GEOLOGIJA *65/2*, 237-250, Ljubljana 2022

https://doi.org/10.5474/geologija.2022.014

Depositional environment of the Middle Triassic Strelovec Formation on Mt. Raduha, Kamnik-Savinja Alps, northern Slovenia

Sedimentacijsko okolje srednjetriasne Strelovške formacije na Raduhi v Kamniško–Savinjskih Alpah, severna Slovenija

Primož MIKLAVC[1] & †Bogomir CELARC[2]

[1]University of Ljubljana, Faculty of Natural Sciences and Engineering, Department of Geology, Aškerčeva c.12, SI-1000 Ljubljana, Slovenia; e-mail: primoz.miklavc@ntf.uni-lj.si
[2]Geological Survey of Slovenia, Dimičeva ulica 14, SI-1000 Ljubljana, Slovenia

Prejeto / Received 14. 11. 2022; Sprejeto / Accepted 12. 12. 2022; Objavljeno na spletu / Published online 21. 12. 2022

Key words: Southern Alps, bituminous limestones, restricted basin, intraformational breccia, Anisian, facies analysis

Ključne besede: Južne Alpe, bituminozen apnenec, zaprti bazen, intraformacijska breča, anizij, faciesna analiza

Abstract

The Raduha section represents a continuation of the research of the Anisian Strelovec Formation in the Kamnik-Savinja Alps. The Strelovec Formation was deposited during the Anisian on a drowned section of the Serla Dolomite carbonate platform in a restricted probably outer ramp environment associated with an intraplatform basin. The base of the section is represented by dolostone breccia containing angular carbonate lithoclasts of shallow-marine origin. This is followed by alternations of laminated and homogenous hemipelagic limestones deposited in a restricted and anoxic environment. Hemipelagic sedimentation was occasionally interrupted by clay input and deposition of sediments from gravity mass flows. Slow filling of the basin lead to a gradual cessation of anoxic conditions and sedimentation of bedded shallow-marine limestones. After shallow water conditions were established, bioclastic dolostone of the Contrin Formation was deposited.

Izvleček

Profil Raduha predstavlja nadaljevanje raziskav anizijske Strelovške formacije v Kamniško-Savinjskih Alpah. V aniziju se je na potopljenem delu karbonatne platforme formiral intraplatformni bazen, v katerem je prišlo do sedimentacije Strelovške formacije na verjetno zunanjem delu karbonatne rampe. Profil se prične z dolomitno brečo s klasti spodaj ležeče anizijske karbonatne platforme. Sledi sedimentacija hemipelagičnih plastnatih laminiranih ter homogenih apnencev v hidrodinamično mirnem in anoksičnem okolju. Umirjene pogoje sedimentacije so občasno prekinili gravitacijski tokovi (sinsedimentni zdrsi in turbiditi), ki so vnesli droben klastični material s kopnega. S počasnim zasipavanjem bazenskega okolja pride do postopne prekinitve anoksičnih pogojev ter sedimentacije plastnatih plitvovodnih apnencev, kar nakazuje na popolno zapolnitev intraplatformnega bazena. Sledi sedimentacija bioklastičnega dolomita zgornjeanizijske Contrinske formacije.

Introduction

Kamnik-Savinja Alps are a part of the eastern Southern Alps (Placer, 2008) which were in the Middle Triassic placed at an intertropical northern latitude of 15°18° (Stefani et al., 2010). In the Anisian, the area was subjected to the extensional tectonic phase, probably caused by regional strike-slip tectonics that are characteristic for most of the Southern Alps (e.g., Masetti & Neri, 1980; Doglioni, 1987). This resulted in the formation of blocks with differential subsidence (De Zanche et al., 1993, 1995; Gianolla et al., 1998; Neri & Stefani, 1998). On the uplifted (less subsided) blocks shallow-water platform sedimentation was continuous (Maurer, 20009), whereas different basinal units deposited on intensively subsided blocks (Masetti & Neri, 1980; Farabegoli et al., 1984; Sudiro, 2002; Brack et al., 2007). A similar synsedimentary Middle Triassic tectonics are also typical for the nearby Balaton Highland and Veszprem plateau, located east of the Southern Alps, where the Anisian Felsöörs Formation deposited on drowning blocks (Haas & Budai, 1995; Budai & Vörös, 2006).

The first evidence for the Middle Triassic rifting phase in the Kamnik-Savinja Alps are thin- to medium-bedded bituminous limestones of the Velika planina member (Gale et al., 2022) and bedded bituminous carbonates and clastic rocks of the Strelovec Formation (Celarc, 2004). Regardless the similarity of facies and macrofossil biota in the Velika planina Member and Strelovec Formation, the relationship is not yet clear. The Strelovec Formation can be traced over the entire NE part of the Kamnik-Savinja Alps and was first defined as a distinct unit by Celarc (2004). In recent years, excavations in the Strelovec Formation have revealed numerous specimens of macrofossil biota, especially vertebrates. Most of the vertebrate finds are complete and articulated fish fossils (Hitij et al., 2010a; Hitij et al., 2010b; Tintori et al., 2014), while reptilian remains belonging to ichthyosaurs and pachypleurosaurs are also locally very common (Hitij et al., 2010a; Hitij et al. 2010b). In addition to vertebrate fossils, the Strelovec Formation is also known for finds of various crustaceans (Gašparič et al., 2019; Laville et al., 2022), including the only horseshoe crab fossil in the Alpine Triassic deposits described by Bicknell et al. (2019), as well as rare echinoderms, bivalves, and plant remains (Hitij et al., 2010b). First detailed sedimentological study of the Strelovec Formation was carried out by Miklavc et al. (2016) in the SW part of the Robanov kot valley (NE part of Kamnik-Savinja Alps). The studied succession was divided into five lithostratigraphic units probably deposited in a shallow restricted basin under disoxic to anoxic conditions. Due to the depositional conditions and later diagenetic processes, namely dolomitization which occurred at the base and in the upper parts of the succession, no age-diagnostic fossils were found. Based on stratigraphic position above the shallow-water Serla Dolomite and below the shallow-water Contrin Formation, the age of the Strelovec Formation was assigned from Pelsonian to Illyrian (Celarc et al., 2013). Due to highly variable thickness and litostratigraphy of the formation, additional studies were necessary. To better understand the sedimentary environment and evolution of the Strelovec Formation, a new detailed stratigraphic section was logged, including transitions with the under- and overlying shallow-marine litostratigraphic units (Serla Dolomite and Contrin Formation).

The aim of this study is to describe and define different lithostratigraphic units of the studied succession, sedimentary processes and depositional environment, and to gain new evidence on the regional evolution of the Anisian basin in the NE part of Kamnik-Savinja Alps.

Geological setting

The studied succession is located on the NW slopes of Mt. Raduha in the NE Kamnik-Savinja Alps (Fig. 1). The succession is exposed along the mountain trail from the Grohat Alpine Meadow (1460 m) towards the top of Mt. Raduha (2062 m).

The Kamnik-Savinja Alps structurally belong to the eastern part of the Southern Alps (Placer, 2008) (Fig. 1). In the Middle Triassic, the area was situated at the SW embayment of the Neotethys

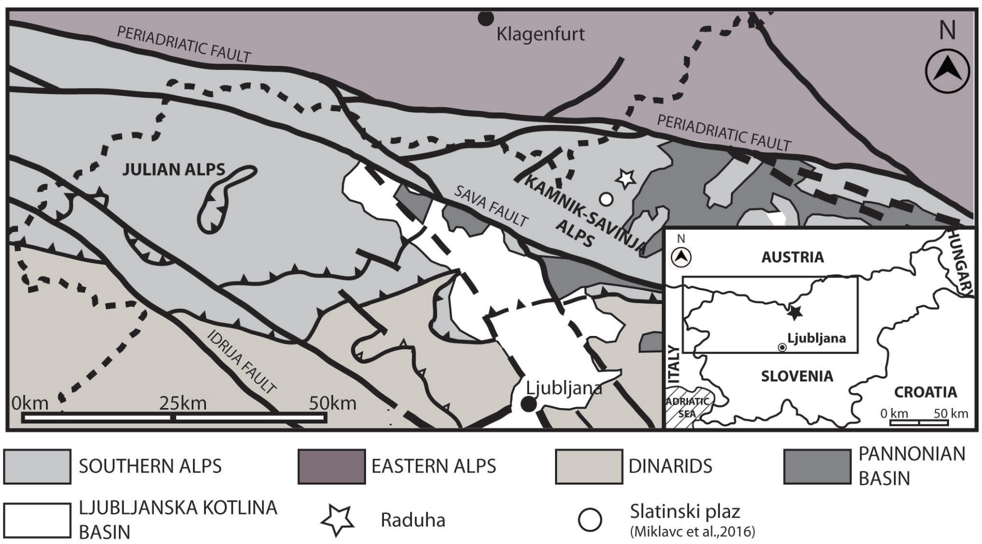


Fig. 1. Structural map of the north-central and north-western Slovenia (simplified after Placer, 2008). The studied section on Mt. Raduha (Kamnik-Savinja Alps) is marked with a star and is located northeast of the previously studied Slatinski plaz section marked by a circle (Miklavc et al., 2016).

