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ORIGINAL ARTICLE

Middle Triassic radiolarite pebbles in the Middle Jurassic Hallstatt Mélange of the Eastern Alps: implications for Triassic–Jurassic geodynamic and paleogeographic reconstructions of the western Tethyan realm

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Abstract The microfacies and biostratigraphy of radiolarite and limestone components in mass-flow deposits from the upper Middle to lower Upper Jurassic Hallstatt Mélange were analyzed. The radiolarite components are of Late Anisian to early Late Ladinian age, the various colored limestone components are Late Triassic Hallstatt pelagics. All components are interpreted as derived from the continental slope towards the Neotethys Ocean (Meliata facies zone). A comparison with preserved successions from the Carpathians, the Pannonian realm, and the Dinarides is presented to strengthen this interpretation. Reworked oceanic crust is missing in the mass-flow deposits. The reconstructed Middle–Upper Triassic sedimentary succession documents the existence of Triassic radiolarites also in the distal passive margin setting of the Eastern Alps. The occurrence of Middle Triassic radiolarites can therefore no longer be used to attribute tectonically isolated units in the whole Circum-Pannonian realm to indicate either Alpine–Carpathian or Dinaride–Hellenide provenance. In addition, the occurrence of Middle Triassic radiolarites in the Jurassic mélanges is no proof for the existence of an ocean (e.g., Meliata Ocean). Middle Triassic radiolarites are a common sedimentary feature in the distal passive margin setting of the Neotethys. In contrast, Upper Triassic radiolarites are missing in the passive margin setting and were exclusively deposited on the ocean floor.

Keywords Northern Calcareous Alps · Mélange · Neotethys Ocean · Triassic radiolarians · Conodonts · Paleogeography

Introduction

Component analyses of conglomerates, breccia layers, or turbidite beds are a common tool in sedimentary geology. One classical approach is provenance analysis, the reconstruction of the source area from the clast spectrum of the re-sedimented rocks (Blatt 1967; Zuffa 1980, 1985; Lewis 1984). Whereas the detailed provenance analyses of siliciclastic material is common, provenance analyses of carbonate or radiolarite clasts in conglomerates or breccias remain rare. For reliable results, a macroscopic description of the incorporated clasts has to be combined with microfacies analyses (Flügel 2004) and age dating. Carbonate and radiolarite clasts should be dated by their microfossil content, if possible. Such analyses provide the possibility of an exact reconstruction about the provenance area. The proof of a single component may change plate tectonic and paleogeographic reconstructions substantially.

Triassic radiolarites are crucial sedimentary rocks for paleogeographic and geodynamic reconstructions of the Tethyan realm. They were deposited on the Neotethys passive margin and as sedimentary cover of the Neotethys oceanic crust, which has developed since the Upper Anisian (Gawlick et al. 2008; Ozsvárt et al. 2012). Radiolarites are typical sedimentary rocks (often accompanied with volcanics) of Late Anisian to Ladinian times in the Dinaride–Hellenide mountain chain (for a recent review, see Gawlick et al. 2012a). In contrast, radiolarites have not been reported from the Triassic sedimentary successions of the Alpine–Carpathian mountain belt.

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Middle Triassic radiolarite pebbles in the Middle Jurassic Hallstatt Mélange of the central Northern Calcareous Alps were first described by Gawlick (1993) and dated by the occurrence of multielements of the conodont genus *Gladigondolella*. Gawlick (1993) described the microfacies of these radiolarite pebbles. Kozur and Mock (1997) questioned the existence of Middle Triassic radiolarite clasts in the Salzburg Calcareous Alps and assigned the clasts to the Jurassic. They evoked unusual microfacies and contamination of the residue with conodont fragments from the accompanying limestone clasts.

Recently published paleogeographic maps for the Triassic–Jurassic (e.g., Csontos and Vörös 2004; Stampfli and Kozur 2006; Schmid et al. 2008; Missoni and Gawlick 2011a; Kovács et al. 2011) and the again controversially discussed Triassic–Jurassic geodynamic history in the Circum-Pannonian realm shows the strong need for a reinvestigation of this unique outcrop with biostratigraphic dating and accompanied microfacies analysis of different pebbles. The question: How many Triassic oceans? (Channell and Kozur 1997) in the Alpine/Carpathian and Dinaride/Hellenide mountain chains is still topical.

In this study, combined microfacies and radiolarian data of the radiolarite pebbles of the Lammer Basin fill (Strubberg Formation) in the central Northern Calcareous Alps (Fig. 1) are presented for the first time. Reinvestigation of the radiolarite clasts yielded poorly preserved Late Anisian to? Late Ladinian radiolarians. They occur in mass-flow deposits together with Upper Triassic Hallstatt Limestone clasts.

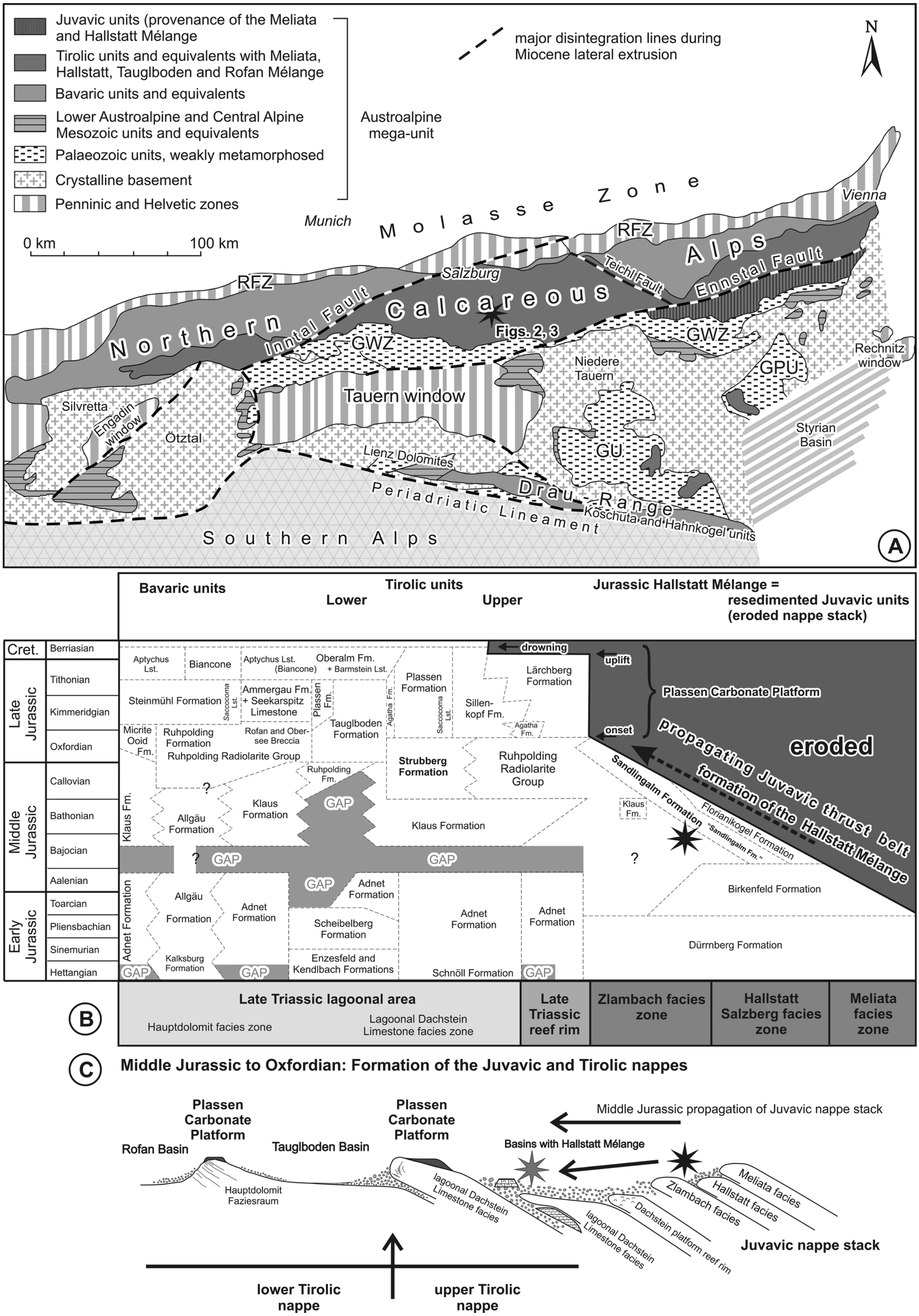
Triassic paleogeography: how many oceans and the Meliata problem—controversies

Radiolarite occurrence is widely used for the reconstruction of the provenance of "exotic" tectonic units (terranes in other terminology: Vozár et al. 2010), either of Alpine–Carpathian or Dinaride–Hellenide derivation (for latest review see Kovács et al. 2010, 2011). This resulted in contrasting paleogeographic maps for Triassic times: e.g., the reconstruction of an independent Meliata Ocean between the Alpine–Carpathian realm and the tectonic units in the Pannonian realm (Transdanubian Range, Bükk = Pelso Composite Terrane; Kovács et al. 2010) or the Eastern Alps/Pannonian realm and the Southern Alps/Dinarides, or in between the Dinarides (e.g., Stampfli and Kozur 2006). In other paleogeographic reconstructions, where the Eastern Alps and Western Carpathians should be the northern margin and the Southern Alps and Dinarides the southern margin of the Neotethys ocean, this facies characteristics, together with the structural vergence, is used as an argument to explain the paleogeographic provenance of the

Fig. 1 **a** Geological overview of the Eastern Alps (modified after ▶ Frisch and Gawlick 2003). The described locality Lammeregg is situated within the central part of the Northern Calcareous Alps south of Salzburg (indicated by a *star*). *GPU* Graz Paleozoic unit, *GU* Gurktal unit, *GWZ* Greywacke zone, *RFZ* Rhenodanubian Flysch zone. **b** Simplified stratigraphy of the Jurassic of the Northern Calcareous Alps with an overview of the common formation names according to Gawlick et al. (2009). In the text, discussed Jurassic formations are written in *bold letters*. Modified after Missoni and Gawlick (2011a, b). *Fm* formation, *Lst* limestone. The *star* indicates the depositional age and paleogeographic position of the studied mass-flow deposits. **c** Formation of the Middle to Early Late Jurassic Juvavic and Tirolic nappe stack. The *black star* indicates the original depositional area of the studied mass flows, later transported in a piggyback manner into the Strubberg Formation (*grey star*)

"Pelso Composite Terrane" in the Southern Alps/Dinarides area (for a recent review, see Kovács et al. 2011), later displaced by strike-slip movements. The time of this eastward movement of the "Pelso Composite Terrane" along strike-slip faults is controversial, and assigned by different authors to the Jurassic, Cretaceous, Paleogene, or Neogene. Today, an intra-Jurassic sinistral facies offset is favored following the model of Frank and Schlager (2006) (Kovács et al. 2011). In contrast, Lein et al. (1997) have documented a late Early Cretaceous onset of strike-slip tectonics of the different units of the Drau-Range and its easternmost continuation, the Transdanubian Range (Pelso unit). The model of Lein et al. (1997) fits with that the easternmost parts of the Pelso unit (including Meliata unit) were thrust over the West Carpathian Veporic units in the early Late Cretaceous (Plašienka et al. 1997). Therefore, in several paleogeographic reconstructions, a single ocean model with a more-or-less south–north-striking margin (Neotethys Ocean) is favored (for the latest review, see Missoni and Gawlick 2011a, b), and the existence of an independent oceanic realm between the Western Carpathians and the Pelso units resp. the Eastern Alps and the Southern Alps is rejected.

