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The Zottachkopf Formation (Lower Permian; Cisuralian), a new stratigraphic unit of the Rattendorf Group, Carnic Alps, Austria/Italy

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14 Text-Figures, 15 Plates

In memoriam Erik Flügel (1934–2004)

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Zottachkopf Formation
Lower Permian (Cisuralian)
Sedimentology
Stratigraphy
Foraminifera
Carnic Alps
Austria/Italy

Content

Abstract

The Zottachkopf Formation is a new lithostratigraphic unit of the Upper Pennsylvanian–Lower Permian Rattendorf Group in the Carnic Alps (Southern Alps) that underlies the Trogkofel Formation in the Trogkofel-Zottachkopf massif. The Zottachkopf Formation is a succession of thin- to medium-bedded limestone with some siliciclastic influx in the lower part and locally intercalated algal mounds in the upper part. The total thickness is approximately 184 m.

Limestone of the Zottachkopf Formation contains a diverse fossil assemblage and almost all limestone beds contain oncoids. Sediments of the lower part that contain siliciclastic material are interpreted as deposits of a low- to high-energy nearshore shelf environment. Microfacies and fossil assemblages of the bedded limestone facies of the middle and upper parts indicate deposition in a shallow, normal marine, open shelf environment above the storm wave base. Intercalated mounds are similar in composition to the mounds of the overlying Trogkofel Formation.

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The fusulinid assemblage of the Zottachkopf Formation is very similar to that of the Zweikofel Formation but is less well studied. Thus, the biostratigraphic age of the Zottachkopf Formation is still unclear. The absence of glacioeustatic cycles in the Zottachkopf Formation indicates that glacioeustatic sea-level fluctuations did not occur during deposition of the Zottachkopf Formation.
The Zottachkopf Formation seems to have been deposited after the "Artinskian Warming Event" during a period (late Artinskian–Kungurian) when glaciation on the southern hemisphere was almost absent and therefore glacioeustatic sea level fluctuations did not occur. This indicates that the Zottachkopf Formation is younger than the Zweikofel Formation and most probably is of late Artinskian age.

Die Zottachkopf-Formation (Unterperm; Cisuralium), eine neue stratigraphische Einheit innerhalb der Rattendorf Gruppe, Karnische Alpen, Österreich/Italien

Zusammenfassung

Die Zottachkopf-Formation ist eine neue lithostratigraphische Einheit der oberkarbonen bis unterpermischen Rattendorfer Schichtgruppe in den Karnischen Alpen (Südalpen) und unterlagert die Trogkofel-Formation im Trogkofel-Zottachkopf-Massiv.
Die Zottachkopf-Formation ist eine Abfolge aus dünn- bis mittelgebankten Kalken mit siliziklastischem Einfluss im unteren Teil und lokal eingeschalteten Algenmounds im oberen Teil. Die Gesamtmächtigkeit beträgt ungefähr 184 m.
Die Kalke der Zottachkopf-Formation enthalten eine diverse Fossilvergesellschaftung und fast alle Kalkbänke enthalten Onkoide.
Die Sedimente im unteren Teil der Abfolge enthalten siliziklastisches Material und werden als Ablagerungen eines niedrig- bis hochenergetischen, küstennahen Schelfbereiches interpretiert.
Mikrofazies und Fossilinhalt der gebankten Kalkabfolge des mittleren und oberen Abschnittes weisen auf Ablagerung in einem flachen, normal marinen, offenen Schelfbereich oberhalb der Sturmwellenbasis hin. Eingeschaltete Algenmounds sind in ihrer Zusammensetzung ähnlich den Mounds der überlagernden Trogkofel-Formation.
Die Fusulinidenvergesellschaftung der Zottachkopf-Formation ist sehr ähnlich jener der Zweikofel-Formation, allerdings weniger gut untersucht. Daher ist eine genaue biostratigraphische Einstufung der Zottachkopf-Formation nach wie vor unklar. Das Fehlen glazioeustatischer Zyklen in der Zottachkopf-Formation weist darauf hin, dass glazioeustatische Meeresspiegelschwankungen während der Sedimentation der Zottachkopf-Formation nicht aufgetreten sind.
Die Zottachkopf-Formation wurde offensichtlich nach dem „Artinskian Warming Event" während einer Periode abgelagert, in der Vergletscherungen auf der südlichen Hemisphäre weitgehend verschwunden waren.
Dies weist darauf hin, dass die Zottachkopf-Formation jünger als die zyklisch aufgebaute Zweikofel-Formation ist und sehr wahrscheinlich im späten Artinskium abgelagert wurde.

Introduction

Detailed sedimentological studies of the Lower Permian succession at Zweikofel, Trogkofel and Zottachkopf in the central Carnic Alps showed that the bedded limestone facies that underlies the massive Trogkofel Limestone at Trogkofel and Zottachkopf and until now was ascribed to the Zweikofel Formation differs significantly from the Zweikofel Formation at Zweikofel and Garnitzenbach (as defined by Krainer, 1995a).

For this bedded limestone facies, that underlies the Trogkofel Formation in the Trogkofel and Zottachkopf massif, Schaffhauser et al. (2010) proposed the term Zottachkopf Formation (of the Rattendorf Group).

