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The Type Section of the Lower Permian Zweikofel Formation (Rattendorf Group; Carnic Alps, Austria)

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Abstract

A type section (lectostratotype) and reference section of the Lower Permian Zweikofel Formation of the Rattendorf Group in the Carnic Alps (Austria) are defined and described in detail. The mixed siliciclastic-carbonate Zweikofel Formation is 94 – 106 m thick and consists of a cyclic succession of thin- to thick-bedded fossiliferous limestone and five intercalated, thin intervals of siliciclastic sediments. The siliciclastic intervals consist of siltstone, sandstone and fine-grained, quartz-rich conglomerate with grain size up to about 5 cm. Fossils indicate deposition in a shallow-marine nearshore environment. The carbonate facies is characterized by moderate- to high-energy facies types (bioclastic, oolitic and oncolitic grainstone to packstone) and low- to moderate-energy facies types (bioclastic and oolitic wackestone to packstone, floatstone and rare *Girvanella* bindstone). A diversified faunal and algal assemblage indicates deposition in a shallow neritic, normal-saline, low- to high-energy environment.

Intercalated siliciclastic horizons enable a subdivision of the two sections (Zweikofel and Garnitzenbach) into 6 depositional sequences that contain almost equal numbers of parasequences. Sequence boundaries are drawn at the erosional lower contacts of the siliciclastic intervals. Parasequences are 2 - 10 m thick. Three types of parasequences are distinguished. Limestone successions are composed of well-developed shallowing upward parasequences. The parasequences are interpreted as high-frequency cycles caused by glacio-eustatic sea-level fluctuations of the Gondwana Glaciation.

Within the Zweikofel Formation five fusulinid assemblages are distinguished at Zweikofel, indicating late Hermagorian to Yakhtashian (approximately Artinskian) age.

In both studied sections, thin-bedded fossiliferous limestone of the uppermost Zweikofel Formation is sharply overlain by massive *Tubiphytes-Archaeolithoporella* mound facies of the overlying Trogkofel Limestone.

Das Typusprofil (Stratotypus) und ein Referenzprofil der unterpermischen Zweikofel Formation der Rattendorfer Gruppe in den Karnischen Alpen (Österreich) werden definiert und im Detail beschrieben. Die gemischt siliziklastisch-karbonatische Zweikofel Formation ist 94 – 106 m mächtig und besteht aus einer zyklischen Abfolge von dünn- bis dickgebankten, fossilführenden Kalken und fünf zwischengeschalteten dünnen siliziklastischen Horizonten. Die siliziklastischen Horizonte bestehen aus Siltstein, Sandstein und feinkörnigen, Quarz-reichen Konglomeraten mit Korngrößen bis 5 cm. Fossilien weisen auf Ablagerung in einem flachmarinen, küstennahen Environment. Die Karbonatfazies ist charakterisiert durch mäßig bis hochenergetische Faziestypen (bioklastische, oolithische und onkolithische Grainstones bis Packstones) und niedrig bis mäßig energetische Faziestypen (bioklastische und oolithische Wackestones bis Packstones, Floatstones und selten *Girvanella*-bindstones). Die hochdiverse Faunen- und Algenvergesellschaftung weist auf Ablagerung in einem flachneritischen, normalsalinaren, niedrig- bis hochenergetischen Environment.

Die zwischengeschalteten siliziklastischen Horizonte erlauben eine Untergliederung der zwei Profile (Zweikofel, Garnitzenbach) in 6 Ablagerungssequenzen, die in beiden Profilen aus einer annähernd gleichen Anzahl von Parasequenzen aufgebaut sind. Sequence boundaries werden an der erosiven Basis der siliziklastsichen Horizonte gezogen. Parasequenzen erreichen eine Mächtigkeit von 2 – 10 m. Es werden drei Typen von Parasequenzen unterschieden. Kalkabfolgen zeigen deutlich ausgebildete shallowing upward Parasequenzen. Die Parasequenzen werden als hochfrequente Zyklen interpretiert, entstanden als Folge glazioeustatischer Meeresspiegelschwankungen der Gondwana-Vereisung.

Im Zweikofel-Profil können fünf Fusulinen-Vergesellschaftungen unterschieden werden, die oberes Hermagorian bis Yakhtashian (Artinskian) anzeigen.

In beiden untersuchten Profilen werden die dünn gebankten, fossilführenden Kalke der Zweikofel Formation mit einer scharfen lithologischen Grenze von massigen Trogkofelkalken überlagert, die in einer *Tubiphytes – Archaeolithoporella* Mound Fazies ausgebildet sind.

1. Introduction

The Zweikofel Formation of the Rattendorf Group in the central Carnic Alps along the Austrian/Italian border is well exposed and has been studied during the last decades with regard to its sedimentological and paleontological aspects. Nevertheless, a type section that fulfills the rules of the International Commission on Stratigraphy (ICS) has never been established.

The aim of this paper is to define a type section (lectostratotype) and reference section following the rules of the ICS, to provide a detailed description of the Zweikofel Formation, and to discuss the depositional environment, sequence stratigraphy and biostratigraphy based on fusulinaceans.

2. Previous Studies and Nomenclature

In the Carnic Alps geological investigations started in the middle of the 19th Century, distinguishing Paleozoic and Triassic sediments. The discovery of important faunas (Tietze, 1870; Stache, 1872a, 1872b, 1873) improved the stratigraphy of the Paleozoic succession ("Gailtaler Schichten"). Determination of fusulinids (Tietze, 1870; Stache, 1873a, b) allowed correlation with successions containing similar faunas from North America and Russia (Suess, 1870).

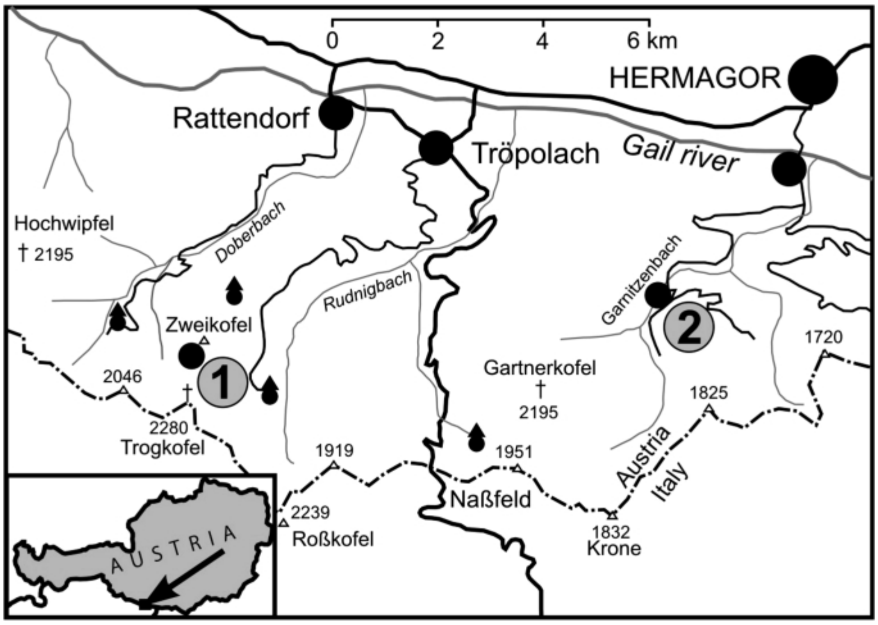


Figure 1: Map showing the location of the lectostratotype section at Zweikofel (1) and reference section at Garnitzenbach (2) of the Zweikofel Formation in the Carnic Alps.

Stache (1872b, 1873a) suggested a Permian age for the Uggowitz Breccia (=Tarvis Breccia) and the overlying light grey dolomites. Frech (1894) discussed a Triassic age for the light grey dolomites of Gartnerkofel, Trogkofel and Roßkofel. He distinguished Lower Carboniferous marine sediments (shale) and Upper Carboniferous marine sediments with intercalations of terrigenous deposits.

Geyer (1895, 1896) first recognized that in the Trogkofel area the Upper Carboniferous siliciclastic and carbonate sediments including fusulinid-bearing limestones are overlain by grey and red, bedded limestone containing "*Schwagerina*", and finally by the massive Trogkofel Limestone. He correlated the "*Schwagerina*" Limestone with the "*Schwagerina*" Stage (Horizon) of the Urals and assumed a Permian age for the "*Schwagerina*" bearing limestone and overlying massive Trogkofel Limestone.

Later, Kahler (1931) recognized that the "*Schwagerina*" Limestone is divided into a lower and upper "*Schwagerina*" Limestone, separated by a predominantly clastic interval that he later (Kahler, 1932; Kahler and Heritsch, 1932; Kahler, 1934) named Grenzlandbänke (Grenzland Beds). Due to the similar lithology, this clastic interval had previously been assigned to the Late Carboniferous Auernig Beds.

Heritsch et al. (1933) proposed a new stratigraphic subdivision of the Upper Carboniferous and Lower Permian succession of the Carnic Alps. Sediments of the Postvariscian transgression were termed "Naßfeld Schichten," consisting of "Auernig Schichten" and "Rattendorfer Schichten" (divided into Lower "Schwagerina" Limestone, Grenzlandbänke, Upper "*Schwagerina*" Limestone), overlain by the Trogkofel Limestone.

Originally the Upper "*Schwagerina*" Limestone included the bedded limestone below the massive Trogkofel Limestone in the Trogkofel massif (Trogkofel and Zottachkopf) as well as at Zweikofel (Heritsch, 1943).

Kahler and Kahler (1937) described the 60 - 70 m thick succession of dark grey, thin- bedded limestone below the massive Trogkofel Limestone exposed at the northern slope of Zottachkopf as the type section of the Upper "*Schwagerina*" Limestone.

Later (e.g. Kahler, 1947), Lower and Upper "*Schwagerina*" Limestone were renamed as Lower and Upper *Pseudoschwagerina* Limestone (Tab. 1) because of taxonomic nomenclature problems with the original name Schwagerina (Dunbar and Skinner, 1937).

Felser and Kahler (1963) noted that the Upper *Pseudoschwagerina* Limestone is also well exposed at the western slope of Zweikofel.

Kahler (1983, 1985, 1986, 1992) dated the Upper *Pseudoschwagerina* Limestone, which is characterized by the abundance of *Pseudoschwagerina* (*Zellia*), as late Asselian.

Figure 2: Steep western face of the Zweikofel massif showing the type section of the Zweikofel Formation (well-bedded facies in the lower half of the picture; Z), underlain by the Grenzland Formation (G) and overlain by massive facies of the Trogkofel Group (upper half of the picture; T). The red lines mark the measured section.

The red limestone from locality "Höhe 2004" yielded a fusulinid fauna including *Pseudoschwagerina geyeri*, first recognized by Kahler and Kahler (1938), indicating a younger age than that of the Upper *Pseudoschwagerina* Limestone.

Kahler (1983, 1986, 1992) dated these red limestones as Sakmarian and therefore ascribed them to the Trogkofel Limestone.