Ocean (e.g., Haas et al., 1995; e.g. Stampfli et al., 2002; Schmidt et al., 2008). From the late Permian to the Early Triassic and early Middle Triassic, the eastern part of the Southern Alps belonged to the extensive shalow marine shelf, locally known as the Slovenian Carbonate Platform (Buser, 1989). In the Middle Triassic, during the rifting phase, the uniform platform was dissected into blocks with different subsidence. The earliest evidence for the extension is the Anisian formation of shallow intraplatform basins (Buser, 1989; Bertotti et al., 1993).

The eastern part of the Kamnik-Savinja Alps, where the studied succession is situated, consists of Triassic sedimentary succesions (Teller, 1898; Seidl, 1908; Mioć et al., 1983; Celarc 2003, 2004; Celarc et al., 2013) (Fig. 2), which come into tectonic contact with Paleozoic rocks along a steep fault south of Mt. Olševa (Celarc, 2002). Early stratigraphic subdivision of the area was given by Mioć et al. (1983). They stated that the oldest rocks of the investigated area are Lower Triassic carbonates and siliciclastic rocks of the Werfen Formation, followed by Anisian massive crystalline dolomites and Ladinian rocks overlain by a Savinja thrust sheet composed of Upper Triassic massive limestones. Later, Celarc (2003, 2004) proposed a new lithostratigraphic division of Kamnik-Savinja Alps, in which he proved that the Middle Triassic successions are in a normal contact with the older Werfen Formation, and that the Savinja thrust does not exist (Fig. 2A). Triassic sequence on Mt. Raduha starts with Werfen Formation, which is composed of alternating marlstone, marly limestone, sandstone and oolithic limestone. These rocks are overlain by grey massive, rarely bedded Lower Serla Dolomite (Anisian). Both formations belong to the Slovenian Carbonate Platform (Buser, 1989). During the Middle Triassic tectonic phase, the Anisian carbonate platform was covered by well-bedded carbonates and clastic rocks of the ?Pelsonian to Illyrian Strelovec Formation (Miklavc et al., 2016) (Fig. 2B). After shallow water sedimentation was restored, the Contrin (Illyrian) carbonate platform of massive, rarely bedded limestones and dolomites prograded over the basinal successions (Celarc et al., 2013). Younger Triassic rocks, mainly represented by red nodular limestone (Loibl Formation), pyroclastics and volcanics or carbonate breccia (Uggowitz Formation), thin-bedded limestone (Buchenstein Formation) and massive carbonate (Schlern Formation) are not present on the NW slopes of Mt. Raduha, but outcrop on the SE slopes of Mt. Raduha and on the NW slopes of the Robanov kot valley (Celarc et al., 2013) west of the study area.

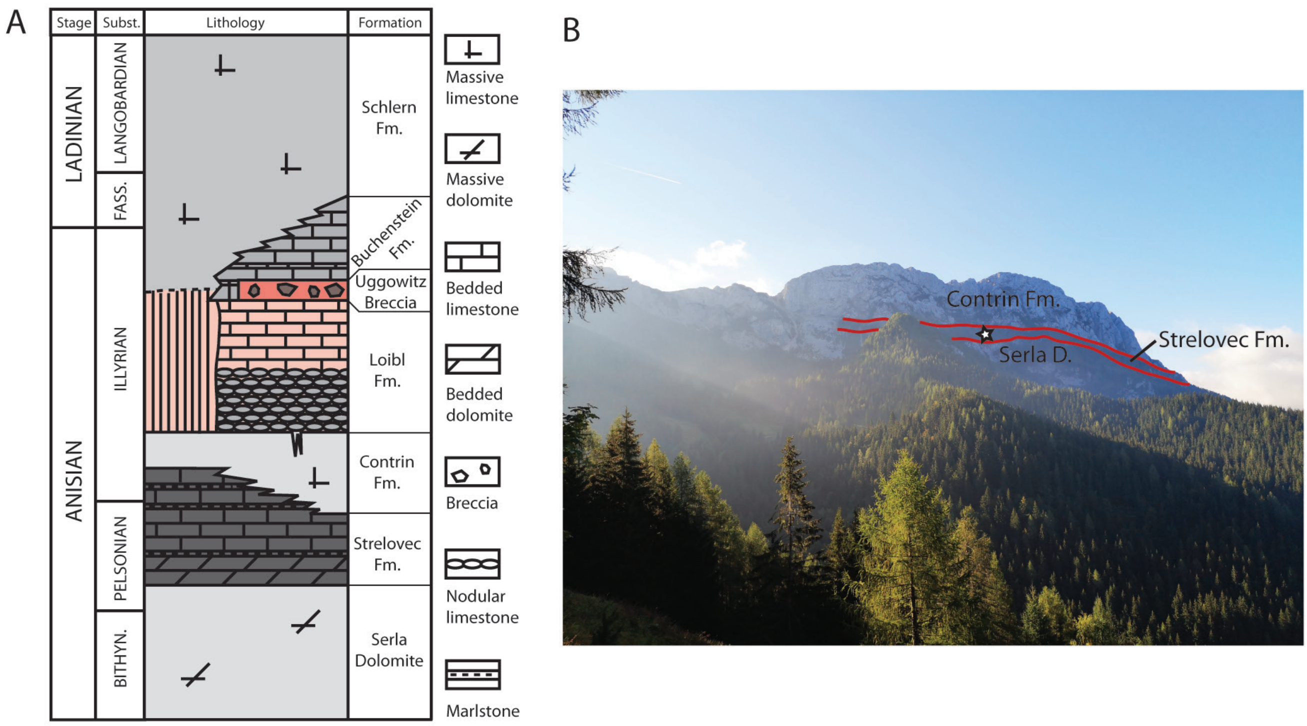


Fig. 2. A) Middle Triassic lithostratigraphic units of NE part of Kamnik-Savinja Alps (Celarc et al., 2013); B) Middle Triassic stratigraphy on NW slopes of Mt. Raduha (Raduha section is marked with a star).