The Zweikofel Formation, with its type section at Zweikofel (Krainer, 1995a; Krainer & Schaffhauser, 2012), is a mixed siliciclastic-carbonate, cyclic succession of thin- to thick-bedded fossiliferous limestone and five intercalated thin intervals of siliciclastic sediments that allowed a subdivision of the Zweikofel Formation into depositional sequences and parasequences (Krainer & Schaffhauser, 2012).

The bedded limestone facies (Zottachkopf Formation) is absent at Zweikofel where the boundary between the Zweikofel Formation and overlying Trogkofel Formation is a surface of erosion, documented by a truncation surface and locally by up to more than 15 m thick, coarse carbonate breccias composed of reworked limestone clasts displaying facies similar to the Zweikofel Formation (Krainer et al., 2009). Obviously, the bedded limestone facies (Zottachkopf Formation) has been eroded at Zweikofel.

The aim of this paper is a detailed description and definition of the bedded limestone facies (Zottachkopf Formation) that underlies the Trogkofel Formation in the Trogkofel and Zottachkopf massif following the rules of the International Commission on Stratigraphy (ICS).

The description includes lithology, lower and upper boundary, microfacies, fossil assemblage, biostratigraphy, reconstruction of the depositional environment and comparison with the Zweikofel Formation.

Location and methods

We investigated the Zottachkopf Formation at several sections in the Trogkofel-Zottachkopf massif in the central Carnic Alps close to the Austrian/Italian border where the formation underlies the massive Trogkofel Limestone (Text-Fig. 1).

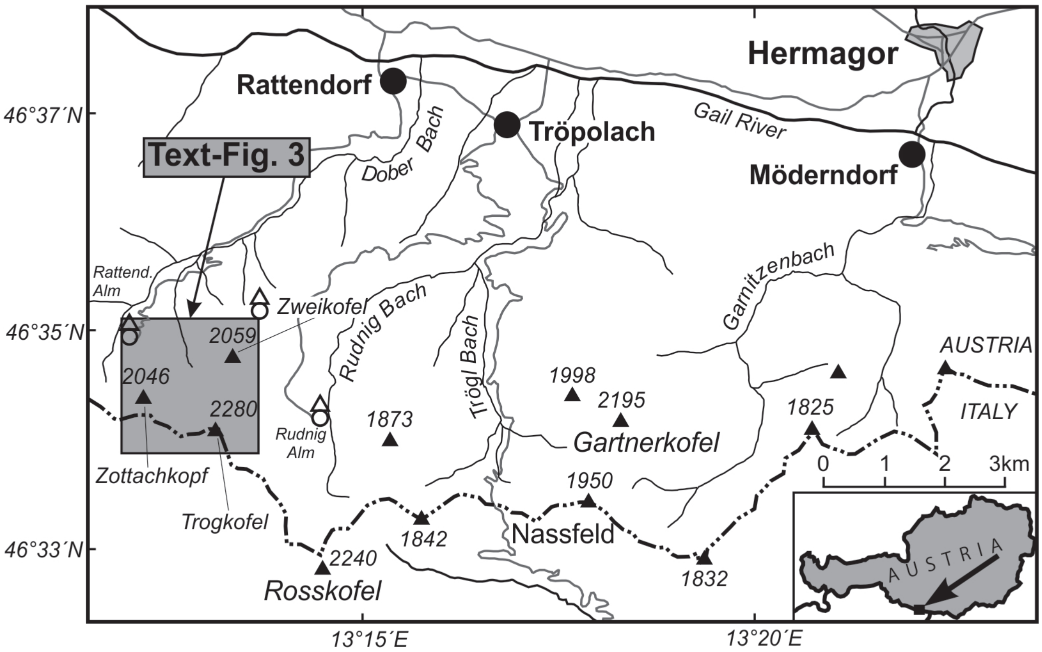
The type section of the Zottachkopf Formation is located at the base of the steep northern slope of the Trogkofel (sections TNA – lower part, TNB – main part, and TNC – upper part). Reference sections are located on the southern and southwestern side of Trogkofel (TKS, TKW) where the upper part of the Zottachkopf Formation and basal part of the overlying Trogkofel Formation are well exposed. We also studied the Zottachkopf Formation at the sections Trogkar (section ZT) and Zottachkopf (section Z). Most of these sections include also the lowermost part of the Trogkofel Formation. The locations of the studied sections are shown in Text-Figures 2 and 3.

Text-Fig. 1.
Zweikofel massif (left) and Trogkofel-Zottachkopf massif (right). View towards southeast.