Krainer (1995) proposed the new term Zweikofel Formation for the older term "Upper *Pseudoschwagerina* Limestone," because it did not correspond to the rules of the International Stratigraphic Commission, which recommends avoiding taxonomic names in stratigraphic nomenclature.

Forke (1995) included the red limestone in the Upper *Pseudoschwagerina* Limestone = Zweikofel Formation and dated the entire Zweikofel Formation as Sakmarian. He correlated the lower boundary of the Sakmarian with the base of the Zweikofel Formation.

Schönlaub and Forke (2007) dated the Zweikofel Formation as late Sakmarian to early Artinskian; they also stated that red limestones occur near the base of the Zweikofel Formation.

The sediments of the Rattendorfer Group were studied by Homann (1969), Flügel (1968, 1974), Flügel et al. (1971), Buggisch et al. (1976) with regard to their microfacies and fossil assemblages (smaller foraminfers and algae).

The problems concerning the stratigraphy of the Zweikofel Formation and overlying Trogkofel Limestone are related to the unclear stratigraphic position of the red limestone facies at Höhe 2004 - Trogkar, which yielded a fusulinid fauna that differs from the "classical" sections of the Zweikofel Formation, particularly at Zweikofel and Garnitzenbach.

Detailed sedimentological studies at Zweikofel, Trogkofel and Zottachkopf showed that the bedded facies that underlies the massive Trogkofel Limestone at Trogkofel and Zottachkopf differs significantly from the Zweikofel Formation at Zweikofel and Garnitzenbach. The bedded facies, originally termed "Oberer Schwagerinenkalk" (Upper *Schwagerina* Limestone), is characterized by dark grey, thin-bedded limestone containing abundant small oncoids. In the lower part, siliciclastic sedimentary rocks and reddish limestones rich in crinoid fragments occur. Locally mounds are developed, particularly south of Zottachkopf.

This bedded facies does not show any cyclic pattern as known from the Zweikofel Formation at Zweikofel and Garnitzenbach. From these reddish limestones, Forke (1995) and Forke (2002) described a conodont fauna that ranges from upper Sakmarian to Artinskian.

At Zweikofel and Garnitzenbach the Zweikofel Formation displays a cyclic pattern with intercalated thin siliciclastic horizons, oolitic limestone, algal limestone, and oncoidal limestone with large oncoids, all lacking in the bedded facies.

Up to now this bedded succession below the massive Trogkofel Limestone at Trogkofel and Zottachkopf, which differs in

Figure 3: Close look on the steep western face of the Zweikofel showing the upper part of the well-bedded Zweikofel Formation, overlain by a massive limestone facies of the Trogkofel Group.

Lithologic/lithostratigraphic name	Area	Author
Schwagerinenkalk ("*Schwagerina*" Limestone)	Trogkofel area	Geyer 1895, 1896
Unterer und Oberer Schwagerinenkalk (Lower and Upper *Schwagerina* Limestone)	Trogkofel and Zweikofel area	Kahler 1931
Oberer Schwagerinenkalk (Upper *Schwagerina* Limestone)	Type section at Zottachkopf	Kahler 1937
Unterer und Oberer Pseudoschwagerinenkalk (Lower and Upper *Pseudoschwagerina* Limestone	Trogkofel and Zweikofel area	Kahler 1947
Red Limestone of Höhe 2004 (=Trogkofel Limestone)	Trogkofel area	Kahler 1983, 1986, 1992
Zweikofel Formation (for Upper *Pseudoschwagerina* Limestone)	Zweikofel area	Krainer 1995
Red Limestone of Höhe 2004 (=Zweikofel Fm.)	Trogkofel area	Forke 1995
Zottachkopf Formation (for Upper *Pseudoschwagerina* Limestone at the type section at Zottachkopf, non-cyclic)	Trogkofel area	Schaffhauser et al. 2010
definition of the Zweikofel Formation (cyclic)	Zweikofel area, Garnitzenbach	this paper

Table 1: The historical development of the lithostratigraphic term Zweikofel Formation.

facies and age, has been considered as an equivalent of the “Zweikofel Formation” as developed at Zweikofel or Garnitzenbach.

The section that Forke (1995) reported from the Trogkar and described as the Upper *Pseudoschwagerina* Limestone = Zweikofel Formation (Forke, 1995, Fig. 5 and 12) is not a continuous section but consists of fault-bounded fragments. The section is in tectonic contact with the overlying Trogkofel Limestone, and there are additional, almost horizontal faults within the section.

Outcrops at the base of the northern cliff of Trogkofel show that the reddish limestone occurs near the base of an approximately 120 m thick succession of mainly thin-bedded limestone.

This bedded facies is not an equivalent of the Zweikofel Formation as redefined by Krainer (1995), with the type section at Zweikofel. As the bedded facies differs in age and facies, Schaffhauser et al. (2010) proposed a new formation termed Zottachkopf Formation.

The type section of the Zottachkopf Formation is located at the base of the steep northern slope of the Trogkofel. Reference sections are located on the southern side of Trogkofel and Zottachkopf and at the northern slope of Zottachkopf. The Zottachkopf Formation will be described in detail in a separate paper.

3. Location

The type section (lectostratotype) of the Zweikofel Formation is located at the steep western slope of the Zweikofel massif north of the Trogkofel between ca. 1800 and 1900 m asl in the central Carnic Alps, southern Austria (coordinates: 13°13´10´´ East/46°34´47´´North; UTM WSG84 33 East 363536 North 5160026) (Figs. 1, 2, 3).

The reference section is located along Garnitzenbach between 1020 and 1080 m asl (coordinates: 3°19´53´´ East/46°35´14´´ North; UTM WSG84 33 East 372172 North 5160609). The distance between both sections measures 8.7 km (Fig. 1).

The uppermost part is also well exposed at the eastern side of the Zweikofel massif.

4. Method

Detailed sections were measured and sampled at Zweikofel and Garnitzenbach. 175 samples were collected at Garnitzenbach and 155 samples at Zweikofel. From all samples thin sections were prepared for microfacies analysis. From fusulinid limestones numerous oriented thin sections were prepared for identification of the fusulinids. Microfacies types are defined after the classification scheme of Dunham (1962), modified by Embry and Klovan (1971)

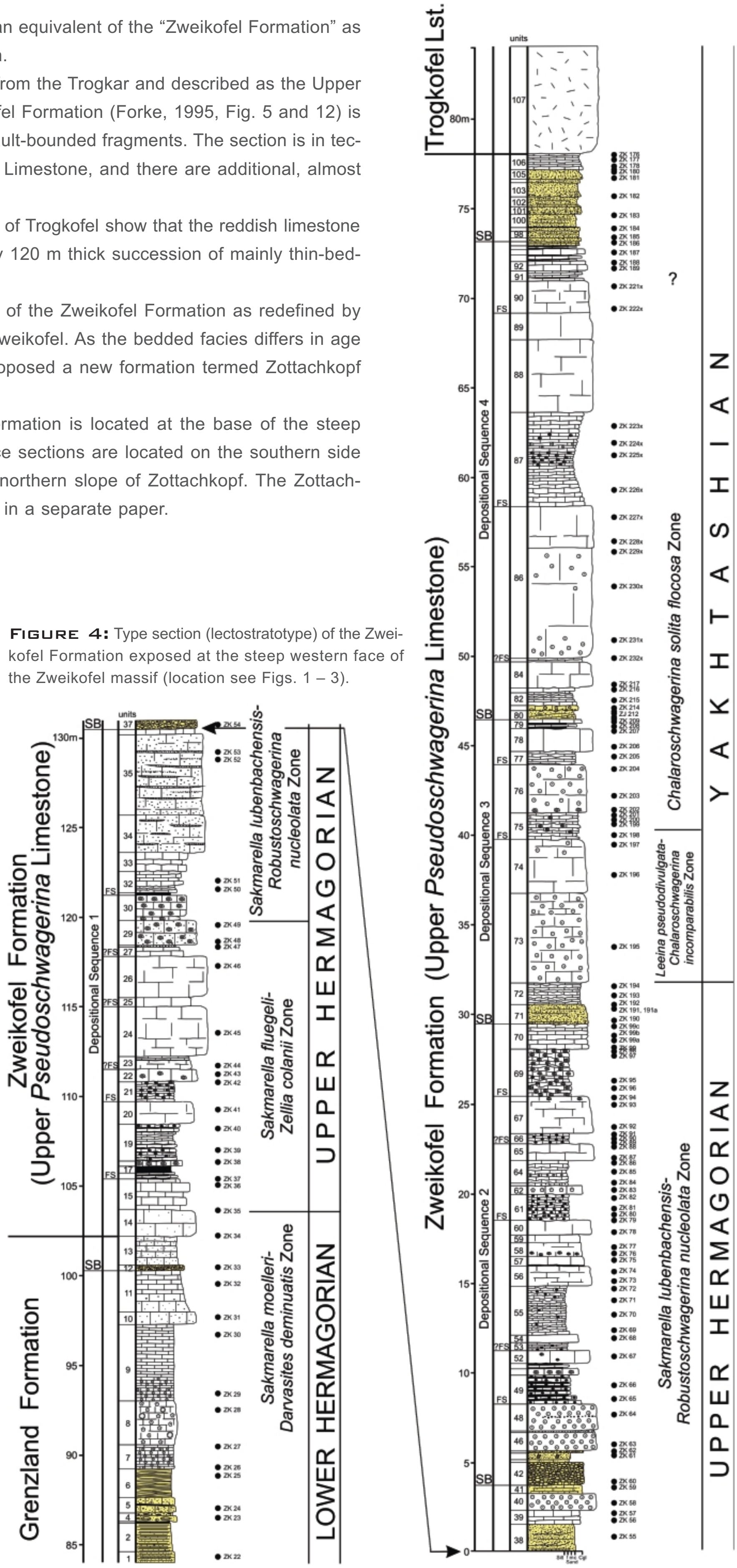
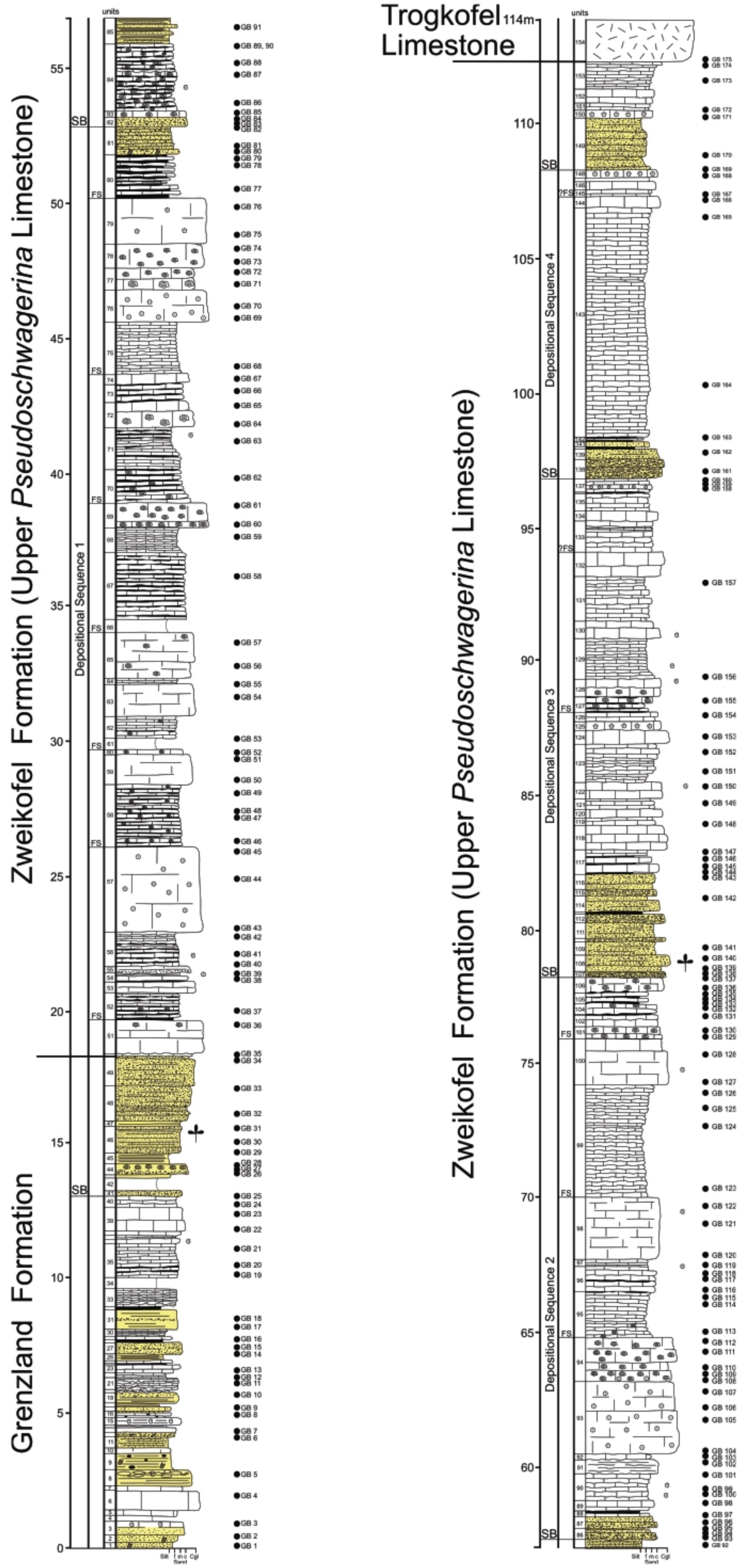