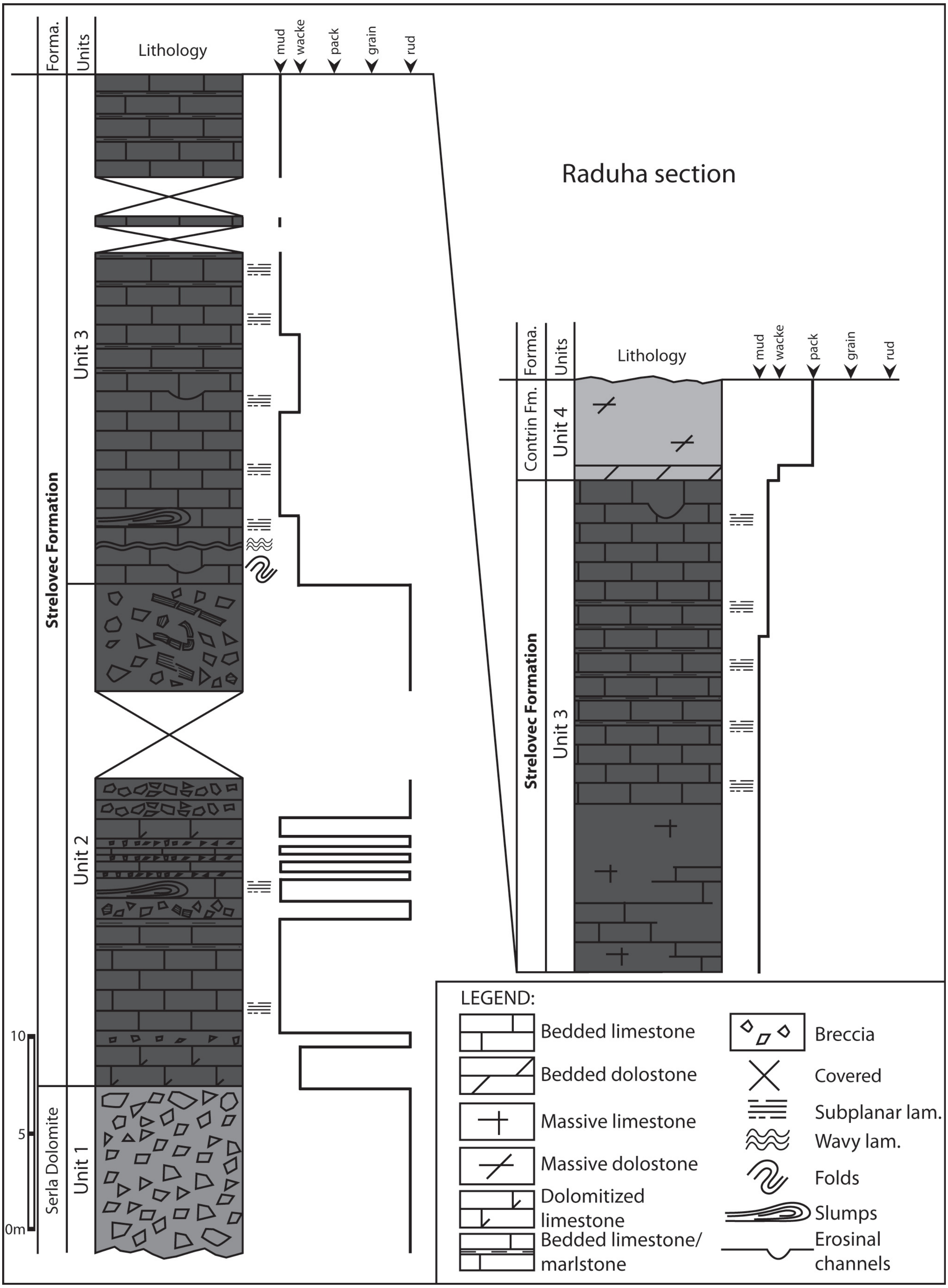


Fig. 3. Lithological and sedimentological characteristics of the Raduha section.

Materials and methods

On the NW slopes of Mt. Raduha, a stratigraphic section of almost perfectly exposed Anisian basinal succession was logged according to the standard sedimentologic procedure. Visual description of the exposed sediments was documented on 1:50 scale graphic log. A total of 25 samples were collected, out of which thin sections for sedimentological analysis were prepared. The latter was conducted on Zeiss Axioplan 2 microscope using plane and polarised light. The thin sections were photographed using a Zeiss AxioCam Hrc camera. Limestones and dolomites were classified according to Folk (1959) and Dunham (1962). To better determine and interpret sedimentary textures and structures, eight rock slabs were polished and then scanned using an Epson perfection V750 PRO scanner.

Lithostratigraphic units of Raduha section

The Raduha section (46°24'47,54''; 14°44'20,39'') (Fig. 3) is 87 m long and is characterised by dark grey and black laminated to medium bedded bituminous limestones intercalated with marls and, in the lower part of the succession with beds of intraformational breccias. This basin sediments overlay grey massive brecciated dolostones of the Serla Dolomite. The uppermost part of the succession is characterised by a transition from bedded basinal limestones to light grey massive dolostones of the Contrin Formation. The section is divided into four distinct lithostratigraphic units.

Lithostratigraphic Unit 1: grey massive dolostone breccia, uppermost Serla Dolomite

The base of the Raduha section is 6,9 m thick and is represented by grey massive dolostone breccia (Fig. 4A) of Unit 1.

Dolostone breccia in the lower part of the unit is composed of lithoclasts of shallow water limestone with microbialite and undetermined sparitic bioclasts (Fig. 6a). The matrix is composed of microsparite. Only locally are clasts cemented with calcite spar. In the upper part of

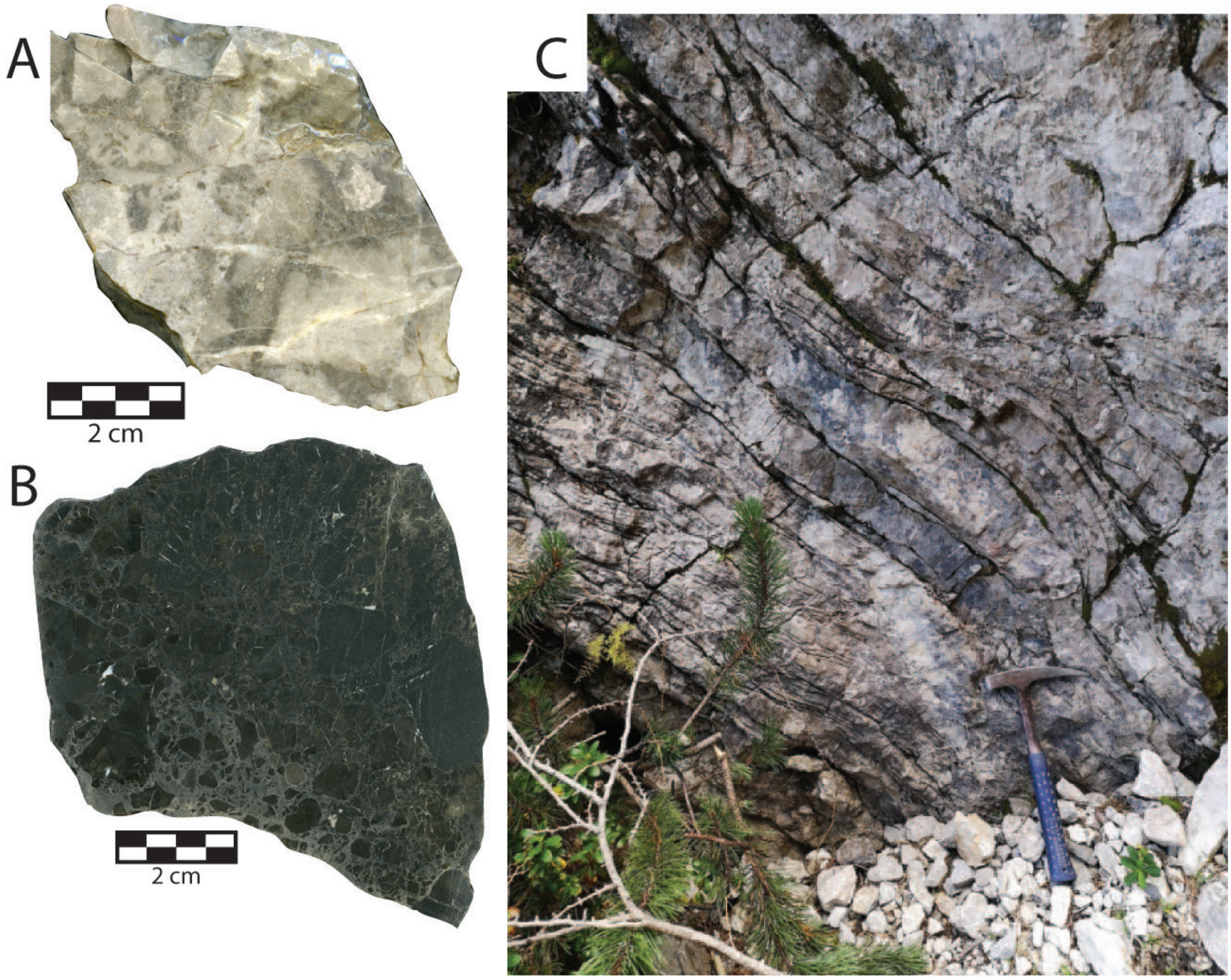


Fig. 4. Lithostratigraphic Units 1 and 2: A) polymictic dolostone breccia of Unit 1; B) polished slab of intraformational breccia of Unit 2; C) thin- to medium bedded limestone of Unit 2 with laterally variable bed thickness (?hummocky cross-stratification) .

