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Erosion of a Jurassic ophiolitic nappe-stack as indicated by exotic components in the Lower Cretaceous Rossfeld Formation of the Northern Calcareous Alps (Austria)

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Abstract: The microfacies and biostratigraphy of components in mass-flow deposits from the Lower Cretaceous Rossfeld Formation of the Northern Calcareous Alps in Austria were analysed. The pebbles are classified into six groups: 1) Triassic carbonates (uppermost Werfen to basal Gutenstein Formations), 2) Upper Jurassic to lowermost Cretaceous carbonates (Oberalm Formation and Barmstein Limestone), 3) contemporaneous carbonate bioclasts (?Valanginian to ?Hauterivian), 4) siliceous pebbles (radiolarites, ophicalcites, siliceous deep-sea clays, cherts), 5) volcanic and ophiolitic rock fragments and 6) siliciclastics such as quartz-sandstones and siltstones. The radiolarites show three age groups: Ladinian to Early Carnian, Late Carnian/Norian and Late Bajocian to Callovian. The Middle Triassic radiolarites are interpreted as derived from the Meliata facies zone or from the Neotethys ocean floor, whereas the Late Triassic radiolarites give evidence of the sedimentary cover of the Neotethys ocean floor. During late Early to early Late Jurassic, the Triassic to Early/Middle Jurassic passive margin of the Neotethys attained a lower plate position and became obducted by the accreted ocean floor of the Neotethys Ocean. The accreted ocean floor was contemporaneously eroded and resedimented in different deep-water basins in front of the nappe-stack. These basin fills were subsequently incorporated in the orogen forming mélanges in this complex ophiolitic nappe-stack. The Middle Jurassic radiolarites are interpreted as the matrix of these mélanges. Together with the volcanic and ophiolitic material the siliceous rocks were eroded from this ophiolitic nappe-stack in Early Cretaceous times and brought by a fluvial system to the Rossfeld Basin within the Tirolic realm of the Northern Calcareous Alps. The different fining-upward sequences in the succession of the Lower Cretaceous Rossfeld Formation can be best explained by sea-level fluctuations and decreasing tectonic activity in the Jurassic orogen.

Key words: Triassic, Jurassic, Early Cretaceous, Northern Calcareous Alps, Rossfeld Formation, component analyses, conglomerates, radiolarians.

Introduction

Component analyses of conglomerates, breccia layers or turbidite beds are a common tool in sedimentary geology. One of the most interesting research fields within this topic is to reconstruct with the help of the clast spectrum the source (provenance) area of the resedimented rocks (Blatt 1967; Zuffa 1980, 1985; Lewis 1984). Whereas the detailed provenance analyses of siliciclastic material are a widespread and commonly used practice, with an enormous amount of published examples, provenance analyses of carbonate or radiolarite clasts in conglomerates remain rare. A macroscopic description of the incorporated clasts in the field is the basic work to do, but 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 can change existing plate tectonic and paleogeographical reconstructions completely. Some examples from the Northern Calcareous Alps are: the upper Middle to lower Upper Jurassic Strubberg (e.g. Gawlick 1993, 1996, 2000; Gawlick & Frisch 2003; Gawlick et al. 2009a), Tauglboden (e.g. Gawlick et al. 1999, 2007, 2009a, 2012; Gawlick & Frisch 2003), Sandlingalm (Gawlick et al. 2007, 2009a, 2010a) and Sillenkopf Formations (Missoni et al. 2001; Gawlick & Frisch 2003; Missoni 2003; Gawlick et al. 2009a). The Early Cretaceous of the Northern Calcareous Alps also include resedimented oligo- to polymictic conglomerates, coarse-grained breccias and arenitic turbidite beds (e.g. Berriasian turbidites — Krische & Gawlick 2010). The Valanginian to Lower Aptian (e.g. Tollmann 1976; Oberhauser 1980; Plöchinger 1990) siliciclastic dominated sedimentary rocks are known as the Rossfeld Formation (Ro in Fig. 1A) and Lackbach beds (Darga & Weidich 1986). A detailed microfacies component analysis including age dating of the components of these mass-flow deposits is still lacking.

The studying of these Lower Cretaceous formations started with the beginning of modern geological field work at the end of the 19th century and has continued to modern times.

Alongside chemical or sedimentological investigations, minor work was done on the analyses of the component spectrum of the coarse-grained conglomerate and breccia beds. Until now only macroscopically obtained results of the components were presented apart from some data from the Lackbach beds (Darga & Weidich 1986). Some of the first microfacies results are also known from the uppermost Hauterivian to Lower Barremian conglomerate levels (Immel 1987) of the Rossfeld Formation at the type locality (Missoni & Gawlick 2011a).

The occurrence of mixed siliciclastic, magmatic (ophiolite suite and contemporaneous volcanic clasts), metamorphic, radiolaritic and carbonate lithoclasts, as well as carbonate bioclasts indicate the polymictic character of these Lower Cretaceous deposits (e.g. Kühnel 1929; Weber 1942; Del-Negro 1949, 1983; Pichler 1963; Schweigl & Neubauer 1997a; Missoni & Gawlick 2011a; Krische 2012). Krische (2012) compiled all sedimentological, macroscopical, microfacies and biostratigraphical data from the mass-flow deposits of the Rossfeld Formation.

In contrast to the almost un-investigated radiolarite pebbles (Table 1), the other pebbles from the ophiolite suite like dolerites, mafic volcanites, intermediate/basic magmatites, ultrabasic rocks and serpentinites were well described (e.g. von Eynatten & Gaupp 1999). Also the typical heavy minerals like chromium spinel, hornblende, green calcium-rich amphiboles, and brown amphiboles indicate an ophiolitic source area (Woletz 1963; Faupl & Pober 1991; Schweigl & Neubauer 1997a; von Eynatten & Gaupp 1999). Chromium spinel, for example, was also observed in the Barremian to Albian Oštrc Formation (Os in Fig. 1A) of northwestern Croatia (Lužar-Oberiter et al. 2009, 2012) and in the Upper Barremian to Albian Vranduk Formation (Vr in Fig. 1A) of Bosnia (Mikes et al. 2008). These two formations show a lot of lithological and microfacies similarities to the Upper Barremian to Lower Aptian Grabenwald Member (Fuchs 1968; Plöchinger 1968, see also Schlagintweit et al. 2012a) of the uppermost part of the Rossfeld Formation. Our data (summarized in Krische 2012) show, in addition to chromium spinel, the occurrence of zinc-rich chromites, berezowskite (aluminia-magnesia-rich chromite), ilmenite and titanite in the Upper Valanginian part of the Rossfeld Formation of Bad Ischl and Gartenau.

Similar Early Cretaceous clastics (turbiditic sandstones to conglomerates — Sztanó 1990) of Barremian to Albian age, which derived from obducting and colliding plate fragments, as revealed by ophiolite-derived clasts (Császár & B. Árgyelán 1994), metamorphics of a mixed-provenance orogenic belt and coeval shallow-water debris are typical also in the Transdanubian Range (e.g. Gerecse Mountains; Császár et al. 2012) or the Western Carpathians (Mišík et al. 1980; Jablonský et al. 2001). The mid-Cretaceous Western Carpathian occurrences would fit in their paleogeographical position better to the East Alpine Losenstein Formation and not to the Rossfeld Formation (compare Faupl & Wagreich 2000).

The until recently commonly accepted reconstruction of the Early Cretaceous geodynamic history of the Northern Calcareous Alps should show a convergent regime indicated by a coarsening upward trend (Faupl & Tollmann 1979; Decker et al. 1987) in the Upper Valanginian to Aptian Rossfeld Formation (Del-Negro 1960; Pichler 1963; Plöchinger 1968; Faupl 1978; Faupl & Tollmann 1979; Schweigl & Neubauer 1997a,b; von Eynatten & Gaupp 1999). This Rossfeld cycle presumably ended in late Early Cretaceous times (Plöchinger 1968; Schweigl & Neubauer 1997a,b; Schorn & Neubauer 2011) with the final overthrusting of the Tirolic nappe by the Juvavic nappes. Contemporaneously the ophiolitic material was eroded and should have been mixed with the eroded Juvavic component spectrum.

Another concept was introduced in the discussion by Gawlick et al. (2008) who interpreted the Rossfeld Formation as the molasse stage within an underfilled foreland basin (Tauglboden/Oberalm Basin) in front of the Neotethyan Belt (Missoni & Gawlick 2011b). In this alternative scenario, the process of nappe emplacement started already in the Middle Jurassic and continued at least until the early Late Jurassic. Decreasing tectonic activity with the evolution of shallow-water carbonate platforms in the late Jurassic and the earliest Cretaceous (e.g. Gawlick et al. 2009a, 2012) was followed by an increasing siliciclastic input in this basin from the Late Berriasian onwards (Gawlick & Schlagintweit 2006; Missoni & Gawlick 2011a). Some tectonic activity in the Early Cretaceous influenced the Jurassic ophiolitic nappe-stack as well as the foreland (e.g. Northern Calcareous Alps) only locally (e.g. Schlagintweit et al. 2008, 2012b). The sedimentological evolution of the contemporaneous Lower Cretaceous Rossfeld Formation and the Lackbach beds was mainly controlled by sea-level fluctuations and to some degree also by decreasing tectonic activity.

Within this study, combined microfacies and biostratigraphic data of the siliceous pebbles of the Rossfeld Formation are presented for the first time. The results show Triassic radiolarite clasts as the most exotic components occurring within the conglomerates and breccias. Triassic radiolarites are completely unknown in the passive margin sedimentary succession of the Northern Calcareous Alps. They have been found only as resedimented pebbles in the Middle Jurassic Florianikogel Formation (Mandl & Ondrejičková 1991). Those Triassic radiolarite pebbles in the Jurassic basin fill are exclusively of Middle Triassic age and were derived from the continental slope facing the Neotethys Ocean (Meliata facies zone in the sense of Gawlick et al. 1999). Accompanying components are always distal Hallstatt Limestone clasts of Late Triassic age (e.g. Mandl & Ondrejičková 1991, 1993; Kozur & Mostler 1992; Gawlick 1993).

Middle and Upper Triassic radiolarites from the Neotethys ocean floor are known as pebbles in the basal Gosau conglomerates (Gosau Group) in the southeastern Northern Calcareous Alps (Schuster et al. 2007; Suzuki et al. 2007). From

Table 1: Summarized table of the siliceous rocks described so far from the Rossfeld conglomerate and breccia beds.

Location	Authors	Described siliceous rocks
Bad Ischl	Medwenitsch (1949, 1958)	yellow, red, grey radiolarite
Gartenau	Plöchinger (1968, 1974)	no occurrence described
Weitenau	Plöchinger (1955, 1968)	chert
Rossfeld	Kühnel (1929), Weber (1942), Del-Negro (1949, 1983), Plöchinger (1955, 1990), Pichler (1963)	red radiolarite, dark-red, brown, black, grey, green chert

these Upper Cretaceous conglomerates a complete ophiolitic suite including the overlying sedimentary sequence can be reconstructed. The findings of components of Middle Jurassic amphibolites (Schuster et al. 2007), age-equivalent to the metamorphic soles as known from the Dinarides (e.g. Dimo 1997; Karamata 2006), Albanides (Dimo-Lahitte et al. 2001) and Hellenides (e.g. Roddick et al. 1979; Spray & Roddick 1980) were also important. The existence of Anisian and Upper Triassic radiolarites (e.g. Chiari et al. 1996; Dimitrijević et al. 2003; Goričan et al. 2005; Bortolotti et al. 2006; Gawlick et al. 2008, 2009b) together with the ophiolitic suite and Middle Jurassic metamorphic soles prove the existence of a today eroded ophiolitic nappe-stack that was located close to the Eastern Alps (southern Northern Calcareous Alps). In the Dinarides/Albanides/Hellenides, where different ophiolite imbricates are separated by amphibolites and/or radiolaritic-ophiolitic mélanges, in places the Triassic radiolarites are preserved as the sedimentary cover of basalts or gabbros (e.g. Jones et al. 1992; Halamić & Goričan 1995; Pamič et al. 2002; Goričan et al. 2005; Gawlick et al. 2008).