Figure 4: Type section (lectostratotype) of the Zweikofel Formation exposed at the steep western face of the Zweikofel massif (location see Figs. 1 – 3).



(see also Wilson 1975 and Flügel, 2004).

5. Description of Type Section (Stratotype) and Reference Section of the Zweikofel Formation

5.1 Thickness, Lower and Upper Boundary

The type section at Zweikofel measures 102 m (Fig. 4), and the reference section at Garnitzenbach is 95 m thick (Fig. 5). Outcrop quality is excellent; at both locations the succession is almost completely exposed.

Kahler (1932) and Kahler and Heritsch (1932) described the Grenzland Formation, which underlies the Zweikofel Formation, as a succession composed predominantly of sandstone, less abundant conglomerate and minor limestone. Forke (2002) and Schönlaub and Forke (2007), fixed the lower boundary of the Zweikofel Formation at the base of a quartz conglomerate within a dominantly siliciclastic succession. According to the original definition this succession is part of the Grenzland Formation. We therefore draw the lower boundary at the base of the first thicker interval of bedded limestone (unit 14; Fig. 4), about 36 m above the boundary of Forke (2002) and Schönlaub and Forke (2007).

The upper boundary is drawn at the base of the massive Trogkofel Limestone. At Zweikofel a thin carbonate breccia is locally developed at the base of the Trogkofel Limestone above an erosional surface on top of the Zweikofel Formation (Krainer et al., 2009).

5.2 Lithofacies of siliciclastic rocks

At both sections five thin siliciclastic horizons are intercalated, which

Figure 5: Reference section of the Zweikofel Formation exposed at Garnitzenbach (location see Fig. 1).

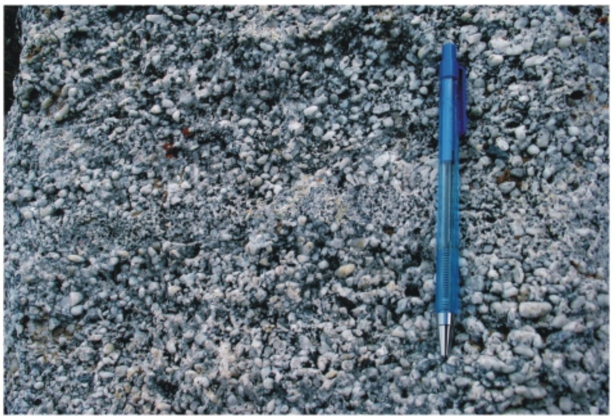


Figure 6: Well rounded and well sorted, fine-grained quartz conglomerate from the lower part of the Zweikofel Formation at Zweikofel (unit 42 of Fig. 4).

range in thickness from 0.6 to 4.5 m.

The siliciclastic horizons are composed of siltstone to fine-grained sandstone, sandstone and fine-grained conglomerate.

Siltstone to fine-grained sandstone is grey to brownish, massive to indistinctly laminated, and locally bioturbated. The fine-grained sandstone of horizon 4 at Zweikofel displays hummocky crossbedding. Thickness ranges from 0.2 to 1.9 m. The rock may be carbonate cemented. Locally plant debris is present, and a few small quartz grains may occur. Locally, thin calcareous siltstone beds are intercalated. Rarely, marine fossils such as crinoid fragments are present. In horizon 4 at Zweikofel dark grey mud chips up to 4 cm large float in the fine-grained sandstone.

Sandstone is medium to coarse grained, well rounded and well sorted, carbonate cemented and partly crossbedded.

Conglomerate beds are 0.2 to 1.3 m thick. At Zweikofel conglomerate is almost entirely composed of quartz (Fig. 6), whereas at Garnitzenbach lydite grains are common (Fig. 7). The grains are mostly well rounded, and sorting varies from well to moderately sorted (clast supported) to moderately to poorly sorted (mostly matrix supported). The maximum grain size is 3 cm (Fig. 6). The conglomerate beds appear massive to indistinctly bedded and carbonate cemented. Most conglomerate beds display erosive lower contacts (Fig. 8).

Figure 7: Zweikofel Formation exposed at Garnitzenbach showing a thin bed of fine-grained quartz-conglomerate (A) overlain by thin sandstone (brownish, lower right; B), thin wavy bedded to nodular limestone (C), indistinctly bedded oolitic limestone (D) and massive oncolitic limestone (E). Thickness of succession shown on the photograph is approximately 10 m.

At Zweikofel conglomerate beds occur in horizons 1, 2, 3 and 5, and at Garnitzenbach in horizons 1, 2, 3 and 4.

In both sections a thin limestone succession is intercalated between siliciclastic horizons 1 and 2: 2.2 m of fusulinid-limestone, oolitic limestone and micaceous limestone at Zweikofel, and 2.7 m of thin, wavy to nodular bedded limestone with thin shale intercalations. Limestone contains abundant oncoids up to about 5 cm in diameter, echinoderm fragments, brachiopods and bellerophontid gastropods.

All siliciclastic horizons display sharp lower and upper contacts, and are under and overlain by dark grey, bedded fossiliferous limestone. The lower contact is commonly erosive. Erosive contacts may also occur within silicicalstic horizons (horizon 1 and 2 in both sections).

5.3 Petrography of conglomerate and sandstone

5.3.1 Fine-grained conglomerate to pebbly sandstone

The fine-grained quartzose conglomerates to pebbly sandstones are clast supported and poorly to moderately sorted, and at Zweikofel are also well sorted. Conglomerates commonly show a bimodal grain-size distribution of large, well rounded to rounded grains and small subangular grains. The grains are cemented by calcite; locally fine-grained matrix is present (Fig. 10A, B).

Quartz is the dominant grain type. Detrital polycrystalline quartz is very common. The individual crystals in the quartz grains vary in size. Rarely, quartz grains with equant or elongated to strongly elongated subindividuals occur that indicate a metamorphic origin (Fig. 10A). Monocrystalline quartz is less common. Some quartz grains show undulatory extinction.

Detrital feldspar (K-feldspar, plagioclase) is very rare, and most grains are strongly altered.

Rock fragments are common among the larger grains and include igneous, sedimentary and metamorphic types. Volcanic rock fragments include porphyritic grains composed of quartz and/or feldspar in a fine-grained groundmass and basaltic types composed of a meshwork of plagioclase laths, which are altered. Sedimentary rock fragments are composed of calcareous siltstone (quartz, mica, carbonate minerals), black-colored chert (lydite), carbonate lithoclasts and chert. Chert is commonly altered and replaced by microcrystalline carbonate minerals. Metamorphic rock fragments are composed of quartz, mica, feldspar or quartz and mica (muscovite, chlorite). The degree of foliation among the single grains differs significantly. Accessory minerals observed in thin section are tourmaline, zircon, rutile and apatite.

Detrital mica (muscovite, chlorite) is rare.

The pebbly sandstones also contain a small amount of fossil fragments like echinoderms, bryozoans, fusulinids (Fig. 10A), brachiopods, gastropods, algae and small foraminifers.

Typical diagenetic features are cementation by carbonate minerals (quartz cement is extremely rare), replacement of quartz by carbonate minerals, fractures filled by calcite cement, dedolomitization of optically-zoned euhedral to subhedral and anhedral dolomite crystals of idiotopic to hypidiotopic and xenotopic fabric (only at Zweikofel section).

5.3.2 Sandstone/Siltstone to calcareous sandstone/siltstone

Sandstone/siltstone is moderately to well sorted, and composed of quartz grains, commonly monocrystalline, which are subangular to subrounded (Fig. 10C). Many quartz grains show undulatory extinction. Polycrystalline quartz (small individual crystals), chert, mica (muscovite, chlorite, biotite), feldspar and rock fragments (carbonate clasts, metamorphic clasts) are present in varying amounts or even lacking. Accessory minerals like tourmaline or zircon are rare. Fossil fragments (echinoderms, fusulinids, smaller foraminifers) are rare to moderate (Fig. 10C), and oncolitic fragments occur locally. Compared to the quartzose conglomerate, the content of detrital feldspar (K-feldspar, plagioclase) is higher, but most of the grains are strongly altered to clay minerals (Fig. 10D). The siltstone is carbonate cemented. Carbonate minerals have replaced quartz, feldspars and rock fragments. This facies type is associated with oncolitic grainstone (overlying the siltstones) and conglomerate.