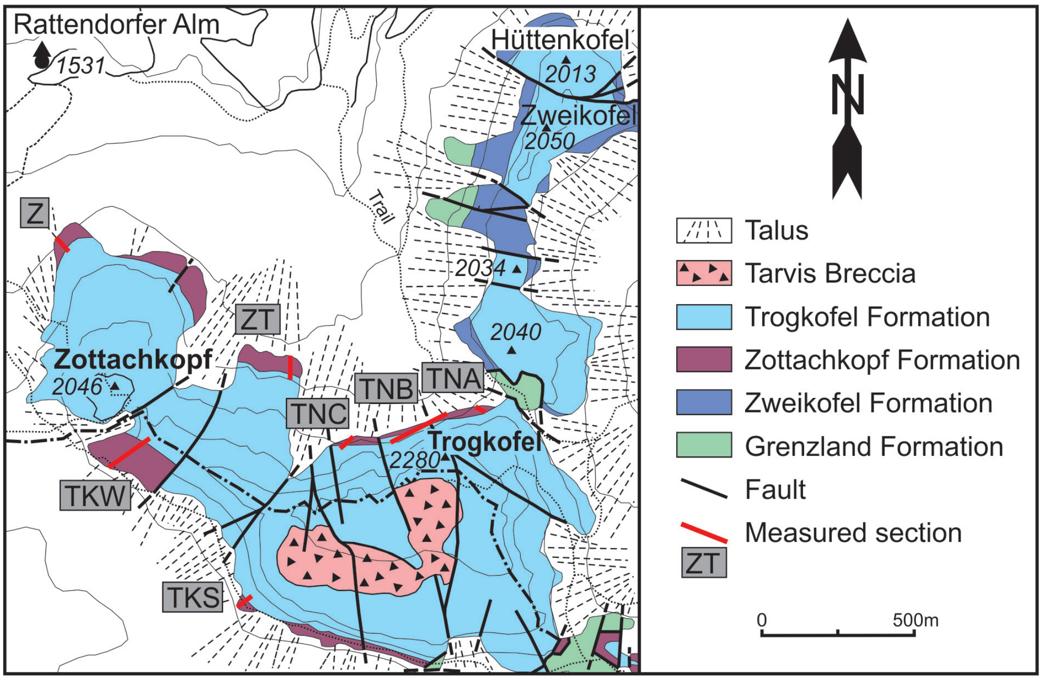
From all collected samples of the measured sections, thin sections were prepared for microfacies analysis and determination of fossils, particularly calcareous algae and foraminifers. Limestones were classified following the classification of DUNHAM (1962), modified by EMBRY & KLOVAN (1971), see also FLÜGEL (2004).

Historical background

Late Palaeozoic sediments of the Carnic Alps and fossils have been studied by Austrian, Italian and German scientists, starting with the work of FRECH (1894), GEYER (1896, 1899), GORTANI (1906), SCHELLWIEN (1892, 1898), STACHE (1872, 1874, 1878), TARAMELLI (1895a, b), TIETZE (1870), VINASSA DE REGNY (1906) and others at the end of the 19th century. These studies were continued between the two World Wars by HERITSCH (1928, 1929, 1934, 1939, 1943), HERITSCH et al. (1934), KAHLER (1931, 1939, 1942), and KAHLER & KAHLER (1937a, b, 1938, 1941) who established the basic stratigraphic scheme (summary in HERITSCH, 1943). After World War II, palaeontological and biostratigraphical studies as well as geological mapping were intensified resulting in geological maps of the Nassfeld-Pramollo area (KAHLER & PREY, 1963; SELLI, 1963a, b; VENTURINI, 1990a; SCHÖNLAUB, 1987; SCHÖNLAUB & FORKE, 2007), in refined biostratigraphical subdivisions (especially of the Late Carboniferous and Early Permian, based on fusulinids; KAHLER, 1983, 1985, 1986a, b). Since 1970 de-



Text-Fig. 2.
Map showing location of the study area in the Trogkofel-Zottachkopf massif in the central Carnic Alps along the Austrian-Italian border.



Text-Fig. 3.
Simplified geologic map of the Trogkofel–Zottachkopf–Zweikofel area in the central Carnic Alps with locations of the studied sections TNA, TNB, TNC, ZT, Z, TKS and TKW.

tailed microfacies analyses were undertaken and facies models were developed that describe depositional patterns of reef and non-reef shelf sediments of the Late Palaeozoic succession (e.g., Buggisch et al., 1976; Buttersack & Boeckelmann, 1984; Flügel, 1968, 1970, 1974, 1977, 1980, 1981, 1987; Flügel et al., 1971, 1997; Forke et al., 1998; Krainer, 1991, 1992, 1995a, 2007; Krainer et al., 2003; Massari & Venturini, 1990; Massari et al., 1991; Samankassou, 1997, 1998, 1999, 2002, 2003; Sanders & Krainer, 2005; Venturini, 1990b, 1991).

An excellent overview on the Palaeozoic succession of the Carnic Alps has been published by Schönlaub (1979). Most palaeontological studies of Late Palaeozoic rocks concerned fusulinids, predominantly due to the long-lasting work by Kahler, later by Forke (Forke, 1995a–c, 2000, 2002; Forke et al., 1998) and Davydov (Krainer & Davydov, 1998; Davydov & Krainer, 1999; Davydov et al., 2013), calcareous algae (Homann, 1972; Flügel & Flügel-Kahler, 1980; Krainer et al., 2019a), conodonts (Forke, 2002), smaller foraminifers (Vachard & Krainer, 2001a, b; Krainer et al., 2019a) and corals (Felser, 1937a, b, 1970; Homann, 1970). Boersma and Fritz studied fossil plants (summary in Fritz & Krainer, 2006, 2007).

Recently Novak & Forke (2006), Schönlaub et al. (2007), Novak et al. (2019) and Forke (2021) provided a summary on the Late Palaeozoic succession of the Carnic Alps.

