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The Rigelj Formation, a new lithostratigraphic unit of the Lower Permian in the Karavanke Mountains (Slovenia/Austria)

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Abstract
The Rigelj Formation is a new lithostratigraphic unit of the Lower Permian Rattendorf Group in the Karavanke Mountains. The Formation is up to 105 m thick and mainly composed of siliciclastic and fossiliferous carbonate sediments that are entirely of shallow-marine setting. Conglomerates are interpreted as shoreface deposits, sandstones as deposits of the upper to lower shoreface, and fossiliferous siltstones as offshore deposits. Fossiliferous limestones were deposited in a shallow, open-marine shelf environment of moderate to low energy (wackestone, floatstone) and strong water turbulence (packstone, rudstone). The siliciclastic and carbonate lithotypes form some well-developed backstepping cycles starting with conglomerates, overlain by sandstones, siltstones and fossiliferous limestones that formed in an open shelf environment without siliciclastic influx. Similar sedimentary cycles are developed in the Grenzland Formation of the Carnic Alps.

The fusulinid fauna indicates that the Rigelj Formation ranges in age from the late Asselian to the middle Sakmarian. In the western Karavanke Mountains and near Trögern, the Lower Permian lithostratigraphic succession is very similar to the succession in the Carnic Alps with Tarvis Breccia resting on the Trogkofel Limestone and the Goggau Limestone. Unlike this, in the central part of the Karavanke Mountains (Dovžanova Soteska–Mt. Pleschiwetz/Plešivec area) the Rigelj Formation is erosively overlain by the Tarvis Breccia. The stronger diversification of the sedimentary environments within the Karavanke-Carnic Alps in the Lower Permian after the uniform sedimentation in the Upper Carboniferous can be attributed to block-faulting.

1. Introduction

In the Karavanke Mountains, Upper Paleozoic (Upper Carboniferous–Lower Permian) sedimentary rocks are exposed in the Slovenian as well as the Austrian part of the Southern Alps. Due to strong Alpine deformation, complete sections are very rare and Upper Paleozoic rocks are often exposed in form of tectonically isolated outcrops. Due to poor outcrop quality, lack of complete sections and strong tectonic deformation, these rocks have rarely been studied in detail in the past (see Heritsch, 1943).

In the central Carnic Alps which are located along the Austrian/Italian border approximately 90 km west of the central Karavanke Mountains, the Upper Paleozoic sedimentary succession is less deformed and the Upper Carboniferous–Lower Permian formations are well exposed in mostly complete sections (summaries in Schönlaub and Forke, 2007 and Novak et al., 2019). While Upper Carboniferous lithostratigraphic successions of the Carnic Alps and Karavanke Mountains are almost identical in facies and in fossil content, there are significant differences in the facies of the Lower Permian between the two mountain ranges.

The aim of this paper is (1) the description and documentation of a new lithostratigraphic unit (Rigelj Formation) of the Lower Permian succession of the Karavanke Mountains including lithology, petrography of siliciclastic sedimentary rocks, microfacies of carbonate sedimentary rocks and fossil assemblage, (2) discussion of the biostratigraphy of the Rigelj Formation and (3) comparison with similar successions (Grenzland Formation, Zweikofel Formation) of the Carnic Alps.

2. Historical background

In the Karavanke Mountains, Teller (1898) included the Lower Permian sedimentary rocks into the "Upper Carboniferous" succession, which he divided into three horizons. Schellwien (1898, 1900) described a rich fauna from the reddish "Trogkofelkalk" of the Dovžanova Soteska (Dovžan Gorge, Teufelsschlucht) which he dated as "Permocarboniferous". This limestone body was later studied in detail by Heritsch (1933, 1938), who described the lithological characteristics, coral species and revised Schellwien's brachiopod determinations. He correlated this variegated limestone with the Permian Trogkofel Limestone.

The light grey fossiliferous limestone near Trögern which Teller (1898) included into the "Upper Carboniferous" was later ascribed to the Trogkofel Limestone and dated as Permian (Heritsch, 1943). From the black bedded limestones within the mixed carbonate-siliciclastic succession overlying the massive reddish "Trogkofelkalk" in the Dovžanova Soteska, Kahler and Kahler (1937) described a new fusulinid species *Pseudochwagerina carniolica* and ascribed these beds to the Lower Permian (Asselian) "Obere Pseudoschwagerinenschichten".

Kochansky-Devidé and Ramovš (1966) and Kochansky-Devidé (1970, 1971) studied the fusulinoidean fauna in the western Karavanke Mts. and ascertained that the biostratigraphic subdivision from the Carnic Alps (Heritsch et al., 1934) can also be applied to the Karavanke Mountains with only minor modifications. They found lithostratigraphic equivalents of the Auernig Beds of Gzhelian and "Orenburgian" age, Upper Pseudoschwagerina Limestone of Asselian age, and Trogkofel Limestone of Sakmarian to Artinskian age. The main difference was that they assumed two developments of the Trogkofel Beds; besides the Trogkofel Limestone they described the "Clastic Trogkofel Beds" composed of red and grey, locally fossiliferous shale, siltstone, sandstone and quartz conglomerate with intercalated thin beds of dark grey limestone. The concept of the Clastic Trogkofel Beds was established in the Outer Dinarides (Ortnek area) in southern Slovenia (Ramovš, 1963; Ramovš & Kochansky-Devidé, 1965) and then later applied to the Karavanke Mountains (Ramovš, 1968). The stratigraphic range and paleogeographic position of the outcrops at Ortnek and to the south-east in Croatia (Gorski Kotar) is still poorly constrained. Clastic Trogkofel Beds were supposed to contain reworked bio- and lithoclasts from the Auernig Beds, the Lower and Upper Pseudoschwagerina Limestone, and the Grenzland Beds (Ramovš, 1968, 1972, 1976a, 1982; Kochansky-Devidé et al., 1973; Buser, 1974, 1980).

Kahler (1983) determined fusulinids from isolated outcrops at the northern side of the Koschuta/Košuta (several localities SW and SE of Zell Pfarre) which in the Carnic Alps occur within the Lower Permian Grenzland and Zweikofel Fms. and the Goggau Limestone. Kahler also described Lower Permian fusulinids from the locality Remscheniggraben and Vellachtal south and southeast of Eisenkappel.

On the Basic Geologic Map of Slovenia 1:100.000, sheet Celovec (Klagenfurt) (Buser and Cajhen, 1978; Buser, 1980), the described succession was assigned to the Trogkofel Beds (Trogkofel Limestone and Clastic Trogkofel Beds). Rocks exposed on the southern slope of Mt. Pleschiwetz/Plešivec were mapped as Clastic Trogkofel Beds with lenses of massive Trogkofel Limestone, overlain by Tarvis Breccia that forms the peak of Pleschiwetz/Plešivec (Buser & Cajhen, 1978).

On the geologic map of the Austrian part of the Karavanke Mountains (eastern part) Bauer (1981) distinguished Upper Carboniferous "Auernigschichten" and Lower Permian (Unterrotliegendes) "Trogkofelkalk", and locally "klastische Trogkofelschichten" in which he included the Tarvis Breccia (see Bauer et al., 1983). Bauer (1981) also mapped rocks exposed on Mt. Pleschiwetz as "Clastic Trogkofel beds". According to Tollmann (1985) the Late Paleozoic succession of the Karavanke Mountains is composed of Auernigschichten, overlain by Rattendorfer Schichten (Untere Pseudoschwagerinenschichten, Grenzlandbänke, Obere Pseudoschwagerinenschichten) and Trogkofelkalk.

The most complete succession of Upper Carboniferous to Lower Permian sedimentary rocks of the Karavanke Mountains is exposed in the Dovžanova Soteska near Tržič, on the southern side of the Koschuta/Košuta. Permian limestone was long thought to be equivalent to the Trogkofel Limestone in the Carnic Alps. Buser and Forke (1996) first questioned this correlation based on the findings of conodonts. Subsequently, Forke (2002) and Novak (2007a, b) studied this section and provided a detailed sedimentologic, paleontologic and stratigraphic description. They showed that the facies of the Lower Permian succession at Dovžanova Soteska differs from that of the Carnic Alps (particularly equivalents of the Grenzland Formation). They divided the sedimentary succession between the underlying Schulterkofel Fm. and overlying Tarvis Breccia into the Dovžanova Soteska Formation, Born Formation and Rigelj Beds, which approximately correlate to the Grenzland Formation of the Carnic Alps (see summaries in Novak and Skaberne, 2009, and Novak et al., 2019).

3. Study area

The type section of the Rigelj Formation is exposed in the Dovžanova Soteska [Dovžan Gorge; written as Dolžanova in older publications and known as Teufelsschlucht (Devil's Gorge) in the German-language literature], 2.6 km NE of the town of Tržič (Neumarkt) in northern Slovenia (46°23′00″ N, 14°19′40″ E). Parts of the composite section are located at both, the south-eastern and the north-western slope of the Tržiška Bistrica river valley, on the slopes of Čepca and Rigelj respectively. The location of both sections is shown in Figure 1, the section Rigelj is shown in Figure 2a.

The reference section of the Rigelj Formation is located on the SSE side of the summit of Mt. Pleschiwetz/Plešivec at the Austrian-Slovenian border in the central Karavanke

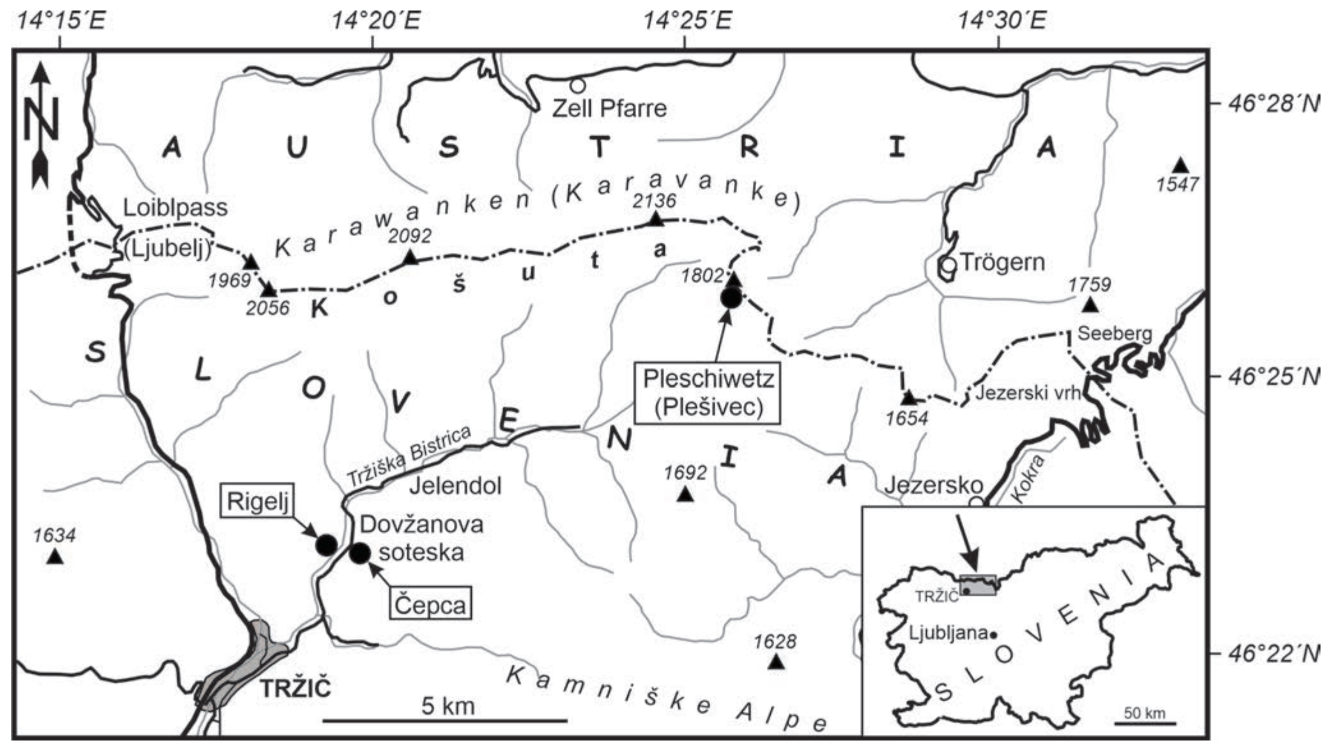

Figure 1: Map showing the location of the studied sections at Dovžanova Soteska (Dovžan Gorge) and at Mt. Pleschiwetz/Plešivec in the central Karavanke Mountains.