5.4 Lithofacies of carbonate rocks

The limestone facies is composed of the following main lithotypes:

1) Thin, wavy bedded to nodular, fossiliferous dark grey micritic limestone with thin, dark grey shale partings (Fig. 7). Bed thickness is 3 - 20 cm; individual units are 0.4-1.5 m thick. Fossils observed in the field include calcareous algae, echinoderms, fusulinids, brachiopods, rare gastropods and very rare solitary corals. Thin, wavy bedded to nodular limestone is the most common lithofacies at Garnitzenbach where individual units are up to 8.6 m thick. Bed thickness is 5 - 20 cm. Bellerophontid gastropods are present in distinct horizons. This lithofacies is mainly composed of MF 8 (floatstone, particularly algal floatstone) and MF 7 (bioclastic wackestone to packstone), and very rarely of MF 9 (*Girvanella* bindstone).
2) Thin, wavy bedded to nodular fossiliferous dark grey micritic limestone containing abundant oncoids (oncolite). Thin, dark grey marly shale layers are intercalated that locally contain small brachiopods. Fossils observed in the limestone beds are algae, fusulinids, echinoderms, bryozoans, and brachiopods. Oncolite units are 0.5 - 2.6 m thick. The typical microfacies is MF 6 (oncolitic floatstone) (Fig. 9).
3) Medium- to thick-bedded, grey fossiliferous limestone containing crinoids, fusulinids and algae, and at Garnitzenbach also gastropods, brachiopods and small oncoids. Thickness ranges from 0.2 to 1 m at Zweikofel, and 0.2 to 1.2 m at Garnitzenbach. Common microfacies are different types of bioclastic grainstone to packstone (MF 2).
4) Indistinctly bedded to massive grey limestone containing abundant ooids or crinoids, 1 - 8 m thick at Zweikofel, and up to 3 m thick at Garnitzenbach (Fig. 7). The typical microfacies is MF 3 (oolitic grainstone to packstone), subordinate MF 4 (oolitic wackestone to packstone) and MF 5 (oncolitic grainstone to packstone).
5) Indistinctly bedded to massive grey limestone unit in the lower part of the Zweikofel Formation with quartz grains up to 2 cm in diameter loosely scattered and intercalations of thin sandstone lenses up to 5 cm thick. This lithofacies is composed of MF 2 (bioclastic grainstone to packstone) and MF 7 (bioclastic wackestone to packstone).

Figure 8: Fine-grained, calcite-cemented, well rounded and partly well sorted quartz conglomerate overlying fossiliferous limestone with erosive contact. Type section at Zweikofel (unit 42 of Fig. 4).

Figure 9: Large oncoids with diameters up to 10 cm embedded in dark grey, fossiliferous marly shale. Type section at Zweikofel (unit 69 of Fig. 4).

6) Medium- to thick-bedded limestone containing abundant small oncoids (1 - 3 cm in diameter), and subordinately echinoderms, calcareous algae, brachiopods and fusulinids, is up to 1.7 m thick (Fig. 7). This type is absent at Zweikofel. The common microfacies are MF 2 (bioclastic grainstone to packstone) and MF 5 (oncolitic grainstone to packstone).

5.5 Microfacies-types of limestone

5.5.1 MF 1: Mixed siliciclastic-carbonate grainstone to packstone

This microfacies type contains up to 40 % quartz grains and is moderately to poorly sorted. Some clasts show alignment (Fig. 10E).

Larger quartz grains are rounded to subrounded, and smaller quartz grains are mostly subangular; some are angular. Mono- and polycrystalline quartz grains are abundant. Chert grains are rare. Rock fragments composed of quartz and mica (muscovite) occur.

Carbonate grains include intraclasts, micritized ooids, peloids and fragments of oncoids. Common fossils are echinoderms, bryozoans, fusulinids, phylloid algae, green algae (*Epimastopora*, *Globuliferoporella*), smaller foraminifers (*Globivalvulina*, calcivertellids, *Tetrataxis*, *Nodosinelloides*, *Tuberitina*, *Climacammina*), *Girvanella*, plant fragments, "*Ortonella myrae*" = *Homannisiphon*, and gastropods.

The rock is cemented by microcrystalline to drusy sparite, and frequently also granular calcite; echinoderms show syntaxial overgrowths.

5.5.2 MF 2: Bioclastic grainstone to packstone

Bioclastic grainstone to packstone is poorly sorted. Large bioclasts like fusulinids or echinoderms are abraded (Fig. 10F).

The grainstone to packstone is composed of abundant bioclasts, rare intraclasts, some oncoids (with nuclei of phylloid algae and encrustations by *Girvanella*, *Claracrusta* and micritic layers), very rare ooids and peloids. Some samples contain small detrital quartz grains.

Bioclasts, particularly phylloid algae, are often encrusted by *Girvanella* or *Claracrusta*.

Common fossils are algae (*Neoanchicodium*, *Anchicodium*?, *Epimastopora*, *Globuliferoporella*, *Pseudoepimastopora*), echinoderms and some fusulinids, smaller foraminifers (*Geinitzina*, *Endothyra*, *Tetrataxis*, *Nodosinelloides*, calcivertellids), calcareous sponges, *Tubiphytes*, bryozoans, gastropods, *Pseudovermiporella*, *Parachaetetes*, *Girvanella*, "*Ortonella myrae*," and trilobites.

One type contains abundant algal spores and fragments of phylloid algae (Fig. 10H). Additionally, intraclasts and oncoids (composed of phylloid algae, *Girvanella* and *Claracrusta*) are present.

Another type is a grain- to packstone rich in echinoderm fragments (Fig. 10G). Besides echinoderms this microfacies contains bryozoans, fusulinids, gastropods, green algae and *Homannisiphon*.

The grainstone/packstone is cemented by granular to drusy sparite. A poorly-sorted bioclastic packstone is composed of reworked ooids and echinoderm fragments and contains pelmicritic matrix. A poorly to moderately sorted grainstone composed of abraded bioclasts contains small angular to subangular quartz grains (up to 30 %).

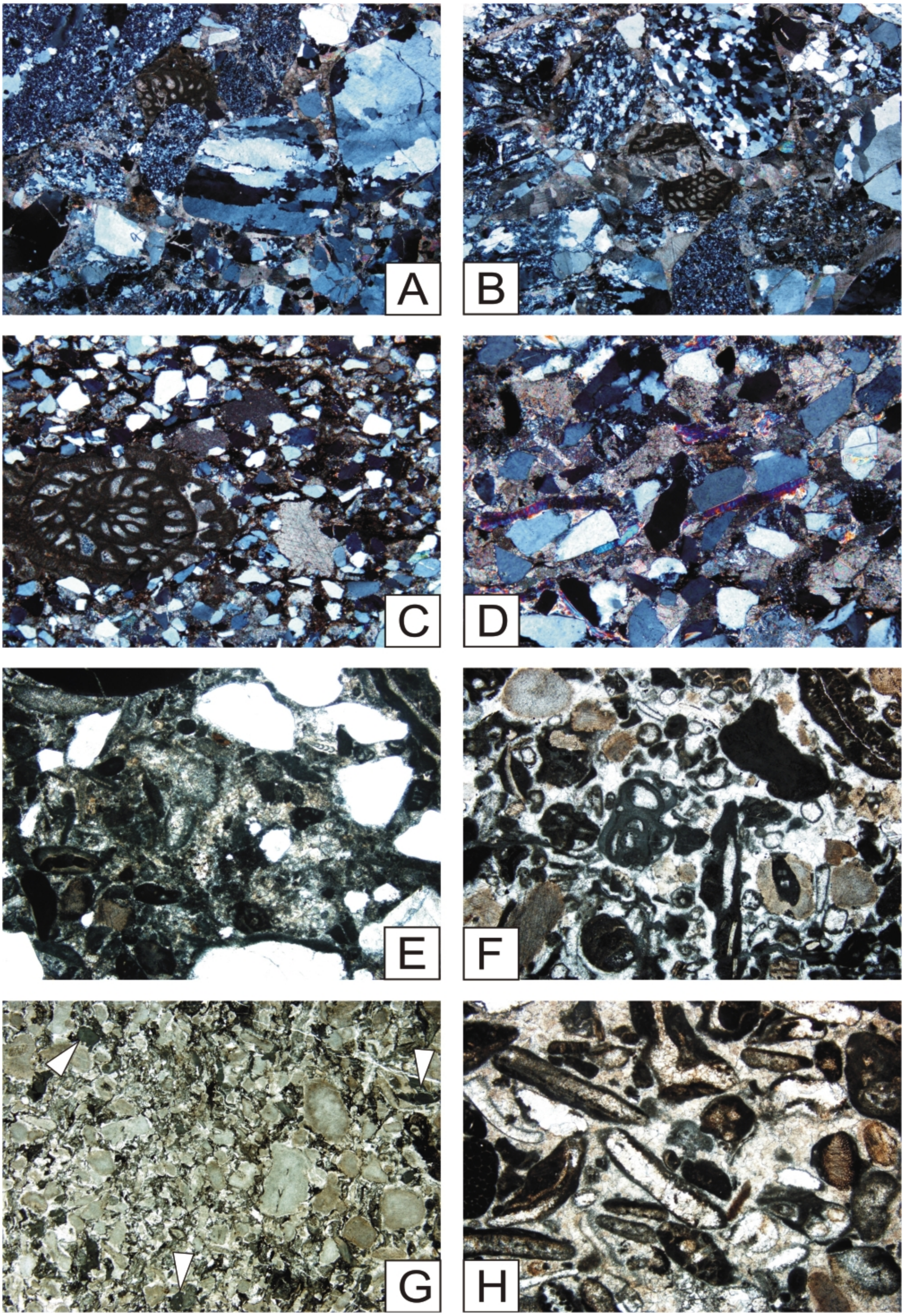
Syntaxial overgrowths on echinoderm fragments are common. Frequently replacement dolomitization is observed.

Samples from the upper part of the Zweikofel section show meteoric vadose diagenesis (sample ZK 227x).