Geyer (1896) named limestones that occur above the Auernig Group and contain *Schwagerina* “Schwagerinenkalk” (*Schwagerina* Limestone): He correlated this *Schwagerina* Limestone with the Lower Permian “Schwagerinenstufe” (*Schwagerina* stage) of the Ural Mountains.

Heritsch et al. (1934) recognized that the *Schwagerina* Limestone of Geyer (1896) is divided into a lower (“Unterer Schwagerinenkalk”) and upper *Schwagerina* Limestone (“Oberer Schwagerinenkalk”), separated by the Grenzland Formation (“Grenzlandbänke”). Kahler (1931) recognized that the Grenzland Formation that is composed of alternating siliciclastic and carbonate sediments and therefore was considered as part of the Auernig Group, contains a fusulinid assemblage similar to that of the *Schwagerina* limestones and is therefore also of Lower Permian age. Heritsch et al. (1934) introduced the term “Rattendorfer Schichten” (Rattendorf Group) in which they included the Lower *Schwagerina* Limestone, the Grenzlandbänke and the Upper *Schwagerina* Limestone. Due to changes in the systematics of fusulinids, Kahler (1947) renamed the *Schwagerina* limestones into Lower and Upper *Pseudoschwagerina* Limestone. Finally, Krainer (1995a) introduced the terms Schulterkofel Formation for Lower *Pseudoschwagerina* Limestone and Zweikofel Formation for Upper *Pseudoschwagerina* Limestone.

The bedded limestone facies (Zottachkopf Formation) at the base of the Trogkofel Formation in the Trogkofel-Zottachkopf massif, originally termed “Oberer Schwagerinenkalk” (Upper *Schwagerina* Limestone; Kahler & Kahler, 1937a, b), is characterized by dark grey, thin-bedded limestone containing abundant small oncoids. In the lower part siliciclastic sediments and reddish limestones rich in crinoid fragments occur. Locally, algal mounds are developed, particularly south of Zottachkopf. This bedded succession at Trogkofel and Zottachkopf was ascribed to the “Upper *Schwagerina* Limestone” (= Zweikofel Formation) by Heritsch et al., 1934; Kahler & Kahler, 1937a, b; Flügel, 1968, 1970, 1974; Flügel et al., 1971; Homann, 1972; Kahler, 1986a.

Geological setting

In the Carnic Alps, the Variscan Orogenic Phase culminated during the middle Westphalian and was followed by block- and wrench faulting resulting in the formation of discrete sedimentary basins (Venturini, 1982, 1990b, 1991). These basins were filled with deltaic to shallow marine sediments of the Late Carboniferous Bombaso Formation and Auernig Group, and the Late Carboniferous/Early Permian Rattendorf and Trogkofel Groups. This sedimentary succession uncomfortably overlies the folded Variscan basement.

Rattendorf Group

The Rattendorf Group consists of shallow marine carbonate and siliciclastic sediments of nearshore, inner shelf and outer shelf environments. The succession is divided into the Schulterkofel, Grenzland, Zweikofel and Zottachkopf formations.

Schulterkofel Formation

This formation is approximately 155 m thick at the type section and composed of three depositional cycles consisting of shallow marine limestones and thin siliciclastic sandstone and siltstone intervals, which form the bases of the depositional sequences and were deposited during relative sea-level lowstands. During transgression, well-bedded fossiliferous limestones and massive algal mounds accumulated. Bedded cherty limestones with marl intercalations are interpreted as deposits that formed during relative sea-level highstands with water depths of some tens of meters. Fusulinid-rich limestone beds occur at different stratigraphic levels, particularly at the base and on top of the siliciclastic intervals (see Buggisch et al., 1976; Flügel, 1974, 1977; Forke et al., 1998; Homann, 1969; Krainer et al., 2003; Samankassou, 1997, 1999).

Based on fusulinids the Schulterkofel is dated as late Gzhelian (basal part belongs to the *Daixina sokensis* Zone, followed by the *Daixina (Bosbytauella) bosbytauensis–D. robusta* Zone). The Carboniferous/Permian boundary is within the uppermost part of the Schulterkofel Formation. The uppermost few meters contain *Schellwienia bornemanni, Zigarella panjiensis* and *Likharevites inglorious* indicating early Asselian age (Forke et al., 1998; Krainer & Davydov, 1998).

Grenzland Formation

The Lower Permian (Asselian–Sakmarian) Grenzland Formation was originally described as a 60–120 m thick, partly cyclic sequence of predominantly shallow marine siliciclastic sediments (quartz-rich conglomerates, sandstones and siltstones) and intercalated thin, fossiliferous limestone intervals (Buttersack & Boeckelmann, 1984; Boeckelmann, 1985; Schönlaub & Forke, 2007).

Due to Alpine tectonics, a complete section of the Grenzland Formation is not exposed. Our own investigations have shown that the Grenzland Formation is more than 300 m thick. The lower part (50–100 m), which conformably rests on fossiliferous limestone of the Schulterkofel Formation, is non-cyclic, entirely siliciclastic and composed of siltstone, sandstone and rare, fine-grained conglomerate. The middle and upper parts are a cyclic succession of quartz-rich conglomerate and cross-bedded sandstone of a nearshore facies, hummocky cross-bedded sandstone of the lower shoreface, offshore siltstone and shale and fossiliferous limestone forming well-developed parasequences. In the middle and upper parts, at least 15 cycles (parasequences) are recognized that range in thickness from 10 m to 30 m.