Location, methods and material

The localities around Gartenau, Weitenau, Lackbach, Bad Ischl and Rossfeld (Fig. 1B) are the classical areas in the central Northern Calcareous Alps (Fig. 2A) with Lower Cretaceous sedimentary successions. The uppermost Jurassic to Lower Cretaceous basin fills of most of those areas were mapped and investigated in detail by Krische (2012). One key-section from the Lower Cretaceous Rossfeld Formation, the locality Gartenau (Fig. 1B), is presented in this study. One main concern was to extract radiolarians from the radiolarite pebbles in order to date the reworked clasts and to reconstruct their provenance area. The radiolarites were processed in diluted (3 %) hydrofluoric acid. A detailed summary of the common formations of the Northern Calcareous Alps (according to Gawlick et al. 2009a) is given in Fig. 2B (modified after Missoni & Gawlick 2011a,b). Rock samples, thin sections, residues, and photographed radiolarian samples are stored at the University of Leoben, Department of Applied Geosciences and Geophysics, Chair of Petroleum Geology (former Chair of Prospection and Applied Sedimentology).

Results

The Gartenau section (see Figs. 1B, 3, also known as the Hangendenstein quarry or the Leube quarry) south of Salzburg, near the villages of St. Leonhard and Gartenau, was investigated several times in the last 100 years. It is part

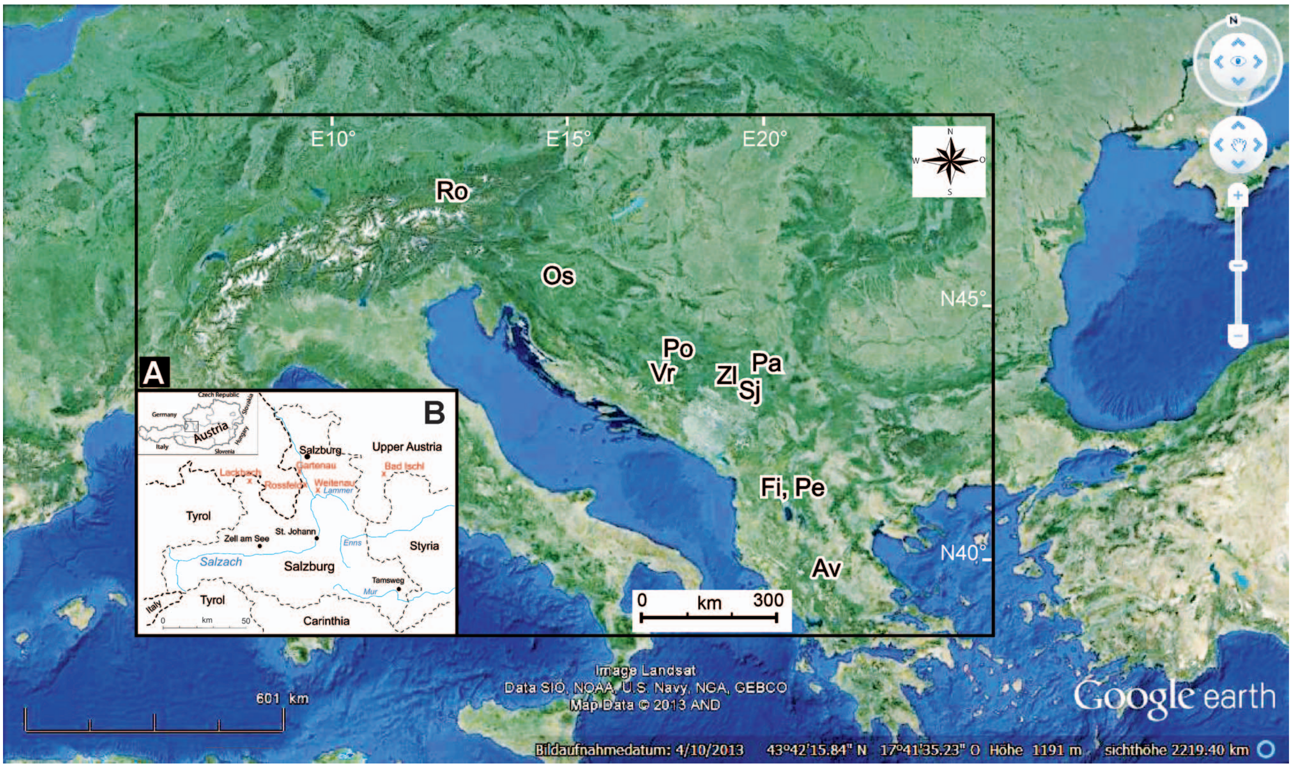

Fig. 1. A — General overview of localities and formations mentioned in the text. Av — Avdella Melange, Inner Hellenides, Greece; Fi — Firza Formation, Mirdita Ophiolite Zone, Albania; Os — Oštrc Formation, Northwestern Dinarides, Croatia; Pa — Paraflysch, Vardar Zone, Serbia; Pe — Perlat Formation, Mirdita Ophiolite Zone, Albania; Po — Pogari Formation, Bosnia and Herzegovina; Ro — Rossfeld Formation, Northern Calcareous Alps, Austria; Sj — Sjenica Mélange, Dinaridic Ophiolite Belt, Serbia; Vr — Vranduk Formation, Bosnian Flysch, Bosnia and Herzegovina; Zl — Zlatibor Mélange, Dinaridic Ophiolite Belt, Serbia. Modified Google Earth Landsat image. **B** — Austria in detail: Studied section in Salzburg (Gartenau) and comparable localities of Lower Cretaceous sedimentary rocks mentioned in the text.

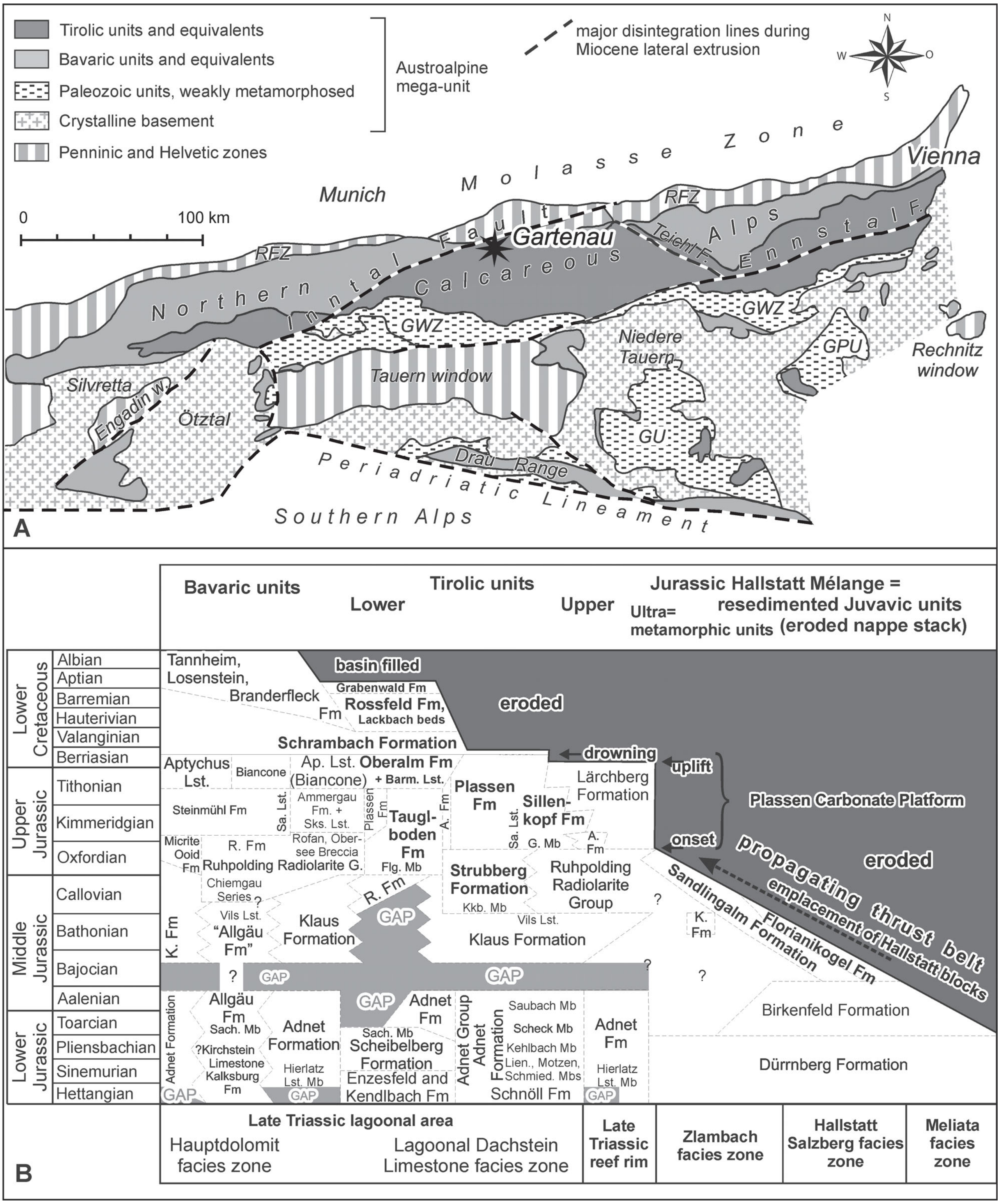

Fig. 2. A — Geological overview of the Eastern Alps (modified after Frisch & Gawlick 2003). The described locality Gartenau is situated within the central part of the Northern Calcareous Alps (indicated by a star). Abbreviations: GP — Graz Paleozoic unit, GU — Gurktal unit, GWZ — Greywacke zone, RFZ — Rhenodanubian Flysch zone. **B** — Stratigraphy of the Northern Calcareous Alps with an overview of the common formation names according to Gawlick et al. (2009). Upper Jurassic and Lower Cretaceous formation names used in the text are written in bold letters. Modified after Missoni & Gawlick (2011a,b). Abbreviations: A. Fm — Agatha Formation, Ap. Lst. — Aptychus Limestone, Barm. Lst. — Barmstein Limestone, Flg. Mb — Fludergraben Member, G. Mb — Gotzen Member, K. Fm — Klaus Formation, Kkb. Mb — Klauskogelbach Member, Lien. Mb — Lienbach Member, R. Fm — Ruhpolding Formation, Sa. Lst. — *Saccocoma* Limestone, Sach. Mb — Sachrang Member, Schmied. Mb — Schmiedwirt Member, Sks. Lst. — Seekarspitz Limestone.