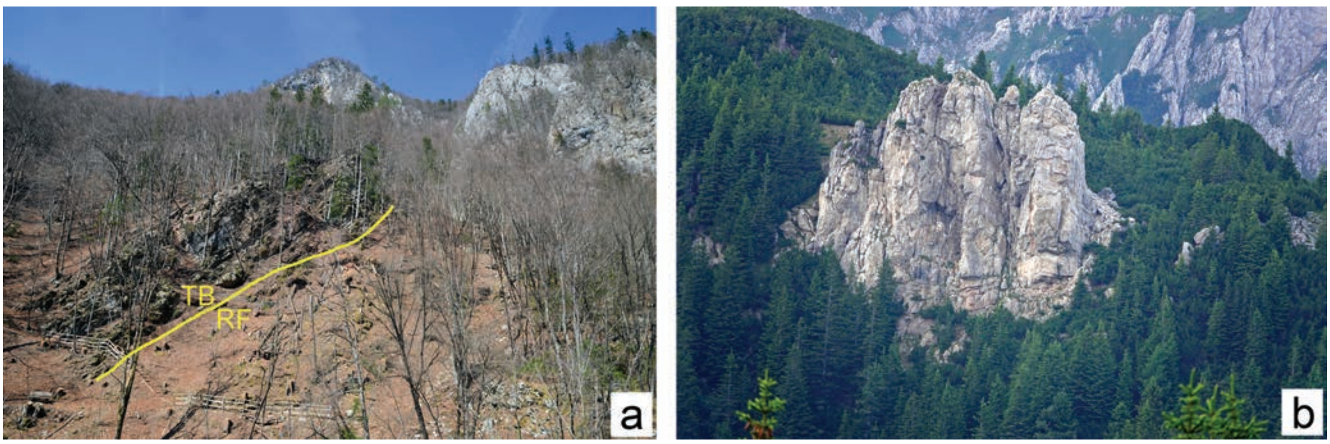

Figure 2: **(a)** Rigelj type section exposing the upper part of Rigelj Formation (RF) and the contact with Tarvis Breccia (TB). **(b)** Mt. Pleschiwetz/Plešivec reference section.

Mountains (46°26´00´´ N, 14°25´57´´ E) approximately 10 km NE of the type section. The section was measured on the Slovenian part, about 30–50 m aside the state border (Figs 1 and 2b). The Rigelj Formation is also well exposed in the steep walls south of Schenkwiese on the northeastern side of Mt. Pleschiwetz on the Austrian side.

4. Rigelj Formation

The name is derived after the slope that is called Rigelj, where the upper part of the formation with characteristic fossils is exposed. At the type section in the Dovžanova soteska the exposed thickness of the Rigelj Formation is approximately 105 m (Novak, 2007a). The lower part is poorly exposed and the contact to the underlying Born Formation is tectonically overprinted. The upper boundary to the overlying Tarvis Breccia is a well exposed erosional disconformity. The measured reference section on Mt. Pleschiwetz/Plešivec is approximately 70 m thick. The lowermost 10 m represent the uppermost Born Formation. The overlying succession of quartz-rich conglomerates with dominantly carbonate matrix and intercalated limestone, sandstone and siltstone, for which Novak (2007a) introduced the informal term "Rigelj Beds" is almost completely exposed on Mt. Pleschiwetz,

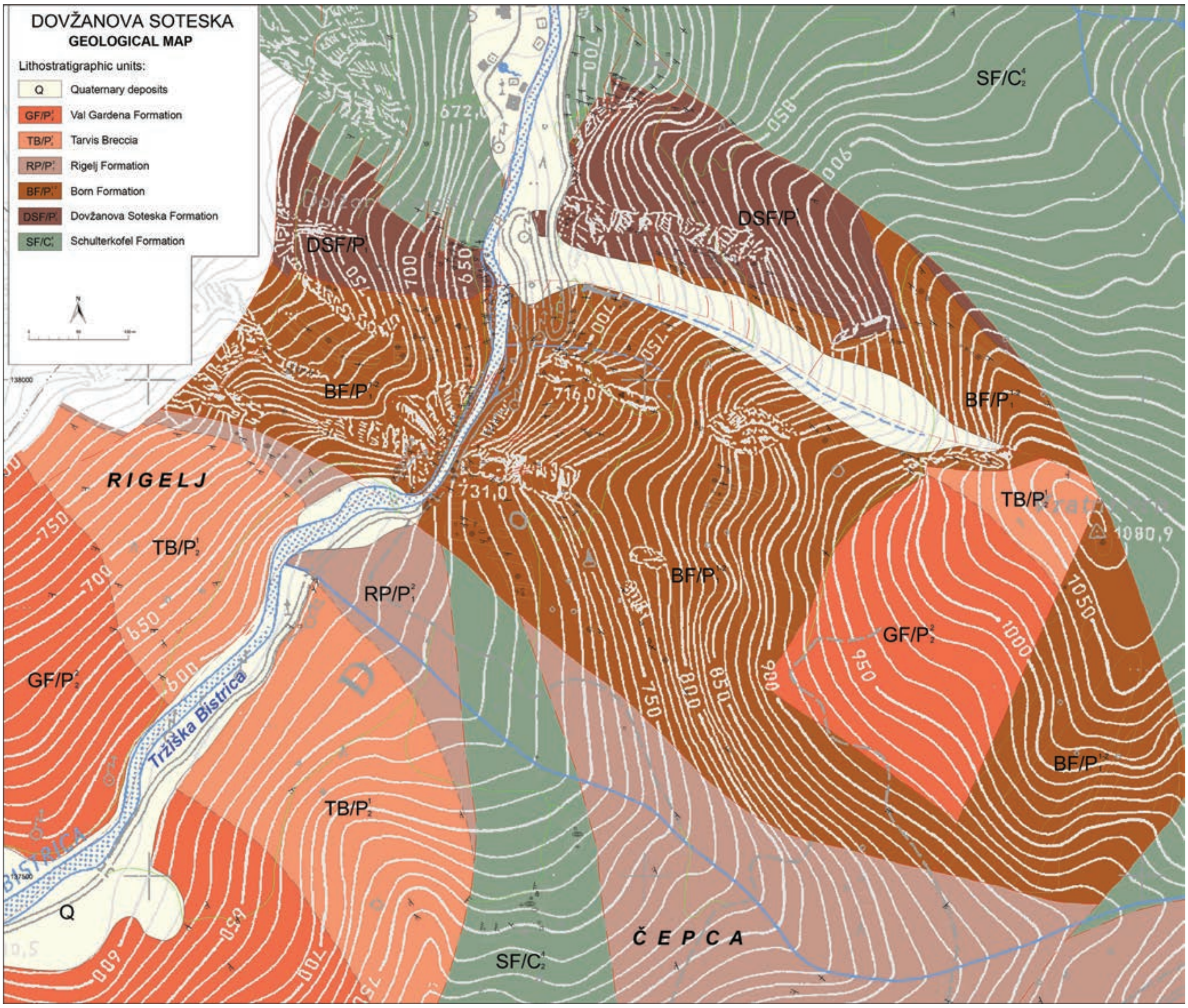

Figure 3: Geological map of Dovžanova Soteska (after Novak, 2007a).

although the succession displays some tectonic deformation. The Rigelj Formation at the reference section is approximately 58 m thick. The contact to the underlying Born Formation is sharp and well exposed; the contact to the overlying Tarvis Breccia is covered.

4.1 The Dovžanova Soteska type locality

The Rigelj Formation at the type locality in the Dovžanova Soteska (Figs 3 and 4) was described as Rigelj Beds by Novak (2007a). Additional field research in order to clarify the correlation with the Pleschiwetz/Plešivec reference section showed that the lithostratigraphic logs published by Novak (2007a) require some corrections. Particularly section Čepca 1 (Č 1) does not reflect the discontinuities of the composite section clear enough. Additional studies of the microfacies showed (1) that conglomerates in the lower part of the Čepca 1 section (between metres 34 and 47) contain carbonate cement, (2) that the thickness of two units were overestimated, and (3) that the beds shown in the middle part of the Čepca 1 section (between metres 47 and 67.5) in fact belong to the Born Formation.

At the type locality in both sections Čepca and Rigelj the sedimentary rocks of the Rigelj Formation overlie limestones of the Born Formation with a tectonic contact (Fig. 3). The Rigelj Formation can be subdivided into a lower, dominantly siliciclastic part (approximately 41 m thick) and an upper, dominantly carbonate succession that is approximately 64 m thick.

4.1.1 Uppermost Born Formation

The upper part of the Born Formation in the Dovžanova Soteska consists of almost 200 m of dark grey to black bedded limestones. Thin (5–10 cm) limestone beds are often folded and interbedded with irregular 1 mm to several cm thick shale layers. Both, limestone and shale interbeds contain numerous thalli of phylloid algae, smaller foraminifera, fusulinoideans, and in some places large planispiral euomphalid gastropods. The original

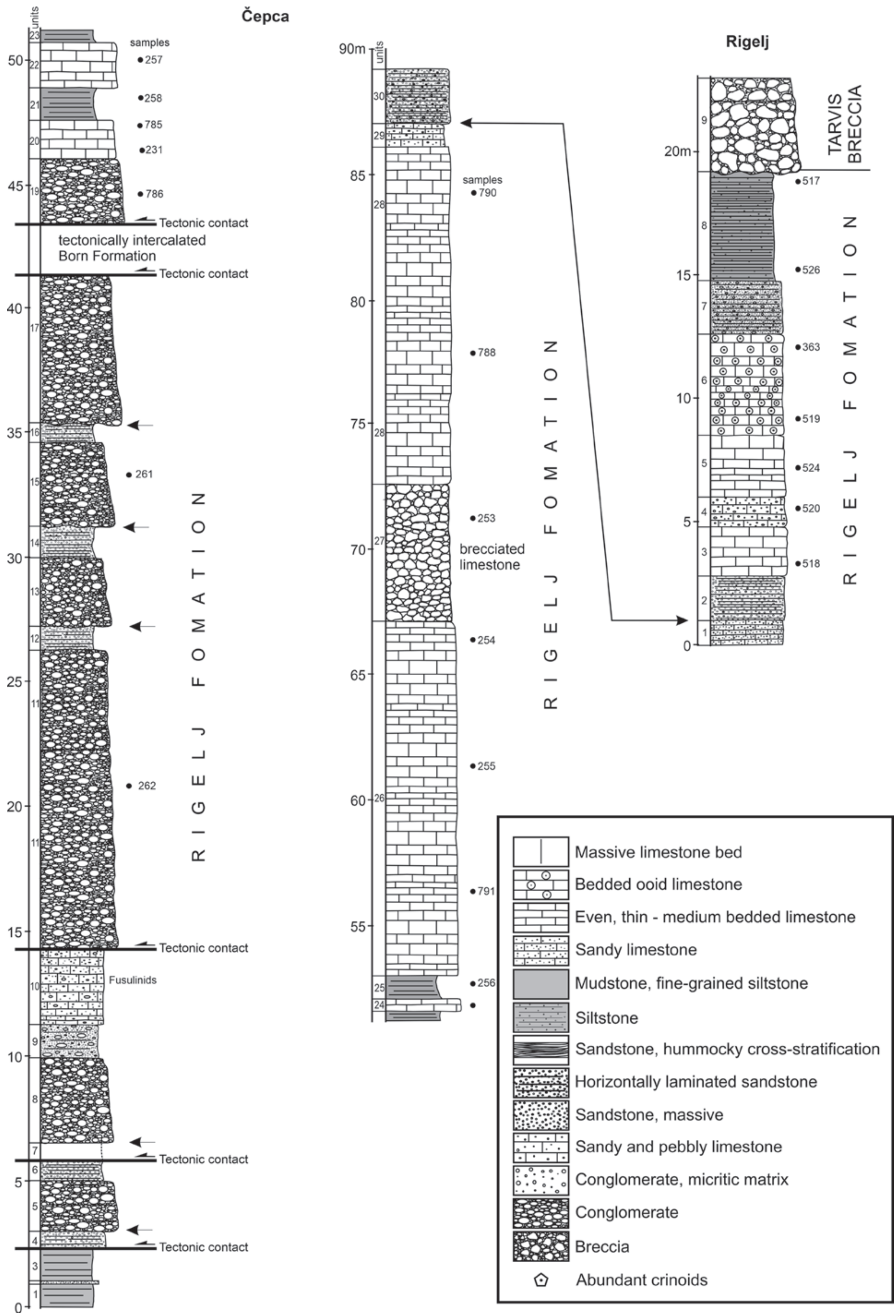

Figure 4: Measured lithostratigraphic section through the Rigelj Formation (type section) at Čepca and Rigelj. Location see Figure 1.

texture was modified by the intense bioturbation, differential early diagenetic cementation, and the differential solubility of clay-rich and carbonate-rich sediments during late diagenetic processes connected with pressure-solution. Evenly-bedded sediments were transformed into wavy or nodular bedded limestone.

In an 80 cm thick horizon of brownish-grey siltstones and marlstones underlying a massive 2 m thick *Anthracoporella* algal mound in the uppermost part of the Born Formation, a scarce but highly diverse faunal association of cephalopods *Agathiceras* cf. *uralicum* (Karpinsky), Marathonitidae indet. and Pseudorthoceratidae indet., corals of the *Lophophyllidium* group, brachiopods, gastropods, echinoids, and paraconulariids was recorded (Novak, 2007a). The algal mound is capped by 1 m of fossil-free black shale, overlain by a 4 m thick horizon of grey, thin-bedded marly limestone with thin shale partings and abundant fossils. The uppermost part of the Born Formation can be traced in a gully above the road-tunnel, but after approx. 20 m a major fault crosses the section (Fig. 3). All (micro)facies types with identical fauna, characteristic of the Born Formation, described in the lower part of the Mt. Pleschiwetz/Plešivec reference section, do occur in isolated outcrops of tectonic lenses within this fault zone, but their relationship is impossible to discern. The succession described at Mt. Pleschiwetz/Plešivec very likely represents the normal succession between the reddish micritic limestone as the last unit of the uppermost Born Formation in the section and carbonate-cemented conglomerates of the Rigelj Formation as the first to follow on the southern side of the fault zone.