The cyclic succession coincides with the maximum extent of the Gondwana glaciation in the southern hemisphere, which occurred during the Asselian–early Sakmarian (Fielding et al., 2008; Isbell et al., 2003). The cycles (parasequences) are interpreted to be caused by glacioeustatic sea-level fluctuations (Krainer, 2012). Fusulinids indicate Asselian–Sakmarian age (Davydov et al., 2013).

Zweikofel Formation

The Zweikofel Formation is a cyclic sequence 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. Schönlaub & Forke (2007) report a maximum thickness of 135 m. Limestones contain abundant fossils, particularly calcareous algae (Homann, 1972), smaller foraminifers (Flügel et al., 1971), fusulinids, corals, bryozoans, brachiopods, gastropods, bivalves, ostracods, rare trilobites and echinoderm fragments. Flügel (1968), Buttersack & Boeckelmann (1984) and Sanders & Krainer (2005) described the microfacies of the Zweikofel Formation. Small algal mounds occur in the lower part (Forke, 1995c; Samankassou, 2003). Cycles indicate repeated shifting from nearshore to offshore environments in an open marine shelf lagoon with normal water circulation (Flügel, 1981). Compared to the Schulterkofel and Grenzland formations, the limestones are characterised by more diverse fossil assemblages and microfacies types (Flügel, 1970, 1981; Flügel et al., 1971).

According to Krainer & Schaffhauser (2012), the Zweikofel Formation at the type section (Mount Zweikofel) and at Garnitzenbach creek is 94–106 m thick and consists of a cyclic succession of thin- to thick-bedded fossiliferous limestone and five intercalated, thin intervals of siltstone, sandstone and fine-grained, quartz-rich conglomerate. Fossils indicate deposition in a shallow-marine nearshore environment. The carbonate facies is characterized by moderate- to high-energy microfacies types (bioclastic, oolitic and oncolitic grainstone to packstone), and low- to moderate-energy microfacies types (bioclastic and oolitic wackestone to packstone, floatstone and rare cyanobacterial bindstone). A diverse fossil assemblage indicates deposition in a shallow, neritic, normal-saline, low- to high-energy environment (Krainer & Schaffhauser, 2012).

The Zweikofel Formation can be divided into six depositional sequences (parasequences) that are interpreted as high-frequency cycles caused by glacioeustatic sea-level fluctuations of the Gondwana Glaciation (Krainer & Schaffhauser, 2012). At the type section, Davydov et al. (2013) distinguished five fusulinid assemblages within the Zweikofel Formation that indicate late Hermagorian to Yakhtashian (approximately Artinskian) age.

Recently, the Zweikofel Formation was studied by Calvo González (2022) and Calvo González et al. (2023a, b). Microfacies analysis of the Zweikofel Formation records relatively moderate sea-level fluctuations on the order of a few tens of meters (~30–40 m). According to Calvo González et al. (2023a, b) the minor sea-level amplitudes of the Zweikofel Formation may be linked to the demise of ice sheets during the final stage of the Late Palaeozoic ice age. The non-cyclic Zottachkopf Formation was deposited after the collapse of the ice sheets at the Asselian–Sakmarian boundary. Calvo González (2022) and Calvo González et al. (2023a, b) dated the Zweikofel Formation as late Asselian and the overlying Zottachkopf Formation as latest Asselian–Sakmarian (see chapter "Biostratigraphy").

Zottachkopf Formation

The bedded limestone facies that underlies the Trogkofel Formation in the Trogkofel-Zottachkopf massif is characterised by dark grey, thin-bedded limestone containing abundant small oncoids. In the lower part, siliciclastic sediments and reddish limestones rich in crinoid fragments occur. Locally, algal mounds are developed, particularly south of Mount Zottachkopf. This bedded succession at Mount Trogkofel and Mount Zottachkopf was ascribed to the "Upper *Schwagerina* Limestone" (= Zweikofel Formation) by Heritsch et al. (1934), Kahler & Kahler (1937a, b), Flügel (1968, 1970, 1974), Flügel et al. (1971), Homann (1972), and Kahler (1986a).

We will show that this bedded limestone facies is not an equivalent of the Zweikofel Formation, but is probably younger and displays a different facies, and we therefore introduced the new term Zottachkopf Formation for this bedded limestone facies that underlies the Trogkofel Formation in the Trogkofel-Zottachkopf massif (Schaffhauser et al., 2010).

Lithology

A complete section of the Zottachkopf Formation is not exposed. The best outcrops are located on the northern side of the Trogkofel and Zottachkopf massif (sections TNA, TNB, TNC, Trogkar and Zottachkopf). Additionally, two sections were measured on the southwestern and southern side of the Trogkofel massif (Trogkofel West and Trogkofel South) where the uppermost Zottachkopf and the boundary to the overlying Trogkofel Formation are well exposed (Text-Figs. 4–7, location see Text-Fig. 3).