In the Alpine–Carpathian mountain chain, Triassic radiolarites are commonly inferred to derive exclusively from the Meliata Ocean (e.g., Kozur 1991; Mock et al. 1998). Rare occurrences of Middle Triassic radiolarites in a Middle Jurassic radiolaritic matrix, mainly in the southeastern Northern Calcareous Alps (Kozur and Mostler 1992; Mandl and Ondrejičková 1991, 1993; Mandl 1996) were interpreted as indicative for this oceanic realm (Meliata-Hallstatt Ocean). Gawlick et al. (1999) questioned the exclusive derivation of Middle Triassic radiolarites from the Neotethys ocean floor and attributed Middle Triassic radiolarites (if they are associated with Anisian shallow-water carbonates and/or Late Triassic open-marine limestones) as originally deposited in the most distal passive margin setting, which is on the continental slope towards the Neotethys. This resulted in the need of a redefinition of the controversial term "Meliata" (Kozur et al. 1996; Mello et al.


Juvavic units (provenance of the Meliata and Hallstatt Mélange
Tirolic units and equivalents with Meliata, Hallstatt, Tauglboden and Rofan Mélange
Bavaric units and equivalents
Lower Austroalpine and Central Alpine Mesozoic units and equivalents
Palaeozoic units, weakly metamorphosed
Crystalline basement
Penninic and Helvetic zones
Austroalpine mega-unit
major disintegration lines during Miocene lateral extrusion
N
0 km
100 km
Munich
Molasse Zone
Vienna
RFZ
Salzburg
Northern Calcareous Alps
Inntal Fault
Teichl Fault
Ennstal Fault
Figs. 2, 3
GWZ
Niedere Tauern
GPU
Rechnitz window
Tauern window
Silvretta
Engadin window
Ötztal
Lienz Dolomites
GU
Styrian Basin
Drau Range
Periadriatic Lineament
Koschuta and Hahnkogel units
Southern Alps
A
Bavaric units
Tirolic units
Lower
Upper
Jurassic Hallstatt Mélange = resedimented Juvavic units (eroded nappe stack)
Cret.
Berriasian
Late Jurassic
Tithonian
Kimmeridgian
Oxfordian
Middle Jurassic
Callovian
Bathonian
Bajocian
Aalenian
Early Jurassic
Toarcian
Pliensbachian
Sinemurian
Hettangian
Aptychus Lst.
Biancone
Aptychus Lst. (Biancone)
Oberalm Fm. + Barmstein Lst.
Plassen Formation
drowning
uplift
Lärchberg Formation
Plassen Carbonate Platform
Steinmühl Formation
Saccocoma Lst.
Ammergau Fm. + Seekarspitz Limestone
Plassen Fm.
Agatha Fm.
Tauglboden Formation
Saccocoma Lst.
Sillenkopf Fm.
Agatha Fm.
onset
eroded
propagating Juvavic thrust belt formation of the Hallstatt Mélange
Micrite Ooid Fm.
Ruhpolding Formation
Rofan and Obersee Breccia
Ruhpolding Radiolarite Group
Strubberg Formation
Ruhpolding Radiolarite Group
Sandlingalm Formation
Florianikogel Formation
"Sandlingalm Fm."
Ruhpolding Fm.
Klaus Fm.
Allgäu Formation
Klaus Formation
GAP
Klaus Formation
Klaus Fm.
?
Birkenfeld Formation
Adnet Formation
Allgäu Formation
Adnet Formation
Adnet Formation
Scheibelberg Formation
Adnet Formation
Adnet Formation
Dürrnberg Formation
Kalksburg Formation
Enzesfeld and Kendlbach Formations
Schnöll Formation
Late Triassic lagoonal area
Hauptdolomit facies zone
Lagoonal Dachstein Limestone facies zone
Late Triassic reef rim
Zlambach facies zone
Hallstatt Salzberg facies zone
Meliata facies zone
B
C
Middle Jurassic to Oxfordian: Formation of the Juvavic and Tirolic nappes
Plassen Carbonate Platform
Plassen Carbonate Platform
Middle Jurassic propagation of Juvavic nappe stack
Rofan Basin
Tauglboden Basin
Basins with Hallstatt Mélange
Hauptdolomit Faziesraum
lagoonal Dachstein Limestone facies
lagoonal Dachstein Limestone facies
Dachstein platform reef rim
Zlambach facies
Hallstatt facies
Meliata facies
Juvavic nappe stack
lower Tirolic nappe
upper Tirolic nappe

1997; Kozur and Mock 1997; Csontos 2006): The Meliata unit consists of different tectonic units, metamorphosed (Bôrka unit) and slightly or non-metamorphosed units (Meliata unit s. str.), tectonic and sedimentary mélanges. Mock et al. (1998) reinvestigated the Meliata-type locality and documented the olistostromal character of the type section. Kovács et al. (2010, 2011) redefined the term Meliata as corresponding to a distinct facies belt in Triassic–Jurassic times regardless of the recent tectonic position or metamorphic overprint. For the type area in the Western Carpathians, the term Meliaticum (as a tectonic collage) should also include oceanic material and still several tectonic units were integrated: Bôrka, Meliata s. str., and Jaklovce. As a consequence, Aubrecht et al. (2010, 2012) started to distinguish the terms Meliata Facies Zone for the Triassic–Jurassic facies belt of the Neotethys passive margin before its tectonic incorporation in the Middle Jurassic accretionary prism and the term Meliata Mélange for the tectonically dismembered Meliata facies belt, including the oceanic domain and the Jurassic basin fills in front of the advancing nappe pile. The term Meliata Mélange includes mélanges of both sedimentary and tectonic origin, in parts with a Middle to Late Jurassic metamorphism (Maluski et al. 1993; Faryad and Henjes-Kunst 1997). In the type section at Meliata, only reworked material from the Meliata Facies Zone occurs: indicative blocks and pebbles are Anisian shallow-water limestones, Late Anisian to Ladinian radiolarites, and Carnian dark grey strongly recrystallized limestone clasts, all in a Middle Jurassic dark grey argillaceous-radiolaritic matrix. All pebbles and blocks derive from the distal passive margin, the Meliata Facies Zone; mass flows and some tens of meters-big Triassic blocks in a Middle Jurassic argillaceous-radiolaritic matrix (Kozur et al. 1996; Mock et al. 1998) clearly document a sedimentary origin. According to the age of the matrix and the facies characteristics of the pebbles of the type section, the Meliata Basin is one of the first basins formed in front of the newly formed nappe stack of the propagating obducting ophiolite nappe stack.

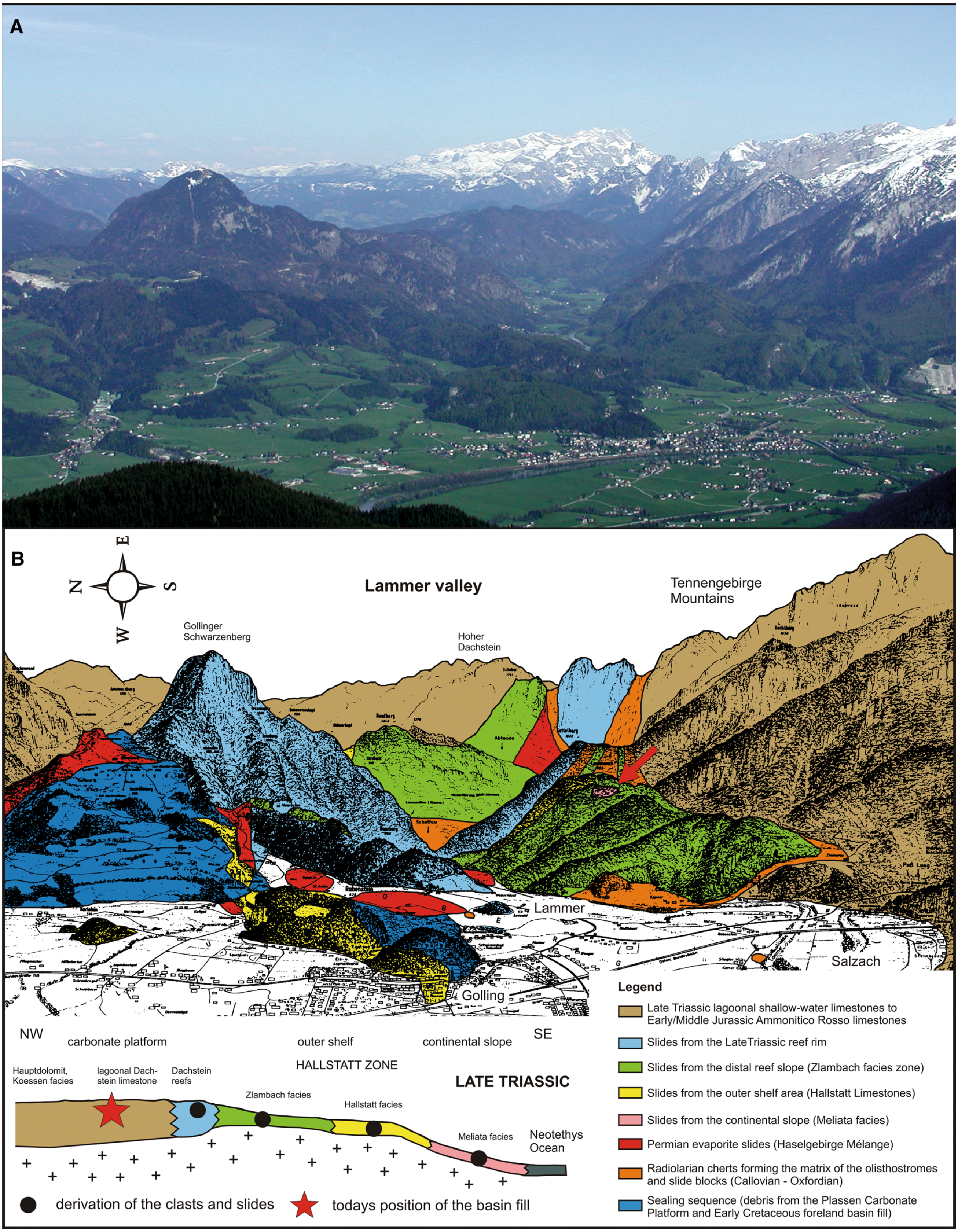
In the Northern Calcareous Alps, the equivalent of the Meliata Mélange is defined as the Hallstatt Mélange, which accumulated in a series of trench-like basins formed in front of the advancing nappe pile (Frisch and Gawlick 2003; Missoni and Gawlick 2011b). The Jurassic sedimentary basin corresponding to the Meliata Basin is defined as the Florianikogel Basin (Gawlick et al. 2009 for latest review). In the Northern Calcareous Alps, different basins were distinguished. Based on their matrix ages and their reworked component spectrum, a propagating nappe front can be inferred (see Gawlick et al. 2012b for the latest review). The distinction of different basins has been missing in the Meliata unit until now. This underlines the need for further detailed investigations of the Meliata Mélange in its wider