Microfacies

The most common microfacies type of the black bedded limestone is intensely bioturbated bioclastic mudstone to phylloid algal bafflestone. Bioturbation burrows were filled with calcite spar. Stacked phylloid algae acted as bafflers of the micritic sediment. Stylolitic seams indicate later compaction and significant pressure solution.

Characteristic microfacies are also wacke- to packstones in which slightly abraded tests of fusulinoideans (*Darvasites* spp., »*Triticites* sp.«) with micritized peripheries suggest their pre-depositional transport. The *Anthracoporella* mound is composed of floatstone with rare fragmented crinoid stems in the lowermost part and bafflestone of the micritic algal core facies in the upper part. Laterally occuring flanking beds of wacke- to packstone contain bryozoans, *Tubiphytes*, phylloid algae, foraminifera, and echinoderm fragments.

The marly limestone on top is composed of bioclastic wackestone to floatstone containing abundant fusulinoideans (*Staffella* sp., *Schubertella australis* Thompson & Miller, *Quasifusulina* sp., *Dutkevitchia* aff. *complicata* (Schellwien), *D.* cf. *splendida* (Bensh), *Pseudoschwagerina* sp., *Sphaeroschwagerina* sp., *Paraschwagerina* aff. *mukhamedjarovica* Rauzer-Chernousova, »*Pseudofusulina*«), smaller foraminifera (*Endothyra*, *Hemidiscus*, *Syzrania*, *Tezaquina*, *Nodosinelloides*?, *Ammovertella*, *Calcitornella*, *Monogenerina*, *Cribrogenerina*, *Deckerella*, *Spireitlina*, *Tetrataxis*), various cystoporid, trepostomid and fenestellid bryozoans, algae (*Anthracoporella spectabilis* Pia, *Eugonophyllum*, *Epimastopora alpina* Kochansky & Herak, *Globuliferoporella symetrica* (Johnson), *Anchicodium*), ostracods and *Tubiphytes*. Cystoporid bryozoans (*Fistulipora*) and *Tubiphytes* commonly encrust other bioclasts.

4.1.2 Rigelj Formation at the Čepca type section

The Čepca type section represents the lower part of the Rigelj Formation. It is composed of alternating shale-siltstone, sandstone, pebbly sandstone, conglomerate, and various types of limestone (Fig. 4).

The lower 41 m of the exposed section are composed of dominantly siliciclastic sedimentary rocks. The section starts with 2.3 m of shale to siltstone with thin sandstone beds intercalated. The overlying 3.6 m of carbonate-cemented quartz sandstone with gradual transitions to conglomerate are bounded by tectonic contacts (Fig. 5a). Beds are 10–25 cm thick. Conglomerate is clast supported and composed of well rounded and well sorted polycrystalline quartz grains with diametres between 0.3 and 1 cm. Grains are cemented by coarse crystalline calcite. Rare bioclasts are represented by strongly abraded crinoids, bryozoans and brachiopod shells.

The overlying unit 8 of massive quartz conglomerate is 3.4 m thick and forms the base of a fining upward cycle that is 7.7 m thick. The conglomerate is poorly sorted and composed of subrounded to well rounded pebbles. Their average diameter is 4 cm with maximum diametres exceeding 10 cm. Most abundant are grey polycrystalline quartz pebbles, subordinately black chert (lydite) pebbles and mica are present. The conglomerate grades upward into pebbly sandstone and, with increasing amount of carbonate, into dark-grey fossiliferous pebbly limestone (Fig. 5b). The pebbly sandstone unit is 2.6 m thick. Beds of almost uniform thickness (30 cm) consist entirely of quartz grains. These beds are very well sorted and internally stratified with larger (up to 2 cm), well rounded pebbles being concentrated in approx. 5 cm thick layers overlain by fine-grained, cross-bedded sandstone.

The pebbly sandstone is overlain by a bedded pebbly limestone unit that is 2.7 m thick and tectonized in the upper part. Bed thickness is 15–40 cm. The limestone is composed of bioclastic pack- to grainstone with numerous abraded tests of fusulinoideans (*Schubertella* sp., *Sphaeroschwagerina carniolica*, *Sphaeroschwagerina* cf. *citriformis*), algae, bryozoans, crinoid and brachiopod fragments in sandy mixed siliciclastic and carbonate matrix. One limestone bed consists of oolitic grainstone with quartz grains and bioclasts forming the nuclei of ooids. All beds contain an admixture of up to 1 cm large quartz pebbles. This succession is overlain by thick, massive to bedded, coarse-grained and poorly-sorted quartz conglomerates overlain by thin sandstone units

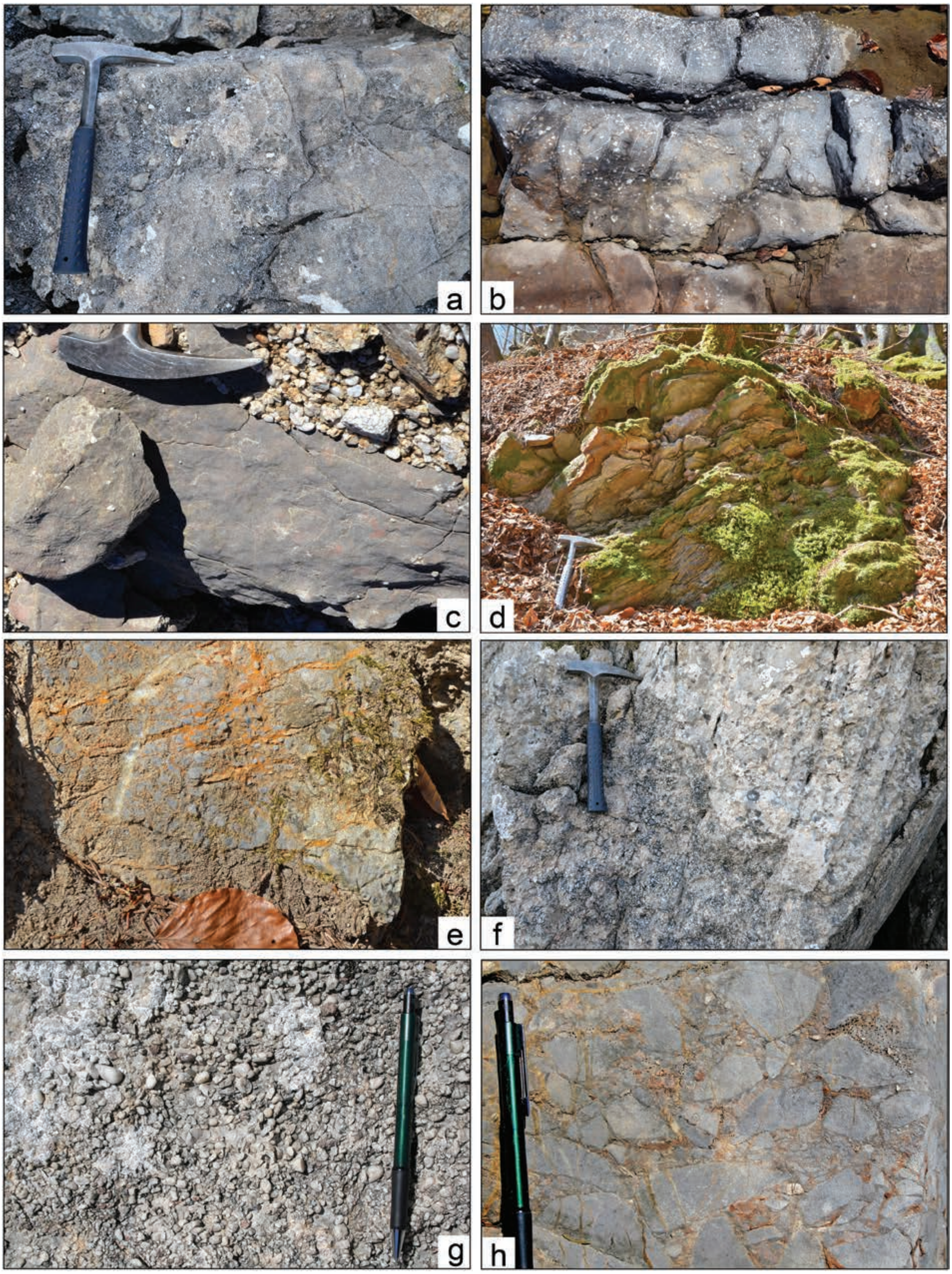

Figure 5: Lithofacies types of the Rigelj Formation at the Čepca and Rigelj type-sections and at the Pleschiwetz/Plešivec reference section. (a) Carbonate-cemented quartz sandstone with gradual transitions to conglomerate from the lower part of the Rigelj Formation at section Č 1. (b) Pebbly sandstone and dark-grey fossiliferous pebbly limestone. Section Č 1. (c) Variegated, light to dark grey, partly brecciated reddish limestone. Section Č 1. (d) Thin-bedded calcarenite and sandstone in the base of section R 1. (e) Black bedded limestone with numerous sphaeroschwagerinids, weathered out from the rock surface. Section R 1. (f) Fine-grained quartz conglomerate with carbonate matrix displaying erosive contact with limestone. Section Pleschiwetz/Plešivec. (g) Fine-grained conglomerate from the lower part of the Rigelj Formation at Mt. Pleschiwetz/Plešivec, composed of well-rounded quartz grains and micritic matrix. (h) Tarvis Breccia exposed at Mt. Pleschiwetz/Plešivec, composed of reworked Lower Permian carbonate rocks (mainly Trogkofel Limestone) and some small quartz grains.

forming four fining upward cycles up to 12 m thick. Conglomerate units display an erosive base and are clast supported. Quartz pebbles are up to 15 cm in diameter, 5 cm at average, poorly-sorted with moderately to well rounded clasts near the base. They grade upwards to medium-sized, moderately to well sorted pebbles forming indistinctly developed bed sets that are up to 1.5 m thick and rarely display trough cross-stratification. Intercalated sandstone units are 0.7 to 1.8 m thick, coarse-grained and display horizontal lamination or trough-crossbedding.

This siliciclastic succession is overlain by a dominantly carbonate succession that starts with 6.8 m of black, thin-bedded fossiliferous limestone and intercalated thin shale-siltstone. Limestone beds are 4 to 15 cm thick.

This unit grades upwards into a 33.5 m thick succession of indistinctly bedded to massive, variegated, light to dark grey, partly reddish limestone and intercalated brecciated reddish limestone (Fig. 5c). In a tectonically dislocated block of this limestone exposed in the Potarje village about 600 m east of the measured section Holzer & Ramovš (1979) and Ramovš (1988) discovered a small colony of the compound rugose coral *Yokoyamaella (Yokoyamaella) stillei* (Heritsch).

The limestone succession ends with 3 m of thin bedded crinoid calcarenite, gradually passing into quartz sandstone. The upper contact with the Tarvis Breccia is covered.

Microfacies

In the lower part, the black, thin-bedded limestone is composed of mudstone to wackestone with numerous fragmented brachiopod shells, rare fusulinids (*Dutkevitchia* cf. *splendida* (Bensh), *Dutkevitchia* sp.), smaller foraminifera, bryozoans, ostracods and echinoderms. In the upper part, floatstone/bafflestone with recrystallized thalli of phylloid algae is the predominant microfacies type. The indistinctly bedded to massive variegated limestone unit is composed of the following microfacies types:

a) Coarse-grained breccia with clasts of micritic limestone (mudstone) and intrabiomicritic to intrabiosparitic pack- to grainstone. These clasts contain typical reef-building organisms with predominant encrusting problematic cyanophycean *Tubiphytes obscurus* Maslov accompanied by the microproblematic organism *Bacinella*, calcareous sponges (e.g. *Peronidella* Hinde) and recrystallized calcitic shells. The groundmass is composed of pelmicrite and two generations of sparry calcite cement (first isopachous rim cement, followed by drusy calcite) (Fig. 6a).
b) The most common microfacies is bioclastic grainstone with a diverse assemblage of dasycladacean algae (*Mizzia cornuta* Kochansky & Herak, *Epimastopora likana* Kochansky & Herak, *Atractyliopsis carnica* Flügel, *Neoanchicodium catenoides* Endo), algal spores and other algae (*Ortonella morikawai* Endo). Less common are bioclasts of fusulinid foraminifera (*Pseudofusulinoides?* sp., *Darvasites* sp., and *Rugosochusenella* sp.), smaller foraminifera, fragments of echinoderms, brachiopods and gastropods. Abiotic components are aggregate grains and peloids (Fig. 6b). In some parts, the microproblematicum *Bacinella* is the predominat rock-forming organism.
c) Algal bioclastic grainstone in which broken thalli of the dasycladacean alga *Mizzia* predominate. Rare fusulinoideans, echinoderms and intraclasts also occur. The grainstone is cemented by fibrous rim cement, vadose silt and blocky sparite (Fig. 6c). Limestone is slightly dolomitized.
d) Bioclastic wackestone with fragmented gastropod and brachiopod shells, echinoderms, bryozoans, and ostracods, thalli of *Anthracoporella spectabilis* Pia, and many smaller foraminifera (*Geinitzina*, *Ammovertella*, *Deckerella*, *Climacammina*, and *Tetrataxis*).