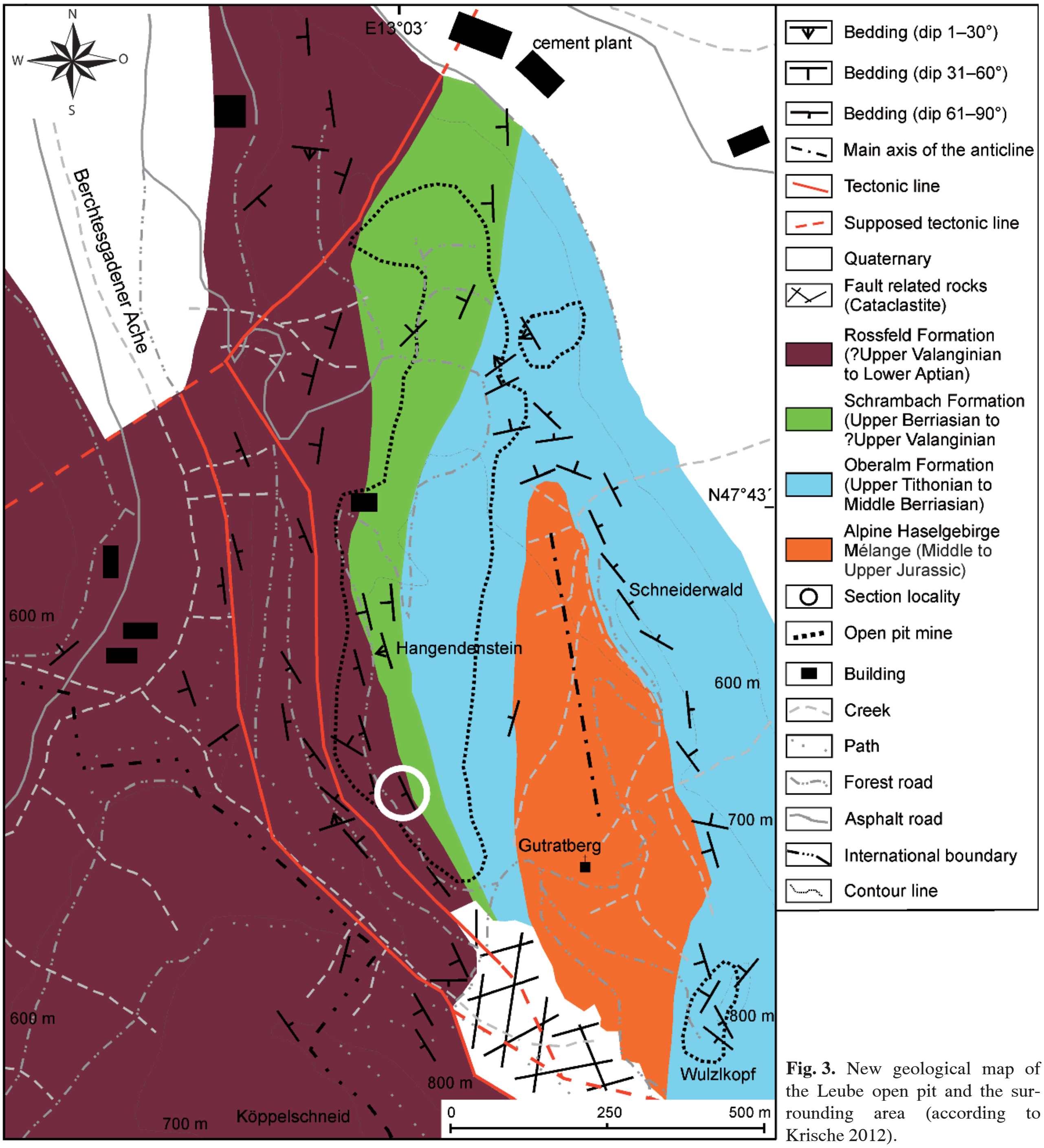

Fig. 3. New geological map of the Leube open pit and the surrounding area (according to Krische 2012).

of the Lower Tirolic unit (Frisch & Gawlick 2003) in the Northern Calcareous Alps. Due to rapid changes of the outcrop situation caused by ongoing exploitation in the open pit mine, a correlation of sections described by different authors is difficult (see Plöchinger 1974; Steiger 1992; Reháková et al. 1996; Boorová et al. 1999; Dorner et al. 2009, summarized in Krische 2012). Recent studies are done by Bujtor et al. (2013) and Krische et al. (2013). A complete description of the Gutratberg section and a basic map (Fig. 3) of the surrounding area is given in Krische (2012). A well bedded limestone-marl succession of Late Berriasian to Early Valanginian age (Krische 2012; Bujtor et al. 2013; Krische et al. 2013) is known as the Schrambach Formation (Fig. 3). According to biostratigraphic results of Boorová et al. (1999) the uppermost part of the Schrambach Formation is indicated as Late Valanginian in age.

With an erosional contact, the mud-supported, conglomeratic Rossfeld Formation truncates the Schrambach Formation (Fig. 4). The conglomerates are composed of angular to rounded, blocky and gravel-sized lithoclasts (carbonates, siliciclastics, siliceous, magmatic and metamorphic rocks) and carbonate bioclasts, surrounded by a clayey matrix (Fig. 4B,C).

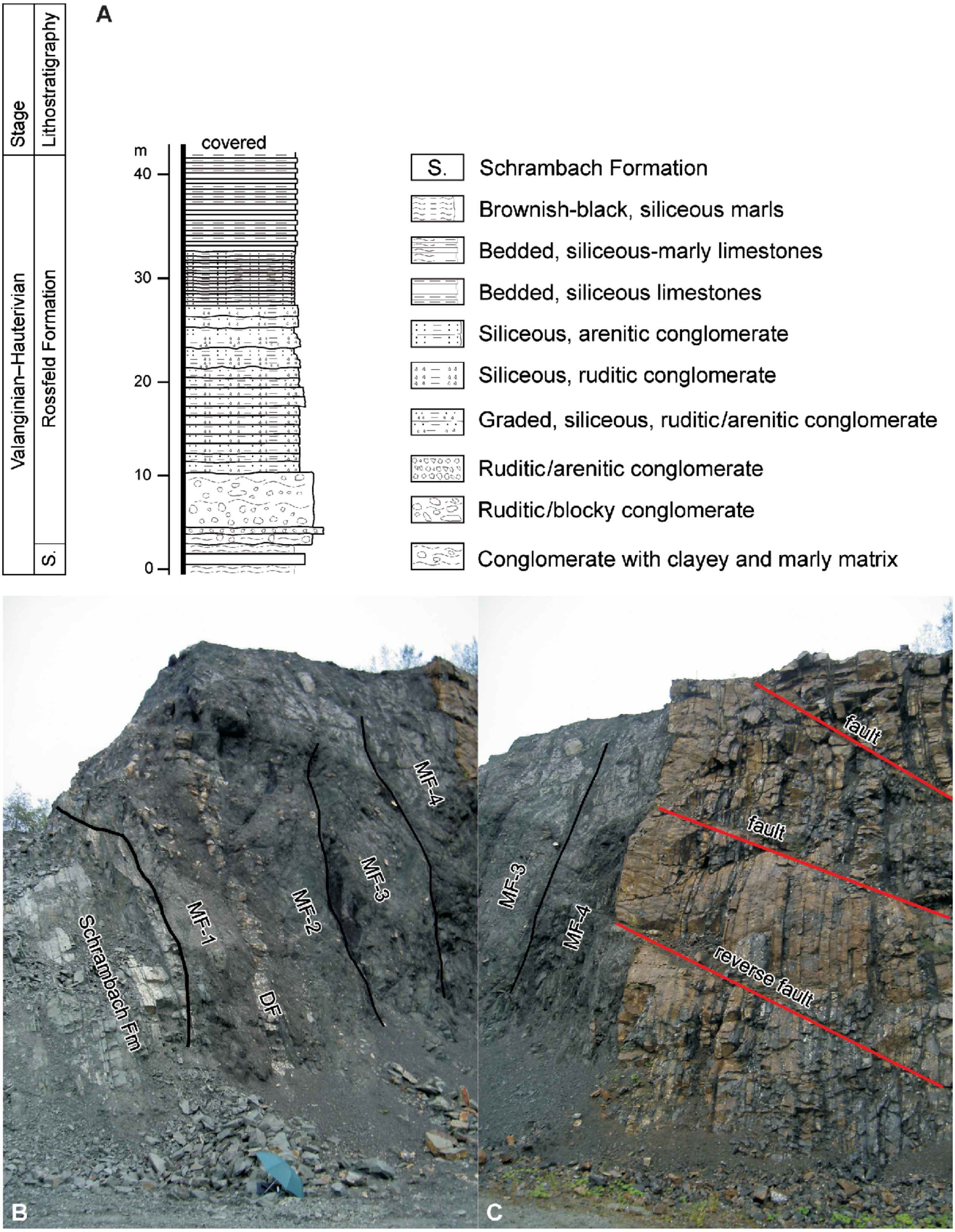

Fig. 4. A — Studied section of the Rossfeld Formation in the southern part of the Leube open pit mine. **B** — Erosional contact between the Schrambach Formation and the Rossfeld Formation at the outcrop and overlying mud- and debris-flows of the basal Rossfeld Formation. **C** — The mud dominated lower part of the Rossfeld Formation is followed by bedded, siliceous cemented arenites. Indicated are also gently southwest inclined faults, which are interpreted as northeast directed reverse faults of probably Neogene age. **Abbreviations:** DF — debris-flow, MF — mud-flow.

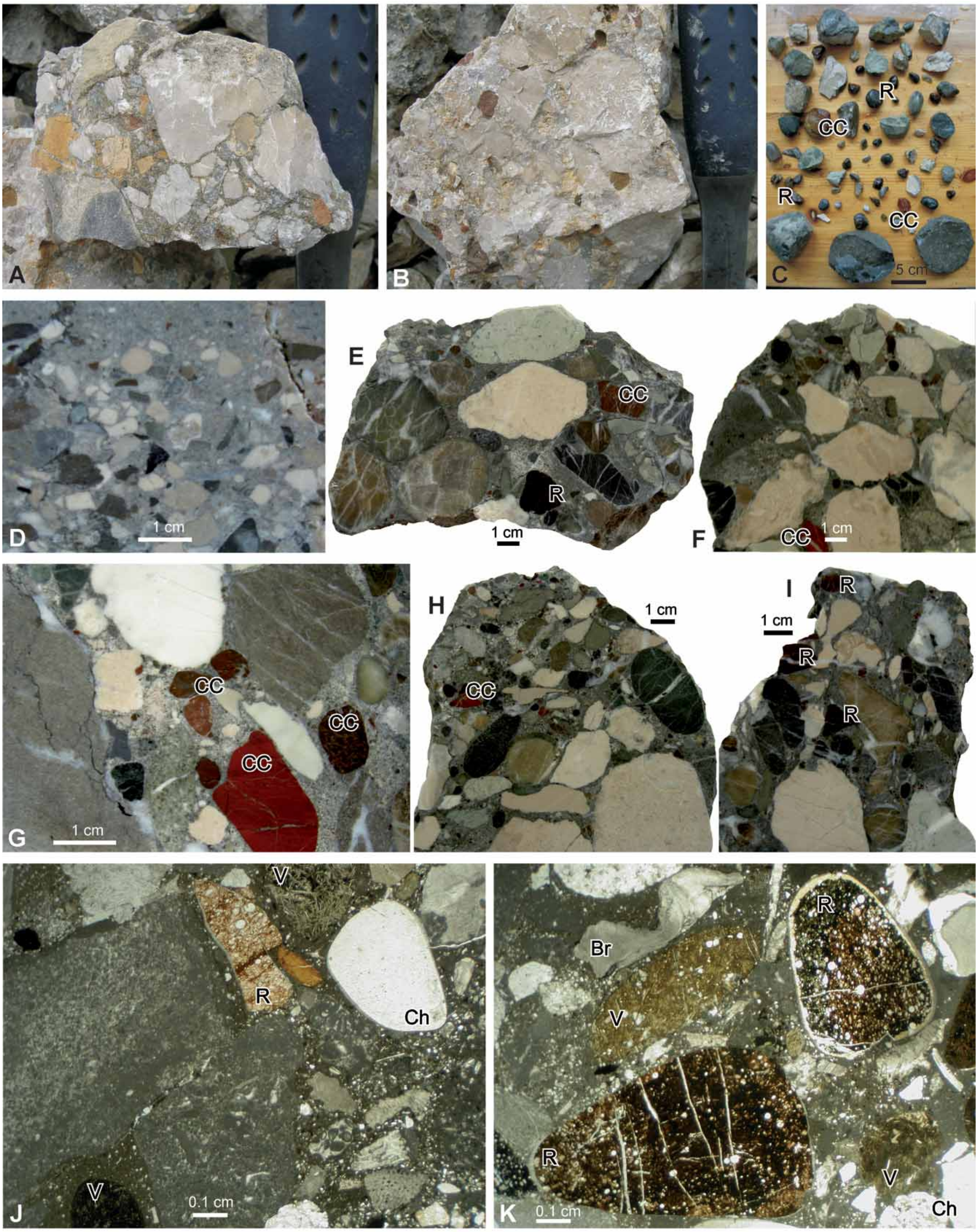

Fig. 5. Macroscopic appearance and microfacies of the coarse-grained breccias and conglomerates at the studied section. **A, B** — Typical Rossfeld conglomerate at the outcrop, sampled from the cemented debris-flow bed. **C** — Washed and sorted lithoclastic components from a mudflow. **D–I** — Cut samples of the oligo- to polymictic, cemented breccia and conglomerate beds. D — L10; E–I — L11; J, K — Microfacies of the lithoclastic, component supported, sandy to gravel sized breccias/conglomerates with different carbonate lithoclasts beside radiolarites, cherts and volcanites. **J** — L22, **K** — L19. **Abbreviations:** Br — brachiopod shell, CC — chertyfied clay, Ch — chert, R — radiolarite, V — volcanite. Scale: A–B — hammer shaft. Scale-bar: C — 5 cm, D–I — 1 cm, J-K — 0.1 cm.