5.5.3 MF 3: Oolitic grainstone to packstone

Oolitic grainstone to packstone is moderately to well sorted, and subordinately very well sorted (Fig. 11A). Very well to well sorted oolitic grainstone contains only very few bioclasts (small

Figure 10: Thin section photograph of fine-grained conglomerate, sandstone and limestone of the Zweikofel Formation,
A: Fine-grained quartz conglomerate with bimodal grain-size distribution composed almost exclusively of quartz grains. Rare fragments of broken fusulinid tests occur. The larger grains are subrounded or rounded polycrystalline quartz and chert. Individual crystals within a polycrystalline grain show elongate shape (in the centre of the photomicrograph) indicating a metamorphic origin or may strongly vary in size. Among the small quartz grains which are mainly subangular, monocrystalline quartz is most common. Replacement of quartz by carbonate minerals can be observed in chert grains (grain in the upper part of the photomicrograph). The conglomerate is cemented by carbonate minerals. Sample GB93, width of photograph is 6.3 mm, crossed nicols.
B: Fine-grained quartz conglomerate with well rounded polycrystalline quartz grain (composed of more or less equant quartz crystals) in the centre of the photomicrograph which is overgrown by carbonate minerals. Fractured quartz grains are cemented by carbonate minerals (upper left corner of the photomicrograph). Sample GB93, width of photograph is 6.3 mm, crossed nicols.
C: Fine-grained sandstone containing fusulinids and echinoderm fragments. Angular to subangular monocrystalline quartz is the prevailing grain type. Sample GB133, width of photograph is 3.2 mm, crossed nicols.
D: Calcite-cemented sandstone composed of detrital quartz, mica (muscovite) and few strongly altered feldspar grains. Sample GB142, width of photograph is 12 mm, crossed nicols.
E: Mixed siliciclastic-carbonate packstone consisting of subangular to subrounded quartz grains (white grains), single peloids and mixed skeletal grains (algal and echinoderm fragments, benthic foraminifers). Sample ZK191, width of photograph is 6.3 mm, plane light.
F: Moderately sorted bioclastic grainstone composed of echinoderm fragments, *Tubiphytes*, phylloid algae encrusted by *Girvanella*, algal spores (white spherical grains) and bryozoan fragments. Several skeletal grains display micriti envelopes. The grainstone is cemented by drusy to granular calcite. Sample ZK67, width of photograph is 6.3 mm, plane light.
G: Poorly sorted crinoidal pack- to grainstone with a low amount of other skeletal grains (e.g. *Tubiphytes*; arrows) and rare intraclasts. Sutured contacts of grains are common. Locally syntaxial overgrowths on echinoderm fragments occur. Sample GB50, width of photograph is 20 mm, plane light.
H: Moderately sorted bioclastic grainstone rich in phylloid algal fragments commonly encrusted by *Girvanella*. Additionally calcareous green algae, echinoderm fragments and single intraclasts are present. The components display distinct abrasion. Syntaxial overgrowths on echinoderm fragments occur (in the lower right corner). Sample ZK214, width of photograph is 6.3 mm, plane light.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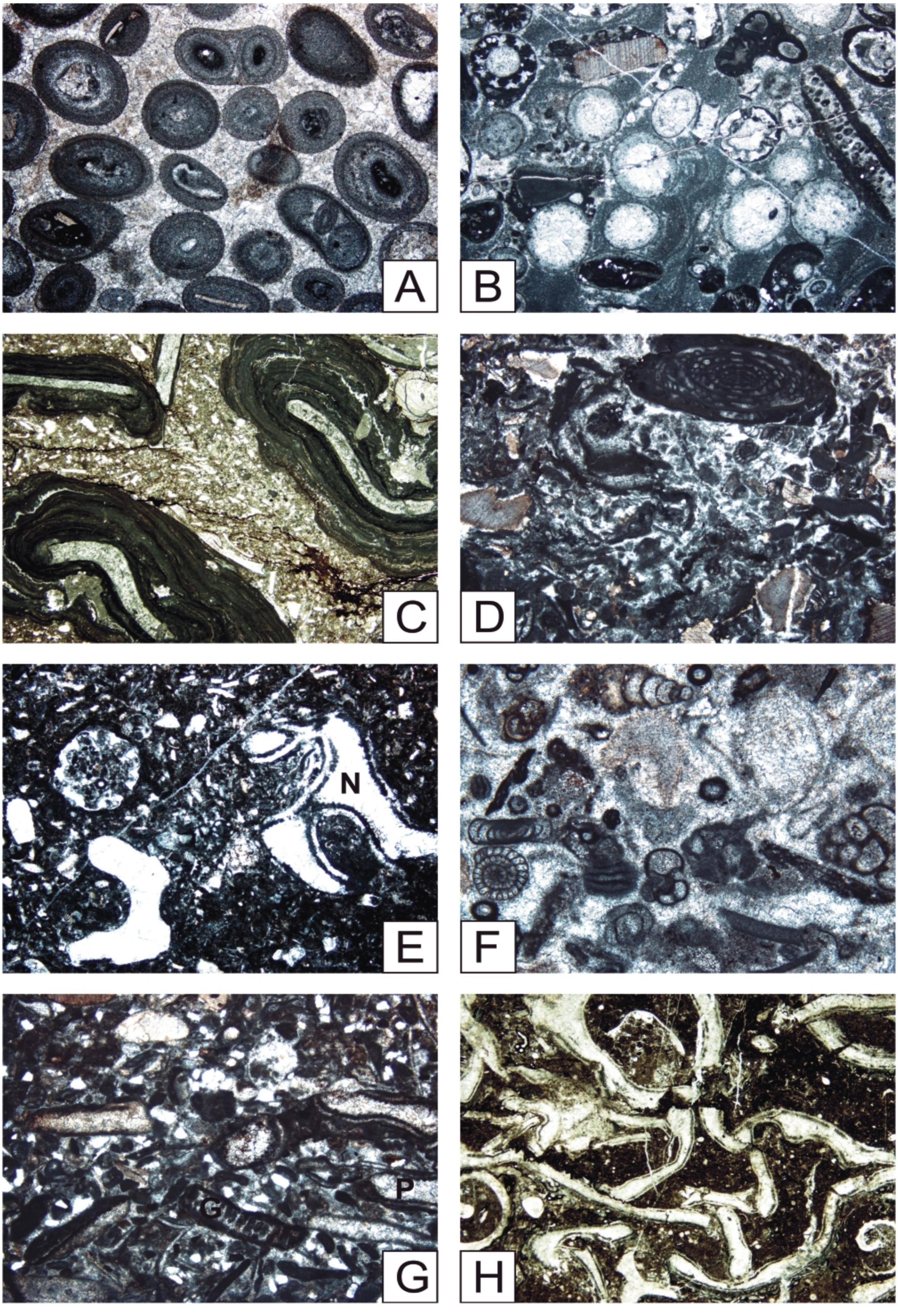
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fusulinids, smaller foraminifers). In moderately sorted grainstone additional grains such as intraclasts, peloids and bioclasts (fusulinids, small foraminifers, green algae, echinoderms, gastropods, bryozoans) occur.

Ooids show concentric laminae, but are often micritic with obliterated laminae. The nuclei are formed of calcivertellid foraminifers, *Girvanella*, fragments of echinoderms and algae. Some multiple ooids occur: two or three single ooids form the nucleus of a large ooid. Some ooids are encrusted by sessile foraminifers, which are again coated by a new cortex. Very large ooids show fragments of echinoderms as a second nucleus.

Recrystallization locally caused oomoldic porosity (see Flügel, 2004). Superficial ooids are common. Restricted horizons in thin section show distorted ooids caused by strong compaction. The oolitic grainstone to packstone is cemented by microcrystalline to granular to drusy calcite cement; isopachous fringes of cement may occur. Replacement dolomitization of the nucleus or even the entire ooid is also observed.

5.5.4 MF 4: Oolitic wackestone to packstone

The oolitic wackestone to packstone is moderately to well sorted. Bioturbation occurs in section GB. The micritic matrix is partly washed out. Bioclasts include green algae (*Mizzia*, *Gyroporella*), phylloid algae (*Neoanchicodium*), *Ellesmerella*, small foraminifers (*Endothyra*, *Geinitzina*, *Nodosinelloides*, *Calcivertella*, *Globivalvulina*), fusulinids, echinoderms, and gastropods (Fig. 11B).

Some bioclasts are encrusted by *Girvanella* and sessile foraminifers. Several multiple ooids occur. Ooids consist of concentric laminae, and many ooids are micritized. Encrusting organisms like sessile foraminifers interrupt the concentric laminae of the cortex. The oolitic wackestone to packstone is cemented by drusy to granular calcite sparite. This microfacies type is rare in the Zweikofel Formation.

Figure 11: Thin section photographs showing microfacies types of the Zweikofel Formation. All photographs were taken under plane light.
A: Very well sorted oolitic grainstone composed of concentric ooids and single multiple ooids. Two or three small ooids form the nucleus surrounded by a cortex of concentric laminae. Small foraminifers and other bioclastic fragments form the nuclei of the ooids. Individual cores are dolomitized (ooids on the upper left side of the photomicrograph). The grainstone is cemented by drusy to granular calcite. Sample Zk64, width of photograph is 6.3 mm.
B: Oolitic pack- to wackestone, moderately to poorly sorted and containing micritic matrix. Ooids are partly dissolved and show remnants of concentric laminae. Additionally calcareous green algae and intraclasts occur. Sample ZK57, width of photograph is 6.3 mm.
C: Oncolitic floatstone with strongly recrystallized fine-bioclastic matrix. The cores of the oncoids are formed of phylloid algae which are encrusted by *Grivanella* (dark grey laminae), *Claracrusta* and *Efluegelia*. Borings and disrupted parts in oncoids are filled with matrix. Swarms of dissolution seams with dark insoluble residue are present between the oncoids. Sample ZK66, width of photograph is 34 mm.
D: Poorly sorted bioclastic packstone composed of fusulinids, echinoderm fragments and benthic foraminifera. Additionally, single fragments of phylloid algae encrusted by *Girvanella* occur. Sample ZK75, width of photograph is 6.3 mm.
E: Bioclastic wackestone, poorly sorted, composed of phylloid algae (*Neoanchicodium*, N), calcareous green algae and benthic foraminifera in a fine-grained bioclastic matrix. Sample ZK216, width of photograph is 6.3 mm.
F: Foraminiferal packstone with echinoderm fragment (upper part of the photomicrograph), *Girvanella* and other strongly recrystallized bioclasts. Sample ZK205, width of photograph is 3.2 mm.
G: Small detrital quartz grains in a bioclastic packstone. The bioclasts include phylloid algae (P), calcareous green algae (G) (both are commonly encrusted by *Girvanella*), benthic foraminifera and some echinoderm fragments. Sample ZK187, width of photograph is 6.3 mm.
H: Algal floatstone composed of abundant fragments of *Neoanchicodium*. The algal blades are encrusted by *Pseudovermiporella* and *Girvanella*. Subordinately gastropod shells (at the lower right and left margin of the photomicrograph) and small foraminifera occur. Sample GB99, width of photograph is 18 mm.

5.5.5 MF 5: Oncolitic grainstone to packstone

This microfacies type is poorly to moderately sorted. The rock contains oncoids, a few lithoclasts (small quartz grains and intraclasts composed of micrite and bioclasts) and peloids. Ooids may occur, and they are frequently encrusted by *Girvanella* or display oomoldic porosity. Many grains are abraded.

Common fossils are echinoderms, phylloid algae (*Neoanchicodium*, *Anchicodium*?), fusulinids, small foraminifers (*Calcivertella*, *Geinitzina*, *Nodosinelloides*, *Globivalvulina*, *Tetrataxis*), green algae, algal spores, ostracods, *Efluegelia*, *Claracrusta*, and calcisponges.

The nuclei of the oncoids are formed of bryozoans, phylloid algae, fusulinids, fragments of echinoderms, gastropods and other shell fragments, and by lithoclasts (oolitic pack- to wackestone). The nucleus is encrusted by *Girvanella*, *Claracrusta*, small sessile foraminifers, *Archaeolithophyllum*, *Pseudovermiporella*, *Eflugelia*, calcivertellid foraminifers and *Tuberitina*. Where small quartz grains are present, quartz is attached to the laminae. Replacement dolomitization and stylolites as well as syntaxial overgrowths on echinoderm fragments occur in some of the samples.