4.1.3 Rigelj Formation at the Rigelj type section

The Rigelj type section represents the upper part (19 m) of the Rigelj Formation (Fig. 4). The succession is composed of alternating siltstone, sandy siltstone, fine-grained sandstone, fossiliferous calcareous sandstone and indistinctly thin bedded fossiliferous dark-grey limestone.

Above the tectonic contact to the underlying limestone of the Born Formation a thin-bedded calcarenite and sandstone unit with a thickness of 2.8 m is exposed (Fig. 5d), which is very similar to the sandstone in the upper part (unit 30) of the Čepca section.

The sandstone is overlain by a 5.7 m thick horizon (units 3–5) of black limestone beds of irregular thickness (4–25 cm). Limestone is slightly dolomitized and contains large quantities of medium- to well-rounded quartz pebbles with diameters up to 1 cm in several beds. Originally, the rock was an intrabiomicritic packstone with *Tubiphytes*, sessile microforaminifera, tubiform algae, rare fusulinoideans, bryozoans, crinoids, sponge spicules, quartz grains and abundant fine-grained pyrite crystals. Later, the limestone recrystallized and was brecciated in-situ. Calcite veins display at least three generations of syntectonic cement.

The uppermost 4 m thick carbonate unit (unit 6) consists of very hard black, bedded limestone. Individual beds are 5–15 cm thick. Numerous globular sphaeroschwagerinids are weathering out from the rock surface (Fig. 5e). This bedded limestone grades into calcareous sandstone in its uppermost part that is overlain by 2.2 m of fine-grained quartz sandstone (unit 7) and 4.3 m of brownish-grey fossiliferous sandy siltstone (unit 8). Upwards, the colour of siltstone changes to purple and thin interbeds with accumulations of elongated fusulinid tests belonging to *Quasifusulina tenuissima* (Schellwien) occur. Locally, the skeletal siltstone contains thick-shelled gastropods, bivalves, brachiopods, echinoderms, and phylloid algae. On the surfaces, fossils are mostly dissolved and only moulds can be seen. This siltstone with marine biota is very similar to the silty matrix between the clasts in the Tarvis Breccia, which overlies the siltstone with an erosional unconformity.

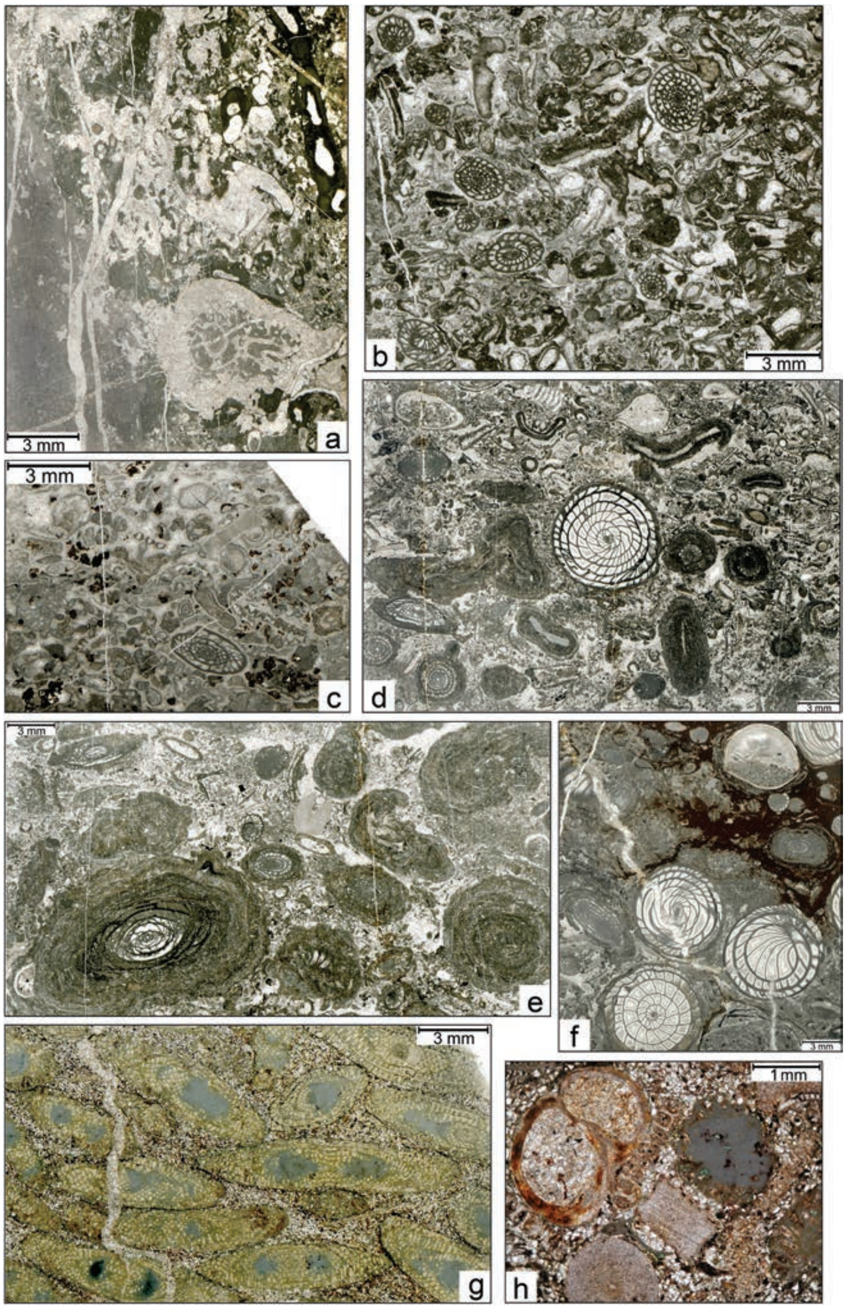

Figure 6: Microfacies types of the Rigelj Formation at the Čepca and Rigelj sections. (a) Limestone breccia. A micritic limestone clast with an uneven contact with intrabiomicritic to intrabiosparitic pack- to grainstone can be seen on the left edge of the picture. It contains typical reef-building organisms with predominant encrusting problematic cyanophycean *Tubiphytes obscurus*, accompanied by problematic *Bacinella* (upper left), calcareous sponges (e.g., *Peronidella* at the bottom) and recrystallized calcitic shells. The matrix is composed of pelmicritie and two generations of sparry calcite cement (first isopachous rim cement, followed by a drusy calcite). Sample 253zg_03, section Č 1. (b) Bioclastic grainstone containing a high diversity of dasycladacean (*Mizzia*, *Epimastopora*, *Neoanchicodium*) and other algae (*Ortonella morikawai* in the middle of the right edge). Other bioclasts are fusulinoideans and smaller foraminifera, echinoderms and fragments of brachiopod and gastropod shells. Abiotic components are aggregate grains and peloids. Sample 548_03. (c) Algal bioclastic grainstone in which mostly broken thalli of the dasycladacean algae *Mizzia* predominate. Rare fusulinoideans, echinoderms and intraclasts occur also. The matrix is composed of fibrous rim cement, vadose silt and blocky sparite. Limestone is slightly dolomitized. Sample 549_01. (d–e) Oncoidal grain- to packstone. Osagia-type composite oncoids are constructed of calcitic microtubes of encrusting foraminifera (*Hedraites*, *Apterinella*), porostromate cyanobacteria (*Girvanella*) and problematic red algae (*Claracrusta*), that overgrow other skeletal grains. Highly diverse assamblage of bioclasts is represented by fusulinoideans, palaeotextularians, brachiopods, echinoderms, bivalves, gastropods, ostracods, dasycladacean (*Epimastopora*, *Globuliferoporella*), and codiacean (*Neoanchicodium*) algae. This type of limestone was deposited in restricted shelf lagoons but also in high-energy environment on the open shelf edges (Flügel, 1977, 2010). Samples 519_03, 519_15, section R 1. (f) Partially dolomitized upper horizon of the oncoid limestone. Geopetal fillings of intragranular pores in bioclasts (e.g., brachiopod shell in the upper right corner. Sample 519_01, section R 1. (g) Fusulinid siltstone. An interesting monospecific suite of elongated fusulinoidean (*Quasifusulina tenuissima*) tests has been redeposited in quartzitic silty sediment. Imbrication of tests suggests current transport mechanism. Biotite in the terrigenous matrix has been altered by chloritization to pennine. Sample 526_12, section R 1. (h) Skeletal quartz siltstone of the uppermost bed of the Rigelj Formation underlying the Tarvis Breccia. Bioclasts are represented by gastropods, echinoderms, phylloid algae *Epimastopora* and fusulinid foraminifera (dark grey particle in middle right is a transverse section of *Quasifusulina tenuissima* through the axial filling). Polarized light. Sample 526_02, section R 1.

Microfacies

The lower part of the black, bedded limestone (unit 6) consists of fossiliferous oncoidal grain- to packstone which contains up to 2 cm large *Osagia*-type oncoids. They are formed of sessile tubular microforaminifera (*Hedraites*, *Apterinella*), porostromate cyanobacteria (*Girvanella*) and problematic red algae (*Claracrusta*), encrusting other skeletal grains (Figs 6d and 6e). The diverse fossil assemblage is represented by fusulinid foraminifera (predominantly *Sphaeroschwagerina carniolica* (Kahler & Kahler), and *Pseudochusenella* sp. and less common *Sphaeroschwagerina* cf. *asiatica* (Miklucho-Maklay), *Quasifusulina tenuissima* (Schellwien), *Q.* sp., *Rugosochusenella* sp., *Pseudoschwagerina* sp., *Boultonia willsi*, smaller foraminifera (*Endothyra*, *Cribrogenerina*, *Climacammina*, and *Geinitzina*), brachiopods, echinoderms, bivalves, gastropods, ostracods, dasycladacean, and phylloid algae (*Epimastopora alpina* Kochansky & Herak, *E. piae* Bilgütay, *Globuliferoporella symetrica* (Johnson), and *Neoanchicodium catenoides* Endo). Upper beds of the oncoid limestone display geopetal fillings of intragranular pores in bioclasts that are partly dolomitized (Fig. 6f).

4.2 Pleschiwetz/Plešivec reference section

At Mt. Pleschiwetz/Plešivec the uppermost part of the Born Formation and the overlying Rigelj Formation are exposed along the Austrian/Slovenian border (Figs 1 and 7).

4.2.1 Uppermost Born Formation

The uppermost exposed 10 m of the Born Formation are composed of grey to reddish micritic limestone, which is medium (20–30 cm) to thick bedded. Bedding is even to slightly wavy. In the lower part, a 15 cm thick fine-grained conglomerate bed containing abundant well rounded and well sorted quartz grains with an average diameter of 0.5 and a maximum diameter of 1 cm is intercalated. The conglomerate is grain supported and contains micritic matrix. In the middle (unit 7), a reddish limestone with a thickness of 80 cm is intercalated, which in the lower part contains abundant rounded quartz grains with diameters up to 3 cm (average 0.5–1 cm). The quartz grains are embedded in micritic limestone and display a matrix-supported texture. The amount of quartz decreases upward.

4.2.2 The Rigelj Formation

The Rigelj Formation of the reference section on Mt. Pleschiwetz/Plešivec conformably overlies the Born Formation and can be lithologically divided into a lower part, which is 36 m thick, and an upper part, which measures 22 m (Fig. 7).

Lower part

The lower part is composed of fine-grained quartz conglomerate with carbonate matrix and limestone which form four transgressive (deepening upward) cycles. Cycle thickness increases from base (3.8 and 3.3 m) to the top (25 m).

Conglomerates display an erosive base (Fig. 5f) and grade upward into limestone with minor quartz (lower two cycles) and limestone containing abundant quartz grains (upper two cycles). Quartz conglomerate appears massive to indistinctly stratified. Quartz grains are well rounded and locally the conglomerate is well sorted. Conglomerate is clast-supported and contains micritic matrix (Fig. 5g). Quartz grains predominate, rarely black chert grains (lydite) and reddish quartz grains are observed. Grain size ranges between 0.5 and 2 cm, maximum grain size is 7 cm. Conglomerate units are 1.7 to 16 m thick. The two intercalated limestone intervals in the lower part are light grey, indistinctly wavy bedded to massive and contain minor amounts of quartz. Thickness are 2.1 and 0.7 m. The uppermost 9 m are composed of limestone containing abundant quartz grains, up to a few cm in diameter, floating in the limestone matrix. Intercalated are thin, quartz-rich lenses and layers. Limestone is massive to indistinctly bedded.

In fine-grained quartz conglomerate various types of polycrystalline quartz grains are distinguished, all displaying strongly undulose extinction. One group of polycrystalline quartz grains is composed of coarse subindividuals and is not schistose, the other group is composed of small subindividuals and displays schistosity ("stretched metamorphic grains"). The matrix is recrystallized micrite which contains fossil fragments including echinoderms, shell debris (bivalves?), rare fusulinids and other recrystallized skeletal grains.

The uppermost 9 m is composed of mixed siliciclastic carbonate conglomerate containing abundant quartz grains that float in fossiliferous micritic matrix. Larger quartz grains are well rounded and dominantly composed of various types of polycrystalline quartz. The small, sand-size quartz grains are angular to subangular and dominantly monocrystalline. Rarely schistose metamorphic rock fragments composed of quartz and muscovite are present. The matrix is recrystallized carbonate containing echinoderms, ostracods, rare fusulinids and other recrystallized skeletal grains, and micritic intraclasts. Other types are wackestone-packstone with abundant quartz grains, bioclastic wackestone, bindstone, bioclastic mudstone and packstone-rudstone.