They are defined as pelite-rich mud-flow deposits (mud-supported conglomerate, “Parakonglomerat”). Four macroscopically different mud-flow events occur in the studied section (Fig. 4A,B,C). The first two events are intercalated by a cemented debris-flow. The debris-flow bed is a clast-supported conglomerate/breccia, composed of lithoclasts with microsparitic carbonate cement and/or different fine-sandy material filling the pore space (Fig. 5). The lithoclast groups are the same as in the mud-flows (Fig. 5). A special feature within the mud-flow deposits are blocks up to 10 cm in diameter of siliceous cemented concretions. They are built up from different gravel-sized lithoclasts. The bulk of radiolarite pebbles, on which this study is focused, occur within the mud-flows, the concretions and the cemented debris-flow. The conglomerate and breccia beds as well as the bedded arenitic rocks of the hanging wall show a significantly smaller amount of radiolarite and other siliceous pebbles.

Macroscopic data

The radiolarite pebbles are generally subrounded to rounded. Macroscopically, they also differ in colour; red radiolarites are the most abundant (Table 2).

Microfacies

Qualitative analyses of the microfacies of the radiolarite pebbles show different microfacies types (Figs. 6, 7) which can be related to their depositional environment and their stratigraphic age (Table 3).

Table 2: Semi-quantitative analysis of the collected and etched radiolarite pebbles (in total 75 pebbles) by their colour.

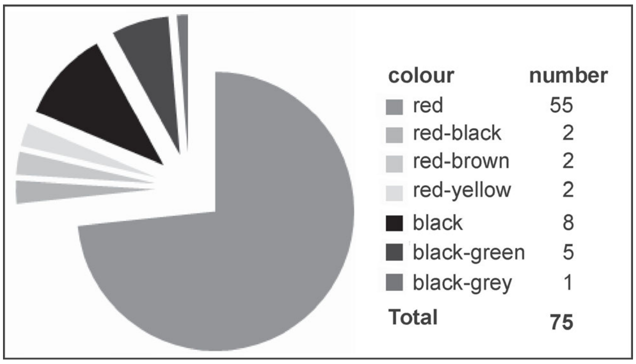

Table 3: Age of radiolarite pebbles inferred from their microfacies.

Microfacies	Possible stratigraphic age range
black radiolarian wackestone with big, spherical radiolarians	Anisian/Ladinian
black-red radiolarite	Anisian/Ladinian?
laminated, yellowish radiolarian wackestone with clay layers	Anisian/Ladinian?
black-yellow radiolarian wackestone with big, spherical radiolarians	Anisian/Ladinian
red radiolarian wackestone with spherical and conical radiolarians	Anisian/Ladinian
red-brown radiolarian packstone with spherical radiolarians	Anisian/Ladinian
red radiolarian packstone with small, spherical radiolarians	Upper Triassic (Carnian?)
red radiolarian chert with big, spherical radiolarians	Upper Triassic
red radiolarian chert with spherical radiolarians of different size	Upper Triassic?, Upper Jurassic?

Table 4: Radiolarite pebbles of undifferentiated microfacies and not determinable age (Triassic or Jurassic).

Microfacies
laminated, red-black radiolarite
red radiolarite
laminated, red radiolarite
red, slightly recrystallized radiolarian wackestone
green radiolarite
red-yellow radiolarian chert with filaments
light, fine-grained recrystallized radiolarian packstone

Some of the radiolarite pebbles cannot be assigned to any typical microfacies or to a specific age (Table 4).

In addition, radiolarites (e.g. yellow radiolarian wackestones, red radiolarites) overprinted by enhanced pressure and/or temperature and radiolarites with transported, brittle deformation (in general with completely siliceous cemented veins) occur. Ophicalcitic rocks, brown-black siliceous marlstones, red/blackish-red/yellowish-red siliceous (deep-sea) clays and whitish-light, microcrystalline cherts complete the siliceous component fraction of the basal part of the Rossfeld conglomerate at the Gartenau section.

Radiolarian dating

Radiolarite samples were taken from the different mud and mass-flows of the Gartenau quarry section (Fig. 4). Radiolaritic pebbles of adequate size and appropriate frequency for sampling occur within the mud-flows at the base of the Rossfeld succession. Nine out of the tested 75 pebbles yielded determinable radiolarians. The preservation of radiolarians is mostly very poor, rare specimens could be identified at the species level. The radiolarians are listed in Tables 5 and 6, and illustrated in Figures 8 and 9. Generic names have been updated according to O’Dogherty et al. (2009a,b). For species that cannot be assigned to any valid genus, the name of the genus is accompanied by a question mark (e.g. *Dictyomitrella*? *kamoensis* Mizutani & Kido, *Stichomitra*? *annibill* Kocher). Short taxonomic notes are given in the plate captions where necessary.

Triassic

The Triassic assemblages (Table 5, Fig. 8) were dated with the zonation proposed by Kozur & Mostler (1994), the range chart of Ladinian to Rhaetian species compiled by Tekin (1999), and the range chart of revised Triassic genera constructed by O’Dogherty et al. (2009a, 2010). We note that Tekin (1999) as well as Kozur & Mostler (1994) used a threefold subdivision of the Carnian, while O’Dogherty et al. (2009a, 2010) adopted the twofold subdivision (considering the Cordevolian as part of the Julian). Here we follow the

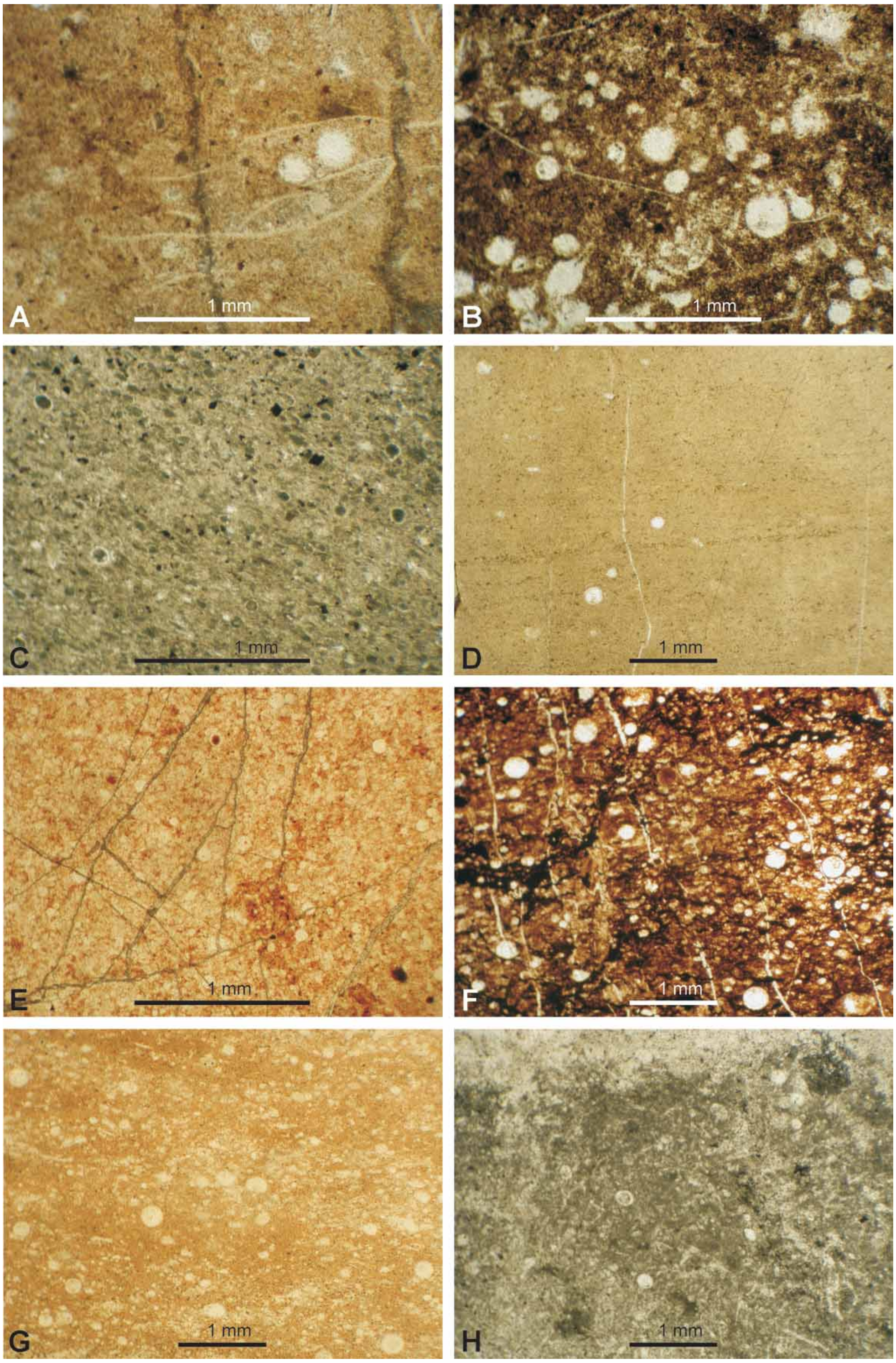

Fig. 6. Characteristic microfacies photographs of radiolarite pebbles of the Rossfeld Formation. **A** — Red radiolarite. Radiolarian wackestone with some recrystallized, spherical radiolarians and shell remnants, L103. **B** — Red radiolarite. Radiolarian wacke- to packstone with recrystallized, spherical radiolarians and a dark, clayey matrix, ?Anisian/?Ladinian, L108. **C** — Greenish-black hemipelagic limestone. Packstone with sparite and micrite clasts and some preserved radiolarians within fine-grained, recrystallized matrix, L130. **D** — Greenish-black radiolarite. Laminated mudstone with rare recrystallized, spherical radiolarians and diagenetic pyrite, L131. **E** — Red radiolarite. Radiolarian wackestone with recrystallized, spherical radiolarians. The whole rock-sample shows strong chertification, L273. **F** — Red radiolarite. Radiolarian packstone with recrystallized, spherical radiolarians of different size and a dark, clayey matrix, Anisian/Ladinian, L296. **G** — Reddish-black radiolarite. Radiolarian wacke- to packstone with recrystallized, spherical radiolarians and some shell remnants. Biostatigraphic age Ladinian, see text and Table 5, L297. **H** — Greenish-grey radiolarite. Radiolarian wackestone with recrystallized, spherical radiolarians and some shell remnants, L309. Width of photo: D, F–H — 0.5 cm; A–C, E — 0.25 cm.