Fig. 2 **a** View from the west showing the Lammer Basin fill (Gawlick 1996; Gawlick et al. 2012b). **b** Geological interpretation of the landscape picture. The basin fill consists of allochthonous material of different age and facies provenance, which generally derives from the outer shelf area transitional to the Neotethys Ocean. Reconstruction of the Triassic shelf configuration after Gawlick et al. (1999) with derivation of the pebbles and slide blocks. The studied locality is marked by a *red arrow* ▶

type area. Only a complete revision of all occurrences attributed to the Meliata unit in the Western Carpathians will allow (a) a detailed reconstruction of the Jurassic orogeny and (b) a reconstruction of the younger polyphase tectonic motions, which scattered the Jurassic paleogeography.

Geological setting

The studied locality is situated in the western peak area (area around 013°12′32″E, 47°34′52″N; WGS84) of Mount Lammeregg in the central Northern Calcareous Alps. Mount Lammeregg is a kilometer-sized slide block in the Callovian–Oxfordian Lammer Basin fill (Figs. 2, 3) and belongs to the Strubberg Formation (Fig. 1b) (for details see Gawlick 1996; Gawlick and Suzuki 1999). The block consists of Upper Triassic Pötschen dolomite and limestone with reefal debris (for details see Gawlick 1996, 1998) and originated from the Zlambach Facies Zone (Fig. 2b). On top of this km^2-sized block, exotic mass flows are preserved. They consist of components of Middle Triassic shallow-water limestones, Middle Triassic radiolarites, and Upper Triassic Hallstatt Limestones. These mass flows were deposited during early basin formation in the Zlambach Facies Zone. Later they were transported in a piggyback manner to their final, secondary position within the Lammer Basin. There, they are covered by younger mass-flow deposits of the Lammer Basin fill. As resedimentation in the Lammer Basin started in the Late Callovian and culminated in the Early Oxfordian (details in Gawlick et al. 2009), the transported mass flows on top of Mount Lammeregg are older but cannot be exactly dated. Mass flows, which consist exclusively of reworked Hallstatt Limestone material in a radiolarite matrix, occur in the nearby Salzkammergut region to the east. There Gawlick et al. (2007) distinguished the older Sandlingalm Basin around Mount Sandling with the Sandlingalm Formation as the basin fill (Fig. 1b). In the type region of the Sandlingalm Basin, resedimentation started in the Early Callovian and prevailed until the Middle Oxfordian (Gawlick et al. 2007; cf. Mandl 2013). Gawlick et al. (2009) redefined the Sandlingalm Formation as a series of basin fills formed in sequence in front of the propagating Hallstatt nappes (for details, see Missoni and Gawlick 2011b). The reworked material in these basin fills derived exclusively from Hallstatt


A
B
N
E
S
W
Lammer valley
Tennengebirge Mountains
Gollinger Schwarzenberg
Hoher Dachstein
Lammer
Salzach
Golling
NW
carbonate platform
outer shelf
continental slope
SE
HALLSTATT ZONE
LATE TRIASSIC
Hauptdolomit, Koessen facies
lagoonal Dachstein limestone
Dachstein reefs
Zlambach facies
Hallstatt facies
Meliata facies
Neotethys Ocean
derivation of the clasts and slides
todays position of the basin fill
Legend
Late Triassic lagoonal shallow-water limestones to Early/Middle Jurassic Ammonitico Rosso limestones
Slides from the LateTriassic reef rim
Slides from the distal reef slope (Zlambach facies zone)
Slides from the outer shelf area (Hallstatt Limestones)
Slides from the continental slope (Meliata facies)
Permian evaporite slides (Haselgebirge Mélange)
Radiolarian cherts forming the matrix of the olisthostromes and slide blocks (Callovian - Oxfordian)
Sealing sequence (debris from the Plassen Carbonate Platform and Early Cretaceous foreland basin fill)

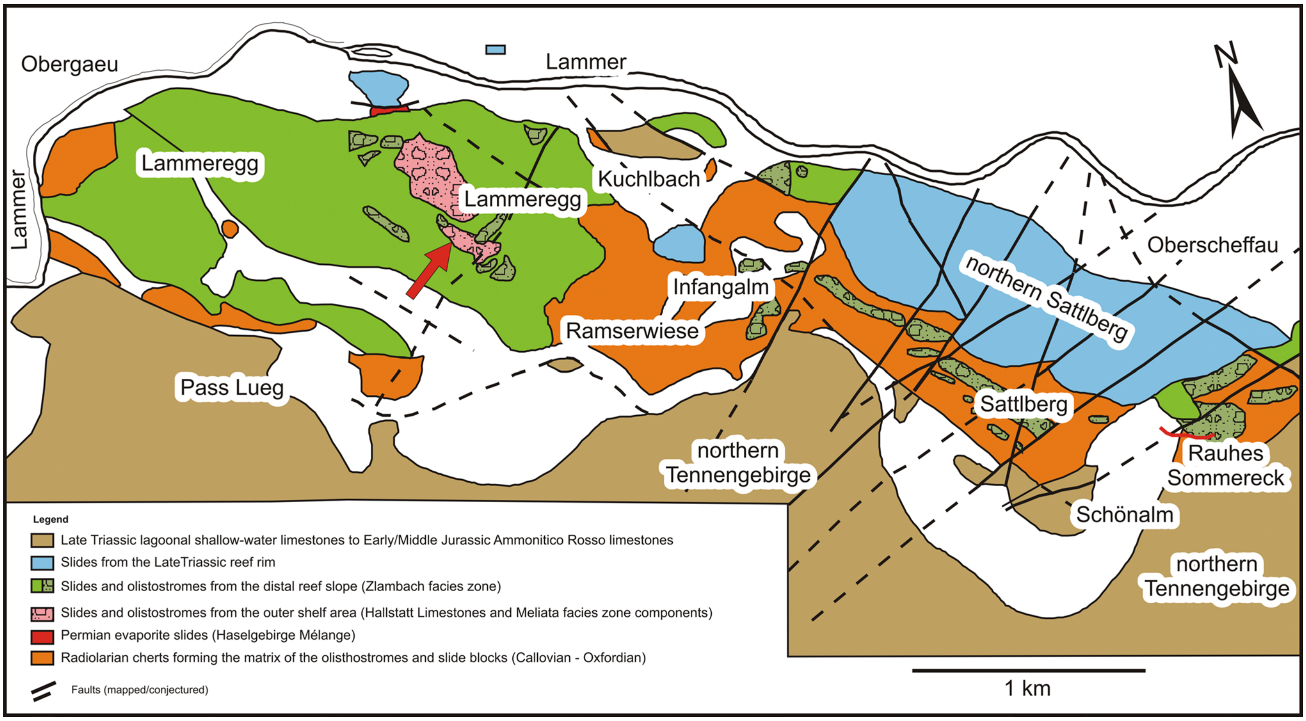


Fig. 3 Geological map of the study area (modified after Gawlick 1996). The studied mass flows are indicated by the *red arrow*

Limestone. More southward, in the Bad Mitterndorf area, O'Dogherty et al. (2015) dated the onset of resedimentation of Hallstatt Limestone blocks as Late Bajocian to Bathonian. However, Triassic radiolarite clasts were previously not recognized in the Salzkammergut region, indicating that Middle Triassic radiolarite intercalations do not exist in the distal shelf sedimentary successions (Hallstatt facies). In the Late Anisian to Ladinian, various colored Hallstatt Limestones were deposited (Krystyn 2008). From the presence of radiolarite, it can be concluded that the mass flows on top of Mount Lammeregg represent a very early phase of contraction and basin formation, at least older than Late Bajocian–Bathonian.

The polymictic mass flows (Fig. 4) directly overlie the sedimentary succession of the km^2-sized Lammeregg block. Radiolarite components are very rare and in most cases 1–2 cm in size. Grey and reddish Hallstatt Limestone clasts are dominating. First investigations of the bigger Hallstatt Limestone blocks on top of Mount Lammeregg were carried out by Häusler (1981), who recognized a Late Triassic age (Middle Carnian, Late Carnian, Early Norian) for the Hallstatt Limestones.

Materials and methods

Radiolarite and limestone pebbles were sampled from different localities of the mass flows on top of Mount Lammeregg. Radiolarite pebbles a few centimeters in size and appropriate frequency for sampling occur only in distinct places. The radiolarite clasts were isolated from the grain-supported breccias by dissolving the limestone clasts and the scarce matrix in acetic acid. Conodonts from the limestone clasts were also extracted with this procedure. The remaining radiolarite samples were processed in diluted (3 %) hydrofluoric acid.

Results

Radiolarite pebbles: radiolarian dating and microfacies

Around 20 radiolarite clasts were processed, but only two radiolarite pebbles yielded a few identifiable radiolarians. The preservation of radiolarians is mostly very poor, and rare specimens could be identified at the species level (Fig. 5). The sample B385 yielded Late Anisian to early Ladinian radiolarians, based on the shape of the two specimens of *Pseudostylosphaera* (Dumitrica, pers. comm.). The sample B389 yielded early Late Ladinian (early Longobardian) radiolarians, based especially on the occurrence of the radiolaria species *Muelleritortis firma* (Kozur 2003; O'Dogherty et al. 2010).