Microfacies

Limestone, intercalated in the lower part, consists of rudstone, wackestone to floatstone and wackestone to packstone. Rudstone contains a diverse fossil assemblage of echinoderms, shell debris probably derived from bivalves, bryozoans, small foraminifera, ostracods and *Tubiphytes*. Few quartz grains up to 5 mm in diamter are present, some encrusted by cyanobacteria. Pore space is filled with micrite. Wackestone to floatstone is composed of few large, completely recrystallized shell fragments and many smaller bioclasts including echinoderms, bryozoans, small foraminifera, ostracods, calcisponges (?), calcareous algae (?) and rare *Tubiphytes* floating in

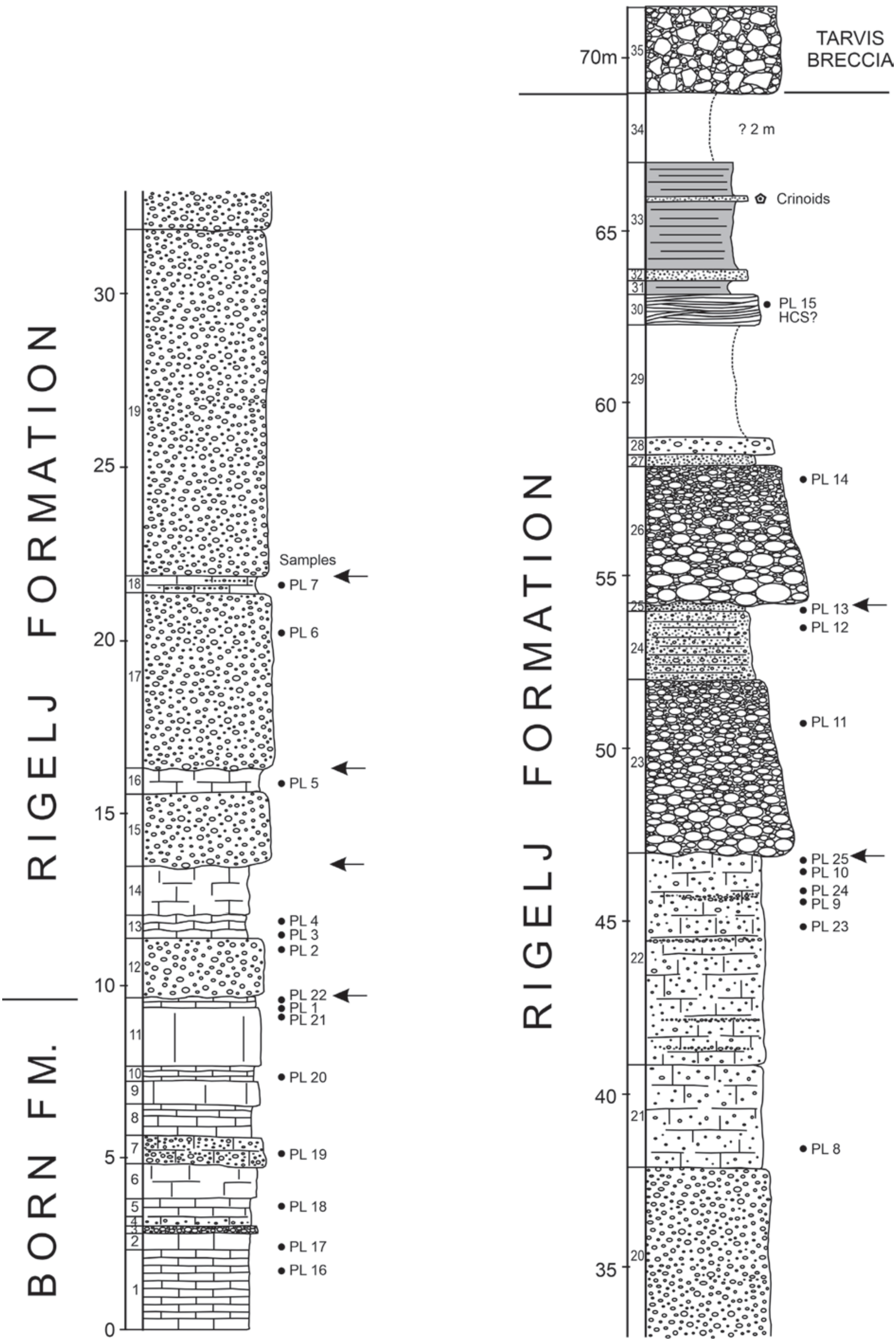

Figure 7: Measured lithostratigraphic section through the Rigelj Formation at Mt. Pleschiwetz/Plešivec. Location see Figure 1. See legend in Figure 4.

peloidal micrite. Nonskeletal grains are intraclasts and few small quartz grains. Some of the skeletal grains are encrusted by cyanobacteria (Figs 8a and 8b).

Wackestone to packstone is indistinctly laminated and contains fragments of echinoderms, ostracods, calcareous algae, tubular foraminifera, rare fusulinids and numerous recrystallized skeletons. Nonskeletal grains include peloids, intraclasts and few detrital quartz grains. Skeletal and nonskeletal grains are embedded in micrite (Figs 8c and 8d).

Upper part

The upper part of the Rigelj Formation is composed of the following lithofacies types:

a) Conglomerate, clast supported, moderately to well sorted, composed of moderately- to well-rounded quartz grains of the same types as in the lower part. Rarely dark grey to black chert grains (lydites) are present. Maximum grain size is 16 cm, mostly < 4 cm. Individual conglomerate beds are up to 5 m thick and commonly display normal grading, rarely trough cross-bedding. The base is erosive.
b) Sandstone is massive, horizontally laminated or trough-crossbedded. Individual sandstone units are up to 2 m thick. Sandstone may contain few quartz pebbles up to 4 cm in diameter. Fine-grained sandstone in the upper part of the section displays hummocky cross-bedding and contains higher amounts of micas.
c) In the uppermost part of the section, a thin, fine-grained calcareous sandstone bed is intercalated which contains few fossil fragments (crinoids, brachiopods).
d) Siltstone-mudstone is up to 1 m thick, with thin intercalations of fine-grained sandstone.

These lithofacies form two well developed fining-upward parasequences at the reference section, each 5–7 m thick, starting with conglomerate with erosive base, grading into sandstone. North of the reference section, a cyclic succession of 7 fining-upward parasequences is developed (approximately 11 m thick), composed of conglomerate, sandstone and siltstone. In siltstone meander-like trace fossils are present.

Petrography

The fine-grained conglomerate is moderately to poorly sorted, clast-supported, grains are mostly subrounded, and are composed of various types of polycrystalline quartz and rare monocrystalline quartz. The conglomerate is well washed and contains small amount of matrix (Fig. 8e).

The coarse-grained sandstone is poorly sorted, grain supported, grains are dominantly subangular to subrounded (Fig. 8f). Dominant grain type is poly- and monocrystalline quartz. Other grain types, such as fine-grained metamorphic rock fragments of quartz and mica, rock fragments of quartz and feldspar, untwinned potassium feldspars and few mica (muscovite) and opaque grains are present in small amounts. Accessory grains are greenish tourmaline and zircon. The sandstone contains fine-grained matrix, locally pseudomatrix derived from the alteration of detrital feldspars. The fine-grained sandstone is moderately sorted and displays similar composition, but contains higher amounts of muscovite (Fig. 8g). Some of the detrital quartz grains display authigenic overgrowths.

Fossil assemblage

Limestones and mixed siliciclastic-carbonate rocks of the Rigelj Formation on Mt. Pleschiwetz contain a moderately to highly diverse fossil assemblage. Most common fossil fragments are echinoderms (mostly crinoids) and bivalve shell fragments, bryozoans and ostracods. *Tubiphytes*, fusulinids (mostly fragmented tests of *Sphaeroschwagerina carniolica* (Kahler & Kahler) and *Dutkevitchia* sp.) and smaller foraminifera (tubular forms, rare *Tuberitina, Endothyra, Geinitzina?*) are present in many samples (Fig. 8h). One sample (PL 25) contains abundant *Komia*, undeterminable algal fragments are observed in some of the samples. *Bacinella* is present in two samples, gastropods and calcisponges are rare. Siltstone and sandstone rarely contain fossil plants and meandering trace fossils.

5. Interpretation of the depositional environment

At both sections of the Rigelj Formation, Mt. Pleschiwetz/Plešivec and Čepca, quartz conglomerates composed of moderately- to well-rounded quartz grains and carbonate matrix containing strongly fragmented fossils indicate deposition in a high-energy, shallow marine nearshore depositional environment. The carbonate-free conglomerates are also composed of moderately- to well-rounded quartz grains displaying moderate to well sorting and are also interpreted to represent deposits of a shoreface environment.

Shoreface deposits are generally preserved in progradational and transgressive sequences (Bourgeois & Leithold, 1984). In general, processes of sediment transport and deposition on the shoreface are complex and dependent on wave motion, currents induced by shoaling waves and other currents such as tidal currents or longshore currents (Hart and Plint, 1995; Plint, 2010). According to Hart and Plint (1995) shorface conglomerates are often crudely bedded and composed of amalgamated units. Crossbedded conglomerates are the product of migrating gravelly ripples. Most of the shoreface conglomerates can be interpreted as the product of gravel bedload sheets.

Conglomerates of the Rigelj Formation are similar to the conglomerates of the Baytree Member of the Cardium Formation that are up to 12 m thick, display an erosive base, are composed of well rounded, massive to amalgamated, clast-supported units and crossbedded units. Massive conglomerates are interpreted as deposits of longshore currents, crossbedded conglomerates as products of migrating wave ripples (Hart and Plint, 1989).