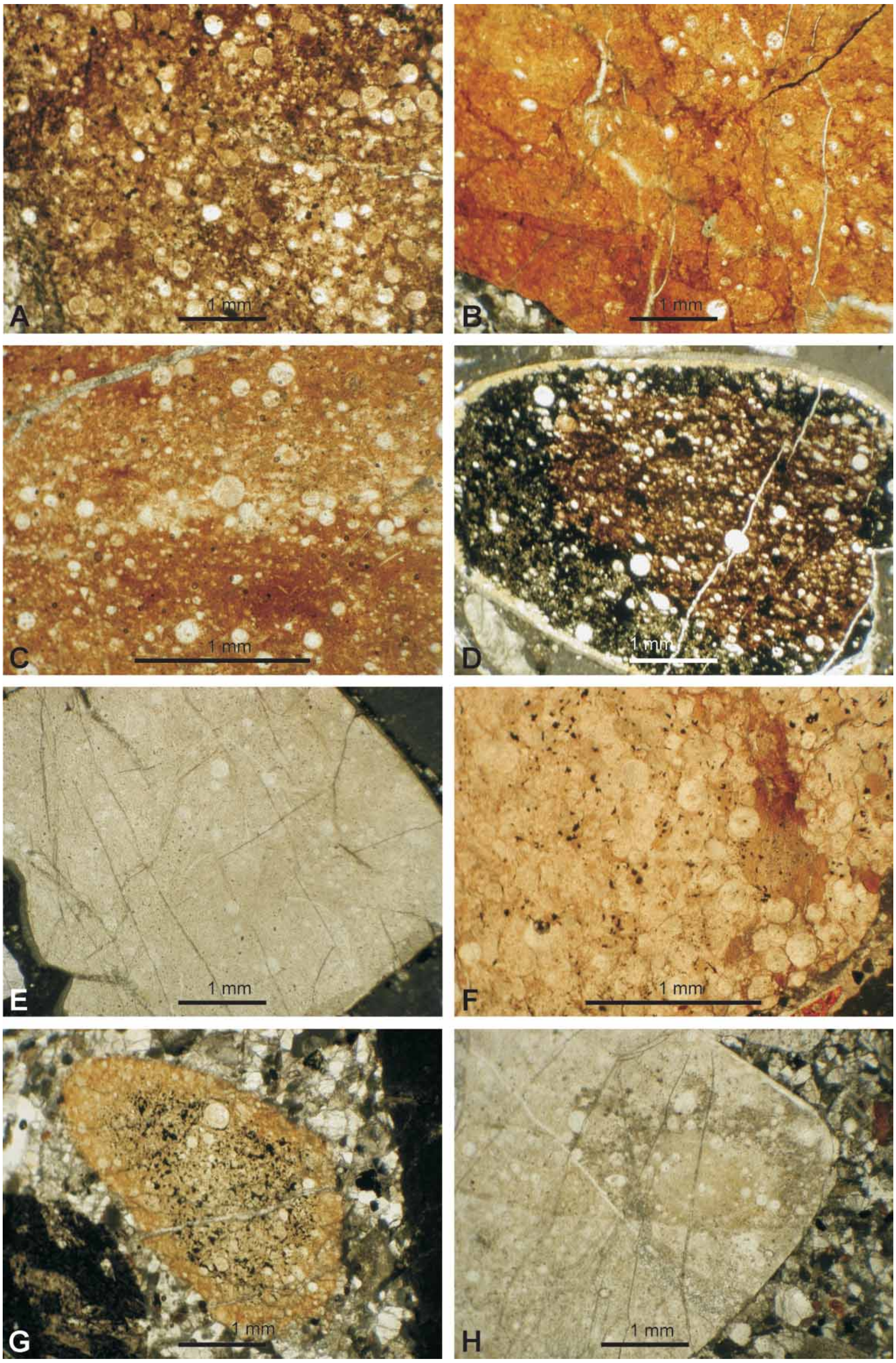

Fig. 7. Characteristic microfacies photographs of radiolarite pebbles of the Rossfeld Formation. **A** — Red radiolarite. Radiolarian packstone with spherical radiolarians and a clayey matrix, L11. **B** — Reddish-yellow radiolarite. Radiolarian wackestone with recrystallized, spherical radiolarians and some shell remnants, L11. **C** — Red radiolarite. Laminated wacke- to packstone with rare shell remnants and clayey matrix. **D** — Reddish-black radiolarite. Loose packstone with recrystallized radiolarians of different size and dark, clayey matrix, Anisian/Ladinian, L19. **E** — Light coloured radiolarite. Radiolarian wackestone with recrystallized, spherical radiolarians and shell fragments, slightly overprinted by enhanced temperature and/or pressure, L19. **F** — Radiolarian packstone with recrystallized, spherical radiolarians, slightly overprinted by enhanced temperature and/or pressure, L11. **G** — Yellow radiolarite. Radiolarian wackestone with recrystallized radiolarians and fine-grained ore minerals. **H** — Light coloured radiolarite. Radiolarian wackestone with recrystallized, spherical radiolarians, slightly overprinted by enhanced temperature and/or pressure, L11. Width of photo: A–B, D–E, G–H — 0.5 cm; C, F — 0.25 cm.

twofold subdivision but we additionally refer to early Early Carnian or late Early Carnian, where needed. The age of samples is discussed below in their inferred chronological order.

Sample L297

Reddish-black radiolarite. The assemblage is characterized by numerous *Muelleritortis* species including *Muelleritortis cochleata* (Nakaseko & Nishimura), which has given its name to the Ladinian *Muelleritortis cochleata* Zone (Kozur & Mostler 1994; see Kozur 2003 for the correlation with ammonoid and conodont zones). *Annulotriassocampe eoladinica* Kozur & Mostler apparently also last occurs in the Ladinian (Kozur & Mostler 1994; Tekin & Mostler 2005). Some still undescribed multicyrtid nassellarians (*Conospongocyrtis*? spp., Fig. 8.7, 8) are associated, and are also known to exist in the *Muelleritortis cochleata* Zone (see pl. 3, figs. 35–36 in Hauser et al. 2001).

Sample L52

Greenish-red radiolarite. The sample contains fragments of Muelleritortiinae. This subfamily is restricted to the Ladinian and Early Carnian (O'Dogherty et al. 2009a, 2010), it does not extend above the early Early Carnian (Cordevolian) to be more precise (Kozur & Mostler 1996). An assignment to the Ladinian is indicated by *Triassocampe scalaris* Dumitrică, Kozur & Mostler which last occurs in this stage (Tekin 1999). The associated genus *Paurinella* was supposed to make its last occurrence in the Ladinian (O'Dogherty et al. 2009a, 2010) but has been proven to range up to the late Early Carnian *Tetraporobrachia haeckeli* Zone (Dumitrică et al. 2013).

Sample L40

Red radiolarite. The sample contains fragments of Muelleritortiinae, but lacks other taxa, diagnostic of either Ladinian or Carnian. *Corum kraineri* Tekin also spans the Ladinian and early Early Carnian (Tekin 1999).

Sample L295

Red radiolarite. This sample contains several genera (*Dumitricasphaera*, *Triassocingula*, and *Xiphothecaella*) that first occur in the Ladinian and continue at least to the Late Carnian (O'Dogherty et al. 2009a, 2010). *Angulopaurinella,* which last occurs in the late Early Carnian (see Dumitrică et al. 2013) is associated. *Canesium*? *cucurbita* Sugiyama, is characteristic of the late Ladinian and Early Carnian (Sugiyama 1997; Tekin 1999; Tekin & Göncüoğlu 2007; Sayit et al. 2011). The absence of Muelleritortiinae in this relatively diverse assemblage suggests that the sample is more probably Early Carnian than Ladinian in age.

Sample L26

Red radiolarite. The genus *Xipha* ranging from the Late Carnian to the Middle Norian (O'Dogherty et al. 2009a, 2010) defines the age of this sample. *Betraccium* and *Japonocampe* confirm that the sample is not older than the Late Carnian.

Table 5: Middle and Late Triassic radiolarian taxa from the mass-fows deposits in the Rossfeld Formation (see section Fig. 4). The age assignment of the samples is shown in the bottom row.

Radiolarian taxa samples	**L297**	**L52**	**L40**	**L295**	**L26**
Angulopaurinella dentispinosa Dumitrică & Tekin				cf.	
Angulopaurinella sp.				X	
Annulotriassocampe baldii Kozur				X	
Annulotriassocampe eoladinica Kozur & Mostler	X				
Betraccium sp.					X
Canesium? *cucurbita* Sugiyama				X	
Capnuchosphaera sp.					X
Conospongocyrtis? spp.	X				
Corum kraineri Tekin			X	cf.	
Corum? spp.			X	X	
Dumitricasphaera trialata Tekin & Mostler				cf.	
Japonocampe sp.					X
Muelleritortis cochleata (Nakaseko & Nishimura)	X				
Muelleritortis expansa Kozur & Mostler	X				
Muelleritortiinae indet. (detached spines)	X	X	X		
Pachus? sp.					X
Paurinella sp.		X			
Pseudostylosphaera nazarovi (Kozur & Mostler)	X				
Pylostephanidium sp.	X				
Triassocampe scalaris Dumitrică, Kozur & Mostler		X			
Triassocingula perornata (Blome)				cf.	
Xipha pessagnoi (Nakaseko & Nishimura)					X
Xiphothecaella sp.				X	
Age	**Ladinian**	**Ladinian**	**Ladinian–Early Carnian**	**Early Carnian**	**Late Carnian–Middle Norian**
Colour	**reddish-black**	**greenish-red**	**red**	**red**	**red**