The microfacies of the radiolarites is poorly preserved (Fig. 6), and very often the pebbles are strongly or completely recrystallized. The preservation of the radiolarians

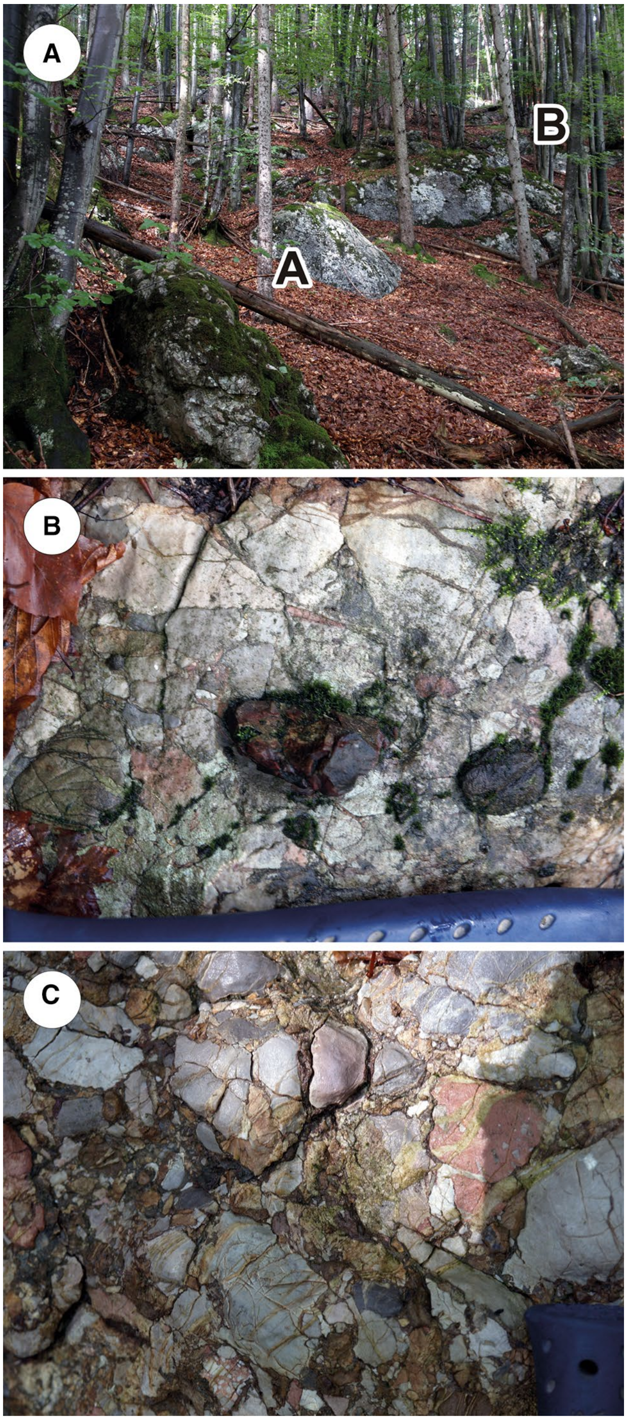


Fig. 4 Macroscopic appearance of the coarse-grained breccias on top of Mount Lammeregg. **a** Field view of the mass-flow deposit. **b** *Reddish-violet* and *greyish* Middle Triassic radiolarite pebbles together with *red* and *grey* Hallstatt Limestone pebbles. The pebble size in this matrix-free poorly sorted breccia is up to 8 cm. **c** Poorly sorted breccia of different Late Triassic *red* and *grey* Hallstatt Limestone clasts and a few 1–2-cm-sized radiolarite clasts. Some components represent an older breccia stage, again reworked. The matrix consists of a fossil-free *yellowish-grey* marl

is therefore very poor in the pebbles (Fig. 5). In some cases, filament-rich greyish-greenish to blackish or reddish-violet radiolarites (Fig. 6a–d), as typical for the Late Anisian (cf. Gawlick et al. 2012a), occur. The reddish-violet to greyish filament-free radiolarites (Fig. 6e, f) are more typical in the Ladinian (compare Kozur and Mock 1997).

Hallstatt Limestone pebbles: conodont dating and microfacies

The microfacies of the Upper Triassic Hallstatt Limestone pebbles (Fig. 7), dated by conodonts (Gawlick 1993, 1996; Tab. 1), resemble in each stratigraphic interval the known microfacies of the Hallstatt Limestone succession of the outer shelf region (Hallstatt facies) (Gawlick and Böhm 2000; Gawlick et al. 2012b). The limestones are richer in radiolarians, filaments, and small ammonoids, suggesting that the whole resedimented succession derived originally from a more condensed depositional realm (compare Krystyn 1980).

The known (partly revised) and some new biostratigraphic data (samples B382–B384) are summarized in Table 1. Based on these dates and microfacies attributes, the pebbles are assigned to the established lithostratigraphic Hallstatt Limestone nomenclature.

Reconstruction of the sedimentary succession

Age dating and microfacies characteristics of the radiolarite and limestone pebbles from the mass flows on top of Mount Lammeregg allow reconstructing a complete Middle to Late Triassic sedimentary succession (Fig. 8). Middle Anisian shallow-water Steinalm Formation clasts, Late Anisian/Early Ladinian, and early Late Ladinian radiolarite pebbles allow to infer “platform” drowning and then a continuous radiolarite deposition from the Illyrian to the early Longobardian. Conodont faunas from this time interval are missing. The accompanying greenish volcanic clasts are interpreted as relics of the Late Anisian volcanism. Limestone deposition started most probably in the Late Ladinian (Late Longobardian) and prevailed until the Early Rhaetian, as proven by conodonts (see Table 1). The Rhaetian Zlambach Formation is proven with foraminifera and marlstone clasts.

This sedimentary succession resembles the known sedimentary successions from the outer shelf region, the continental slope transitional to the oceanic realm, and the oceanic realm near to the continental slope (see chapter "Discussion"). The occurrence of Rhaetian Zlambach Formation pebbles excludes a southern, e.g., Dinaric, provenance (Krystyn 2008).

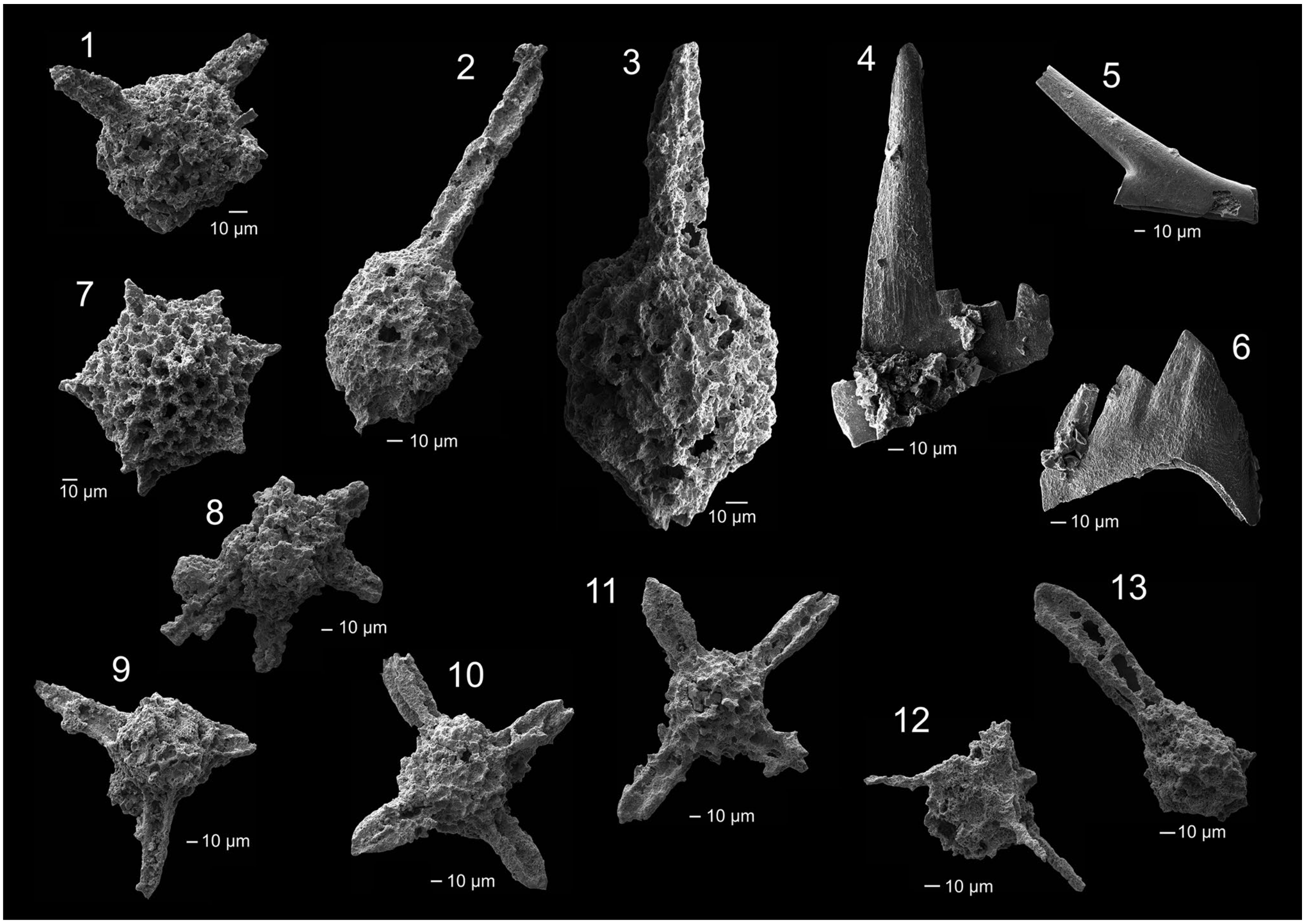


Fig. 5 Radiolarians and conodonts from the Late Anisian to lower Upper Ladinian radiolarite pebbles. *1*, *Hexatortilisphaera* ? sp.; *2*, *Pseudostylosphaera* sp.; *3*, *Pseudostylosphaera* sp.; *4–6*, *Gladigondolella* multielements sensu Kozur and Mostler (1972); *7*, *Pessagnollum* sp. (*1–7* from sample B385); *8*, *Relindella* cf. *symmetrica* (Dumitrica, Kozur and Mostler); *9*, *Cryptostephanidium* cf. *cornigerum* Dumitrica; *10–11*, *Muelleritortis firma* (Gorican); *12*, *Pentactinocarpus tetracanthus* Dumitrica; *13*, *Pseudostylosphaera imperspicua* (Bragin) (*8–13* from sample B389)

Discussion

The lithostratigraphy of the Hallstatt Limestone succession is based on Schlager (1969), Mandl (1984), Krystyn (1980, 2008), and Lein (1987), modified after Gawlick and Böhm (2000), Missoni and Gawlick (2011a), and Gawlick et al. (2012b). Based on bedding type, color, and fossil content, several lithostratigraphic units have been distinguished in the Hallstatt facies (Krystyn 2008; Tab. 1). The litho- and microfacies of these units were controlled by the same environmental/tectonic factors and are thus correlative across the entire shelf, e.g., lithology, microfacies, thickness, and color reflect sea-level changes (in cases also tectonics) and therefore platform progradation (with highstand shedding, grey color, high sedimentation rate), aggradation and emergence (condensation in the basin, reddish colors, low sedimentation rate) (details in Gawlick and Böhm 2000). This type of sedimentary rocks represents the "normal" Hallstatt Limestone sequences (Krystyn 2008): The thickness of the different lithostratigraphic units decreases from proximal to more distal shelf areas and filaments and radiolarians become more frequent. The other Hallstatt Limestone type is rich in cephalopod faunas and extremely condensed. Both types occur together in the Jurassic mélanges at least between the Alps and the Oman Mountains (Krystyn 2008). These characteristics of the individual lithostratigraphic units can be recognized very much in detail even if only small clasts of these units are preserved (Table 2).