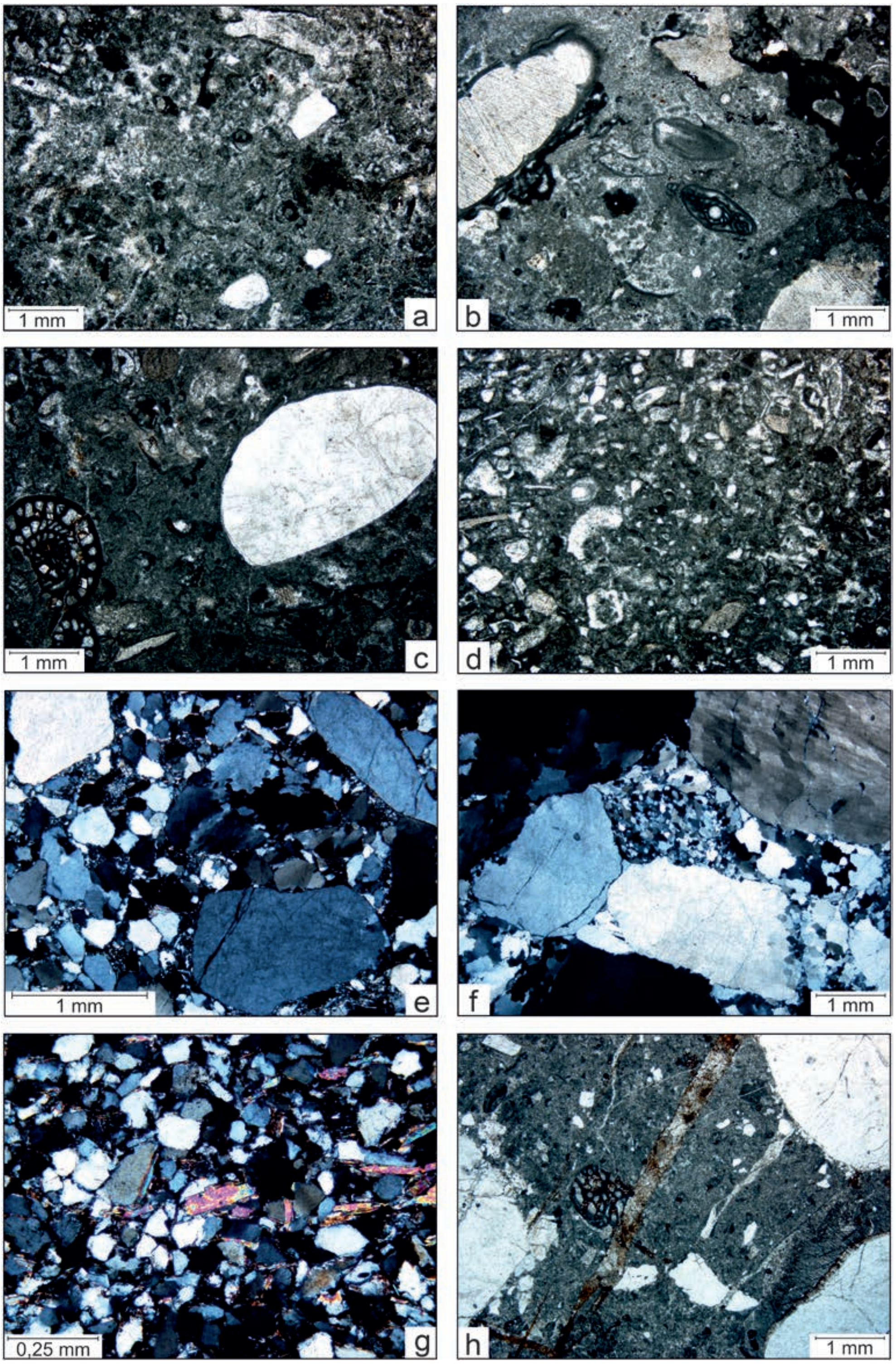

Figure 8: Thin section photographs of fine-grained conglomerate, sandstone and limestone of the Rigelj Formation at Pleschiwetz/Plešivec. (a) Floatstone containing few larger echinoderm fragments, shell debris, smaller foraminifera and few detrital quartz grains up to several mm in diameter floating in micrite. Sample PL 2, plane light. (b) Wackestone to floatstone containing few larger echinoderm fragments, *Tubiphytes* and some small skeletons including fusulinids floating in micrite. Echinoderm fragments are encrusted by cyanobacteria. Sample PL 24, plane light. (c) Wackestone containing few large, rounded quartz grains and small skeletons of echinoderms, bryozoans, fusulinids, recrystallized skeletons, few peloids and micritic intraclasts. Sample PL 7. (d) Wackestone to packstone containing abundant small, recrystallized skeletons, echinoderms, ostracods, calcareous algae, foraminifera and few detrital quartz grains. Sample PL 5, plane light. (e) Fine-grained conglomerate composed of various types of polycrystalline quartz grains, rare monocrystalline quartz grains and small amounts of matrix. Sample PL 11, polarized light. (f) Coarse-grained, poorly sorted sandstone composed of mono- and polycrystalline quartz grains and small amounts of matrix. Grains are mostly subangular to subrounded. Sample PL 14, polarized light. (g) Fine-grained sandstone, well to moderately sorted, composed of abundant monocrystalline quartz, few polycrystalline quartz grains, detrital muscovite and fine-grained matrix. Sample PL 10, polarized light. (h) Fine-grained, mixed siliciclastic-carbonate conglomerate composed of rounded quartz grains up to 1 cm in diameter floating in micritic matrix which contains small detrital quartz grains and few fossils such as fusulinids, echinoderms and ostracods. Sample PL 8, plane light.

We interpret the conglomerates of the Rigelj Formation as shoreface deposits that probably formed by longshore currents and migrating gravely ripples. Conglomerates grade into sandstones which do not display any diagnostic sedimentary structures. We interpret the sandstones as shallow-marine deposits of the upper shoreface.

Fine-grained sandstones, locally containing trace fossils, probably represent lower shoreface deposits. Fossiliferous micaceous siltstone, commonly laminated and locally bioturbated, is interpreted as offshore deposit. The fossil assemblage of the limestone facies (packstone, rudstone) indicates a shallow, open-marine shelf environment of partly high turbulence indicated by the presence of rounded quartz grains with diameters up to a few cm. Muddy limestone microfacies (wackestone, floatstone) suggest deposition in a shelf setting of low to moderate water energy (Plint, 2010).

The lithofacies form well developed fining and deepening upward cycles (parasequences) grading from dominantly siliciclastic beach and upper shoreface deposits to dominantly carbonate sediments of low- to high-energy open shelf environment without siliciclastic influx. Similar cycles are developed in the lower part of the Rigelj Formation at the Čepca section. Such cycles are also described from the Lower Permian (Asselian-Sakmarian) Grenzland Formation of the Carnic Alps which is more than 300 m thick and composed of siliciclastic sediments and intercalated fossiliferous limestone. According to Krainer (2012), the middle (~ 175 m) and upper part (~ 105 m) of the Grenzland Formation in the Carnic Alps represent a cyclic succession of quartz-rich conglomerate and crossbedded sandstone of a nearshore facies, hummocky crossbedded sandstone of the lower shoreface, offshore siltstone and shale and fossiliferous limestone, forming well developed parasequences.

Based on fusulinids, the middle and the upper part are of Sakmarian age. Zircons from an ash layer near the top of the lower part yielded a radiometric age of 296.46 ± 0.11 Ma (middle Asselian) (Krainer, 2012). The cycles coincide with the maximum extent of the Gondwana glaciation in the southern hemisphere which occurred during the Asselian–early Sakmarian and are interpreted to be caused by glacio-eustatic sea-level fluctuations (Fielding et al., 2008; Rygel et al., 2008).

A clear erosional surface at the top of the Dovžanova Soteska Formation suggests that reef mound sedimentation terminated as a result of subaerial exposure at the end of the middle Asselian. During the following transgression, the sedimentary depocentre migrated towards the open-marine inner platform. Sediments of the Born Formation with shallow-marine benthos were deposited in an open marine inner platform setting, repeatedly affected by terrigenous influx from the coast or platform-margin oolitic and sand shoals. Intermediate horizons of paraconglomerates display characteristics of debris flow deposits. Some of the rocky pyramids are built of massive limestone with gregaria type rugose corals *Carinthiaphyllum crasseseptatum* Gräf & Ramovš which formed as isolated patch-reefs within the lagoon (Novak, 2007b; Kossovaya et al., 2020).

The bedded to massive limestones of the Rigelj Formation of the Čepca and Rigelj sections contain a diverse fossil assemblage including abundant calcareous algae (mostly phylloid and dasycladacean algae), benthic smaller foraminifera and fusulinids, subordinately echinoderm fragments, ostracods, bryozoans, calcisponges, brachiopods, bivalves and gastropods. Many limestone beds contain a typical "chloralgal" grain association (Flügel, 2010) composed of dominantly benthic foraminifera and dasycladacean algae. Like *Anthracoporella*, phylloid algae were members of the baffler guild, some phylloid algae also acted as constructors building organic frameworks (Samankassou and West, 2002; Flügel, 2010). Phylloid algae and probably also dasycladacean algae are believed to have grown in shallow environments with water depths not greater than 30 m (e.g. Johnson, 1961; Konishi and Wray, 1961; Heckel and Cocke, 1969; Toomey and Winland, 1973; Toomey, 1976; Roylance, 1990). According to Johnson (1961), dasycladacean algae are restricted to water depths of less than 12 m.

This indicates that limestones of the Rigelj Formation were deposited in shallow, open marine environments with normal salinity and low to moderate water turbulence (mudstone, wackestone, floatstone) and high-water turbulence (grainstone, packstone, rudstone). The presence of abundant phylloid algae that are still in life position indicates low-energy conditions with water depths of less than 30 m.

The succession of the Rigelj Formation indicates a gradual shift of the facies belts from a shallow high energy storm- and wave-dominated shoreface environment (documented by the conglomerate-dominated facies) to open-marine platform settings (limestone-dominated facies) towards the shelf edge. Siliciclastic sediments were deposited in a transitional higher-energy coastal belt with beach ridges. Sedimentation of black bedded algal limestones with siliciclastic intercalations took place in the inner-shelf environment. In the restricted marine settings, limestones with a low diversity algal association were deposited, while on the open platform with normal water circulation close to the platform edge, sedimentation of limestones with a high diversity algal association took place (Flügel, 1977). Reef limestones and limestone breccias mark the shelf edge setting. The facies of the upper part of the Rigelj Formation suggests a sea-level drop and shift of facies belts back to the open-marine inner platform, where black limestones with high-diversity biota and *Osagia*-type oncoids were formed (Novak, 2007b, Dozet and Ogorelec, 2012). Substantial amounts of fine-grained, well-rounded quartz pebbles in several limestone beds indicate a high-energy depositional environment and periodical terrigenous influx from a distant hinterland. The regressive trend continues with the deposition of sandstones and carbonate siltstones in a high-energy shoreface setting.

6. Biostratigraphy of the Rigelj Formation

The fusulinoidean assemblage of the Born Formation which underlies the Rigelj Formation is characterized by *Sphaeroschwagerina carniolica* (Kahler & Kahler), *Rugosofusulina* cf. *likana* Kochansky-Devidé, *Paraschwagerina mukhamedjarovica* Rauzer-Chernousova, and *Darvasites eocontractus* Leven & Shcherbovich (see Fig. 12). Forke (2002) compared the fusulinoidean fauna of the Dovžanova Soteska Fm. and Born Fm. with that of the southern Urals and pointed out the strong resemblance in both, their generic as well as their specific composition. The accompanying genus *Dutkevitchia*, e.g., *D. complicata* (Schellwien), abundantly occurring in the Born Fm. is also the most common genus in the middle Asselian rocks in the Urals (Forke, 1995, 2002). Species of the genus *Sphaeroschwagerina* and the *Rugosofusulina latispiralis* group are present in many sections in the southern to northern Urals and occur even in the arctic realm (Vachard et al., 2010). Typical faunistic elements for both regions are also *Rugosochusenella paragregaria ascedens* (Rauzer-Chernousova) and *Pseudochusenella pseudopointeli* (Rauzer-Chernousova) (Forke, 2002). *Pseudoschwagerina* species from the lower part of the Born Formation are close to those of the southern Urals (*Pseudoschwagerina uddeni russiensis*, *P. beedei uralensis*), where their first appearance defines the base of the middle Asselian. Thus, the fusulinoidean assemblage of the Born Formation corresponds to the *Sphaeroschwagerina moelleri-Schwagerina fecunda* zone and the lower part of the *Sphaeroschwagerina sphaerica-Schwagerina firma* zone, which indicate middle to late Asselian in the southern Urals (Davydov and Popov, 1986; Forke, 1995, 2002; Davydov et al., 1997; Novak, 2007a, b). It is interesting that also the coeval fusulinoidean fauna (and lithology) of the Kadirler section in NW Anatolia (Turkey) is very similar to that of the Born Formation (Okuyucu and Göncüoglu, 2010).

In the upper part of the Born Formation species of the genus *Darvasites* become very abundant, especially *D. eocontractus* Leven & Shcherbovich and related species that represent primitive forms of this genus. They were found in the lower Sakmarian sections in the Urals as well as in Central Asia (Leven and Shcherbovich, 1980). However, a number of similar species are reported from the Asselian of the Carnic Alps (Krainer and Davydov, 1998; Forke, 2002).

The fusulinoidean assemblage of the Rigelj Formation is represented by *Dutkevitchia* cf. *splendida* (Bensh) (Fig. 9n), *Sphaeroschwagerina* cf. *asiatica* (Miklucho-Maklay) (Fig. 11h), *Quasifusulina tenuissima* (Schellwien) (Figs 9e–m), and *Pseudochusenella* sp. (see Fig. 12) with accompanying *Schubertella* sp. (Figs 9a–c), *Boultonia willsi* (Fig. 9d), *Dutkevitchia* sp. (Fig. 9o), *Pseudochusenella* sp. (Figs 10a–j), *Rugosochusenella* sp. (Fig. 10k), *Pseudofusulinoides?* sp. (Figs 10l–r), *Darvasites* sp. (Figs 11a–d), *Pseudoschwagerina* sp., (Fig. 11e), *Sphaeroschwagerina* cf. *citriformis* (Fig. 11f), and *Sphaeroschwagerina carniolica* (Kahler & Kahler) (Fig. 11g). The correlation with the standard zonation in the southern Urals, based on the common stratigraphic occurrence of fusulinoidean species, is very difficult. There, species of *Sphaeroschwagerina* and *Pseudoschwagerina* are sparse in the upper Asselian and Lower Sakmarian and forms of the *Pseudofusulina sulcata* (*Grozdilovia* sensu Bensh) and *P. moelleri* (*Sakmarella* sensu Bensh) groups are present. On the other hand, the fauna of the Carnic Alps shares many common species with Central Asia and other regions in the Paleotethyan province (Forke, 2002). The apparently increasing divergence in the faunal composition of the southern Urals compared to coeval Paleotethyan faunas during the Sakmarian and Artinskian may have been influenced by the invasion of faunal elements into the southern Urals from the northern Urals and Arctic regions which show a much closer relationship (Forke, 2002). The inferred closure of the Uralian seaway in the south due to the collision of microcontinents during the orogenic evolution of the region was already postulated by other authors (Davydov et al., 1997).

7. Comparison with the Carnic Alps

In the Carnic Alps (Austria/Italy), *Sphaeroschwagerina carniolica* occurs first in limestones of the lower Grenzland Formation together with species of the genus *Pseudoschwagerina* (*P. turbida* Kahler & Kahler, *P. extensa* Kahler & Kahler, *P. confinii* Kahler & Kahler). It correlates with the Asselian deposits of the southern Urals (Forke, 1995, 2002; Krainer and Davydov, 1998). The major part of the Grenzland Formation, particularly the lower part, is composed of predominantly siliciclastic rocks in which fusulinoideans are absent. They occur in intercalated limestones in the middle and upper parts. The uppermost part of the Grenzland Fm. is characterized by the appearance of the Sakmarian genus *Zellia* (Forke, 2002) that is absent in the Rigelj Formation. A fusulinoidean assemblage similar to that of the Rigelj Formation is present in the upper Grenzland Formation (Novak & Forke, 2005) (see Fig. 12). Most of the genera, such as »*Pseudofusulina*«, *Pseudofusulinoides*, *Pseudochusenella*, and *Darvasites*, range also into the Zweikofel Formation, but the most typical faunal elements for the Zweikofel Fm., beside species belonging to the genus *Zellia*, i.e., species of the genus *Robustoschwagerina*, are absent in the Rigelj Formation.