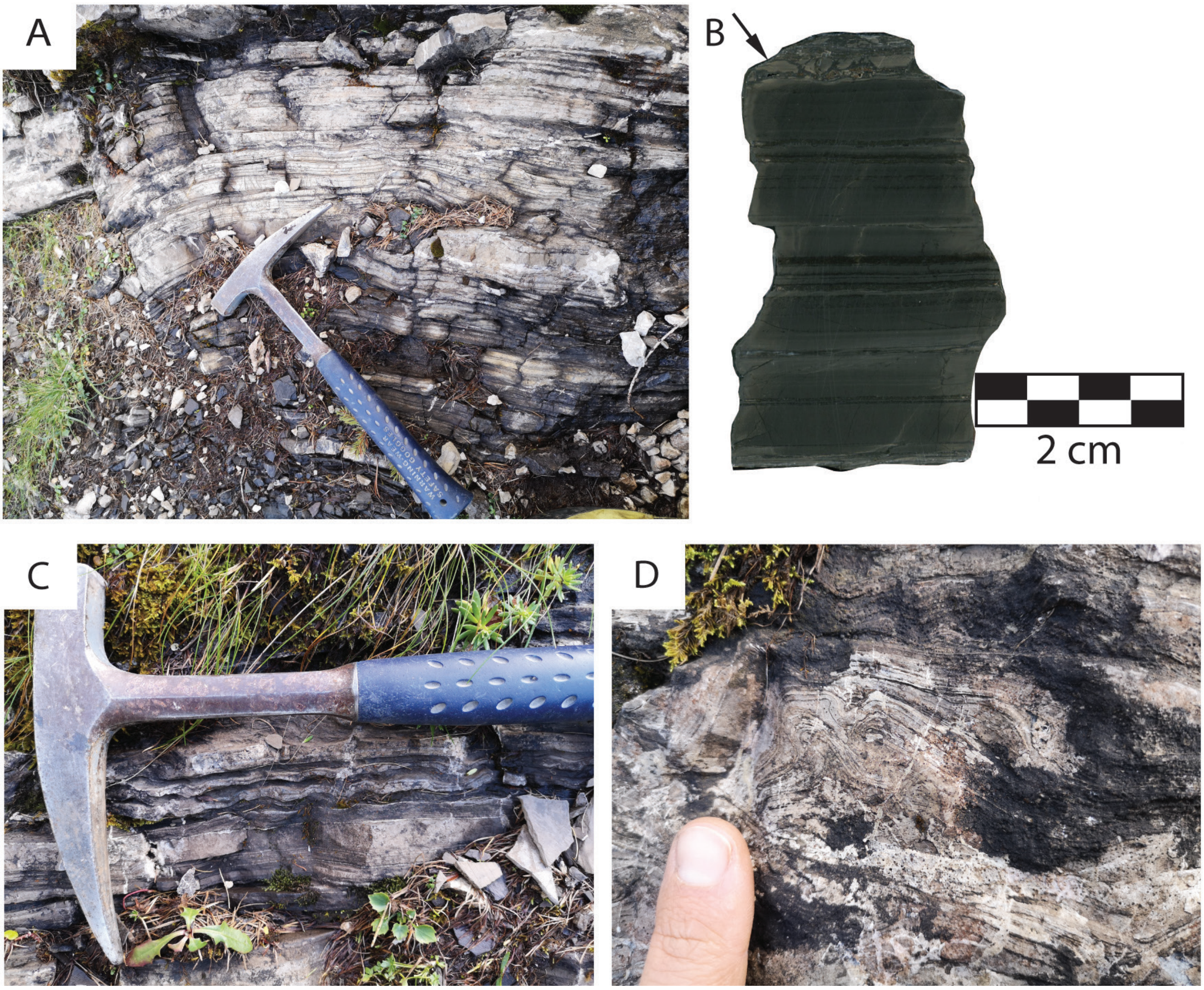


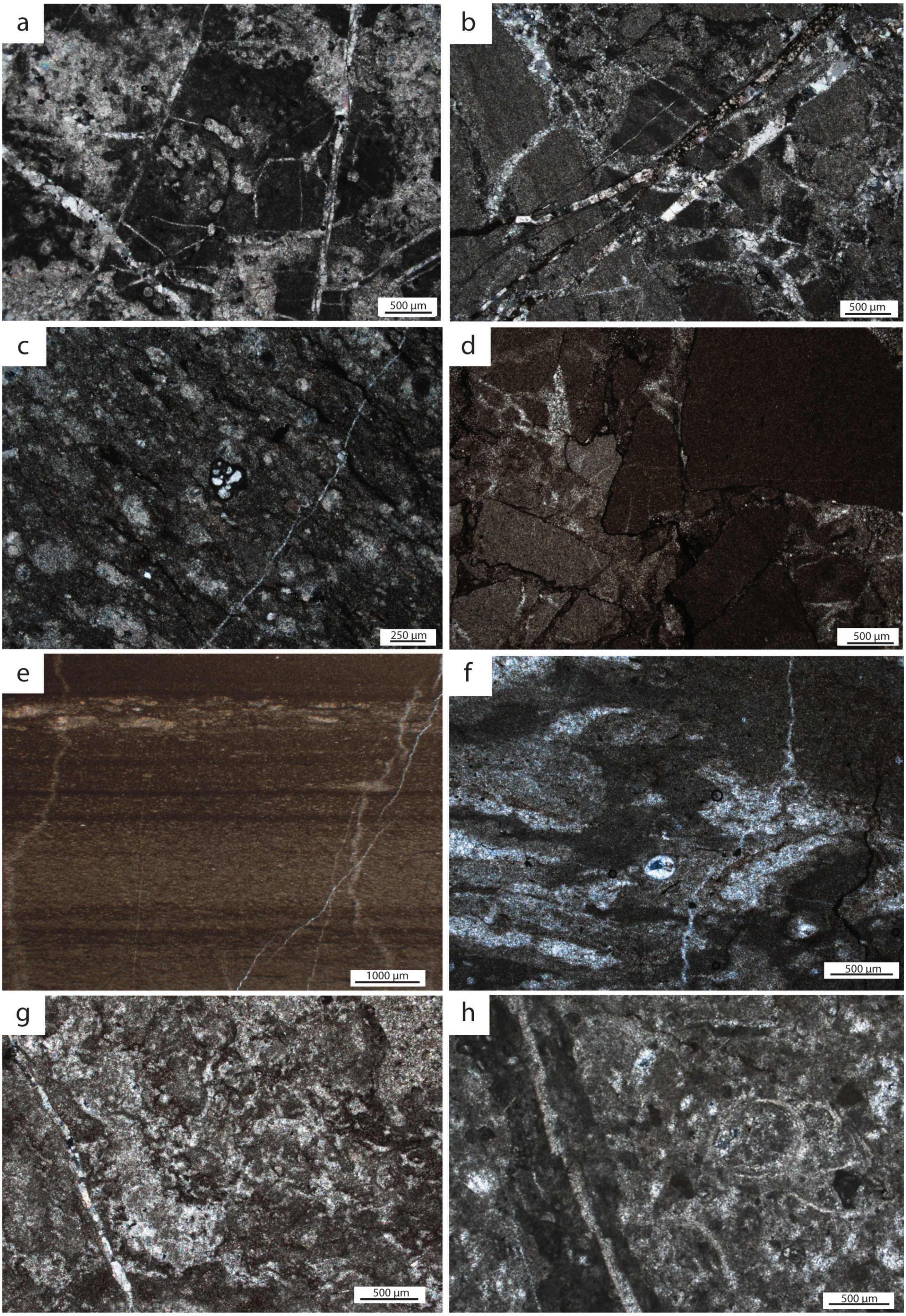
Fig. 5. Lithostratigraphic Unit 3: A) laminated thin- to medium-bedded black limestone; B) polished slab of the laminated limestone. Note rip-up clasts at the top of the sample (arrow); C) wavy bedding probably caused by movement of the semi-consolidated mudstones; D) synsedimentary deformation structures characterised by semi-ductile features.

the unit, clast-supported dolostone breccias are composed of angular granule- to pebble-sized micritic limestone and laminated micritic limestone clasts (Fig. 6b). The majority of clasts are cemented with calcite spar while in parts, microsparite matrix occurs. Strong fracturing of the whole rock and of some individual clasts is common. Some calcite-filled fractures postdate brecciation.