Section TNA (39.4 m) represents the lower part, section TNB (91 m) the main part and section TNC the upper part (74 m) of the Zottachkopf Formation. There is no overlap between sections TNA and TNB. Section TNC is the continuation of TNB and includes the boundary to the overlying Trogkofel Formation. Sections TNA, TNB and TNC are proposed as the type section of the Zottachkopf Formation. The total thickness of the Zottachkopf Formation is approximately 184 m.

The Trogkar section includes 87 m of Zottachkopf Formation and overlying Trogkofel Formation. The Zottachkopf section encompasses the uppermost 34 m of the Zottachkopf Formation and the basal part of the overlying Trogkofel Formation.

Trogkar section (ZT) and Zottachkopf section (Z) are proposed as reference sections for the upper part of the Zottachkopf Formation.

Trogkofel north (section TNA)

The basal 2.4 m thick succession is composed of 1.5 m of massive, grey, fossiliferous limestone containing calcareous algae, crinoid fragments, fusulinids and large gastropods. This massive limestone is karstified. Karst cavities are filled with red, silty karst sediment that contains well-rounded quartz grains with diameters up to 2 cm.

The massive limestone is overlain by 10 cm of thin-bedded limestone, a thicker limestone bed (50 cm) with abundant crinoid fragments, 20 cm of fossiliferous limestone and 10 cm of greenish mudstone (Text-Fig. 4).

Microfacies: The massive limestone bed is composed of bioclastic wackestone (Pl. 1, Fig. A), partly of floatstone to poorly washed grainstone-rudstone containing a diverse fossil assemblage of echinoderm fragments (crinoids), calcareous algae (locally abundant *Anthracoporella*; Pl. 1, Fig. B), many smaller foraminifers, rare fusulinids, small gastropods, *Tubiphytes*, ostracods and bryozoans. Peloids and intraclasts are present, too (Pl. 1, Fig. C).

The fossiliferous limestone bed near the top is a grainstone to packstone (Pl. 1, Fig. D) that is dominantly composed of echinoderm (crinoid) fragments and intraclasts, many bryozoans, few brachiopod shells, fusulinids, smaller foraminifers, rare algae and recrystallized skeletons.

We place the base of the Zottachkopf Formation on top of this greenish mudstone. The basal 2.4 m thick succession thus most likely belongs to the underlying Zweikofel Formation.

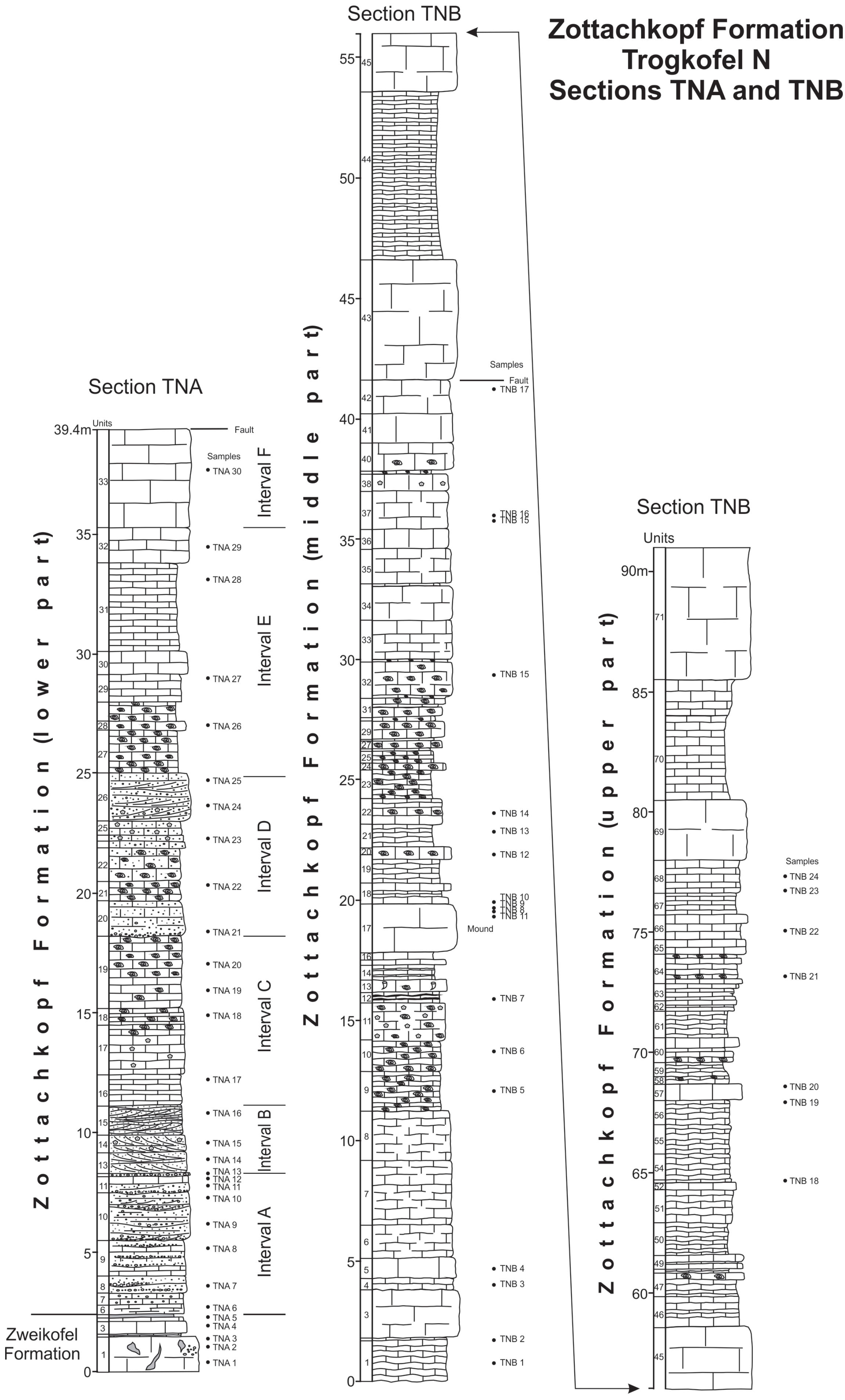
The basal Zottachkopf Formation of the TNA section can be divided into six lithologic intervals (A–F) (Text-Fig. 4).