There are also many sedimentologic similarities between Rigelj Fm. and Grenzland Fm. Matching lithotypes can be found within both, the Grenzland siliciclastic intervals (quartz-rich calcite cemented sandstones and fine-grained conglomerates), as well as the Grenzland carbonate facies types (bioclastic, oolitic and oncolitic wacke- to grainstones) (Flügel et al., 1971; Krainer and Schaffhauser, 2012). The upper part of the Rigelj Formation with predominantly carbonate lithology shows similarities with both, the Grenzland (upper part) and Zweikofel Formations. Characteristic for both formations are also *Girvanella* (*Osagia* type) oncoids (Flügel, 1977, 2004; Krainer and Schaffhauser,

Figure 9: Foraminifera of the family Schubertellidae. (a–c): *Schubertella* spp.: (a) subaxial section, sample 253zg_01, Č 1; (b) axial section, sample 253zg_01_d2, Č 1; (c) oblique section, sample 253zg_01, Č 1. (d): *Boultonia willsi* Lee, 1927, oblique section through the proloculus, sample 520_02, R 1. Foraminifera of the family Fusulinidae. (e–m): *Quasifusulina tenuissima* (Schellwien, 1898): (e) axial section, sample 519_04, R 1; (f) axial section, sample 519_13, R 1; (g) oblique section, sample 519_23, R 1; (h) axial section, sample 526_09, R 1; (i) subaxial section, sample 526_10, R 1; (j) axial section of the juvenile test, sample 526_11, R 1; (k) oblique section through the proloculus, sample 526_11, R 1; (l) half of the test in axial section, sample 526_12, R 1; (m) equatorial section, sample 519_11, R 1. Foraminifera of the family Schwagerinidae. (n): *Dutkevitchia* cf. *splendida* (Bensh, 1962), axial section, sample 257_01, Č 1. (o): *Dutkevitchia* spp., axial section, sample 257_02, Č 1.

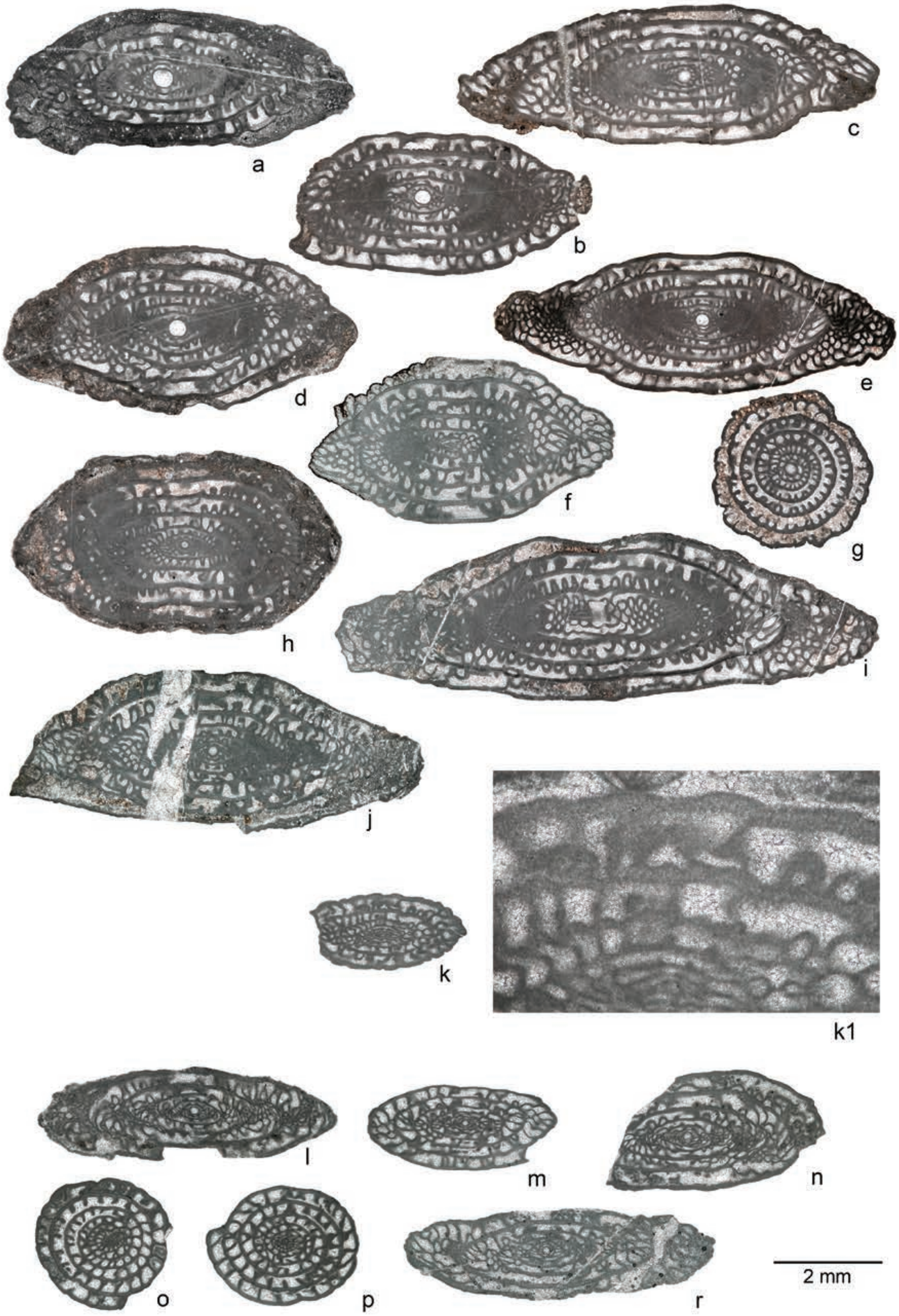

Figure 10: Foraminifera of the family Schwagerinidae. (a–j): *Pseudochusenella* n. sp.: (a) axial section, sample 519_09, R 1; (b) oblique section through the proloculus, sample 519_04, R 1; (c) axial section, sample 519_04, R 1; (d) axial section, sample 519_10, R 1; (e) axial section, sample 519_07, R 1; (f) oblique section, sample 519_12, R 1; (g) equatorial section, sample 519_13, R 1; (h) axial section, sample 519_27, R 1; (i) tangential section, sample 519_23, R 1; (j) axial section, sample 519_26, R 1. (k): *Rugosochusenella* sp.: (k) oblique section, sample 548_01; (k1) detail of the rugose spirotheca, magnified 50x. (l–r): *Pseudofusulinoides?* sp.: (l) axial section, sample 548_01; (m) oblique section through the proloculus, sample 548_01; (n) axial section, sample 548_03; (o) transverse section, sample 548_03; (p) subequatorial section, sample 548_03; (r) axial section, sample 548_04.

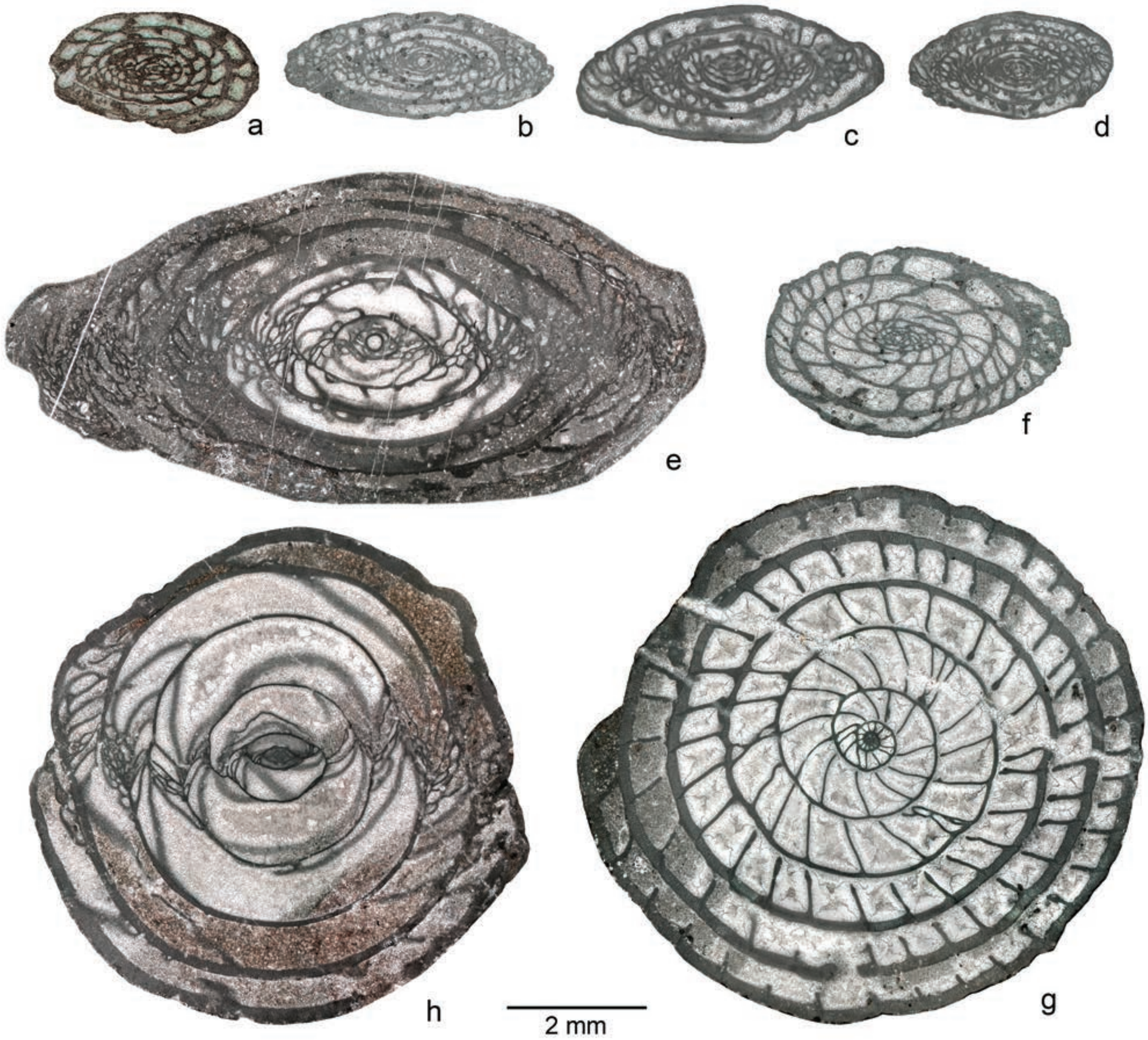

Figure 11: Foraminifera of the family Schwagerinidae. (a–d): *Darvasites* sp.: (a) oblique section, sample 253zg_01, Č 1; (b) axial section, sample 253zg_01, Č 1; (c) tangential section, sample 548_01; (d) oblique section through the proloculus, sample 548_02. (e): *Pseudoschwagerina* sp., axial section, sample 519_15, R 1. (f): *Sphaeroschwagerina* cf. *citriformis* (Kahler & Kahler, 1941), oblique section through the proloculus, sample 253zg_01, Č 1. (g): *Sphaeroschwagerina carniolica* (Kahler & Kahler, 1937), subequatorial section, sample 519_08, R 1. h: *Sphaeroschwagerina* cf. *asiatica* (Miklucho-Maklay, 1949), axial section, sample 519_16, R 1.

2012). Although algal floras usually have a limited biostratigraphic value because of their wide stratigraphic range, some algal communities and bioassociations with other biota seem to be significant for specific platform environments. For outer shelf environments, the high algal and low biotic diversity *Epimastopora* community (with associated *Gyroporella*, *Mizzia*, oncoids, smaller foraminifera, echinoderms and gastropods), the low algal but high biotic diversity *Neoanchicodium* community (together with *Epimastopora*, *Mizzia*, fusulinids, paleotextulariid foraminifera, molluscs and corals) and *Osagia*-oncoid community (together with *Neoanchicodium*, *Epimastopora* and many groups of invertebrates), and the high algal and high biotic algal-spores assemblage (spores of *Mizzia*, *Atractyliopsis*, together with *Neoanchicodium*, *Epimastopora*, oncoids and gastropods) are significant (Flügel, 1977; Krainer et al., 2019a). All these communities are present in the Rigelj Fm. as well. It should also be mentioned that representatives of the genus *Mizzia* (*M. cornuta* Kochansky & Herak) only occur in the Rigelj Fm. and not below. Although they are recorded already from the Schulterkofel Fm. in the Carnic Alps, they are one of the most common algal elements also in the Grenzland, Zweikofel and Trogkofel Formations (Flügel, 1968, 1977; Homann, 1972; Vachard and Krainer, 2001; Krainer et al., 2019a).