Lithostratigraphic Unit 2: black laminated thin bedded limestone intercalated with breccia, lower part of the Strelovec Formation

Unit 2 with thickness of 26 m overlies Unit 1 with a sharp contact. It is characterised by black laminated to medium bedded limestones which are slightly dolomitized in the first 3 m of the unit. Bed thickness ranges from 1 cm to 15 cm, with the exception of a 30 cm thick layer.

Fig. 6. Microfacies of the Raduha section: a) Unit 1; Polymictic dolostone breccia composed of shalow-water clasts. The clasts are cemented by dolomitized microsparite matrix and calcite spar cement. b) Unit 1; Clast-supported dolostone breccia with mudstone and laminated mudstone clasts. Matrix is in places composed of microsparite, while most of the clast are cemented with calcite spar. Fracturing of individual clasts is common. c): Unit 2; Rare foraminifera *Trochammina* in recrystallised intra-bioclastic wackestone (turbidite layer). Streaks and seams of amorphous organic component are common. d) Unit 2; Grain to matrix-supported intraformational breccia. The dominant clasts are mudstones. Note the tightly packed clasts with boundaries due to pressure solution. Matrix is micrite to microsparite. e) Unit 3; Subplanar laminated mudstone/wackestone. Note the microrytmitic pattern which is indicated with alternation of micrite (dark) and microsparite (light) laminae. In rare microsparite laminae, recrystallized, probably detrital grains, oriented parallel to lamination, can be observed (upper part of the section). f) Unit 3; Bioturbation within bioclastic wackestone with rare ostracods. g) Unit 3; Recrystallized bindstone of microbial origin. h) Unit 4; Peloidal bioclastic wacke-packstone with peloids, bivalve shell fragments (overgrown by microbial mats), foraminifers and intraclasts.


a
500 µm
b
500 µm
c
250 µm
d
500 µm
e
1000 µm
f
500 µm
g
500 µm
h
500 µm

Laterally discontinuous beds of limestones (?hummocky) are characteristic for the lower part of the unit (Fig. 4C). Slumps and synsedimentary folds are also common. Limestone intercalates with up to 120 cm thick beds of black intraformational limestone breccia (Fig. 4B) and layers of dark grey marlstone.

Limestone is thin to medium bedded and occasionaly subplanar laminated. Two distinct microfacies types are common for this unit. Peloidal wackestone predominates over recrystallised intra-bioclastic wackestone (Fig. 6c). Peloidal wackestone (grain to matrix ratio of 15:85) is composed of poorly sorted peloids and recrystallised clasts, which are concentrated in bands parallel to stratification, while silicified bioclasts and terrigenuos grains of angular quartz are rare. In recrystallised intra-bioclastic wackestone (grain to matrix ratio of 30:70) grains are mainly represented by recrystallized, probably shallow-marine clasts, peloids and intraclasts. Bioclasts of unknown origin are subordinate. Foraminifers are also very rare (Fig. 6c). Streaks and seams of amorphous organic matter parallel to lamination and silicification of small disolution cavities are also common in this microfacies.

Grain to matrix-supported breccias are intercalated within the limestone in the upper 17 m of the unit. Breccia is polymictic and poorly sorted (Fig. 6d). It is composed of up to 7 cm large, mostly angular to subrounded lithoclasts. Matrix is micrite to microsparite with seams of amorphous organic matter. Some parts of breccia are matrix-free and clasts are cemented with sparry calcite. Sparite-filled fractures indicate fracturing after deposition. Parts of tightly packed clasts with stylolitic contacts are common. The predominant lithoclasts are mudstone, while clasts of bioclastic mudstone and peloidal wackestone also occur.

Lithostratigraphic Unit 3: black laminated thin to medium bedded and massive limestone with intercalated beds of dark grey marlstone and claystone, upper part of the Strelovec Formation

Unit 3 is 50 m thick. In the first 27 m black laminated thin to medium bedded limestone with ranging in thickness from 0,5 cm to 50 cm (thicker beds of 20 cm to 50 cm predominate in the upper part of the unit) (Fig. 5A, B) intercalates with up to 1 cm thick beds of dark grey marlstone and claystone. Limestone in places represents laterally discontinuous beds. Clearly visible erosion channels also occur. Slumps and synsedimentary folds are common (Fig. 5D) while mudstone rip-up clast are rare (Fig. 5B). The slump structures (Fig. 5D) are mostly few dm in scale and up to one meter thick and show evidence for ductile deformation of semi-consolidated laminated mudstones and brittle deformation of consolidated material (breccia). The next 9 m of the unit are represented by massive black limestone which, especially in the lower part, laterally passes into poorly stratified limestone. Black laminated to thin-bedded limestone intercalated with marlstone forms the last 15 m of the unit 3.

Thin to medium bedded limestone is subplanar laminated mudstone, wackestone and bioclastic mudstone and wackestone. Micritic matrix predominates in the mudstone microfacies types, while the grain to matrix ratio in wackestones is 20:80. Subplanar laminae predominate over rare wavy (Fig. 5C) and wavy discontinuous laminae. Lamination occurs due to alteration between micrite (dark, enriched in organic matter) and microsparite or sparitic laminae, which indicates a microrytmitic pattern of the facies (Fig. 6e). In rare cases normal grading from microsparite to micrite occurs. Grains are mainly represented by various recrystallized grains which are oriented parallel to lamination (Fig. 6e). Poorly sorted peloids, intraclasts and ostracods are rare (Fig. 6f). Pyrite crystals are common while terrigenuous angular quartz grains are subordinate. Bioturbation is becoming more common towards the top of the unit (Fig. 6f) while seams and streaks of amorphous organic component are decreassing towards the top of the unit. The uppermost bed of the unit is slightly recrystallized bindstone of microbial origin with rare peloids, foraminifers and bioclasts of unknown origin (Fig. 6g).

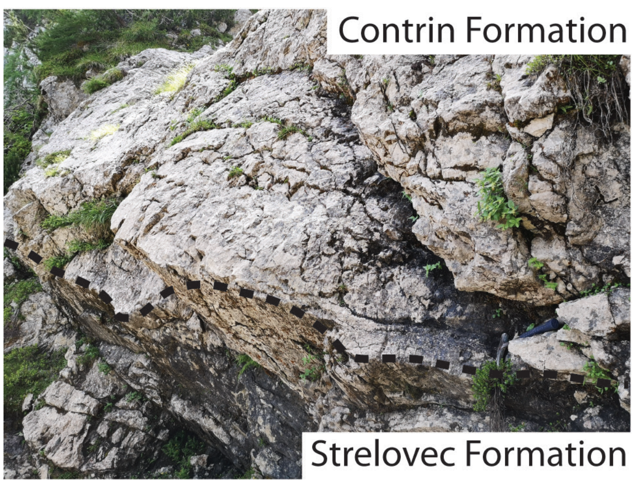


Fig. 7. Sharp contact (dashed line) of the Strelovec and the Contrin Formation.

Massive limestone is characterised by a transition from poorly stratified mudstone with traces of subplanar lamination to homogenuous mudstone. Micritic matrix predominates. Grains are represented by recrystallized clast of unknown origin and rare terrigenous quartz grains. Traces of bioturbation are very rare, marked by more coarse sparry calcite infillings of cavities.

Lithostratigraphic Unit 4: bedded and grey massive dolostone, Contrin Formation

The lowermost 3 m of Unit 4 were logged. The Contrin Formation begins with brownish-grey slightly wawy bedded dolostone with bed thickness of 30 cm, followed by light grey massive dolostone (Fig. 7).

Medium bedded dolomitic mudstone to wackestone is characterised by wavy and wavy discontinuous micritic laminae. Grains are represented by peloids, rare unidentifiable recrystallised bioclasts and framboidal pyrite grains.

Massive dolostone is peloidal bioclastic wackestone and packstone. Grains occupy 30-40 % of the area and are represented by peloids, foraminifers, bivalve shell fragments, crinoid fragments, recrystallized bioclasts and rare intraclasts (Fig. 6h).