Interval A is 5.8 m thick and starts with a dark grey, micritic limestone bed (40 cm) overlain by 5.4 m of grey to dark grey limestone that in the lower part is micaceous. Well-rounded quartz grains with diameters up to 3 cm are dispersed in the limestone. Intercalated are thin layers that are up to several cm thick and contain abundant quartz grains.

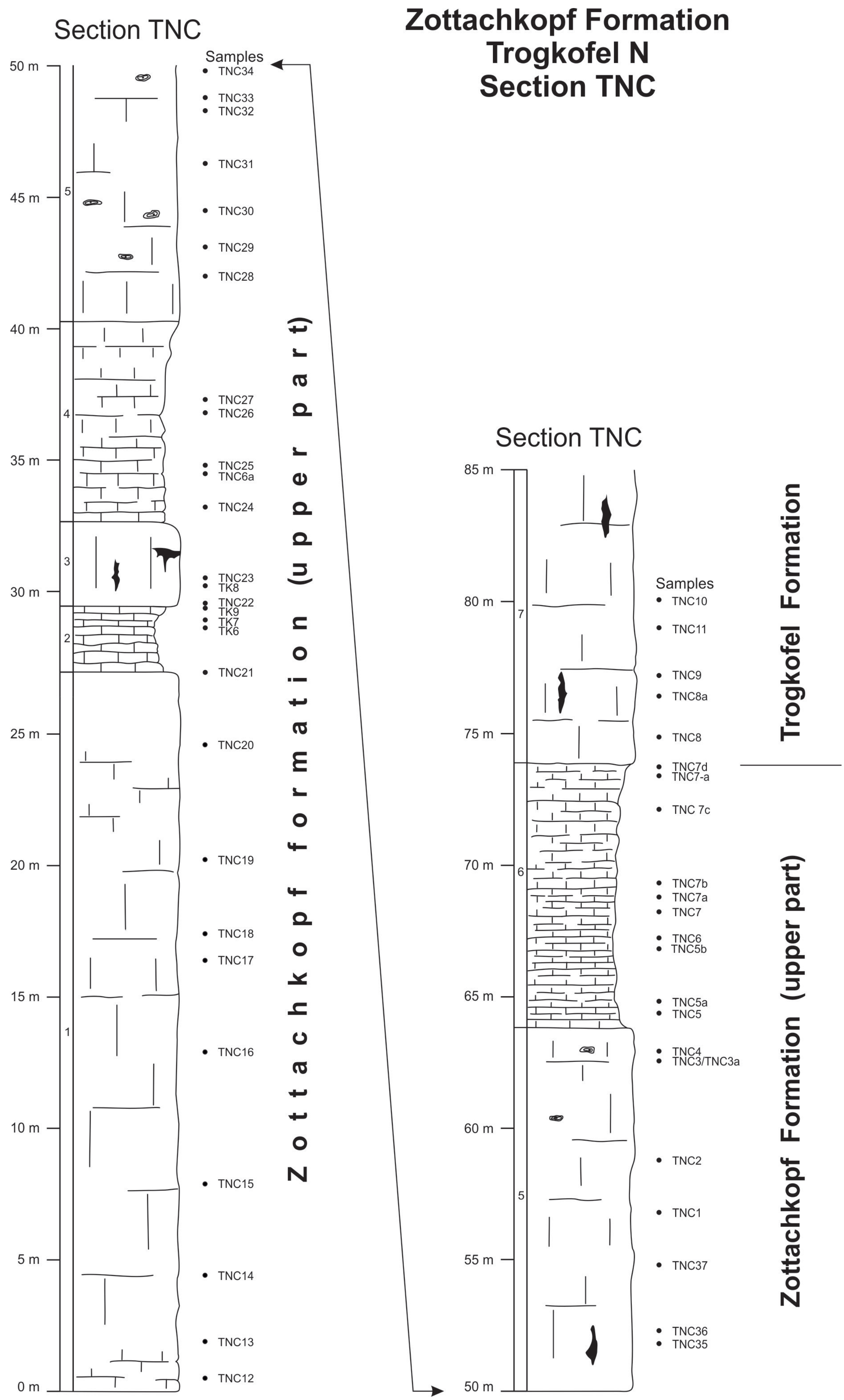
Common sedimentary structures are horizontal lamination, small channels with erosive base filled with cross-bedded sediment, rare ripple lamination and cross-bedding. In the upper part, locally hummocky cross-bedding occurs. Individual channel-fill units are up to 30 cm thick. On top of the succession, a thin, reddish limestone bed is exposed that contains carbonate intraclasts with diameters of 2–3 cm.