5.5.6 MF 6: Oncolitic floatstone

Oncoids are floating within a recrystallized micritic to pelmicritic matrix (section ZK). Additionally, bioclasts and a few lithoclasts occur. Phylloid algae form the nuclei of the oncoids (Fig. 11C). The laminae are formed by *Girvanella* and *Archaeolithophyllum*, and additionally encrusting foraminifers (*Calcivertella*, *Tuberitina*), worm tubes, bryozoans, sponges and *Efluegelia* are present. Some oncoids consist of *Girvanella* and *Claracrusta*. Inclusions of sediment or sparitic patches occur between individual laminae. Several oncoids are bored; the borings are filled with micrite. Frequently geopetal infills in large bioclasts occur. Oncoids are mostly 1 - 5 cm in size; at Zweikofel oncoids up to 14 cm in diameter occur.

5.5.7 MF 7: Bioclastic wackestone to packstone

Poorly to moderately sorted bioclastic wackestone to packstone is the most common microfacies in both sections (Fig.

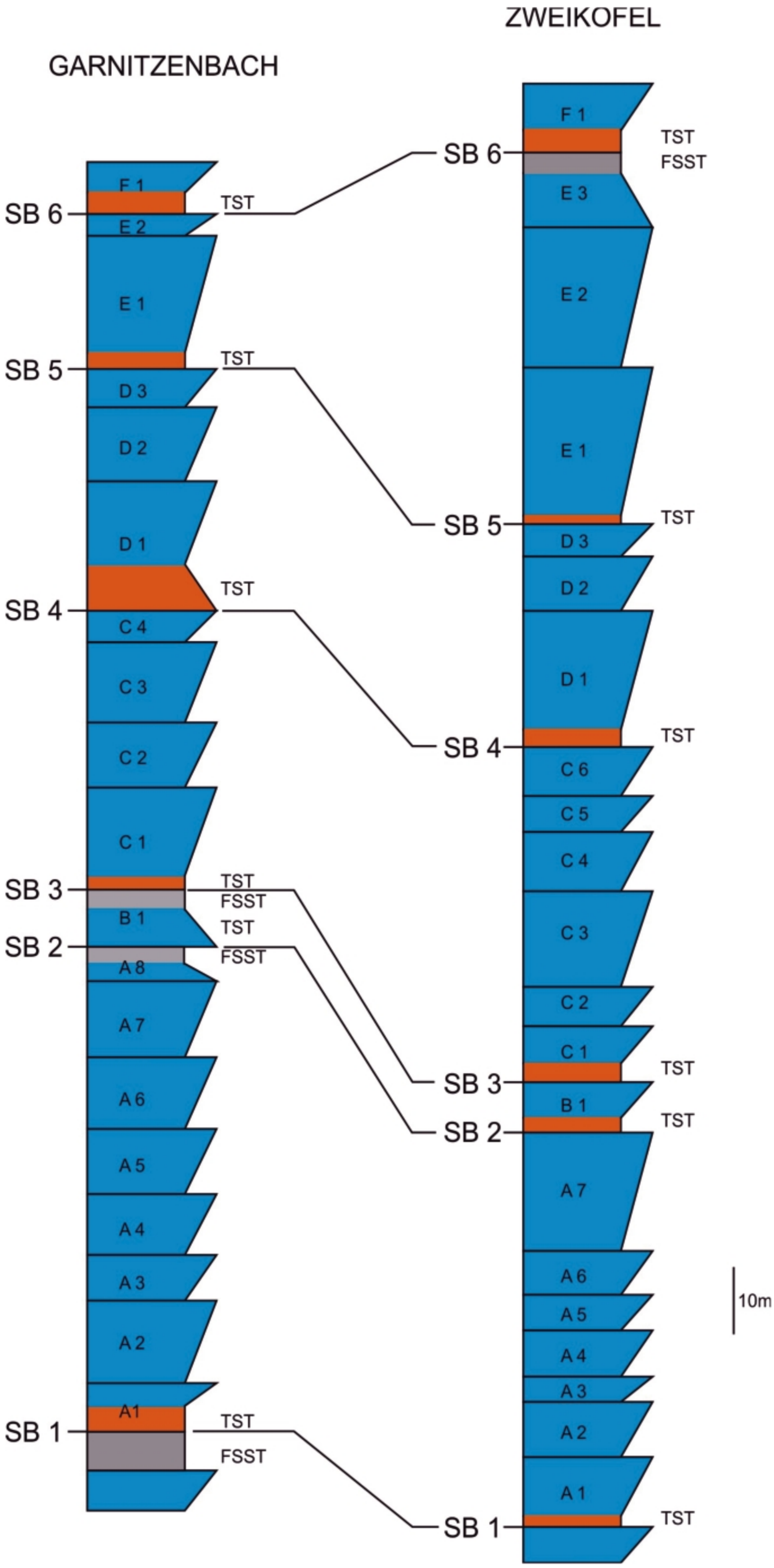


Figure 12: High-frequency cycles (parasequences) of the Zweikofel Formation at Garnitzenbach and Zweikofel. Blue: limestone parasequences, shallowing upward, grey: thin siliciclastic horizons interpreted as falling stage systems tracts (FSST), orange: siliciclastic horizons interpreted as transgressive systems tracts (TST). SB: sequence boundaries.

11D, E). Depending on the dominant type of bioclast (algal spores, calcareous algae, calcivertellid foraminifers, fusulinids, echinoderms) several subtypes can be distinguished. Other fossils such as smaller foraminifers (Fig. 11F), *Tubiphytes*, ostracods, bryozoans, gastropods and brachiopods are present, too. Non-skeletal grains include intraclasts, oncoids, peloids and rare detrital quartz grains (Fig. 11G). The matrix is micrite or pelmicrite. Locally bioclasts are encrusted by *Girvanella*. In highly diverse wacke- to packstones some bioclasts display micritic envelopes, and echinoderm fragments show syntaxial overgrowths. Many wackestones are bioturbated.

A rare type is bioturbated packstone to wackestone composed of *Girvanella* and *Ellesmerella* clasts, subordinate fragments of echinoderms, bryozoans, brachiopod spines, small foraminifers, algal fragments, and spiculae.

Algae: *Girvanella*, *Ellesmerella*, *Efluegelia*, green algae (*Connexia*, *Gyroporella*, *Globuliferoporella*, *Epimastopora*, *Neoanchicodium*, *Mizzia*, *Ungdarella*), phylloid algae (*Neoanchicodium*).

Smaller foraminifers: *Calcivertella*, *Climacammina*, other calcivertellids, *Diplosphaerina*, *Earlandia*, *Endothyra*, *Geinitzina*, *Globivalvulina*, *Hemidiscus*, *Hemigordius*, *Nodosinelloides*, *Pseudovidalina*, *Syzrania*, *Tetrataxis*, *Tuberitina*.

5.5.8 MF 8: Floatstone

In algal floatstone large algal thalli and small bioclasts float within a micritic to (less common) pelmicritic matrix (Fig. 11H). Subordinately intraclasts, small detrital angular to subangular quartz grains, fecal pellets, peloids and oncoids occur. Most of the lithoclasts are subangular, and bioclasts are abraded. Locally bioturbation is observed. Some samples from the lower and the middle part of the ZK section (sample ZK215) contain abundant fusulinids.

The algal thalli belong to the following fossil taxa: *Neoanchicodium catenoides*, *Anchicodium*?, *Eugonophyllum*, *Epimastopora*, and *Globuliferoporella*. Parts of the thalli are dissolved and filled with micritic matrix. Some algae are bored by other organisms (microborings) or encrusted by *Claracrusta*, *Pseudovermiporella*, *Girvanella*, *Archaeolithophyllum*, serpulid worm tubes, *Tubiphytes*, and *Tuberitina*.

The matrix also contains smaller foraminifers (*Calcivertella*, *Tuberitina*, *Geinitzina*, *Globivalvulina*, *Ellesmerella*, *Tetrataxis*, *Nodosinelloide*, *Endothyra*, *Pseudovidalina*, *Climacammina*), fragments of brachiopods, bryozoans, echinoderms, ostracods, calcisponges, gastropods, trilobites, and spiculae.

Stylolites are common. Local replacement dolomitization by anhedral dolomite crystals appears consistently, often close to stylolites.

At Garnitzenbach, floatstone composed of algae and large crinoids stems within a micritic to (less common) pelmicritic matrix occur. The rock contains few oncoids and peloids; in addition to the above mentioned fossils, *Mizzia* and *Ungdarella* are present.

Some algal thalli are encrusted by *Girvanella*, *Ellesmerella*, and *Claracrusta*.

The algal floatstone is associated with bioclastic wackestone to packstone, and peloidal wackestones with abundant algae and small foraminifers.

5.5.9 MF 9: Girvanella Bindstone

The *Ellesmerella/Girvanella* bindstone, which only occurs at Garnitzenbach, contains additional algal fragments (*Neoanchicodium*), small oncoids and bioclasts. Interspersed bioclasts are small foraminifers (*Geinitzina*, *Tuberitina*, *Endothyra*, *Hemigordius*, *Diplosphaerina*), ostracods, gastropods, and fusulinids. The algal thalli are coated by thick oncolitic crusts of *Claracrusta*, *Girvanella*, and *Pseudovermiporella*.

Primary pores are cemented by drusy to blocky sparite, and small pores are filled with microcrystalline cement.

5.6 Depositional environment

According to Schönlaub and Forke (2007), sediments of the Zweikofel Formation accumulated in an open-marine subtidal environment on a complex, articulated carbonate platform with abundant high-energy oolitic shoals and oncolitic beds. These authors note the presence of small mounds at Troghöhe and phylloid algal mounds at Garnitzenbach. We did not observe any mounds in the two studied sections. Subaerial exposure surfaces, which have been reported from the lower part of the Zweikofel Formation at the western flank of Zweikofel, are actually within the uppermost part of the underlying Grenzland Formation.

5.6.1 Siliciclastic sedimentary rocks

Fossil fragments indicate that the siliciclastic sedimentary rocks (siltstone, sandstone, fine-grained conglomerate) were deposited in a shallow marine setting. Detrital grains are derived from metamorphic, igneous (acidic and basaltic volcanic rocks) and sedimentary source rocks. Pebbly sandstone and conglomerate are interpreted as deposits of the upper shoreface, and siltstone and sandstone as the lower shoreface (Sanders and Krainer, 2005).