The Hallstatt Limestone sequence from the Middle Anisian to the Rhaetian reflects the carbonate production in the shallower, but distal shelf areas. After the drowning of the Steinalm ramp in late Middle Anisian, condensed open-marine limestones are typical (Sudar et al. 2013 for latest review). Condensation prevailed more or less until the Late Ladinian; only around the Anisian/Ladinian boundary a short interval with shallow-water

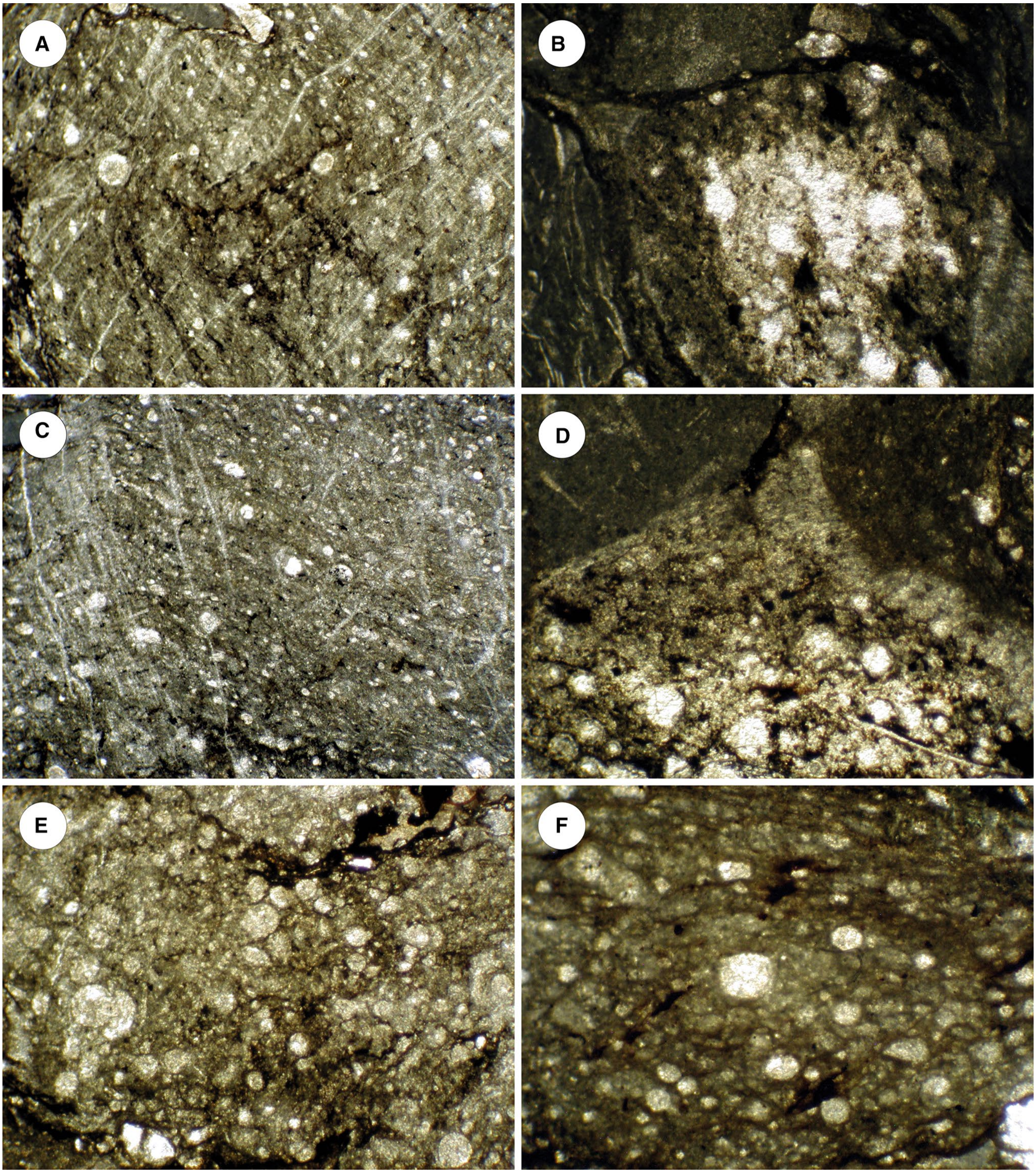
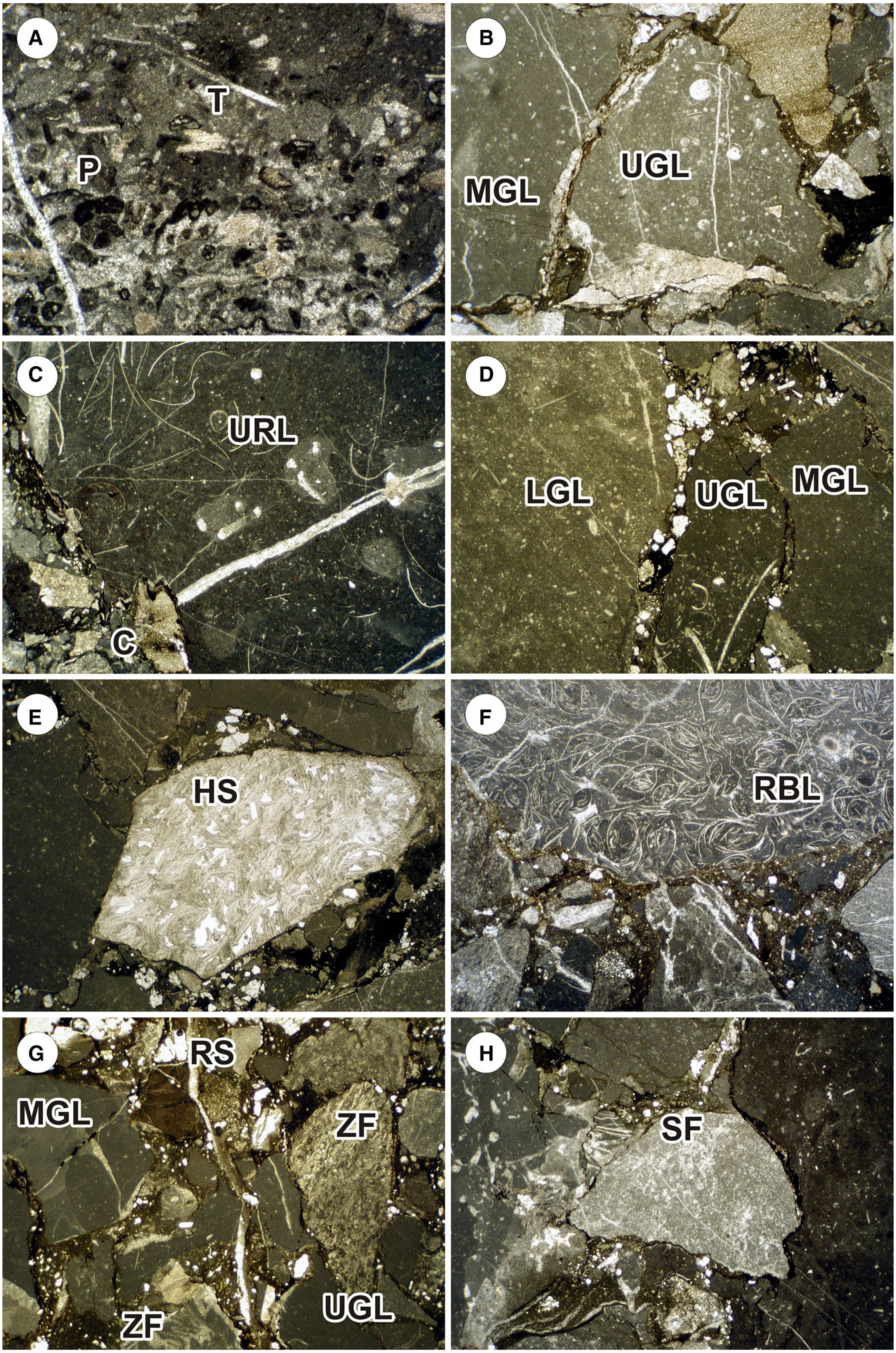


