987).

The Pelsonian Annaberg Formation in the NCA is characterized by dark grey limestone formed in a shallow-marine environment under the influence of benthic microbial communities. According to the review by Moser and Piros (2021), it represents a transitional facies between the Gutenstein and Steinalm Formations and a transitional facies between Steinalm and Reifling Formations (Rabenkogel Member; Lein et al. 2010, 2012). The relatively rich fossil assemblage includes dasycladalean algae, thin-shelled bivalves and conodonts (Gawlick et al. 2021). Thus, in the Hungarian part of the Silica Nappes, the Annaberg Formation can be correlated partly to the lowermost part of the Steinalm Formation (transitional facies from the underlying Gutenstein Formation in the Aggtelek facies area), where microbialite contains dasycladalean algae (cf. Hips 2007), partly to the peculiar subtidal microbial reef facies of the Steinalm Formation (thrombolite in the Szőlősardó and Bódva facies areas, which is described in this paper) and partly to the crinoidal proximal slope facies of the Schreyeralm Formation characteristic in the Szőlősardó and Bódva facies areas (cf. Moser and Piros 2021).

Summarizing the Pelsonian stratigraphical results, (1) the Gutenstein Formation (and its equivalent, fossil-poor basinal carbonate successions) in every Alpine–Carpathian–Dinaridic unit is underlain by the dasycladalean-rich Steinalm Formation; thus, they are not coeval formations. In addition, (2) the formations contain rich fossil assemblages typified by normal-marine water (dasycladalean algae, radiolarians, crinoids and conodonts) overlain on the Gutenstein Formation (cf. Kovács et al. 2011). They are the Steinalm Formation and coeval Reifling Formation (Bódvarákó Formation) and their transitional facies units. (3) These features indicate a peculiar biotic change that implies a sudden change in environmental conditions coevally in shallow-platform and in basinal settings.

In the Pelsonian, the extensional setting connected to the opening of the Neotethys Ocean significantly propagated north-westward. In the southern domains of the Dinaric–Alpine branch, the Early Triassic rifting stage was followed by the Middle to Late Triassic oceanic opening between the Adria Promontory and Laurasia continental margins (e.g., Bortolotti and Principi 2005; Ozsvárt et al. 2012; Bortolotti et al. 2013). The tectonic slices of continental origin within the Mirdita Ophiolite Nappe (Albania) consist of Triassic–Jurassic carbonate successions including Lower Triassic limestone of ammonitico rosso facies and Anisian radiolarian limestone. In addition, slices consisting of magmatic rocks, covered by radiolarite and chert of Anisian age, and Middle Anisian picritic basalts as pillow-lava, have also been identified (e.g., Bortolotti et al. 2005, 2013; Gawlick et al. 2008; Gaetani 2015). This occurrence provides evidence for the opening of the oceanic basin between the Adria and Eurasia Plates in Middle Triassic time. The extension of the oceanic branch likely had significant influence on circulation pathways of carbonate platforms and deep intraplatform basins located to the north. As a result of opening seaways, well-oxygenated, normal-marine water flooded areas previously restricted from large-scale circulation. Spreading of the biota during the Pelsonian in the northern shelf domains was determined by environmental factors that were controlled by the geodynamic evolution of the Dinaric–Alpine oceanic branch.

Latest Middle Anisian (latest Pelsonian) and early Late Anisian (early Illyrian)

From the latest Pelsonian, the dissection of shallow-platform areas accelerated and additional basinal areas developed in the Alpine–Carpathian–Dinaridic domains of the shelf that were connected to thinning of the continental crust (e.g., Lein 1987; Radoičić, 1989; Kovács et al. 1989, 2011; Budai and Vörös 1992; Kovács 1997; Missoni et al. 2001; Lein et al. 2012; Celarc et al. 2013; Sudar et al. 2013; Péró et al. 2015). However, for example in the depositional areas of South Alpine, Bükk, and Inner Dinaridic domains, significant subaerial erosion and terrestrial deposits are recognised (Voltago and Richthofen Conglomerates, Sebesvíz Breccia, Podbukovi Conglomerate; e.g., De Zanche et al. 1993; Velledits 2004; Sudar et al. 2013). The uplift and erosion of the blocks were explained by Middle Triassic compressional tectonics, which likely were related to transpressive movements (Doglioni 1984), and block-faulting (Sudar et al. 2013). In the Silica Nappes, the upper part of the dasycladalean-rich shallow-platform limestone is dissected by neptunian dykes (e.g., Péró et al. 2015). The dasycladalean-rich limestone is overlain by crinoidal limestone, as a proximal slope facies, or red limestone of basinal ammonitico rosso facies (Schreyeralm Formation) that is overlain by grey, cherty limestone/dolomite containing radiolarians (Raming and Reifling Formations; Kovács 1984; Péró et al. 2015). A similar succession occurs in the Slovak part of the Silica Nappes (Havrila 2011) and in the NCA (Piller et al. 2004; Gawlick et al. 2021) as well as in the Dinarides (Sudar et al. 2013).

Slope and basinal limestones in the Silica Nappes are either reddish and varicoloured or grey. The colour of the limestone is a function of the ratio of detritus redeposited from shallow-platform (grey) and micrite matrix (red). The red pigmentation dispersed within micrite matrix is most likely due to the iron (hydro)oxide minerals formed via bacterial mediation, similar to those described from other basinal limestones by Mamet and Préat (2006).

Conclusions

In the western end of the Neotethys (in the Dinaric–Alpine oceanic branch), the Alpine sedimentary cycle was initiated via the Permian transgression. During the Early Triassic, a well-established depositional zonation was developed on the epeiric shallow shelf. From the latest Early Triassic, the shelf differentiation was initiated and the previous facies zonation dissected by the formation of intraplatform basins. This implies the onset of an extensional setting, which was connected to the continental rifting stage of the northern sector of the shelf.

Three stages of the evolution are reconstructed.

1. Latest Early Triassic−Early Anisian: Accelerated subsidence was initiated forming deep intraplatfom basins across large areas. The external domains remained in the peritidal zone and horst blocks were coevally elevated (future Adriatic margin).
2. Middle Anisian: This interval represents a short period of tectonic quiescence in the northern shelf sector. A shallowing-upward sedimentary trend was observed in many intraplatform basinal settings that suggests a relative sea-level fall. In some depositional areas of the future Adriatic margin, the regional erosion was followed by shallow-marine flooding. A large-scale spreading of normal-marine biota took place coevally in previously restricted shallow-platform as well as basinal environments, that was controlled by a significant change in water circulation. The changing of the marine water circulation pattern was likely triggered by the opening of the gateway in the southern sector via switching of the geodynamic setting from rifting to spreading (Albanides, Mirdita Zone).
3. Latest Middle Anisian–early Late Anisian: In the northern sector of the Dinaric–Alpine oceanic branch, normal faulting activity accelerated resulting in the development of additional basinal areas in an extensional setting in the course of continental rifting.

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