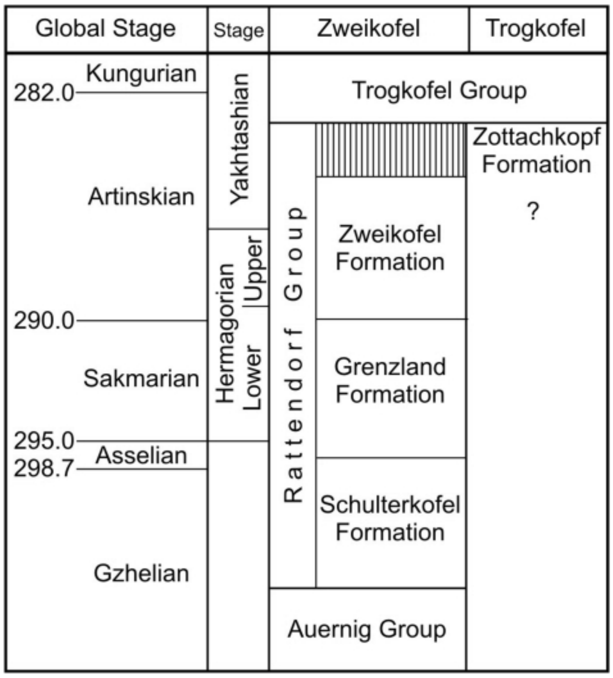


Figure 13: Lower Permian stratigraphy of the Carnic Alps (after Davydov et al., 2012).

5.6.2 Mixed siliciclastic carbonate grainstone to packstone

Mixed siliciclastic carbonate grainstone to packstone containing abundant broken skeletal grains also formed in a shallow marine, high-energy environment.

5.6.3 Carbonate sediments – grainstone facies

Bioclastic grainstone/packstone containing abundant abraded skeletons indicates deposition in a high-energy, shallow marine setting. Oolitic grainstone to packstone represent ooid sand bars that formed in shallow subtidal environment under moderate to high energy conditions slightly below to within the fair-weather wave base. Oncolitic grainstone also suggests shallow marine, moderate to high energy conditions (see Sanders and Krainer, 2005).

5.6.4 Carbonate sediments – wackestone-packstone-floatstone facies

The various types of bioclastic wackestone to packstone containing a diverse fossil assemblage, including abundant calcareous algae, indicate deposition of muddy, commonly bioturbated sediment in a normal, shallow marine environment of low to moderate energy. Local abundance of phylloid algae demonstrates the presence of algal meadows that grew in a shallow marine, subtidal environment within the photic zone under low to moderate water energy.

There are some differences between the two studied sections.

The wackestone-packstone-floatstone facies, particularly algal limestone, is more abundant at Garnitzenbach, whereas the grainstone facies is more abundant at Zweikofel. Fusulinids are abundant at Zweikofel, and rare at Garnitzenbach. Phylloid algae are much more abundant at Garnitzenbach, particularly in the upper part of the section. Differences are also observed in the siliciclastic facies. The upper two horizons (4 and 5) are coarser grained at Zweikofel, and the uppermost horizon 5 is much thicker at Zweikofel (4.5 m) compared to Garnitzenbach (2.2 m).

The depositional environment of the Zweikofel Formation periodically switched between siliciclastic shoreface environment and low- to high-energy, shallow open-marine settings. The Garnitzenbach section was deposited on a slightly deeper and more distal open shelf with abundant low-energy, muddy limestone.

6. Cycles

Thin siliciclastic horizons occur in both sections in a similar stratigraphic position, and have similar facies and thicknesses, allowing subdivision of the Zweikofel Formation into 6 depositional sequences (DS) separated by sequence boundaries (SB) (Fig. 12). The presence of marine fossils in the siliciclastic sedimentary rocks indicate deposition in a shallow marine, nearshore environment.

These siliciclastic horizons formed during periods of falling sea-level and subsequent transgression.

In the lowermost two siliciclastic horizons at Garnitzenbach we draw the sequence boundary (SB 1, SB 2) at the base of pebbly sandstone and fine-grained conglomerate with an erosive lower contact within the siliciclastic horizons. We interpret the thin siliciclastic unit below the SB as sediments deposited during falling sea-level (falling stage systems tract; FSST) and the siliciclastics above the SB as deposits formed during subsequent transgression (transgressive systems tract; TST).

At Zweikofel, the FSST in the lowermost siliciclastic horizon is missing, and the SB is at the base of a thin conglomerate bed at the base of the horizon.

SB 3, SB 4 and SB 5 are drawn at the base of the siliciclastic horizons 3 - 5.

Depositional sequences (DS) are 4 - 37 m thick. The carbonate successions of the thicker depositional sequences 1, 3, 4, 5 are characterized by a repetitive succession of distinct lithofacies resulting in m-scale cyclicity formed of parasequences. We draw the cycle tops where the shoaling facies (massive grainstone to packstone) is sharply overlain by subtidal facies (wackestone, floatstone). These sharp facies boundaries indicate a rapid rise in sea-level and thus mark flooding surfaces.

Parasequences are 2 - 10 m thick. Three types of parasequences occur:

a) Mixed siliciclastic-carbonate parasequences starting with siliciclastic deposits above a sequence boundary (TST), grading into thin-bedded limestone (bioclastic wackestone, floatstone, oncolitic floatstone) representing the highstand systems tract (HST) and locally into thicker-bedded to massive oolitic grainstone/packstone (Fig. 7). The upper boundary is a flooding surface.
b) Mixed siliciclastic-carbonate parasequences starting with bedded limestone (bioclastic wackestone - floatstone) of a HST above a flooding surface, overlain by fine-grained siliciclastic sedimentary rocks that indicate falling sea-level, thus representing the FSST. The upper boundary is a sequence boundary.
c) Shallowing upward parasequences starting with thin-bedded limestone (commonly algal floatstone and oncolitic floatstone), overlain by thicker-bedded bioclastic wackestone and packstone and finally by indistinctly bedded to massive shoal facies of grainstone/packstone. Upper and lower boundaries are flooding surfaces.

Below SB 1 one parasequence is developed at Zweikofel, and two parasequences are developed at Garnitzenbach.

DS 1 is composed of 7 shallowing upward parasequences (A1 - A7) at Zweikofel and 8 shallowing upward parasequences at Garnitzenbach (A1 - A8). Parasequence A1 is a mixed siliciclastic parasequence in both sections, starting with a thin siliciclastic horizon representing a TST. Parasequence A8 at Garnitzenbach is composed of bedded limestone overlain by a thin siliciclastic interval interpreted as FSST. Parasequence A8 is probably eroded at Zweikofel prior to deposition of DS 2.

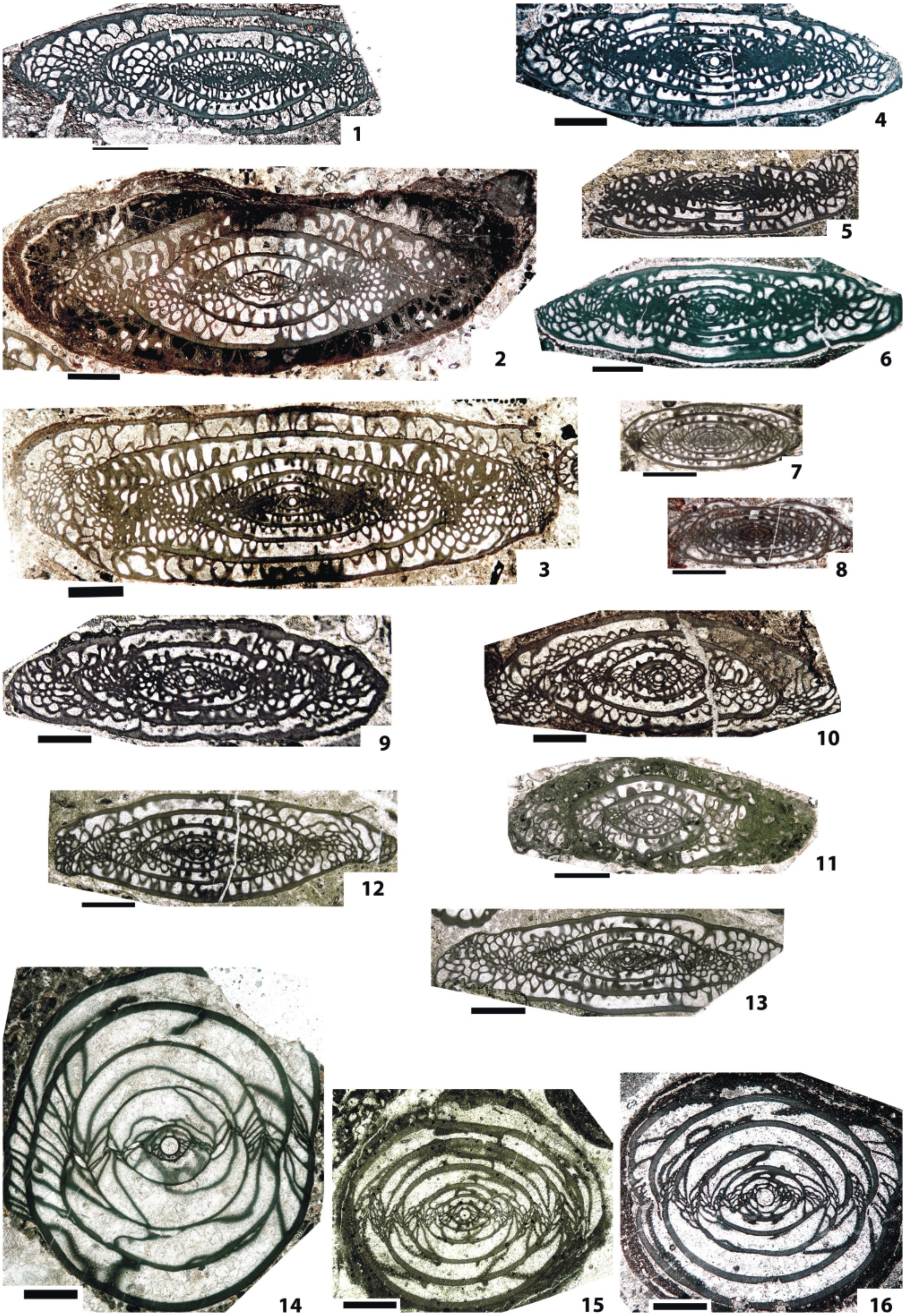
DS 2 is thin and includes one mixed siliciclastic-carbonate parasequence at both sections (B1).

DS 3 starts with a mixed siliciclastic parasequence in both sections (C1), starting with a thin siliciclastic horizon representing a TST, overlain by limestone. Above follow 5 shallowing upward carbonate parasequences at Zweikofel (C2 - C6) and 3 at Garnitzenbach (C2 - C4). At Garnitzenbach parasequences C5 and C6 are probably eroded prior to deposition of DS 4.

At both sections DS 4 starts with a mixed siliciclastic parasequence in both sections (D1), starting with a thin siliciclastic horizon representing a TST, overlain by limestone. Parasequence D1 is overlain by 2 shallowing upward carbonate parasequences (D2 - D3).