Fig. 6 Characteristic microfacies of the Middle Triassic (Upper Anisian to Upper Ladinian) radiolarite pebbles. **a** *Greyish* radiolarite radiolarian wackestone with some recrystallized spherical radiolarians and some filaments, sample B383-1. Width: 0.5 cm. **b** *Greyish-violet* radiolarite strongly recrystallized radiolarian packstone without filaments. Left filament-rich Late Triassic Hallstatt Limestone. Sample B384-1. Width: 0.25 cm. **c** *Grey* radiolarite radiolarian wackestone with strong recrystallization. Sample B383-2. Width: 0.5 cm. **d** *Greyish-violet* radiolarite strongly recrystallized radiolarian packstone with few filaments. The whole rock sample shows strong certification. Sample B384-2. Width: 0.5 cm. **e** *Violet* radiolarite recrystallized radiolarian packstone. Sample B383-2. Width: 0.25 cm. **f** Clay-rich *greyish-black* radiolarite radiolarian wackestone with recrystallized radiolarians. Sample L17-2. Width: 0.25 cm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◂ **Fig. 7** Microfacies of the different pebbles of the Meliata facies zone succession: Steinalm Formation, Hallstatt Limestone, and Zlambach Formation pebbles. **a** Basal Zlambach Formation: resedimented limestones in marls with shallow-water material including foraminifera: (*T*) *Tetrataxis inflata* Kristan; (*P*) *Planiinvoluta* sp. Sample L15a. Width: 0.5 cm. **b** Ammonoidea in radiolarian-rich *upper grey* limestone (*UGL*) clast, *left* a massive *grey* limestone (*MGL*) clast. The smaller clasts are not exactly determinable. Sample B383-1. Width: 1.4 cm. **c** *Upper red* limestone (*URL*) clast, rich in filaments and with some Ammonoidea. The crinoid (*C*) seems part of the matrix. Sample B383-3. Width: 1.4 cm. **d** Polymictic and poorly sorted breccia consisting of different *grey* limestone clasts: *upper grey* limestone (*UGL*), massive grey limestone (*MGL*), and lower grey limestone (*LGL*). Sample B382-1. Width: 1.4 cm. **e** Characteristic clast of the Early Norian *Halobia styriaca* lumachelle (*HS*), quite typical in every Late Triassic Hallstatt Limestone succession. Sample B382-2. Width: 0.5 cm. **f** Poorly sorted grain supported breccia. *Halobia*-rich condensed *reddish-grey* limestone clast of the *Upper* Carnian *red-bedded* limestone (*RBL*). The matrix consists of a reddish fossil-free marl. **g** Poorly sorted grain-supported breccia with brownish components of the Reingraben shale (*RS*). Other components are from the Zlambach Formation (*ZF*), *upper grey* limestone (*UGL*), massive *grey* limestone (*MGL*). Sample L17. Width: 1.4 cm. **h** Polymictic breccia of different Late Triassic Hallstatt Limestone components with a clast of the *Middle* Anisian shallow-water Steinalm Formation (*SF*). Sample B382a. Width: 0.5 cm

carbonate production can be recognized. In the Late Ladinian, the Wetterstein Carbonate Platform cycle started. During the Late Ladinian to early Middle Carnian, this platform exported an enormous amount of micrite to the outer shelf region: A massive light limestone with strong bioturbation is typical. This limestone evolved in the Late Ladinian from radiolarian-rich various-colored micritic limestones, cherty limestones, or radiolarites. The demise of the Wetterstein Carbonate Platform in the Middle Carnian resulted in condensed sequences in the outer shelf area, in parts siliciclastic. The Middle Carnian Reingraben or *Halobia* shales are the basinal equivalent to the siliciclastics of the Lunz/Raibl event in the proximal shelf area. In the Late Carnian, carbonate production again started and culminated in the enormous productive Hauptdolomit/Dachstein Limestone Carbonate Platform with its stepwise drowning from Late Norian/Early Rhaetian onwards (details in Richoz et al. 2012). The Late Carnian red-bedded limestone is thin bedded, often greyish-reddish, and partly strongly condensed. The Early Norian massive light limestone is thick bedded to massive and bioturbated. The Middle Norian upper red limestone is nodular, thin bedded, bioturbated, and condensed. The Late Norian–Early Rhaetian upper grey limestone is massive, thick to thin bedded, often strongly bioturbated. The Rhaetian Zlambach Formation is characterized by a relative thick dark-grey marly sequence, near its base with layers (turbidites) of resediments from a shallow-water area. The Zlambach marls are a characteristic feature of the Alpine/Carpathian realm and are missing in the Dinarides/Hellenides (compare Krystyn 2008).

Similar Triassic sedimentary successions, as reconstructed here for the mass flows on top of Mount Lammeregg in the central Northern Calcareous, are rare in the Alpine–Carpathian–Dinaride mountain belt. The Neotethyan distal passive margin was incorporated in the Middle Jurassic nappe stack of the Neotethyan orogeny (Missoni and Gawlick 2011b) and the sedimentary successions are usually eroded. Only pebbles or larger slide blocks are preserved in the Jurassic mélanges. In a few cases, complete sequences with a longer stratigraphic range are preserved in bigger slide blocks or nappes, which can be compared in their overall sedimentary evolution with the reconstructed sedimentary succession of Mount Lammeregg (Figs. 9, 10).

Vodena Poljana in southwest Serbia (1 in Figs. 9, 10: data from Gawlick et al. 2010; Stanzel 2015): In the area of Vodena Poljana (Zlatar Mountains), south of Nova Varoš, several radiolarite and Hallstatt Limestone blocks occur in a Middle Jurassic radiolaritic matrix. Besides radiolarite and limestone pebbles in different mass-flow deposits, kilometer-sized blocks are also preserved. The bigger blocks consist of relatively complete sedimentary successions, partly overlapping in their stratigraphy. In Vodena Poljana, the sedimentary succession starts with shallow-water Anisian Steinalm Limestone, followed by Pelsonian to early Illyrian red nodular limestones (Schreyeralm/Bulog Limestone). In the relatively thin reddish radiolarites on top of the Bulog Limestone, an Illyrian age is proven by means of radiolarians (Stanzel 2015), which may extend to the Early Ladinian. Early Ladinian grey limestone is overlain by Late Ladinian grey cherty limestones, sometimes with intercalated tuff layers and also with fine-grained resedimented shallow-water debris in the Late Ladinian to? Early Carnian. Middle Carnian is not proven (compare section Canj bay). Reddish-grey nodular limestones are typical of the Late Carnian (Tuvalian), a massive grey limestone occurs in the Early Norian (Lacian) and a red nodular limestone in the Middle Norian (Alaunian). Rhaetian is not proven so far.

Canj bay (road) in the central Budva Zone (2 in Figs. 9, 10: data from Missoni et al. 2014): The preserved complete succession starts with Late Anisian to Ladinian dark grey radiolarites. In the Late Ladinian, radiolarite deposition passed to the open-marine Hallstatt pelagic limestones of Late Ladinian to Early Norian age: In the Late Ladinian–Early Carnian, a reddish-grey nodular limestone was deposited. A Middle Carnian terrigenous interval is missing; instead a long-lasting Middle to early Late Carnian gap occurs. Reddish-grey limestones were deposited in the middle Late Carnian to earliest Norian, followed by Early Norian greyish thick bedded to massive greyish limestones.

A Middle Carnian terrigenous interval is missing; instead, a long-lasting Middle to early Late Carnian gap

Table 1 Biostratigraphic ages from the Hallstatt Limestone samples of the mass flows on top of Mount Lammeregg

Lithostratigraphic name/formation	Conodonts/Foraminifera (Gawlick 1993) revised	This paper (samples B382–B384)	Age
Zlambach Formation	Gawlick (1996): Foraminifera		Rhaetian 2–(3)
Hangendgraukalk (upper grey limestone)		*Epigondolella bidentata* (Mosher)	Late Norian (Sevatian) to Early Rhaetian
Hangendrotkalk (upper red limestone)	*Epigondolella slovakensis* (Kozur); *Epigondolella abneptis* s. str. (Huckriede), *Norigondolella steinbergensis* (Mosher)		Middle Norian (Alaunian 2–3) and Middle Norian (Alaunian 1–2)
Massiger Hellkalk (massive light limestone)	*Norigondolella navicula* (Huckriede), *Epigondo-lella triangularis* (Budurov), *Epigondolella rigoi* (Kozur) (several samples), *Epigondolella primitia* (Mosher)	*Norigondolella navicula* (Huckriede)	Early Norian (Lacian 1 and Lacian 2)
Roter Bankkalk (red-bedded limestone)	*Paragondolella polygnathiformis* (Budurov & Stefanov), *Paragondolella nodosa* (Hayashi)	*Paragondolella polygnathiformis* (Budurov & Stefanov), *Paragondolella carpathica* (Mock)	Late Carnian (Tuvalian 3) and Late Carnian (Tuvalian 2)
Reingraben Shale	*Metapolygnathus* aff. *carnica* Krystyn, *Gladi-gondolella tethydis* (Huckriede), *Paragondolella polygnathiformis* (Budurov & Stefanov)		"Middle" Carnian (Julian)
Hellkalk (lower grey limestone)	*Gladigondolella tethydis* Huckriede, *Paragondolella polygnathiformis* (Budurov & Stefanov)	*Gladigondolella tethydis* (Budurov & Stefa-nov), *Gladigondolella*-ME sensu Kozur & Mostler	Late Ladinian to Early Carnian

Lithostratigraphic names/formation after Krystyn (2008)

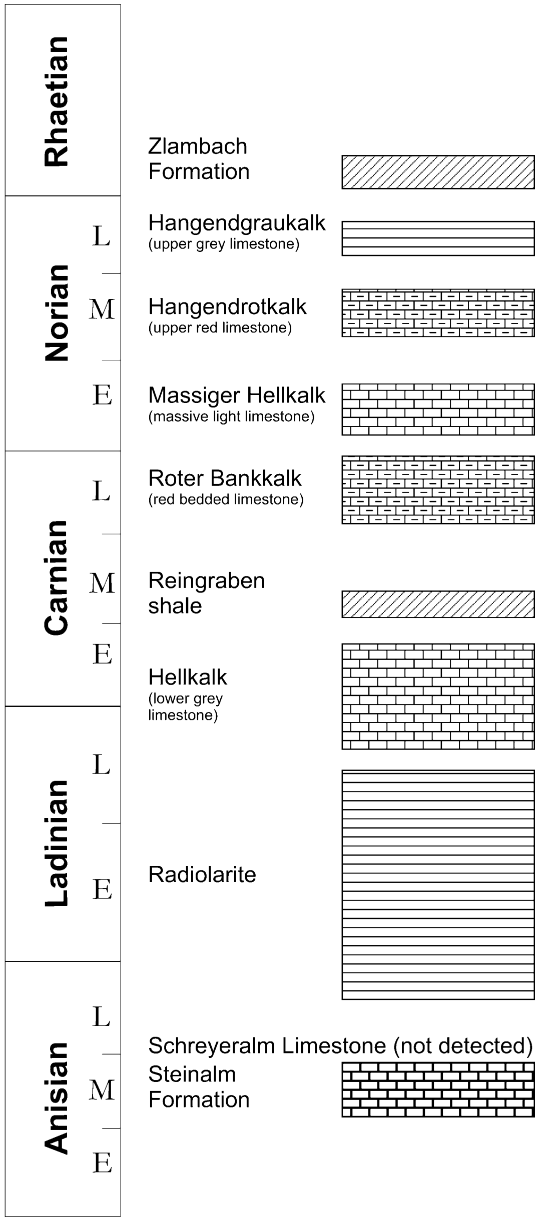

Fig. 8 Reconstruction of the eroded and reworked Middle–Late Triassic sedimentary succession of the Meliata facies zone from components of the mass flows on top of Mount Lammeregg

occurs. The Hallstatt Limestone succession near Canj resembles the Hallstatt Limestone succession elsewhere in the Alpine/Carpathian/Dinaride realm. The Canj Hallstatt Limestone succession was deposited between the Vodena Poljana and Bódvalenke Hallstatt Limestone successions. We thus interpret the depositional realm of the Budva Zone/Montenegro as part of the passive margin facing the Neotethys Ocean to the east (east of the Dinaric platform). In contrast, most authors think that the Budva Basin was a rim basin situated west of the Dinaric platform (e.g., Črne et al. 2011).