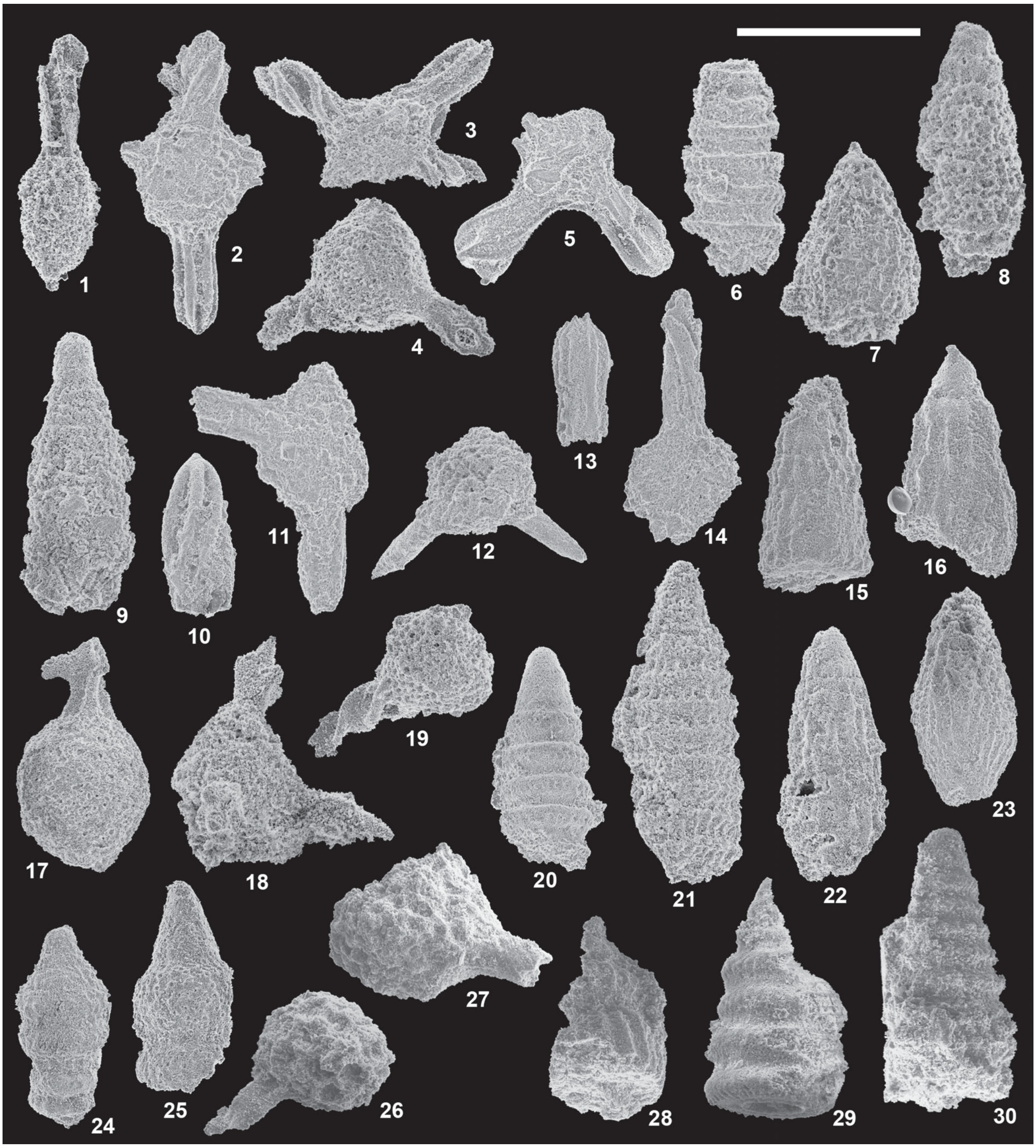

Fig. 8. Middle and Late Triassic radiolarians from radiolarite pebbles in the Rossfeld Formation. For each illustration the magnification (length of scale bar) is indicated. **1–8** — Radiolarians from sample L297. 1 — *Pseudostylosphaera nazarovi* (Kozur & Mostler), scale bar 200 μm. 2–3 — *Muelleritortis cochleata* (Nakaseko & Nishimura), scale bar 200 μm. 4 — *Pylostephanidium* sp., scale bar 150 μm. 5 — *Muelleritortis expansa* Kozur & Mostler, scale bar 300 μm. 6 — *Annulotriassocampe eoladinica* Kozur & Mostler, scale bar 150 μm. 7–8 — *Conospongocyrtis*? spp., scale bar 120 μm. **9–12** — Radiolarians from sample L52. 9 — *Triassocampe scalaris* Dumitrică, Kozur & Mostler, scale bar 150 μm. 10 — Muelleritortiinae indet., scale bar 200 μm. 11 — *Muelleritortis* sp., scale bar 200 μm. 12 — *Paurinella* sp., scale bar 150 μm. **13–16** — Radiolarians from sample L40. 13–14 — Muelleritortiinae indet., scale bar 200 μm. 15 — *Corum kraineri* Tekin, scale bar 120 μm. 16 — *Corum*? sp., scale bar 120 μm. **17–25** — Radiolarians from sample L295. 17 — *Dumitricasphaera* cf. *trialata* Tekin & Mostler, scale bar 200 μm. 18 — *Angulopaurinella* sp., scale bar 120 μm. 19 — *Angulopaurinella* cf. *dentispinosa* Dumitrică & Tekin, scale bar 120 μm. 20 — *Annulotriassocampe baldii* Kozur, scale bar 150 μm. 21 — *Triassocingula* cf. *perornata* (Blome), scale bar 150 μm. This specimen has wider pore frames than the Norian holotype (see Blome 1984, pl. 14, fig. 4, 9, 12, 14, 18), but it matches well the Early Carnian material from Turkey (see *Castrum perornatum* Blome in Tekin 1999, pl. 43, fig. 13). 22 — *Corum* cf. *kraineri* Tekin, scale bar 150 μm. 23 — *Corum*? sp., scale bar 150 μm. 24 — *Xiphothecaella* sp., scale bar 150 μm. 25 — *Canesium*? *cucurbita* Sugiyama, scale bar 150 μm. **26–30** — Radiolarians from sample L26. 26 — *Betraccium* sp., scale bar 100 μm. 27 — *Capnuchosphaera* sp., scale bar 100 μm. 28 — *Xipha pessagnoi* (Nakaseko & Nishimura), scale bar 100 μm. 29 — *Japonocampe* sp., scale bar 100 μm. 30 — *Pachus*? sp., scale bar 100 μm.

Jurassic

The Jurassic assemblages (Table 6, Fig. 9) were dated with the radiolarian catalogue and zonation of Baumgartner et al. (1995a,b) who established 22 Unitary Association Zones (UAZ) for the Middle Jurassic to the Early Cretaceous time interval. The ranges of species according to this zonation are included in Table 6. New data obtained in the last years show that some species have longer ranges than previously established by Baumgartner et al. (1995b). The ranges have been expanded for three species on the list in Table 6. *Eucyrtidiellum pustulatum* Baumgartner ranges up to UAZ 9 (see remarks on the Middle Oxfordian age of *Eucyrtidiellum unumaense* (Yao) s.l. in Beccaro 2004). *Striatojaponocapsa synconexa* O'Dogherty, Goričan & Dumitrică (it was introduced as *Tricolocapsa plicarum* ssp. A in Baumgartner et al. 1995a) now extends up to UAZ 6-7 (Prela et al. 2000; O'Dogherty et al. 2005). *Zhamoidellum ventricosum* Dumitrică ranges down to UAZ 6-7 (Šmuc & Goričan 2005).

Sample L72

Black radiolarite. *Gongylothorax* aff. *favosus* Dumitrică sensu Baumgartner et al. (1995a) constrains the age of the sample to UAZ 7-8 (Late Bathonian–Early Callovian to Middle Callovian–Early Oxfordian). The sample also contains the genus *Striatojaponocapsa* that last occurs in the Late Callovian (O'Dogherty et al. 2009b).

Sample L89

Greenish-black radiolarite. This sample is not older than UAZ 5 (latest Bajocian–Early Bathonian) as inferred from the first appearance datum of *Eucyrtidiellum pustulatum* Baumgartner. It is probably not younger than UAZ 7 (Late Bathonian–Early Callovian) as suggested by the last appearance datum of *Dictyomitrella*? *kamoensis* Mizutani & Kido.

Sample L112

Red radiolarite. Based on the range of *Eucyrtidiellum semifactum* Nagai & Mizutani, this sample is assigned to UAZ 5–7 (latest Bajocian–Early Bathonian to Late Bathonian–Early Callovian). *Striatojaponocapsa synconexa* O'Dogherty, Goričan & Dumitrică is also a good stratigraphic marker. *Gongylothorax* aff. *siphonofer* Dumitrică sensu Baumgartner et al. (1995a) with a conflicting range (UAZ 4 only) is associated. We note that this species has a very sparse record in the zonation of Baumgartner et al. (1995b) and its range must be extended upwards. Recently this species was found in the Callovian (Auer et al. 2007). In the inferred age assignment of this sample we deliberately ignored the proposed first appearance datum of *Parahsuum carpathicum* Widz & De Wever (it was published as *Parahsuum* sp. S in Baumgartner et al. 1995a) in UAZ 7. This first appearance datum is not considered fully diagnostic, because *Parahsuum carpathicum* has a very wide intraspecific variability and many closely similar *Parahsuum* species existed throughout the Middle Jurassic.

Sample L308

Greenish-black radiolarite. The radiolarians in this sample are very poor but undoubtedly Jurassic in age. A small nassellarian, probably a *Gongylothorax* (Fig. 9.21), has very small pores in a pore-frame structure, which is common in cryptocephalic and cryptothoracic nassellarians of Middle and Late Jurassic age. The genus *Canoptum*, whose last occurrence is recorded in the Late Bajocian (O'Dogherty et al. 2009b), also occurs.

Importance for provenance discrimination

Our results clearly demonstrate that determinations by the colour of the radiolarites without microfacies analyses and without dating cannot result in any interpretation of the prove-

Table 6: Middle Jurassic radiolarian taxa from the mass-flow deposits in the Rossfeld Formation (see section Fig. 4). The second column gives the zonal ranges of the species according to Baumgartner et al. (1995b); the arrows indicate that the ranges have been subsequently extended (see the text for references). The zonal assignment of the samples is shown in the bottom row.

Radiolarian taxa samples	**UAZ95**	**L72**	**L89**	**L112**	**L308**
Archaeodictyomitra patricki Kocher		X	X		
Canoptum krahsteinense (Suzuki & Gawlick)					cf.
Dictyomitrella? *kamoensis* Mizutani & Kido	3–7		cf.		
Eucyrtidiellum pustulatum Baumgartner	5–8→	X	X	cf.	
Eucyrtidiellum semifactum Nagai & Mizutani	5–7			X	
Gongylothorax aff. *favosus* Dumitrică sensu Baumgartner et al. (1995a)	7–8	X			
Gongylothorax aff. *siphonofer* Dumitrică sensu Baumgartner et al. (1995a)	4–4			X	
Gongylothorax sp.					X
Hemicryptocapsa buekkensis (Kozur)		X		X	
Hemicryptocapsa yaoi (Kozur)			X	X	
Parahsuum carpathicum Widz & De Wever	7–11			X	
Striatojaponocapsa synconexa O'Dogherty, Goričan & Dumitrică	4–5→	X		X	
Stichomitra? *annibill* Kocher		X			
Transhsuum brevicostatum (Ožvoldová)	3–11		cf.		
Transhsuum maxwelli (Pessagno) gr.	3–10			X	
Zhamoidellum ventricosum Dumitrică	←8–11			X	
Age (UAZones 95)		**7–8**	**5–7?**	**5–7**	
Colour		**black**	**greenish-black**	**red**	**greenish-black**

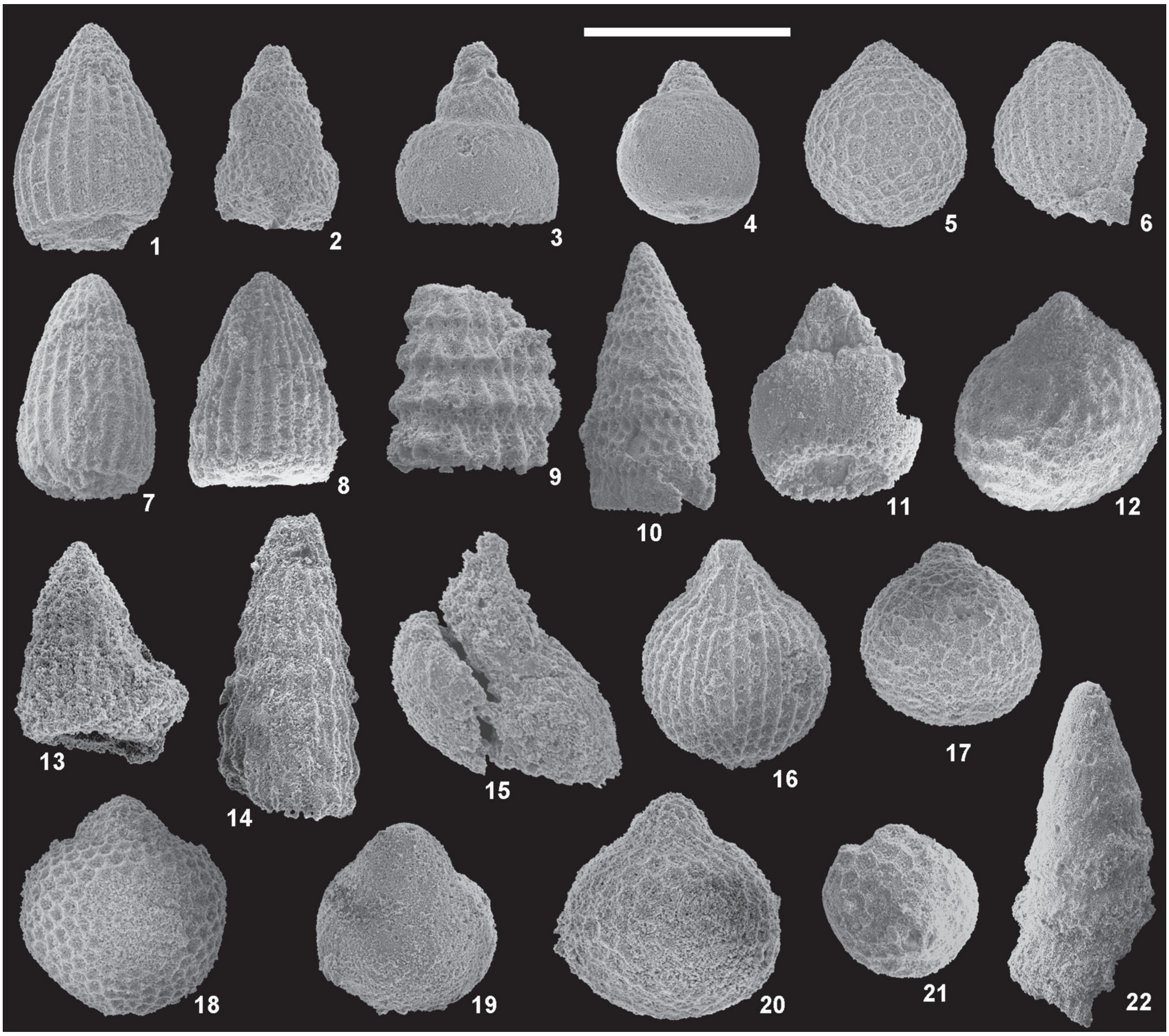

Fig. 9. Middle Jurassic radiolarians from radiolarite pebbles in the Rossfeld Formation. For each illustration the magnification (length of scale bar) is indicated. **1–6** — Radiolarians from sample L72. 1 — *Archaeodictyomitra patricki* Kocher, scale bar 100 µm. 2 — *Stichomitra*? *annibill* Kocher, scale bar 100 µm. 3 — *Eucyrtidiellum pustulatum* Baumgartner, scale bar 100 µm. 4 — *Hemicryptocapsa buekkensis* (Kozur), scale bar 100 µm. 5 — *Gongylothorax* aff. *favosus* Dumitrică sensu Baumgartner et al. (1995a), scale bar 100 µm. 6 — *Striatojaponocapsa synconexa* O'Dogherty, Goričan & Dumitrică, scale bar 100 µm. **7–12** — Radiolarians from sample L89. 7–8 — *Archaeodictyomitra patricki* Kocher, scale bar 100 µm. 9 — *Transhsuum* cf. *brevicostatum* (Ožvoldová), scale bar 120 µm. 10 — *Dictyomitrella*? cf. *kamoensis* Mizutani & Kido, scale bar 100 µm. This specimen has less pronounced circumferential ridges than the type material and also lacks distinct paired pores just below and above the ridges. 11 — *Eucyrtidiellum pustulatum* Baumgartner, scale bar 100 µm. **12** — *Hemicryptocapsa yaoi* (Kozur), scale bar 100 µm. **13–20** — Radiolarians from sample L112. 13 — *Parahsuum carpathicum* Widz & De Wever, scale bar 100 µm. 14 — *Transhsuum maxwelli* (Pessagno) gr., scale bar 150 µm. 15 — *Eucyrtidiellum semifactum* Nagai & Mizutani, scale bar 100 µm. 16 — *Striatojaponocapsa synconexa* O'Dogherty, Goričan & Dumitrică, scale bar 100 µm. 17 — *Gongylothorax* aff. *siphonofer* Dumitrică sensu Baumgartner et al. (1995a), scale bar 100 µm. 18 — *Zhamoidellum ventricosum* Dumitrică, scale bar 100 µm. 19 — *Hemicryptocapsa buekkensis* (Kozur), scale bar 100 µm. 20 — *Hemicryptocapsa yaoi* (Kozur), scale bar 100 µm. **21–22** — Radiolarians from sample L308. 21 — *Gongylothorax* sp., scale bar 100 µm. 22 — *Canoptum* cf. *krahsteinense* (Suzuki & Gawlick), scale bar 120 µm.