Depositional environment

Deposition of fine sediments in the Raduha section, that settled from suspension was occasionally interrupted by slumping. In some cases, slumps evolved into debrites and turbidites which is evident from mass-flow breccia (Flügel, 2010) (Fig. 4B) with clasts of deformated and disintegrated individual beds (Miklavc et al., 2016). That these breccias are a product of resedimentation within the same basin is also supported by predominantly angular (short transport) organic

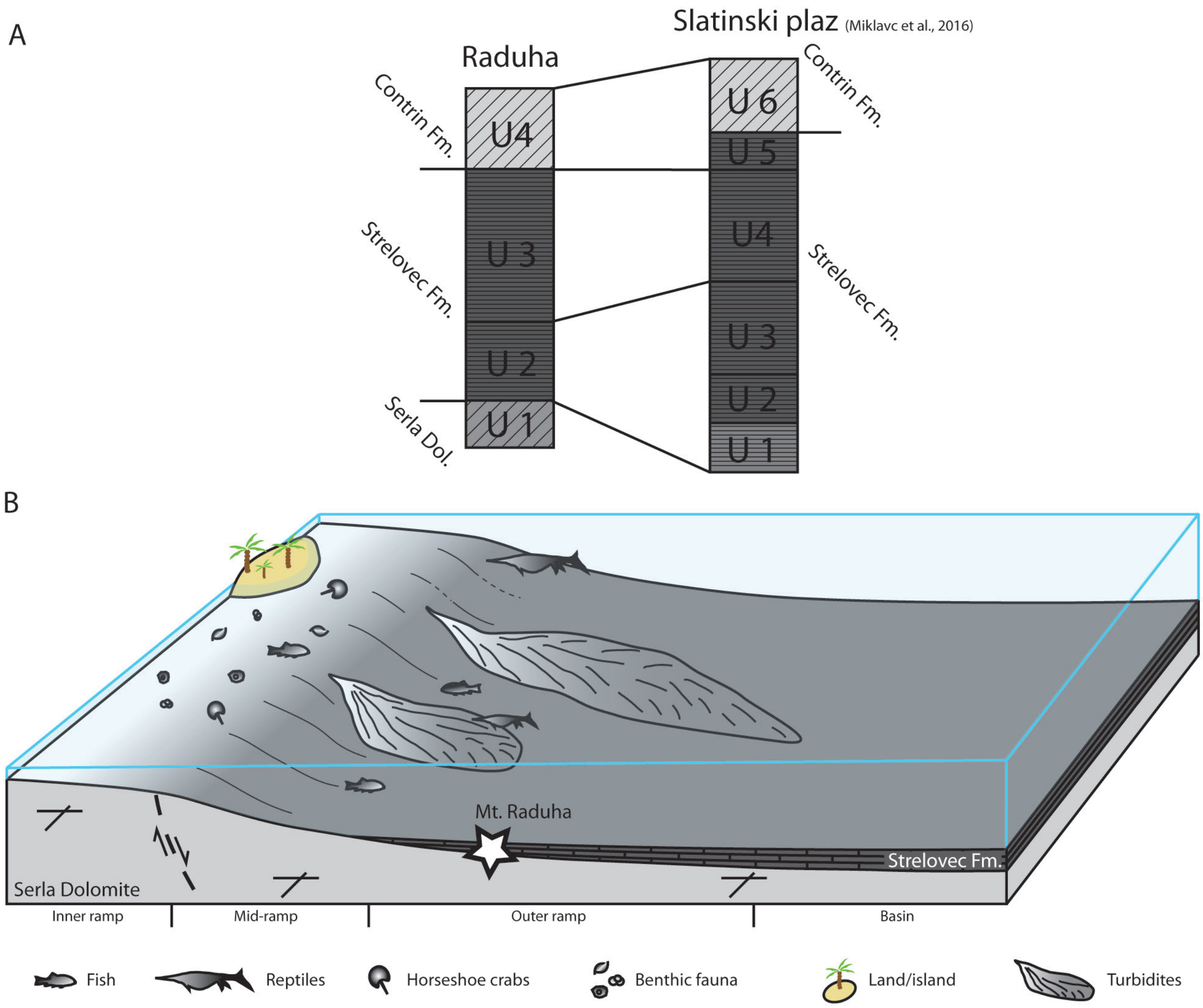


Fig. 8. A) Schematic columns of the Raduha and Slatinski plaz sections (Miklavc et al., 2016) and their correlation between lithostratigraphic units; B) Schematic presentation of the depositional environment of the Strelovec Formation. Relative position of investigated succession on Mt. Raduha is marked with a star.

rich mudstone clasts, with the same facies and texture as underlying beds, within organic-rich mud matrix.

In most cases of laminated mudstone, which is dominant in the lower part of the section (Fig. 5A, B), lamination is subplanar and is mostly homogeneous. Some laminae show grading. Wavy and wavy discontinuous laminations are rare. In some cases, the channels are cut into the underlying beds indicating erosional base surface. Erosional surface is also characteristic for rare laminae containing up to 5 mm in diameter large mudstone rip-up clasts (Fig. 5B). Within homogeneous laminae recrystallised platform-derived grains occur and are oriented parallel to lamination. These characteristics indicate erosion of semi consolidated base sediments and sedimentation from short-lived events related to low-density, fine-grained muddy distal turbidites (Piper & Stow, 1991; Shanmugam, 2002; Stockar, 2010).

Rythmitic interchange of laminated mudstone and homogeneous mudstone is also very common for this section. The absence of stratification in homogeneous beds could be related to the possible presence of weak oscillating bottom currents during the deposition of hemipelagic limestone (Sander, 1989; Bernasconi, 1991) and in the upper part of the succession could also be interpreted as the result of bioturbation.

Very common features of the finely laminated limestones of the Raduha section are relatively high contents of amorphous organic matter, which occurs in the form of streaks and seams parallel to lamination, presence of framboidal pyrite grains, absence of bioturbation in the basal and middle part of the succession and lack of benthic fauna. These features indicate sedimentation in a restricted reducing, anoxic environment.

Mostly in the Unit 3, bedded limestones are intercalated with marls. The periodic input of fine siliciclastic material could indicate periods of humidic climate with strong monsoonal activity (Parrish et al., 1986) which intensified the input of fine-grained material into the basin.

Toward the top of Unit 3 bed thickness increases from few centimeters in the lower part to a few tens of centimeters in the upper part, indicating shallowing of the basin. Higher up in the unit, bioturbation and various bioclasts are common, suggest gradual transition from oxygen-deficient to more oxygenated basin conditions. Deposition of massive grey dolostone with numerous bioclasts, especially foraminifers and fragments of molluscs indicate deposition in moderate to high-energy well-oxygenated subtidal environment.

In view of the observed microfacies and sedimentary structures, the sedimentary succession was deposited on a deepened part of the Anisian platform in a restricted distal part of the carbonate ramp, often under the influence of eutrophic conditions (Fig. 8B).

Discussion

The results of this study suggest that the depositional system of the Strelovec Formation can plausibly be described with a carbonate ramp model linked to an intraplatform basin formed by disintegration of the Anisian carbonate platform (Serla Dolomite), with facies types characteristic for subtidal mid- to outer ramp environment. Ramps are thought to be formed continuously in tectonic regimes characterised by gentle subsidence (Burchette & Wright, 1992; Duda et al., 2015).

Extensional tectonics and sea- level fluctuations are the most probable controlling factors in the formation of the intraplatform basin. Synsedimentary tectonic activity is indicated by the presence of basal polymictic dolostone breccias with angular shallow-marine lithoclasts originating from the underlying Serla Dolomite. Breccias indicate initiation of the tectonically induced subsidence of the area. However, due to Cenozoic deformations of the area, the reconstruction of the geometry of the intraplatform basin is not possible.

Facies types of the Raduha section indicate sedimentation of the Strelovec Formation in a hydrodynamically mostly quiet depositional environment. Considering the absence of typical storm-related features, such as hummocky cross-stratification, and the presence of slumps, fine-grained muddy distal turbidites, and restricted bottom conditions, the sedimentary succession was more likely deposited on the outer part of the ramp, but deposition on middle part cannot be excluded either. In fact, lateral truncation of beds is illustrated in Fig. 4C as an example of hummocky cross-stratification.

This quiet sedimentation was occasionally interrupted by siliciclastic input and deposition of sediments from gravity mass flows. Very similar conditions are characteristic for the Slatinski plaz section (Miklavc et al., 2016) (correlations between the units of the Raduha and Slatinski plaz sections can be seen in Fig. 8A), although due to the greater thickness of the Strelovec Formation in the Slatinski plaz section, sedimentation of this section probably occurred on more distal parts of the ramp environment, compared to the Raduha section. The diversified vertebrate fauna found in Strelovec Formation indicates shallow basin environment in close connection to carbonate platform with near-shore areas inhabitated with different fishes, pachypleurosaurs, ichtyosaurs, and horseshoe crabs (Hitij et al., 2010; Stockar, 2010; Čerňansky et al., 2018; Bicknell et al., 2019; Gale et al., 2022).