The cyclic depositional pattern with repeated shifting of facies zones from shoreface to open-marine platform

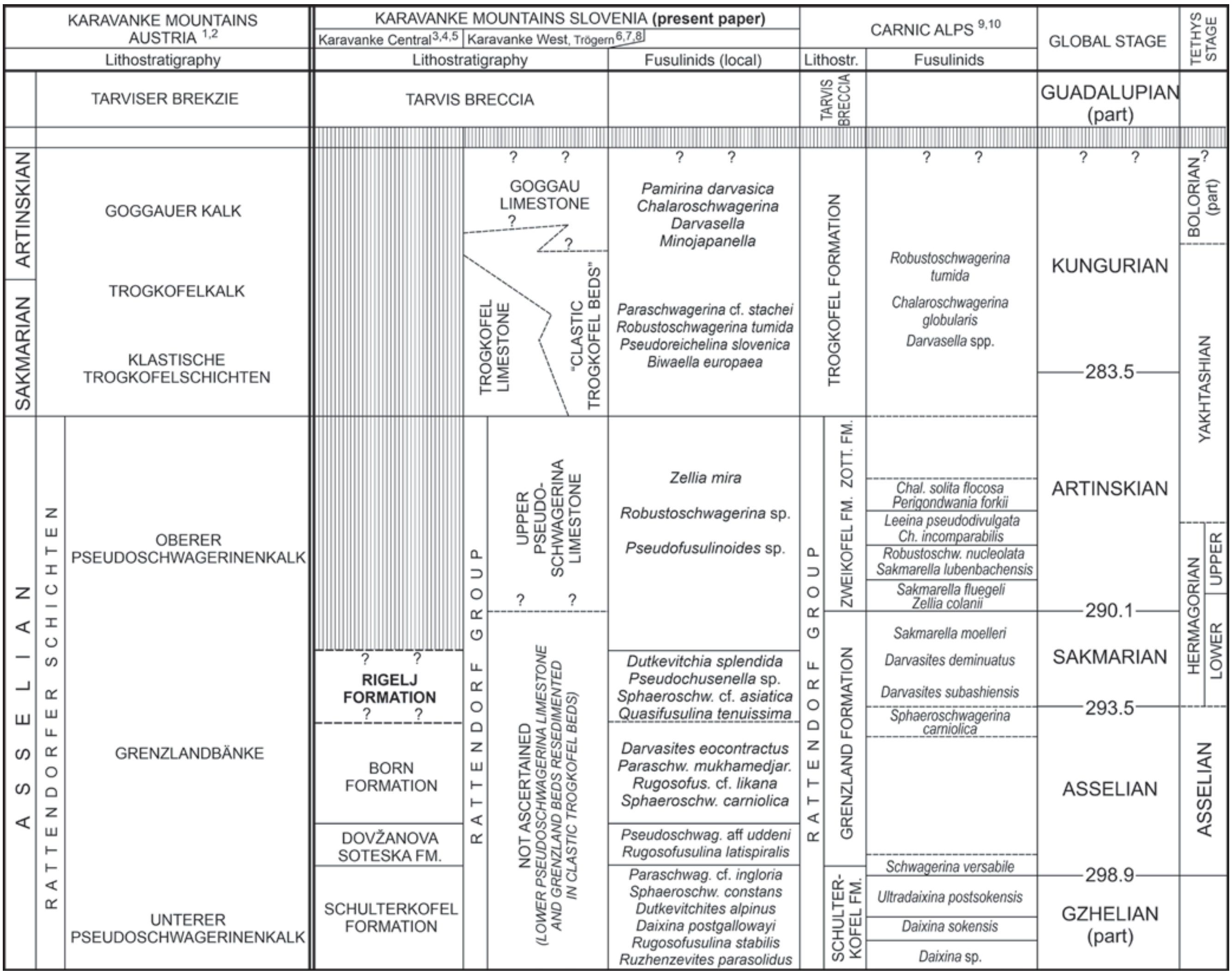

Figure 12: Stratigraphic subdivision of the uppermost Pennsylvanian and Cisuralian (Asselian–Kungurian) sedimentary succession in the Karavanke Mountains and Carnic Alps. References: [1]Bauer (1980), [2]Kahler (1983), [3]Buser and Forke (1996), [4]Forke (2002), [5]Novak (2007b), [6]Ramovš (1968), [7]Kochansky-Devidé (1970), [8]Buser (1974), [9]Krainer and Davydov (1998), [10]Davydov et al. (2013). Correlation with Tethyan scale according to Davydov et al. (2013).

and shelf edge environments is also evident in both formations (Flügel, 1977; Novak, 2007b; Krainer and Schaffhauser, 2012).

These are the reasons for the assumption that the Rigelj Formation corresponds lithologically, but not biostratigraphically, to a part of the Zweikofel Formation. According to the latest results of Davydov et al. (2013), the lower boundary of the Zweikofel Fm. is drawn at the Sakmarian/Artinskian boundary and the upper boundary in middle Artinskian.

The fusulinoidean fauna of the uppermost part of the Grenzland Formation, of the entire Zweikofel Formation and Trogkofel Limestone has no species in common with the fauna of the southern Urals, and even the majority of genera are different (Forke, 2002). This is why Davydov et al. (2013) proposed to establish a Regional Tethyan Chronostratigraphy instead of the global scale in the Carnic Alps as the stage boundaries of the latter cannot be established with necessary precision. The new Hermagorian Stage has been proposed for the succession that correlates with the entire Sakmarian and (approximately) lower Artinskian of the Global Scale (Krainer and Schaffhauser, 2012; Davydov et al., 2013). According to Davydov et al. (2013), the fusulinids indicate a late Asselian to late Early Hermagorian (approx. Sakmarian) age of the Grenzland Formation and Late Hermagorian to early Yakhtashian (approx. Artinskian) age of the Zweikofel Formation. Based on the comparison of the faunal assemblages of the Rigelj Formation with those in the Carnic Alps we conclude that the Rigelj Formation ranges from the late Asselian up to the middle Lower Hermagorian (approx. middle Sakmarian).

The Lower Permian (Asselian–Sakmarian) Grenzland Formation of the Carnic Alps is described as a 60–120 m thick, partly cyclic sequence of predominantly shallow marine siliciclastic and intercalated thin, fossiliferous limestone intervals (Buttersack and Boeckelmann, 1984; Boeckelmann, 1985, 1988; Schönlaub and Forke, 2007). Unfortunately, a complete section of the Grenzland Formation is not preserved due to Alpine tectonics.

Recent investigations have shown that the Grenzland Formation is more than 300 m thick. The lower part is non-cyclic, entirely siliciclastic and composed of siltstone, sandstone and rare, fine-grained conglomerate. Middle and upper parts are a cyclic succession of quartz-rich conglomerate and crossbedded sandstone of a nearshore facies, hummocky crossbedded sandstone of the lower shoreface, offshore siltstone and shale and fossiliferous limestone. In the middle and upper parts, at least 15 cycles (parasequences) are recognized that range in thickness from 10 to 30 meters. The cyclic succession coincides with the maximum extent of the Gondwana glaciation in the southern hemisphere, which occurred during the Asselian–early Sakmarian. The cycles (parasequences) are interpreted to be caused by glacio-eustatic sea-level fluctuations (Krainer, 2012; Krainer et al., 2019a, b).

The Zweikofel Formation is a cyclic succession composed predominantly of dark grey, thin-bedded fossiliferous limestones and intercalated thin intervals of silt- and sandstones and fine-grained, well-rounded and well-sorted quartz-rich conglomerates. Krainer & Schaffhauser (2012) divided the Zweikofel Formation into six depositional sequences (parasequences) that are interpreted as high-frequency cycles caused by glacio-eustatic sea-level fluctuations of the Gondwana glaciation.

There are some differences between the Rigelj Formation and the time-equivalent sedimentary succession of the Grenzland formation of the Carnic Alps.

Well-developed finig-upward (transgressive) cycles are developed in the Rigelj Formation in the lower part of the Čepca section and in the middle of the Pleschiwetz section. Cycles are not developed in the carbonate-dominated upper part of the Rigelj Formation at Čepca and Rigelj. The number of cycles in the Rigelj Formation is much lower than in the Carnic Alps. Sedimentation of the Rigelj Formation was probably influenced by both, glacioeustatic sea-level fluctuations (producing high-frequency transgressive cycles) and tectonic movements which locally overprinted the sea-level fluctuations signature.

8. Discussion

Due to lithologic and age differences Born and Rigelj Formations cannot be correlated with the Upper Pseudoschwagerina Limestone (former name of the Zweikofel Formation) of the Carnic Alps [as by Kahler and Kahler (1937)]. Neither can they be regarded – together with the Dovžanova Soteska Formation – as "carbonate and clastic Trogkofel beds" [as by Ramovš (1963, 1968, 1972) and Buser (1974, 1980)]. All three formations probably represent time-equivalents of the Grenzland Formation, i.e., the middle part of the Rattendorf Group. Therefore, their fusulinoidean assemblages have an important role in filling the gaps in the knowledge of the phylogenetic evolution and stratigraphic range of the occuring genera. To draw a distinction of different facies developments, the new names Dovžanova Soteska Formation, Born Formation (Forke, 2002) and Rigelj Beds (Novak, 2007a, b) were assigned to these units. The Rigelj Beds, named after the hill of Rigelj above the village Čadovlje pri Tržiču, were not given the formal status of lithostratigraphic formation because the section in Dovžanova Soteska, especially its lower part, is incomplete due to tectonics and poor exposures (Novak, 2007a, b). The reference section at Mt. Pleschiwetz/ Plešivec displays normal contact to the underlying Born Formation and the lower part is almost completely exposed with only minor tectonic deformations. These facts allow the introduction of the Rigelj Formation as a formal lithostratigraphic unit.

The type section of the Rigelj Formation is much thicker (105 m) than the reference section at Mt. Pleschiwetz/ Plešivec (58 m). The lowermost part of the reference section correlates with the type section. The middle and upper parts of the type section containing fossiliferous limestones (including fusulinids) are absent at the reference section due to erosion prior to the deposition of the overlying Tarvis Breccia (Fig. 5h).

Block-faulting caused erosion of uplifted blocks, locally as deep as to the Rigelj Formation (upper part of Rigelj Fm.). Time-equivalent sediments of the Zweikofel Fm., Trogkofel Formation and Goggau Limestone have been eroded. Locally near Trögern and in the western Karavanke Mountains the Tarvis Breccia rests on the Trogkofel Limestone.

The concept of Clastic Trogkofel Beds, to which the Rigelj Fm. was formerly assigned, proved to be misleading in all of the re-studied sections in the central Karavanke Mts. (Novak and Forke, 2005; Novak, 2013). The normal cyclic deposition of siliciclastic and carbonate sediments, that is, as a consequence of both high frequency and high amplitudes of sea-level changes related to glacio-eustatic control associated with waxing and waning of the Gondwanan ice caps, characteristic of the Late Carboniferous and Early Permian stratigraphic record worldwide (Samankassou, 1997, 2003; Joachimski et al., 2006; Haq and Schutter, 2008; Krainer and Schaffhauser, 2012; Isbell et al., 2012), has been shown in many lithostratigraphic charts as two laterally almost continuous successions within the Trogkofel Group (e.g. Ramovš, 1976b).

The assumption of reworked fusulinoidean fauna, described by Kochansky-Devidé in many publications (e.g. Kochansky-Devidé et al., 1973) has already been discussed by Forke (2002). He stressed that the fusulinoidean fauna in the Carnic Alps and in the Karavanke Mountains is characterized by more or less parautochthonous assemblages indicated by the strong facies control of several taxa. In high energy, particularly in clastic-influenced environments, pack- to grainstones with concentrations of fusulinoidean shells occur. Shell abrasion due to transportation is clearly visible. This led to an accumulation of taxa over time and a homogenization of originally patchy population distributions. However, the occurrence of reworked, distinctly older faunal elements was not observed (Forke, 2002). Our observations led to the same conclusions.

The discussed issues resulted in crucial errors in correlations of the regional lithostratigraphic units and biostratigraphic zonations in the Southern Alps and consequently led to distorted paleogeographic reconstructions (e.g., Buggisch et al., 1976).

In the area Dovžanova Soteska–Mt. Pleschiwetz/Plešivec the Rigelj Formation is overlain by the Tarvis Breccia with an erosive contact, which probably indicates that block faulting associated with the Saalian movements caused local uplift and erosion of the Zweikofel Formation, Trogkofel Limestone and Goggau Limestone and their equivalents, probably also of a part of the Rigelj Formation before the deposition of the Tarvis Breccia. A detailed study of the clasts in the Tarvis Breccia is needed to confirm the assumption based on the spatial relationships of Lower Permian formations.

9. Conclusion

The Rigelj Formation is a lithostratigraphic unit of the Rattendorf Group in the Karavanke Mountains south and southeast of the Košuta Range in the Dovžanova Soteska–Mt. Pleschiwetz/Plešivec area that is up to 105 m thick and composed of siliciclastic and fossiliferous carbonate sediments. The succession is entirely of shallow-marine origin. Conglomerates are interpreted as shoreface deposits, sandstones as deposits of the upper to lower shoreface, and fossiliferous siltstones as offshore deposits. Microfacies and fossil assemblages of the limestone facies indicates deposition in a shallow, open-marine shelf environment of moderate to low energy (wackestone, floatstone) and strong water turbulence (packstone, rudstone). The siliciclastic and carbonate lithotypes form some well-developed cycles starting with conglomerates, overlain by sandstones, siltstones and fossiliferous limestones that formed in an open shelf environment without siliciclastic influx. Similar cycles are developed in the Grenzland Formation of the Carnic Alps. Fusulinid assemblages of the Born Formation that underlies the Rigelj Formation indicate a middle to late Asselian age. Comparison of the fusulinid fauna of the Rigelj Formation with that of the Rattendorf Group of the Carnic Alps indicates that the Rigelj Formation ranges in age from the latest Asselian to the late Sakmarian. The study shows a stronger diversification of the sedimentary environments within the Karavanke-Carnic Alps in the Early Permian after the uniform sedimentation in the Late Carboniferous, which we assume can be attributed to block-faulting.

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