nance area. The rock colour can only be used as a descriptive feature at the outcrop (see Table 1). Weathered rims of siliceous pebbles give evidence for their surface exposure and their erosion during subaerial weathering. The general subrounded to rounded shape of radiolaritic, magmatic (e.g. basalts, pyroxenites), metamorphic (e.g. serpentinites) and quartz-sandstone pebbles give further evidence for fluvial transport to the depositional area. It can be expected that these pebbles were subsequently rounded by cyclic wave activity in a near-shore setting before being transported to their final depositional area in the deeper basin together with the contemporaneous carbonate and mixed carbonate-siliciclastic material. The radiolarite pebbles with their differences shown by microfacies analyses and biostratigraphic age-dating allow us to re-

Table 7: Paleogeographical origin of the investigated radiolarite pebbles of the Gartenau section.

Age range	Possible paleogeographical origin
Anisian/Ladinian	Meliata facies (continental slope) or Neotethys ocean floor
Ladinian	Meliata facies (continental slope) or Neotethys ocean floor
Ladinian/Early Carnian	Meliata facies (continental slope) or Neotethys ocean floor
Late Carnian/Norian	Neotethys ocean floor
Late Bajocian/Early Callovian	Matrix rock from radiolaritic-ophiolithic mélange
Late Bathonian/Late Callovian	Matrix rock from radiolaritic-ophiolithic mélange

construct their possible primary paleogeographical origins as well as their possible source areas (Table 7). Our results and comparison with data known from the literature (e.g. von Eynatten & Gaupp 1999) demonstrate that radiolarites and rocks from the ophiolitic suite were eroded from an ophiolitic nappe-stack of the Dinarides/Albanides/Hellenides (Neotethyan Belt according to Missoni & Gawlick 2011b).

Discussion

Investigations of the component spectrum from the different mass-flow deposits (see Fig. 1) of the Lower Cretaceous Rossfeld Formation in the Northern Calcareous Alps resulted in a subdivision into different rock groups by macro- and microscopic analysis:

1. Triassic carbonate clasts

Lower and Middle Triassic carbonate material can be observed at all investigated localities (Fig. 1B). From the microfacies analyses these rocks can be described as oolitic limestones and densely packed shell-rich limestones ("Lumachellenkalk") from the uppermost Werfen Formation and the basal Gutenstein Formation.

Middle to Upper Triassic shallow-water carbonate clasts from the Juvavic Dachstein and/or Berchtesgaden nappes as commonly interpreted on the basis of the colour of the clasts and without microfacies analyses (Kühnel 1929; Weber 1942; Medwenitsch 1949, 1958; Del-Negro 1949, 1983; Plöchinger 1955, 1968, 1974, 1990; Pichler 1963) are missing at all the investigated localities (Fig. 1), and in all mass-flow deposits of the Rossfeld Formation (Missoni & Gawlick 2011a; Krische 2012) as well as in the equivalent Firza Formation in Albania (Schlagintweit et al. 2008: Fi in Fig. 1A). The consequence of the pebble analysis is that the generally accepted view that these mass-flows should consist of the eroded material from the Juvavic nappes (e.g. Berchtesgaden and Dachstein Nappes characterized by Triassic carbonate-platform rocks) cannot be confirmed (see Faupl & Tollmann 1979; Schweigl & Neubauer 1997a,b). No single grain deriving from these Triassic carbonate platforms was found in the mass-flows.

2. Tithonian-Berriasian carbonate clasts

The uppermost Jurassic and lowermost Cretaceous shallow-water carbonate clasts derive from the Plassen Carbonate Platform (e.g. Plassen Formation) or represent slope-to-basinal carbonate pebbles (Oberalm Formation and Barmstein Limestone).

3. Valanginian to Hauterivian carbonate clasts

Carbonate clasts (probably Valanginian to Hauterivian) prove the existence of a contemporaneous shallow-water carbonate platform or ramp. Especially the existence of contemporaneous shallow-water carbonate areas, proved by carbonate litho- and bioclasts, was more or less unknown from the Rossfeld Formation but such clasts were described from other similar time-equivalent mass-flow deposits like the Firza-Flysch (Fi in Fig. 1A; Gardin et al. 1996; Bortolotti et al. 1996) or Firza Formation (Fi in Fig. 1A; Firza mass-flows, see Gawlick et al. 2008; Schlagintweit et al. 2008), the Paraflysch of the Vardar Zone (Pa in Fig. 1A; Dimitrijević & Dimitrijević 2009), and the Bosnian Flysch (Vr in Fig. 1A; Mikes et al. 2008).

4. Middle, Upper Triassic, and Middle Jurassic Radiolarite clasts and other siliceous pebbles

The results show that the siliceous pebbles can be classified by their microfacies into different groups: radiolarites, ophicalcitic rocks, siliceous (deep-sea) clays, microcrystalline cherts and brown-black siliceous marlstones. The characteristic microfacies of Anisian/Ladinian (see Gawlick et al. 2008; Gawlick et al. 2009b) and Upper Triassic radiolarites (see Gawlick et al. 2009b) allow a rough age assignment. This microfacies classification for the siliceous pebbles of the Gartenau section can also be used at other locations where siliceous pebble bearing conglomerate and breccia beds of the Rossfeld Formation occur (e.g. Bad Ischl, Rossfeld, Weitenau, see Krische 2012).

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 paleogeographical evolution. In the Late Anisian to Late Langobardian/Early Carnian time interval radiolarites were relatively 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). Upper Anisian to Carnian red-brown radiolaritic rocks from the passive continental slope (Meliata facies) were described by Mandl & Ondrejičková (1991) and Kozur & Mostler (1992) in the Callovian Florianikogel Formation (Northern Calcareous Alps), and by Mock (1980) in the Meliata area. From the Late Carnian on, a mixed siliciclastic-carbonate sedimentation dominated the Meliata facies-region (e.g. Mock 1980; Mandl & Ondrejičková 1991). Uppermost Ladinian to Upper Triassic radiolarites were not detected until now on the distal continental shelf margins towards the Neotethys Ocean, so and they are not expectable 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 huge amount of fine-grained carbonate mud on the distal shelf and partly in the oceanic domain (Gawlick & 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 Upper Triassic ribbon radiolarites are of special interest because they indicate fragments of the Neotethys oceanic realm. Ophicalcitic rocks and colourful siliceous (deep-sea) clays complete the pebble spectrum derived from the ocean floor.

The localities with preserved Neotethyan ophiolites including Middle to lower Upper Jurassic ophiolitic-radiolaritic mélanges show that primary radiolarite deposition also occurred directly on top of the oceanic crust. For example, in the Mirdita Zone of Albania (Fi, Pe in Fig. 1A), reddish-black, red-green and red, well bedded Upper Anisian to Lower Carnian and red Upper Carnian to ?Lower Norian and Norian-Rhaetian radiolarites (Chiari et al. 1996; Bortolotti et al. 2006; Gawlick et al. 2006, 2008; Bortolotti et al. 2013) occur as primary sedimentary cover of the oceanic crust as well as single blocks of different size within the Upper Bajocian to Oxfordian Perlat Mélange (Pe in Fig. 1A; e.g. Chiari et al. 2004; Gawlick et al. 2008). From the Dinaridic Ophiolite Belt of the Zlatibor Mélange (Zl in Fig. 1A; Lower Callovian to Middle Oxfordian) Upper Ladinian to Lower Carnian and Norian radiolarites were described (Gawlick et al. 2010b). Another locality near Sjenica (Zlatar Mountains, Sj in Fig. 1A) contains Lower Ladinian (Fassanian, Gawlick et al. 2009b) and red-green, bedded Upper Carnian to Lower/Middle Norian (Obradović & Goričan 1988; Goričan et al. 1999) radiolarite blocks within the Upper Bathonian to Lower/Middle Callovian or Callovian to Oxfordian mélange (Gawlick et al. 2009b). Remnants of Late Triassic to Jurassic ocean floor are also documented in the Vardar segment of the Neotethys (= Vardar) Ocean to the east (Obradović & Goričan 1988; Pamić et al. 2002; Karamata 2006). Remnants of a Jurassic accretionary complex of the Neotethys with occurrences of Middle and Upper Triassic radiolarites on top of ocean floor basalts were reported from the Medvednica and Kalnik Mountains in northern Croatia (Halamić & Goričan 1995; Pamić et al. 2002; Goričan et al. 2005). This ophiolitic mélange is similar to that in the Darnó Unit in the Pannonian Basin (Kovaćs et al. 2008), which occur here in a narrow zone within the Zagorje-Mid-Transdanubian Unit along the Mid-Hungarian Lineament (Haas et al. 2000; Kiss et al. 2008). Occurrences of Middle and Upper Triassic radiolarites on top of ocean floor basalts in the Avdella Mélange of the Northern Pindos Mountains of Greece (Av in Fig. 1A; Ozsvárt et al. 2012), Argolis (Chiari et al. 2013) or other areas in the Hellenic belt (see Bortolotti et al. 2013 for latest review) are also comparable. Therefore the proof of Middle and Upper Triassic and Middle Jurassic radiolarite pebbles together with ophiolitic material in the Lower Cretaceous Rossfeld Formation is a strong argument for the erosion of an ophiolitic nappe-stack similar to those of the Dinaridic-Hellenic belt south of the present day Northern Calcareous Alps at that time.

5. Volcanites, ophiolitic suite

Ophiolite detritus (e.g. pyroxenites, chromium spinel, …), volcanic material (e.g. basalts) and metamorphic rocks (serpentinites) are comparably long known clasts of the Rossfeld component suite and herein confirmed (see also Krische 2012). The ophiolitic clast spectrum of the Rossfeld Formation can also be documented at other localities with time-equivalent mass-flow deposits including the Firza-Flysch (Fi in Fig. 1A; Gardin et al. 1996; Bortolotti et al. 1996) or Firza Formation (Firza massflows, see Gawlick et al. 2008), the Paraflysch of the Vardar Zone (Pa in Fig. 1A; Dimitrijević & Dimitrijević 2009), the Bosnian Flysch (Vr in Fig. 1A; Mikes et al. 2008), the Pogari Formation (Po in Fig. 1A; Blanchet et al. 1970; Pamić & Hrvatović 2000; Neubauer et al. 2003) and the Oštrc Formation (Os in Fig. 1A; Lužar-Oberiter et al. 2009, 2012).

6. Siliciclastic rock clasts

The investigated siliciclastic rocks such as quartz-sandstones, siltstones and singular quartz-grains complete the mixed conglomerate and breccia component suite.