Anoxic conditions, recognisable by dispersed framboidal pyrite and sediment rich in organic matter (Stockar et al., 2013; Huang et al., 2017), are characteristic for the outer ramp environment. The development of poorly oxygenated conditions could be related to transgressive pulses that transported larger amounts of terrestrial organic debris into the basin, which was later consumed by bacteria (Jenkyns, 1980). Temporary basin anoxic conditions in the lower and middle part of the Strelovec Formation are indicated by well-preserved primary sedimentary textures (lamination) and excellent preservation of vertebrate skeletons (Hitij et al., 2010; Miklavc et al., 2016; Bicknell et al., 2019). Both are possible due to the absence of bioturbation and scavenging of macrofaunal biota. The preservation of skeletons could also be possible due to the growth of microbial mats, which prevent early decay after death (Stockar, 2010). In the Raduha section, absence of benthic fauna is a further indicator of anoxic conditions. Towards the middle ramp, transition from anoxic to more oxygenated conditions is suggested, which is evident from the lighter colour and absence of organic matter in the uppermost part of the Slatinski plaz section (Miklavc et al., 2016) and from bioturbation, which is evident in the last few meters of the Unit 3 in the Raduha section. Oxygenation of the uppermost parts of Strelovec Formation is probably related with shallowing of the basin (Miklavc et al., 2016). Beds of grey to dark marlstone and claystone indicate periods of increased input of sliciclastic material into the basin. These periods could be related to Anisian pulse of humid climate (Parrish et al., 1986; Stefani et al., 2010) and tectonic evolution of the area. During humid period in an otherwise arid and dry Anisian climate, there was also an increase in the vegetation of the land areas, as evident from the fossil plant remains within the Strelovec Formation (Hitij et al., 2010).

Conclusions

The depositional system of the Raduha section can be described as a carbonate ramp. The subtidal facies types were deposited in a restricted, mostly hydrodynamically quiet and probably distal parts of the carbonate ramp, occasionally disturbed by episodic storm deposits and tectonically induced depositional events (slumps, turbidites), partly under anoxic conditions.

After Anisian extensional tectonics, the dolostone breccia of Unit 1 was deposited on the submerged part of the shallow-water carbonate platform, represented by the Serla Dolomite. The Strelovec Formation begins with Unit 2, characterised by mudstone and wackestone deposited from fine-grained muddy turbidites. This exchange of hemipelagic mudstone and turbidite-derived wackestone was occasionally interrupted by slumps, that formed beds of intraformational breccias, and rare clay-rich interlayers. In Unit 3, hemipelagic sedimentation continues with fewer turbidite intercalations and more clay input. This indicates that the area was more tectonically active during deposition of Unit 2 than during Unit 3, where there was a greater amount of gravitational mass-flow deposition. The increased input of fine clastic component in Unit 3 indicates probably more humid climate than in Unit 2. After deposition of Unit 3, the basin was successively filled, as reflected by the deposition of mudstones under more oxygenated conditions and the progradation of shallow-marine bioclastic dolostones from Contrin Formation.

This paper supports the previous interpretation by Miklavc et al. (2016) that the Strelovec Formation in the NE part of the Kamnik-Savinja Alps deposited in the distal parts of the ramp environment. However, some outcrops still need to be investigated to gain a better insight into the evolution of the carbonate ramp environment of the intraplatform basin.

Acknowledgments

This work was financially supported by project IGCP 710: Western Tethys meets Eastern Tethys (Anisian Strelovec Formation in Kamnik–Savinja Alps) and the research program P1-0195 (Geoenvironment and Geomaterials) and is dedicated to the memory of co-author and mentor Bogomir Celarc, who led the way in studying Triassic stratigraphy of Kamnik-Savinja Alps. We would also like to thank two reviewers for thorough and constructive remarks that improve the original version of the manuscript.

References

Bertotti, G., Picotti, V., Bernoulli, D. & Castellarin, A. 1993: From rifting to drifting: tectonic evolution of the South-Alpine upper crust from the Triassic to the Early Cretaceous. Sedimentary Geology, 86: 53–76. https://doi.org/10.1016/0037-0738(93)90133-P

Bicknell, R. D.C, Žalohar, J., Miklavc, P., Celarc, B., Križnar, M. & Hitij, T. 2019: A new limulid genus from strelovec Formation (Middle Triassic, Anisian) of northern Slovenia. Geological Magazine, 156/12: 2017–2030. https://doi.org/10.1017/S0016756819000323

Brack, P., Rieber, H., Mundil, R., Blendinger, W. & Maurer, F. 2007: Geometry and chronology of growth and drowning of Middle Triassic carbonate platforms (Cernera and Bivera/Clapsavon) in the Southern Alps (northern Italy). Swiss Journal of Geosciences, 100: 327–347. https://doi.org/10.1007/s00015-007-1229-x

Bernasconi, S. M. 1991: Geochemical and microbial controls on dolomite formation and organic matter productio/preservation in anoxic environments a case study from Middle Triassic Grenzbitumenzone, Southern alps (Ticino, Switzerland). Ph.D. Thesis, Swiss Federal institute of Technology Zurich: 196 p.

Burchette, T.P. & Wright, V.P. 1992: Carbonate ramp depositional systems. Sedimentary Geololgy, 79: 3–57. https://doi.org/10.1016/0037-0738(92)90003-A

Budai, T. & Vörös, A. 2006: Middle Triassic platform and basin evolution of the Southern Bakony mountains (Transdanubian Range, Hungary). Rivista Italiana di Paleontologia e Stratigrafia, 112/3: 359–371.

Buser, S. 1989: Development of the Dinaric and Julian carbonate platforms and of the Intermediate Slovenian basin (NW Yugoslavia). Mem. Soc. Geol. It., 40: 313–320.

Celarc, B. 2002: Tectonic contact beetwen Paleozoic and Triassic rocks south of Podolševa (Slovenia). Geologija, 45/2: 341–346. https://doi.org/10.5474/geologija.2002.030

Celarc, B. 2003: Preliminarni rezultati geološkega kartiranja severovzhodnega dela Kamniško–Savinjskih Alp. Geološki zbornik, 17. posvetovanje slovenskih geologov. Oddelek za geologijo, Ljubljana: 25–27.

Celarc, B. 2004: Geological structure of the northwestern part of the Kamnik Savinja Alps. Ph.D. Thesis, University of Ljubljana: 137 p.

Celarc, B., Goričan, Š. & Kolar-Jurkovšek, T. 2013: Middle Triassic carbonate-platform breakup and formation of small-scale half-grabens (Julian and Kamnik–Savinja Alps, Slovenia). Facies, 59/3: 583–610. https://doi.org/10.1007/s10347- 012-0326-0

Čerňansky, A. Klein, N., Soták, J., Olšavsky, M., Šurka, J. & Herich, P. 2018: A Middle Triassic pachypleurosaur (Diapsida: Eosauropterygia) from a restricted carbonate ramp in the Western Carpathians 8Gutenstein Formation, Fatric unit): paleogeographic implications. Geologica Carpathica, 69/1: 3–16. https://doi.org/ 10.1515/geoca-2018-0001

De Zanche, V., Gianolla, P., Mietto, P., Siorpaes, C. & Vail, P. R. 1993: Triassic Sequence Stratigraphy in the Dolomites (Italy). Mem. Sci. Geol., 45: 1–27.

De Zanche, V., Gianolla, P., Manfrin, S., Mietto, P. & Roghi, G. 1995: A middle Triassic back-stepping carbonate platform in the Dolomites (Italy): Sequence stratigraphy and Biochronostratigraphy. Memorie di Scienze Geologiche, 47: 135–155.

Doglioni, C. & Bosellini, A. 1987: Eoalpine and mesoalpine tectonics in the Southern Alps. Geologische Rundschau, 76: 735–754. https://doi.org/10.1007/BF01821061

Duda, J.P., Zhu, M. & Reitner, J. 2015: Depositional dynamics of a bituminous carbonate facies in a tectonically induced intra-platform basin: the Shibantan Member (Dengying Formation, ediacaran Period). Carbonate Evaporites, 31: 87–99. https://doi.org/ 10.1007/s13146-015-0243-8

Dunham, R.J. 1962: Classification of carbonate rocks according to depositional texture. In: Ham, W.E. (ed.): Classification of carbonate rocks. AAPG Memoirs, 1: 108–121.