Table 2 Biostratigraphic ages from the Bodvalenke section (3 in Fig. 10; Hungary); (1–7) own samples in addition to the known ages from the literature, in parts with different results

Lithostratigraphic name/formation	Sample no.	Conodonts	Age
Red-grey massive limestone; Roter Bankkalk (red-bedded limestone)	(7) KA 817	*Paragondolella polygnathiformis* (Budurov & Stefanov), *Paragondolella carpathica* (Mock)	Tuvalian 2
Red nodular limestone, bedded; Roter Bankkalk (red-bedded limestone)	(6) KA149 and KA 150	*Paragondolella polygnathiformis* (Budurov & Stefanov), *Paragondolella carpathica* (Mock)	Tuvalian 2
Violet limestone bed in reddish-brownish cherty claystone as equivalent of the Reingraben shale	(5) KA 147	Gladigondolella sp., *Paragondolella foliata* (Budurov), *Paragondolella polygnathiformis* (Budurov & Stefanov)	Julian
Base of the 5-m-thick ammonoid-rich grey limestone; Hellkalk (lower grey limestone)	(4) KA 144	*Gladigondolella tethydis* (Budurov & Stefanov), *Gladigondolella*-ME sensu Kozur & Mostler, *Budurovignathus praehungaricus* (Kovács)	Longobardian 1
Red limestone layer in reddish radiolarite 3 m below the ammonoid-rich grey limestone	(3) KA 143 and Kovács	*Gladigondolella tethydis* Huckriede, *Paragondolella trammeri* (Kozur), *Paragondolella inclinata* (Kovács)	Longobardian 1
Red-grey cherty limestone layer in reddish radiolarite	(2) KA 816	*Gladigondolella*-ME sensu Kozur & Mostler, *Neogondolella pseudolonga* (Kovács, Kozur & Mietto)	Late Illyrian—Fassanian
Grey filament limestone layer in reddish radiolarite	(1) KA 815	*Gladigondolella tethydis* Huckriede, *Neogondolella cornuta* (Budurov & Stefanov)	Middle–Late Illyrian

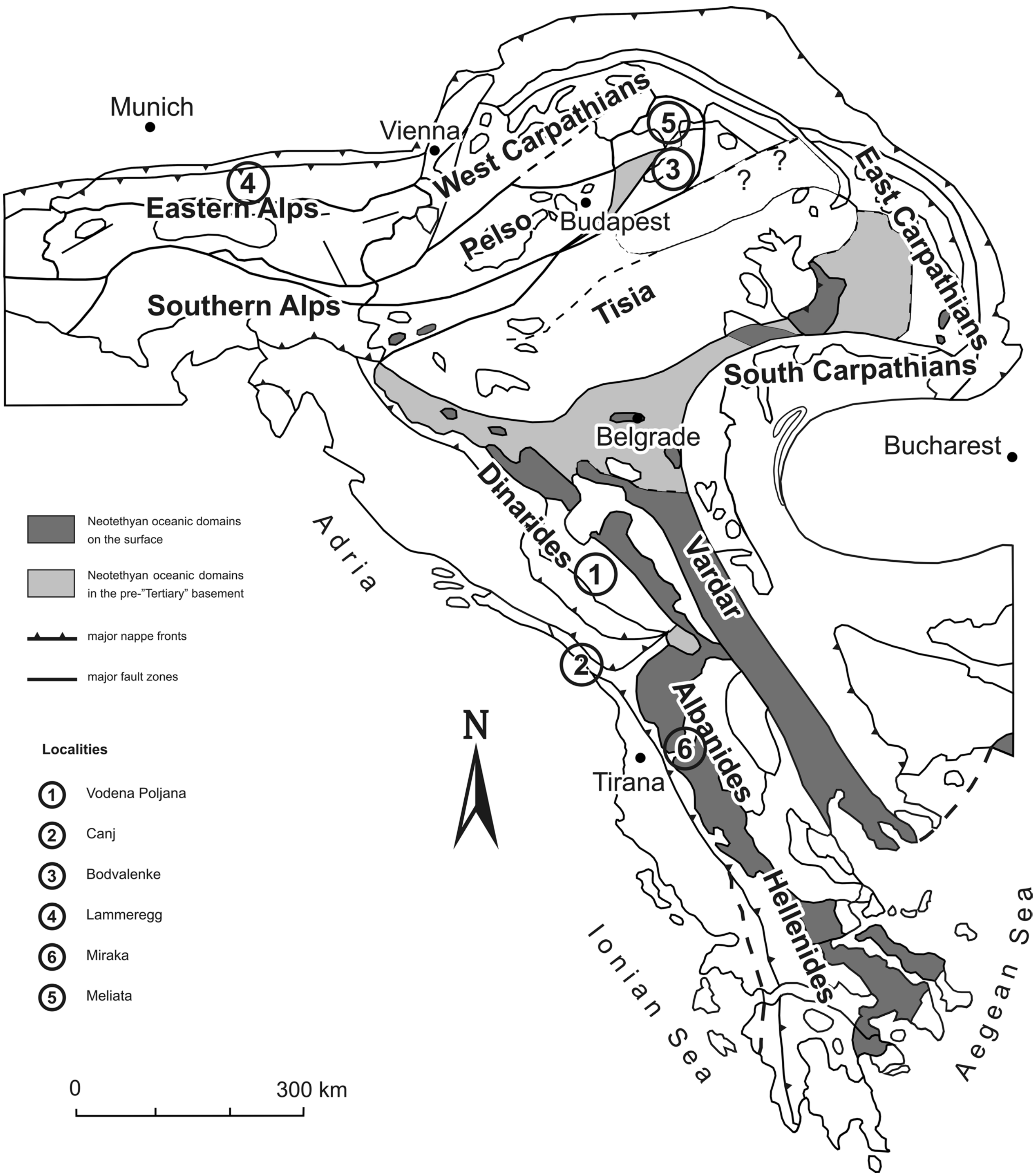

Fig. 9 Map of the Alpine, Carpathian, Dinaride, Albanide, and Pannonian realm with geographic distribution of Neotethyan oceanic crust and the tectonic position of comparable Middle to Late Triassic sedimentary successions (modified after Kovács et al. 2010). *Numbers* of the sections correspond to Fig. 10

Bódvalenke section in northeast Hungary (3 in Figs. 9, 10: data from Kovács et al. 1989; Kovács 2010, and own data—Table 2): In Bódvalenke, the completely preserved sedimentary succession starts with the shallow-water Anisian Steinalm limestone, followed by Pelsonian-Illyrian red nodular limestones (Schreyeralm Limestone). The Illyrian

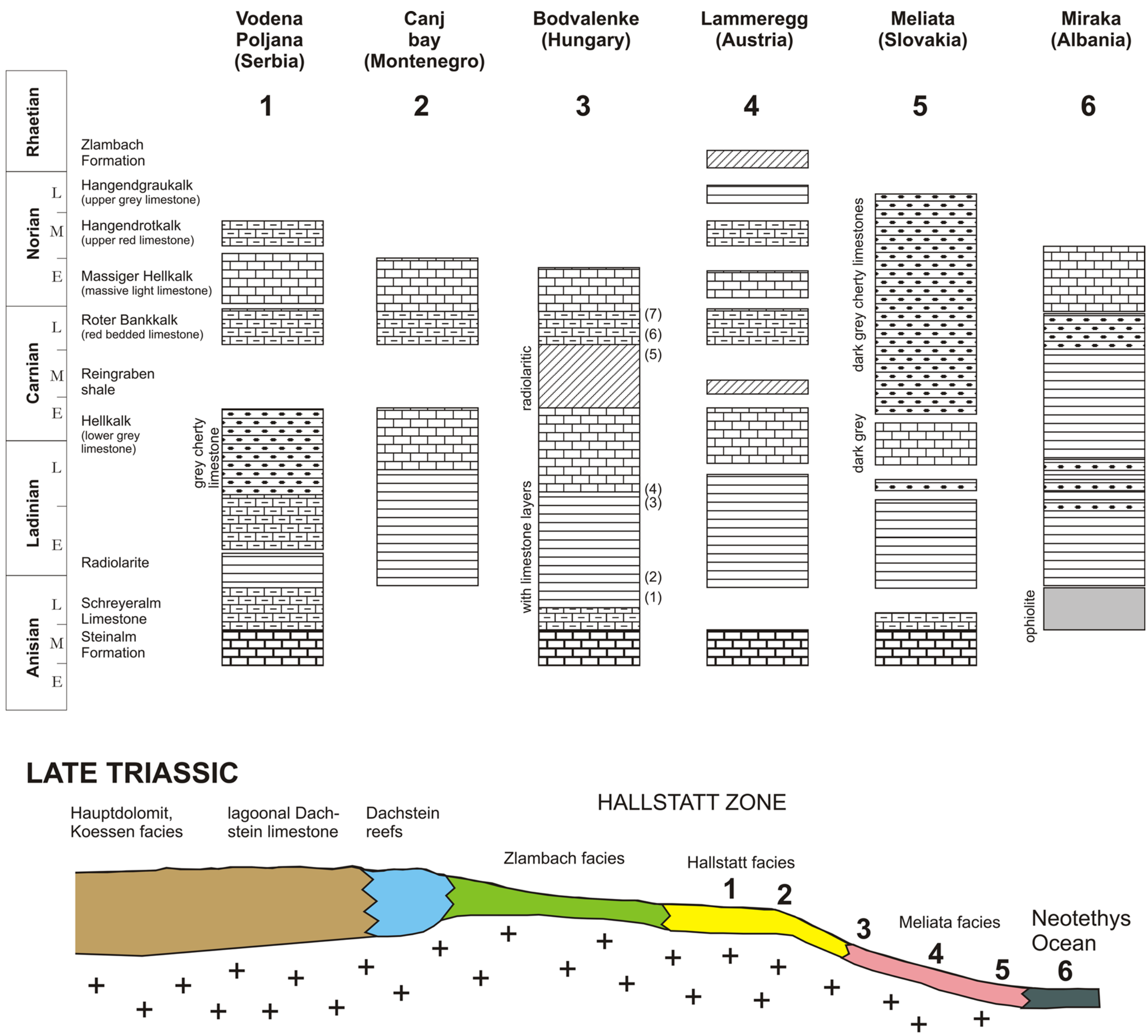

Fig. 10 Schematic reconstruction of the relative paleogeographic position of different sections from the Alpine–Carpathian–Dinaride mountain belt. All sections contain Middle Triassic radiolarites. The depositional area ranges from the distal shelf (Hallstatt facies; Hallstatt Limestone) to the continental slope (Meliata facies) and finally to the true oceanic realm near to the passive margin. *Colors* of the Late Triassic facies belts correspond to Fig. 2. *Numbers* of the sections correspond to Fig. 9

to early Langobardian is characterized by a thick succession of reddish radiolarites intercalated by thin grey micrite layers and reddish-grey cherty limestones. The Longobardian to lower Carnian consists of a thick-bedded to massive grey limestone that is topped by a middle Carnian succession of reddish and grey cherty claystones with carbonate lenses. In the Late Carnian, a red nodular limestone was deposited followed by a grey massive limestone, which passed into the Early Norian.