Jurassic and Cretaceous geodynamic evolution

It is important to note that the Triassic radiolaritic and accompanying siliceous rocks are preserved together with their primary underlying sequences like oceanic crust in the ophiolite belt striking from the Dinarides to the Hellenides, partly as blocks within the ophiolitic-radiolaritic mélanges. In the geodynamic evolution of the central Northern Calcareous Alps the Rossfeld Formation represents the final stage of a sedimentary cycle which had already started in the Late Permian. After a time of crustal extension (Permian to Middle Triassic), and the evolution of a passive continental margin (Middle Triassic to Early Jurassic), the situation changed in the late Early Jurassic. Intra-oceanic thrusting started in the Toarcian (Karamata 2006; Gawlick et al. 2008), ophiolite obduction onto the distal margin (Meliata and Hallstatt zones) started most probably in the Bajocian/Bathonian (e.g. Frisch & Gawlick 2003; Gawlick et al. 2008; Missoni & Gawlick 2011a). In Callovian-Oxfordian times the whole former passive margin became incorporated in this nappe-stack. The accretion of the former passive shelf margin was accompanied by contemporaneous resedimentation into the newly formed carbonate-clastic, radio-laritic wildflysch basins (e.g. Gawlick et al. 1999; Gawlick 2000; Gawlick & Frisch 2003; compare Karamata 2006; Schmid et al. 2008). These deep-water trench-like basins were formed in front of the advancing and rising Neotethys oceanic crust nappe-pile and its sedimentary cover (e.g. Gawlick et al. 1999, 2008; Schlagintweit et al. 2008).

The investigated brown-black siliceous marlstones can be interpreted together with the Middle Jurassic radiolarites (Table 7) as matrix rocks of these mélanges. According to previous and current results the ages of the ophiolitic radiolaritic mélanges along the Neotethyan Belt are Middle to early Late Jurassic, similar to the radiolaritic carbonate-clastic trench fills (= Hallstatt Mélange) in the Northern Calcareous Alps (?Bajocian/Bathonian to Oxfordian, Gawlick & Frisch 2003), and in the Western Carpathians (= Meliata Mélange, e.g. Kozur & Mock 1985, 1995; Mock et al. 1998; Aubrecht et al. 2010, 2012). Resedimented ophiolitic material in the Northern Calcareous Alps first occurs in the ?Bajocian to Callovian Florianikogel Formation (Neubauer et al. 2007) and in the Upper Kimmeridgian/Lower Tithonian Sillenkopf Formation (Missoni et al. 2001). The Hallstatt Mélange in the Eastern Alps and the Meliata Mélange in the Western Carpathians are interpreted as a result of the partial closure of the Neotethys Ocean (Meliata Ocean in the sense of several authors) (e.g. Kozur 1991; Channell & Kozur 1997; Gawlick et al. 1999; Frisch & Gawlick 2003; Csontos & Vörös 2004). Slightly older and age equivalent ?Early/Middle Jurassic (late Early Jurassic to Bajocian according to Babić et al. 2002 and Bajocian to Callovian according to Halamić et al. 1998, 1999) ophiolitic-radiolaritic mélanges occur in Croatia (e.g. Halamić et al. 1999; Babić et al. 2002), Bosnia and Herzegovina (Hrvatović 2006), Serbia (Dimitrijević et al. 2003; Gawlick et al. 2009a,b; Kovács et al. 2011), Albania (Bortolotti et al. 2005, 2013; Gawlick et al. 2008) and Greece (Jones & Robertson 1991; Jones et al. 1992; Stampfli et al. 2003; Bortolotti et al. 2004; Chiari et al. 2012; Ozsvárt et al. 2012; Robertson 2012). Enhanced pressure and temperature together with fluid-flow within the accreted ophiolite nappes and the mélanges led to recrystallization and partial loss of colour of different radiolarites. Brittle tectonic forces cleaved parts of the radiolarites and silica-rich fluid-flows induced siliceous cemented rims and veins.

Shallow-water carbonate platforms evolved from the Late Oxfordian (Auer et al. 2009) on top of the uplifting nappes (Schlagintweit et al. 2003, 2005; Gawlick et al. 2007, 2008), on top of the ophiolites (Schlagintweit et al. 2008, 2012b) and on top of the nappe-stack of the former passive Tethyan margin (e.g. Schlagintweit et al. 2003, 2005; Gawlick et al. 2007, 2008). The life cycle of these platforms was different. On top of the ophiolites uplift and erosion started in the Late Tithonian (compare Kilias et al. 2010; Kostaki et al. 2013) whereas formation of shallow-water carbonates prevailed on top of the southern Tirolic nappe-stack until the earliest Cretaceous. With the final drowning of the Plassen Carbonate Platform in the Late Berriasian (Gawlick & Schlagintweit 2006), the sedimentation pattern also changed in the more northern parts of the Northern Calcareous Alps. At first fine-grained siliciclastic rocks (Schrambach Formation) and later coarser-grained siliciclastic components (Rossfeld Formation) are characteristic. This material was eroded from the uplifting Middle to Late Jurassic nappe-stack or orogen (Neotethyan Belt of Missoni & Gawlick 2011b, see Fig. 10) and started to fill up the remnant basins between the areas of the drowned carbonate platforms. The observed different, biostratigraphically controlled constrained fining upward sequences within the Rossfeld Formation can be best explained by sea-level changes within a sedimentary basin of relative tectonic quiescence or decreasing tectonic activity. Pulses of erosional activity in the Early Cretaceous in combination with sea-level changes (for timing see Gradstein et al. 2004) and some tectonic activity (see Schlagintweit et al. 2012b) were important triggers for the formation of the oligo- to polymictic conglomerate and breccia beds of the Firza, Pogari and Rossfeld Formations and also most probably for the Vranduk and Oštrc Formations. Their component spectra are quite similar but an increase in roundness is observed in a direction approximately perpendicular to the orogen. This trend was induced by fluvial transportation of the radiolaritic, magmatic and siliciclastic rocks from the proximal deposits close to the Neotethyan Belt in contrast to their distal depositional area like the Rossfeld Basin of the Northern Calcareous Alps.

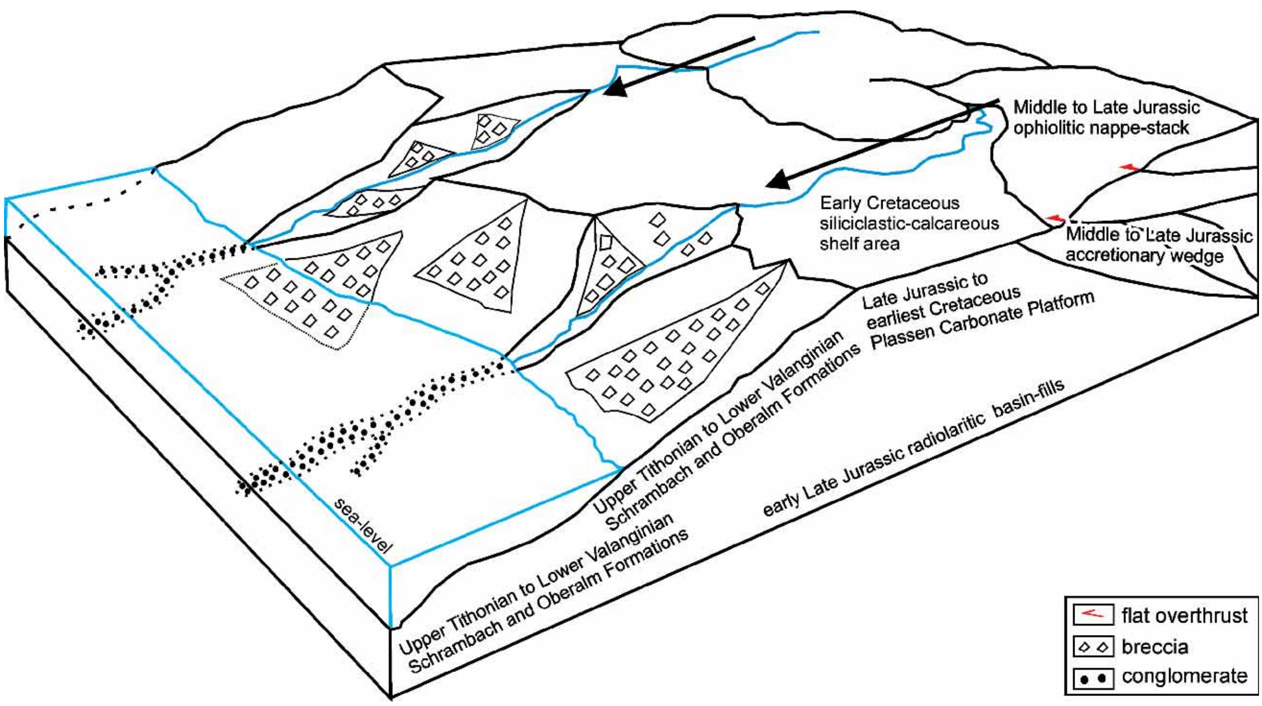

Fig. 10. Evolution of the basal conglomerates of the Rossfeld Formation of Gartenau. After the main sea-level lowstand in the late Early Valanginian the conglomerates were brought by fluvial systems from the exposed hinterland and shelf area to the deeper parts of the basin. Local material from breccia fans was also incorporated in the conglomerates. During the sea-level rise in the Late Valanginian the typical fining-upward sequences of the Rossfeld Formation were deposited, today clearly visible at several outcrops in Bad Ischl, Gartenau, Weitenau and on Rossfeld.

Conclusions

The Upper Triassic radiolarites together with components of the ophiolite suite and Middle Jurassic radiolarites in the Lower Cretaceous Rossfeld Formation of the central Northern Calcareous Alps suggest the following conclusions:

• In Late Jurassic to Early Cretaceous times an obducted ophiolite nappe-pile with intercalated ophiolitic-radiolaritic mélanges was present south of the today's Northern Calcareous Alps;

• These ophiolitic thrust sheets and mélanges must have been similar to those of the Dinaridic Ophiolite Belt in Serbia, the Mirdita ophiolite suite in Albania or the Hellenide ophiolite nappe stack in Greece;

• The Middle Triassic radiolarites represent erosional products of the original sedimentary cover of the Triassic to Early Jurassic Neotethys Ocean floor or less probably from the Meliata facies zone of the passive continental margin;

• The Upper Triassic radiolarites represent erosional products of the original sedimentary cover of the Triassic to Early Jurassic Neotethys Ocean floor;

• The Middle Jurassic radiolarites together with the siliceous marlstones represent erosional products from the matrix of the radiolaritic-ophiolitic mélanges, identical in age and microfacies to those known from the Dinaridic Ophiolite Belt in Serbia or the Mirdita ophiolite suite in Albania or the ophiolitic mélanges in the Hellenides;

• Slightly metamorphosed radiolarites and cleaved radiolarites with siliceous cemented veins prove the existence of enhanced pressure and temperature conditions within the nappe-stack as known from the Dinaridic-Hellenidic realm;

• The Jurassic nappe-stack of the Northern Calcareous Alps was induced by (in today's geographical direction) northward directed ophiolite obduction. The Northern Calcareous Alps together with the Western Carpathians, the units in the Pannonian realm (e.g. Transdanubian Range), the Southern Alps, the Dinarides, the Albanides, and the Hellenides attained a lower plate position and a thin-skinned orogen was formed in front of the northward propagating obducted ophiolites;

• This Jurassic nappe-stack was sealed by Kimmeridgian/Tithonian platforms which prevailed partly until the earliest Cretaceous. Mountain uplift from the latest Jurassic onwards resulted in erosion of the platforms and the underlying nappe-stack. In Early Cretaceous times these erosional products reached the far-away foreland basins;

• The sedimentary cycles in these Rossfeld basins reflect either a) pulses of the decreasing tectonic activity during the Early Cretaceous and/or b) sea-level changes. This resulted in deep erosion of the nappe-stack and is reflected by the coarse-grained mass flows, interpreted as lowstand wedges or lowstand fans, deposited during a relative sea-level lowstand or during the transgressive phase just after maximum regression;

• Resedimented bioclasts in the Rossfeld Formation give evidence for a contemporaneous shallow-water platform/ramp between the today's Northern Calcareous Alps and the eroded ophiolite stack during the Valanginian to Hauterivian time-span, representing a coastal and shallow-marine environment;

• Sedimentological features and component analyses of the Rossfeld Formation support the interpretation of an underfilled foreland basin setting affected by sea-level fluctuations and local tectonics;

• Components of the Triassic to Jurassic passive margin sequence of the Northern Calcareous Alps are missing in the component spectrum, not a single component of a proposed "Juvavic" nappe occurs. Therefore, the Early Cretaceous as the main nappe-thrusting time in the Northern Calcareous Alps as formerly interpreted cannot be confirmed.

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