DS 5 again starts with a mixed siliciclastic parasequence (E1) in both sections. Above follows a shallowing upward car-

Figure 14: Some important fusulinoideans of the Zweikofel Formation (scale bar of all photographs is 1 mm): 1 *Sakmarella moelleri* (Schellwien), 1908, sample ZK 81. 2 *Sakmarella lubenbachensis* sp. nov., sample 10VD171. 3 *Sakmarella fluegeli* sp. nov., sample 10VD171. 4 *Leeina pseudodivulgata* sp. nov., sample ZK 195. 5 *Leeina pseudodivulgata* sp. nov., sample ZK 198. 6 *Leeina pseudodivulgata* sp. nov., sample ZK 197. 7 *Darvasites (Alpites) deminuatis* sp. nov., sample ZK 204. 8 *Darvasites (Alpites) deminuatis* sp. nov., sample 10VD155. 9 *Chalaroschwagerina incomparabilis* (Leven), 1992, sample ZK 197. 10 *Chalaroschwagerina flocosa* sp., sample OPS 10a. 11 *Chalaroschwagerina flocosa* sp., sample ZK 204. 12 *Perigondwania forkii* sp. nov., sample ZK 205. 13 *Perigondwania forkii* sp. nov., sample ZK 205. 14 *Robustoschwagerina nucelolata* (Ciry), sample 10VD172. 15 *Zellia colanii* Kahler & Kahler, 1937, sample ZK 48. 16 *Zellia colanii* Kahler & Kahler, 1937, sample ZK 58.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bonate parasequence at both sections (E2). At Zweikofel, a mixed siliciclastic-carbonate parasequence (E3) is developed above, composed of bedded limestone overlain by a thin siliciclastic interval interpreted as FSST. Parasequence E3 is missing at Garnitzenbach.

The uppermost DS 6 is thin at both sections and is composed of a basal siliciclastic horizon, overlain by bedded limestone forming a mixed siliciclastic-carbonate carbonate parasequence (F1).

The Zweikofel section includes 22, and the Garnitzenbach section 20 parasequences.

7. Paleontology

Most of the fossils described from the "Oberer Pseudoschwagerinenkalk" (Upper *Pseudoschwagerina* Limestone) are from the succession that we assign to the Zottachkopf Formation. These fossils include fusulinids of the Zottachkopf section (Kahler and Kahler, 1937; Kahler, 1983), calcareous algae of sections C and D of Flügel (1966), and Homann (1972), smaller foraminifers of Flügel (1971), corals, and fusulinids from red limestones described by Kahler (1983) and Forke (2002).

From the Zweikofel Formation at Zweikofel and Garnitzenbach Forke (2002) listed fusulinids (Fig. 10, 11). Vachard and Krainer (2001) listed smaller foraminifers, pseudo-algae and algae from both sections.

Brachiopods, bellerophontid gastropods and cm-large crinoid stem fragments are common macrofossils but have never been identified.

From the Zweikofel section Forke (2002) identified the following fusulinoideans:

Schubertella australis, *Boultonia willsi*, *Paraschwagerina nitida*, *Zellia heritschi media*, *Zellia heritschi heritschi*, *Zellia colanii*, *Robustoschwagerina geyeri*, *Pseudochusenella cushmani*, *Paraschwagerina inflate* and *Robustoschwagerina spatiosa*.

From the Garnitzenbach section Forke (2002) listed *Robustoschwagerina geyeri*, *Robustoschwagerina kahleri*, *Pseudochusenella havana* n.sp., *Pseudochusenella cushmani*, *Paraschwagerina nitida*, *Schubertella australis*, *Robustoschwagerina* cf. *beitepensis*, *Zellia* cf. *mira*, and *Boultonia willsi*.

Recently Davydov et al. (2013) provided a detailed study of the fusulinoideans of the Zweikofel Formation at Zweikofel and Garnitzenbach. They listed 18 genera including one new subgenus, 62 species, and 12 new species and subspecies. Some biostratigraphically important fusulinoideans are shown on Fig. 14.

8. Stratigraphy

The Lower Permian succession in the Carnic Alps is composed of the Rattendorf Group and overlying Trogkofel Group of the Pontebba Supergroup. The Rattendorf Group is divided into Schulterkofel Formation, Grenzland Formation and Zweikofel Formation. Schaffhauser et al. (2010) proposed a new lithostratigraphic unit termed Zottachkopf Formation for the approximately 100 m thick bedded facies at the base of the Trogkofel Limestone in the Trogkofel massif. The facies of the Zottachkopf differs significantly from the Zweikofel Formation and is also slightly younger. The Zottachkopf Formation is missing at Zweikofel, where the Zweikofel Formation is overlain by breccias of the basal Trogkofel Limestone, indicating a gap (Fig. 13).

Schönlaub and Forke (2007) ascribed the Zweikofel Formation to the upper Sakmarian - lower Artinskian.

Davydov et al. (2013) distinguish five fusulinid assemblages (zones) within the Zweikofel Formation at Zweikofel (Fig. 4):

1) *Sakmarella moelleri- Darvasites deminuatis* Zone (basal 2 m, up to sample 10VD161)
2) *Sakmarella fluegeli-Zellia colanii* Zone (samples ZK 37 - 10VD165)
3) *Sakmarella lubenbachensis- Robustoschwagerina nucleolata* Zone (samples 10VD168 – 10VD178),
4) *Leeina pseudodivulgata- Chalaroschwagerina incomparabilis* Zone (ZK 195 - ZK 198), and
5) *Chalaroschwagerina solita flocosa* Zone (ZK 204 - ZK 207).

They also propose to use the Tethyan chronostratigraphy instead of the global scale in the Carnic Alps as the stage boundaries of the latter cannot be established with necessary precision. For the same reason the new Hermagorian Stage has been proposed for the succession that correlates with the entire Sakmarian and (approximately) lower Artinskian of the Global Scale. Typical upper Yakhtashian fusulinids of Darvas (Leven, 1980) were found in the lowermost part of the Trogkofel Limestone (Davydov et al., 2013).

Fusulinids of zone 1 are similar to those described from the Grenzland Formation and are usually assigned to the Sakmarian. Fusulinid zones 2 and 3 indicate an age younger than Sakmarian but older than Yakhtashian. These fusulinid zones are assigned to the late Hermagorian. Assemblages 4 and 5 correspond to the lower Yakhtashian. According to Davydov et al. (2013), the fusulinids thus indicate a late Hermagorian to early Yakhtashian (approximately Artinskian) age of the Zweikofel Formation. The red limestone from locality "Höhe 2004" is assigned to the transitional beds (near the base of the Zottachkopf Formation) between the Zweikofel Formation and Trogkofel Limestone.

9. Discussion

The Zweikofel Formation as defined by Krainer (1995) does not include the "bedded facies" at the base of the Trogkofel Limestone at Trogkofel and Zottachkopf. This bedded facies, which was originally assigned to the Oberer Pseudoschwagerinenkalk and regarded as correlative to the Zweikofel Formation at Zweikofel (Schönlaub and Forke, 2007), differs significantly in facies and age, so Schaffhauser et al. (2010) defined this succession as a new lithostratigraphic unit termed Zottachkopf Formation of the Rattendorf Group, lying between the Zweikofel Formation and Trogkofel Limestone.

The bedded facies is absent at Zweikofel and Garnitzenbach, where the contact between the Zweikofel Formation and overlying Trogkofel Limestone is erosional and locally characterized by thick carbonate breccias indicating reworking of the bedded facies prior to deposition of the Trogkofel Limestone (Krainer et al., 2009).

The Zweikofel Formation is a mixed siliciclastic-carbonate succession with well-developed cycles. Intercalated siliciclastic horizons enable a subdivision of the two sections into 6 correlative packages (depositional sequences) that contain almost equal numbers of parasequences. Sequence boundaries are drawn at the erosional lower contacts of the siliciclastic intervals. Limestone successions are composed of shallowing upward parasequences similar to those reported from other late Paleozoic succession (e.g. Ross and Ross, 1987, 1988; Dickinson et al., 1994; Soreghan, 1994; Elrick and Scott, 2010). Thickness trends suggest a high-resolution correlation of both sections with nearly cycle-to-cycle fit.

We interpret these parasequences as high-frequency cycles caused by glacio-eustatic sea-level fluctuations of the Gondwana Glaciation. According to Isbell et al. (2003), during Glacial Episode III (Stephanian to Sakmarian-Artinskian) massive ice sheets were present in Gondwana that produced changes in base level recorded by cyclothems in the Pangean equatorial zone.

Thickness, sedimentary structures and fossils of the siliciclastic horizons indicate deposition in a shallow, nearshore depositional environment during periods of relatively low sea level and strong siliciclastic influx (lowstand or transgressive systems tract).

Carbonate rocks are composed of microfacies indicating high-energy conditions (grainstone-packstone; MF 1, 2, 3 and 5) and moderate to low-energy conditions (wackestone-packstone, floatstone and bindstone; MF 4, 6, 7, 8).

All limestone types contain a diverse fossil assemblage including abundant calcareous algae, smaller foraminifers and fusulinids indicating deposition in open, normal marine shallow water.

Although both sections correlate very well, some differences exist in facies. At Garnitzenbach siliciclastic horizons are finer grained and the well-washed high-energy grainstone facies is less common, particularly in the upper part, indicating a more distal depositional environment compared to Zweikofel.

As the Zweikofel Formation correlates approximately to the early-middle Artinskian, the sediments were deposited within a time span of approximately 6 Ma, resulting in average durations for the 22 parasequences of 273 ka. This is within the time span of 235 – 400 ka which Heckel (1986) estimated for the major cycles of the Kansas cyclothems in the United States Midcontinent which are considered to be of glacio-eustatic origin (e.g. Veevers and Powell, 1987; Ross and Ross, 1988).

10. Conclusion

The Zweikofel Formation is a 94 - 106 m thick cyclic succession of thin- to thick-bedded fossiliferous limestone and five intercalated thin intervals of siliciclastic sediments. Limestone of the grainstone facies was deposited in a moderate to high energy shallow marine environment. Muddy limestone (wackestone-packstone-floatstone facies) containing a diverse fossil assemblage including abundant calcareous algae indicates deposition in a shallow, open marine subtidal environment under low to moderate water energy.

Differences in facies and fossil content between the two studied sections indicate that the Garnitzenbach section was deposited on a slightly deeper and more distal open marine shelf compared to the Zweikofel section, which was deposited in a shallower environment closer to the shore.

The Zweikofel Formation is a mixed siliciclastic-carbonate succession with well-developed cycles. Intercalated siliciclastic horizons enable a subdivision of the two sections into 6 depositional sequences that contain almost equal numbers of parasequences. Sequence boundaries are drawn at the erosional lower contacts of the siliciclastic intervals. Parasequences are 2 - 10 m thick. Three types of parasequences are distinguished. Limestone successions are composed of well-developed shallowing upward parasequences. The parasequences are interpreted as high-frequency cycles caused by glacio-eustatic sea-level fluctuations of the Gondwana Glaciation.

The Zweikofel Formation at Zweikofel and Garnitzenbach contains a rich assemblage of fusulinaceans that allows a subdivision of the Zweikofel Formation into 5 fusulinid zones correlating with the early- middle Artinskian of the Global Time scale.

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