Farabegoli, E., Levanti, D., Perri, M. C. & Veneri, P. 1984: M. Bivera Formation: an atypical Middle Triassic »Rosso Ammonitico« facies from Southern Alps (Italy). Giornale di Geologia, ser. 3, 46/2: 33–46.

Flügel, E. 2010: Mikrofacies of carbonate rocks: analysis, interpretation and application. Springer: New York: 984 p.

Folk, R. l. 1962: Spectral Subdivision of Limestone Types. In: Ham, W.E. (ed.): Classfication of Carbonate Rocks Symposium. AAPG, Memoir 1, 62–84, Tulsa.

Gale, L., Hitij, T., Vičič, B., Križnar, M., Žalohar, J., Celarc, B. & Vrabec, M. 2022: A sedimentological description of the Middle Triassic vertebrate-bearing limestone from Velika planina, the Kamnik-Savinja Alps, Slovenia. Geologia Croatica, 75/1: 101–113. https://doi.org/10.4154/gc.2022.06

Gianolla, P., De Zanche, V. & Mietto, P. 1998: Triassic Sequence Stratigraphy in the Southern Alps (Northern Italy): Defenition of Sequences and Basin Evolution. Mesozoic and Cenozoic Sequence Stratigraphy of European Basins, SEPM Special Publication, 60: 719–747.

Hass, J. & Budai, T. 1995: Upper Permian-Triassic facies zones in the Transdanubian Range. Rivista Italiana di Paleontologia e Stratigrafia, 101/3: 249–266.

Hitij, T., Žalohar, J., Celarc, B., Križnar, M., Renesto, S. & Tintori, A. 2010a: Scopolia; Kraljestvo Tetide, Revija Prirodoslovnega muzeja Slovenije, 5: 197 p.

Hitij, T., Tintori, A., Žalohar, J., Renesto, S., Celarc, B., Križnar, M. & Kolar-Jurkovšek, T. 2010b: New fossil sites with Triassic vertebrate fauna from the Kamnik-Savinja Alps, Slovenia. In Proceedings of International Symposium on Triassic and later Marine Vertebrate Faunas, Beijing: 42–46.

Hitij, T. 2012: Okostje triasnega pahiplevrozavra. National Geographic Slovenija, 2: 17.

Huang, Y., Chen, Z.-Q., Wignall, P.B. & Zhao, L. 2017: Latest Permian to Middle Triassic redox condition variations in ramp settings, South China: Pyrite framboid evidence. Bulletin of the Geological Society of Americ, 129/1-2: 229–243. https://doi.org/10.1130/B31458.1

Jenkyns, H.S. 1980: Cretaceous anoxic events: from continets to oceans. Journal of the Geological Society. 137: 171–188. https://doi.org/10.1144/gsjgs.137.2.0171

Laville, T., Hitij, T., Gašparič, R., Žalohar, J., Forel, M.B. & Charbonnier, S. 2022: The Triassic thylacocephalans from Slovenia: implications for their evolution and diversification. In Proceedings of 8th Symposium on Fossil Decapod Crustaceans, Zaragoza, 70-71.

Masetti, M. & Neri, C. 1980: L' Anisico della Val di Fassa (Dolomiti occidentali). Sedimentologia e Paleogeografia: Ann. Un. Ferrara, 7: 1–19.

Miklavc, P., Celarc, B. & Šmuc, A. 2016: Anisian Strelovec Formation in the Robanov kot, Savinja alps (Northern Slovenia). Geologija, 59/1: 23–34. https://doi.org/10.5474/geologija.2016.002

Mioč, P. 1983: Osnovna geološka karta SFRJ 1: 100.000. Tolmač za list Ravne na Koroškem. Zvezni geološki zavod, Beograd: 69 p.

Neri, C. & Stefani, M. 1998: Sintesi cronostratigrafica e sequenziale dell`evoluzione permiana superiore e triassica delle Dolomiti. Mem. Soc. Geol. It., 53: 417–463.

Parrish, J.M., Parrish, J.T. & Ziegler, A.M. 1986: Permian-Triassic paleogeography and paleoclimatology and implications for therapsid distribution. In: Hotton, N., MacLean, P.D., Roth, J.J. & Roth, C.E. (eds.): The ecology and biology of mammalian-like reptiles, Smithsonian Inst. Press: 109–131.

Piper, D. J. W. & Stow, D. A. V. 1991: Fine - grained turbidites. In: Einsele, G. & Seilacher, A. (eds.): Cyclic and Event Stratification: 360–376.

Placer, V. 2008: Principles of the tectonic subdivision of Slovenia. Geologija, 51/2: 205– 217. https://doi.org/10.5474/geologija.2008.021

Röhl, H.J., Schmid-Röhl, A., Furrer, H., Frimmel, A., Oschmann, W. & Schwark, L. 2001: Microfacies, geochemistry and palaeoecology of the Middle Triassic Grenzbitumenzone from Monte San Giorgio (Canton Ticino, Switzerland). Geol. Insubr., 6/1: 1–13.

Schmid, S.M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., Tischler, M. & Ustaszewski, K. 2008: The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. Swiss Journal of Geosciences, 101/1: 139–183. https://doi.org/10.1007/s00015-008-1247-3

Sander P.M. 1989: The pachypleurosaurids (Reptilia: Nothosauria) from the Middle Triassic of Monte San Giorgio (Switzerland) with the description of a new species. Phil. Trans. Roy. Soc. London, 325/1230: 561–670. https://doi.org/10.1130/B31458.1

Seidl, F. 1907/1908: Slovenska zemlja. Opis slovenskih pokrajin v prirodoznanskem, statističnem, kulturnem in zgodovinskem oziru. Peti del: Kamniške ali Savinjske Alpe, njih zgradba in lice. Poljuden geološki in krajinski opis. 1. zvezek. Matica Slovenska, Ljubljana.

Shanmugam, G. 2002: Ten turbidite myths. Earth-Science Reviews, 58: 311–341. https://doi.org/10.1016/S0012-8252(02)00065-X

Stampfli, G. M., Borel, G. D., Marchant, R. & Mosar, J. 2002: Western Alps geological constraints on western Tethyian reconstructions. In: Rosenbraun, G. & Lister, G. S. (eds.): Reconstruction of the evolution of the Alpine - Himalayan Orogen. Journal of the Virtual Explorer, 7: 75–104.

Stefani, M., Furin, S. & Gianolla, P. 2010: The changing climate framework and depositional dynamics of Triassic carbonate platforms from the Dolomites. Palaeogeography, Palaeoclimatology, Palaeoecology, 290: 43-57. https://doi.org/10.1016/j.palaeo.2010.02.018

Stockar, R. 2010: Facies, depositional environment, and palaeoecology of the Middle Triassic Cassina beds (Meride Limestone, Monte San Giorgio, Switzerland). Swiss J Geosci, 103: 101–119. https://doi.org/10.1007/s00015-010-0008-2

Stockar, R., Adatte, T., Baumgartner, P.O. & Föllmi, K.B. 2013: Palaeoenvironmental significance of organic facies and stable isotope signatures: the Ladinian san Giorgio Dolomite and Meride Limestone of Monte San Giorgio (Switzerland, WHL UNESCO). Sedimentology, 60: 239–269. https://doi.org/10.1111/sed.12021

Teller, F. 1898a: Eisenkappel und Kanker, Zone 20, Col. 11 (Geologische Spezialkarte der k. k. Österrichisch – Ungarischen Monarchie 5453, 1: 75 000). K. k. Geologische Reichsanstalt, Wien.

Tintori, A., Hitij, T., Jiang, D., Lombardo, C. & Sun, Z. 2014: Triassic actinopterygian fishes: the recovery after the end-Permian crisis. Integrative Zoology, 9: 394–411. https://doi.org/ 10.1111/1749-4877.12077

Sudiro, P. 2002: Carbonate slope deposites of the Contrin formation, Costabella area (Western dolomites, NE Italy). Mem. Soc. Geol. It., 57: 19–28.

Žalohar, J. & Hitij, T. 2013: Paleontološke raziskave v anizijskih plasteh strelovške formacije pod Vernarjem. Acta Triglavensia, znanstveno izobraževalni časopis, 2: 42.