This succession with the shallow-water Steinalm limestones clearly indicates the deposition of the Middle to Late Triassic open-marine sedimentary succession on thinned continental crust. The breakup of the Neotethys Ocean and formation of the oldest oceanic crust is dated as Late Anisian (e.g., Goričan et al. 2005; Gawlick et al. 2008; Ozsvárt et al. 2012). This break-up is contemporaneous with the drowning of the Steinalm carbonate ramp everywhere in the Alpine/Carpathian/Dinaride mountain belt (for latest review, see Sudar et al. 2013). Open-marine conditions prevailed until the Late Triassic. A Late Ladinian to Early Carnian shallow-water interval is missing. Therefore the depositional realm of this succession is the distal shelf area or the continental slope transitional to the oceanic realm (Kovács et al. 2011).

Meliata type locality in Slovakia (5 in Figs. 9, 10: data from Kozur and Mock 1973, 1985; Mock 1980; Kozur 1991; Kozur et al. 1996; Mock et al. 1998; Aubrecht et al. 2010, 2012): For review of the various interpretations of the Meliata type locality, see Mock et al. (1998). The type locality Meliata is a relic of a Middle Jurassic basin fill with several Triassic limestone clasts in olistostromes and decameter-sized blocks in a Middle Jurassic argillaceous-radiolaritic matrix. From the blocks and the pebbles in the olistostromes, only an incomplete sedimentary succession can be reconstructed. In addition, most pebbles are strongly recrystallized and allow no microfacies study. The Middle Anisian shallow-water Steinalm limestone is overlain by Late Pelsonian red nodular limestone (Schreyeralm Limestone). In the Illyrian to Ladinian, reddish-violet radiolarites occur as clasts in the basal olistostrome, together with Late Ladinian reddish cherty limestones. The Early Carnian to Late Norian is characterized by strongly recrystallized grey to dark grey limestones. Early and Late Carnian, Early and Late Norian is proven by conodont dating. Early Carnian pebbles are dark grey and without cherts, all younger pebbles are more or less grey cherty limestones. In a few cases, radiolaria wackestones are visible. Also in this section, pure radiolarite deposition seems to have changed in the Late Ladinian to more calcareous cherty limestones. In the Late Triassic exclusively, grey limestones were deposited, which resemble in the Norian the Pötschen Limestone sequence (type locality) from the central Northern Calcareous Alps. This type of grey radiolarian wackestones was recently interpreted to be deposited near the base of the continental slope transitional to the oceanic domain (Missoni and Gawlick 2011a) (Fig. 10).

Miraka in central Albania (6 in Figs. 9, 10: data from Meco 2005; Gawlick et al. 2008): In Miraka, west of Librazhd in central Albania, a slightly dismembered oceanic sedimentary succession from a position near to the continental slope is preserved. Deposition of radiolarites started in the Illyrian and prevailed until the Middle Carnian. In the Late Ladinian–Early Carnian, the radiolarites are more calcareous and often intercalated by micritic limestone beds. In the Late Carnian, the gradual change from pure radiolarites to a radiolarite/limestone succession can be observed. From the Early Norian onwards, a pure open-marine, massive, bioturbated limestone succession was deposited, dated by means of conodonts by Meco (2005).

In all other cases in the Circum-Pannonian realm, the Illyrian to Early Ladinian radiolarites—often accompanied by volcanics—are not overlain by open-marine condensed and various colored limestones (Hallstatt Limestones). In most cases, the radiolarites are overlain by different limestones of the Late Ladinian to Early Carnian prograding Wetterstein Carbonate Platform (for latest review, see Kovács et al. 2010, 2011; Gawlick et al. 2012a).

The investigations of the resedimented siliceous and radiolaritic clasts result in a reconstruction of their possible primary depositional area and give further hints on the geodynamic as well as on the paleogeographic evolution. In the Late Anisian to Late Ladinian time interval, radiolarite deposition was widespread in the Neotethys realm and occurred in the distal shelf areas as red (Bódvalenke-type slide blocks of Kovács et al. 1989) or grey radiolarites, together with basalts (Dimitrijević et al. 2003). Late Anisian to Late Ladinian and Early Carnian red-brown radiolaritic rocks from the passive continental slope (Meliata facies) were described by Mandl and Ondrejičková (1991) and Kozur and Mostler (1992) in the Callovian Florianikogel Formation (Northern Calcareous Alps), and by Mock (1980) in the Meliata area. Mock (1980) considered the Meliata section as typical Dinaric facies. Latest Ladinian to Late Triassic radiolarites were not detected until now on the distal continental shelf margins towards the Neotethys Ocean and they are also not expected within this facies zone (Gawlick et al. 1999, 2008). Shedding from the late Middle and Late Triassic shallow-water carbonate ramps and platforms led to an accumulation of a thick pile of fine-grained carbonate mud on the distal shelf and partly in the oceanic domain (Gawlick and Böhm 2000), for most of the time except the Julian. Accordingly, radiolarites of this age can only be expected in distal oceanic areas (Gawlick et al. 2008). For this reason, uppermost Ladinian to Late Triassic ribbon radiolarites are of special interest because only they indicate fragments of the Neotethys oceanic realm.

The Late Anisian to Ladinian radiolarite interval is widespread in the northwestern Neotethyan realm, especially in the Dinarides. Late Anisian (Illyrian) radiolarite deposition occurred shortly after the main subsidence pulse and the final break-up of the Neotethys Ocean (Gawlick et al. 2008; Ozsvárt et al. 2012; Sudar et al. 2013), accompanied by a first-order transgression (Gianolla and Jacquin 1998). The onset of radiolarite deposition started in a phase when carbonate production nearly completely deceased and corresponds to the onset of intense volcanism in several parts of the Dinarides and Southern Alps (Gawlick et al. 2012a), whereas in the Northern Calcareous Alps and the Western Carpathians volcanic ashes are widespread (e.g., Gallet et al. 1998). Around the Anisian/Ladinian boundary in parts of the Northern Calcareous Alps, the Western Carpathians, the Southern Alps, and northern Dinarides, carbonate production recovered, but intense carbonate production started in the late Ladinian (middle Longobardian) with the evolution of the huge Wetterstein carbonate platforms and equivalents elsewhere (e.g., Missoni et al. 2012). Intense shedding from the platforms resulted in the deposition of open-marine limestones on the distal shelf and the continental slope.

The reasons for the Late Anisian to Ladinian radiolarite interval are rather unexplored Gawlick et al. 2012a). Planktonic carbonate production is neglectable as rock forming process in the Middle Triassic, because calcareous plankton was in the Carnian/Norian in its evolutionary infancy (Bralower et al. 1991). Radiolarite deposition triggered by high fertility and productivity of radiolarians, probably driven by intense river-induced nutrient influx (River Plume Model), as recently discussed for Jurassic radiolarites (Baumgartner 2013) or monsoonal upwelling models (De Wever et al. 2014), can hardly explain the Late Anisian to Ladinian radiolarite interval. Missing Late Anisian–Ladinian siliciclastics in the whole northwestern Neotethyan realm indicate rather minor river influence on the depositional realm and monsoons are normally very effective in a widely open oceanic system, but not in a still-narrow ocean shortly after its opening. Recent discussions about ocean acidification and its role in radiolarian biodiversity dynamics (Kocsis et al. 2014) and productivity, combined with a rapid decrease of carbonate production, may show the way for future investigations. Radiolarians, as organisms with a siliceous test, may have been less affected than carbonate producers by ocean acidification, which may be related to the break up of the Neotethys Ocean accompanied by intense volcanism. Ocean acidification models are not tested for the Middle Triassic.

Conclusions

Middle Triassic radiolarites occur widespread on the passive margin of the Neotethys Ocean (Dinarides). Towards the northwestern end of the Neotethys Ocean (Eastern Alps/Western Carpathians), radiolarites become more restricted to the outermost shelf and continental slope transitional to the oceanic realm (Meliata facies). We derive the following conclusions:

1. The occurrence of Middle Triassic radiolarites cannot be used for paleographic reconstructions. They are not an exclusive element of the Dinarides/Hellenides. They occur also in the Eastern Alps and the Western Carpathians.
2. Neotethys oceanic break-up started in the Upper Anisian. The co-occurrence of Middle Anisian shallow-water carbonates clearly indicates deposition of the Middle Triassic radiolarites in a passive margin setting, resp. the continental slope.
3. The existence of several independent Triassic oceans in the eastern Mediterranean mountain ranges is not supported, as shown by the identical sedimentological evolution of the Triassic outer shelf sequences, which are documented from the Eastern Alps (Meliata-Hallstatt Ocean), the Western Carpathians (Meliata Ocean), the Pannonian realm (between Meliata and Maliac Oceans), the Dinarides (Dinaride Ocean), and the Albanides (Mirdita/Pindos Ocean with Budva Basin).
4. Middle Triassic radiolarites do not necessarily represent erosional products of the original sedimentary cover of the Triassic Neotethys ocean floor. They occur widespread on the distal passive continental margin of the Neotethys Ocean. Their occurrence cannot be used as an argument for an eroded oceanic domain.

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