Microfacies: The micritic limestone bed at the base is composed of fine-grained wackestone that contains abundant peloids and small intraclasts, many small quartz grains, echinoderm fragments, ostracods, shell fragments, rare fusulinids and recrystallized skeletons (Pl. 1, Fig. E).

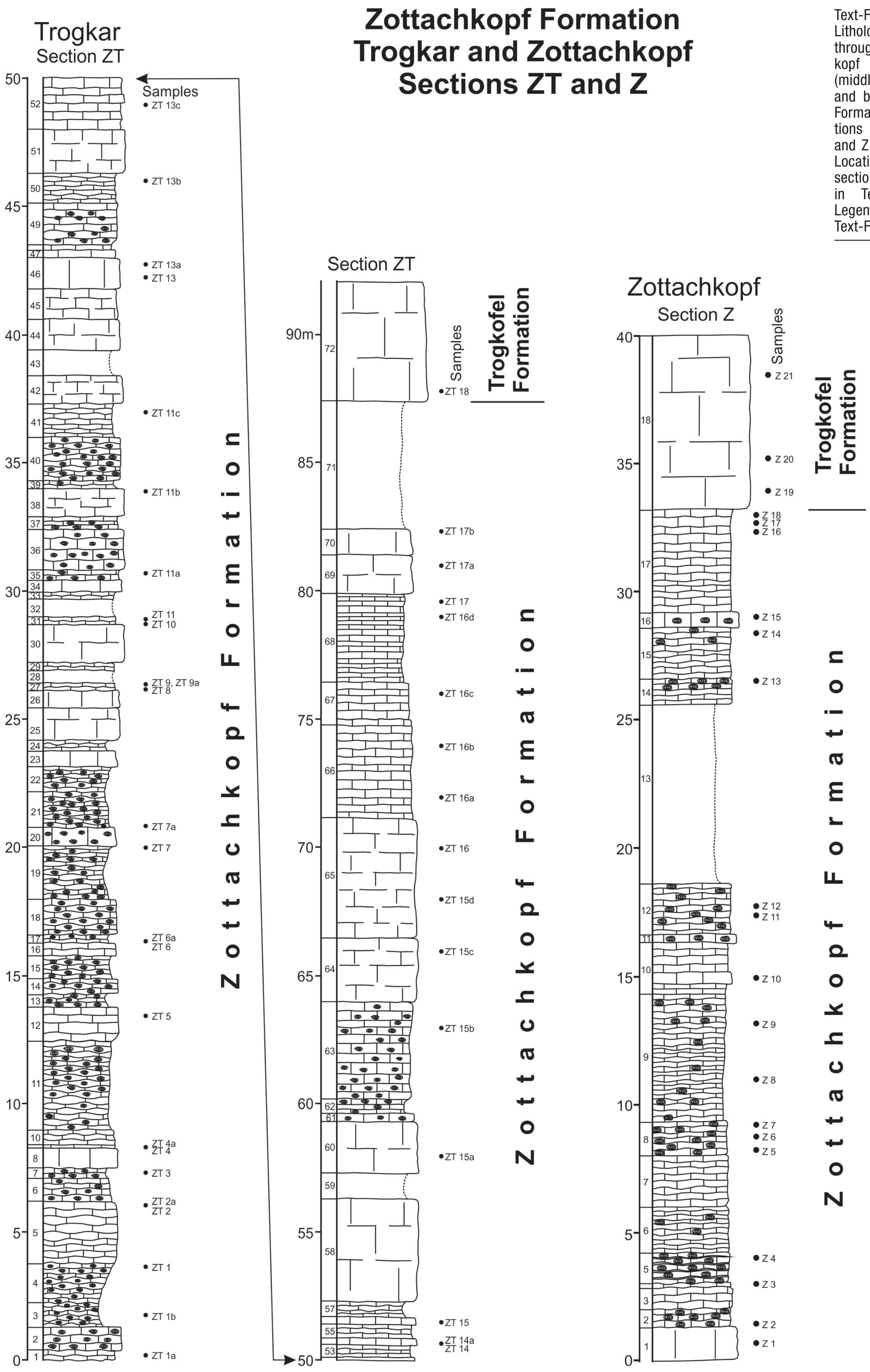
Dark grey limestone is fine-grained, mixed siliciclastic carbonate sandstone, partly siltstone that contains abundant small detrital quartz grains (mostly 0.05–0.2 mm in diameter), carbonate grains, few recrystallized fossil fragments, echinoderms, fusulinids, bryozoans and ostracods (Pl. 1, Fig. F). Embedded are few larger quartz grains with diameters of up to 2 cm. Intercalated limestone beds are composed of wackestone.



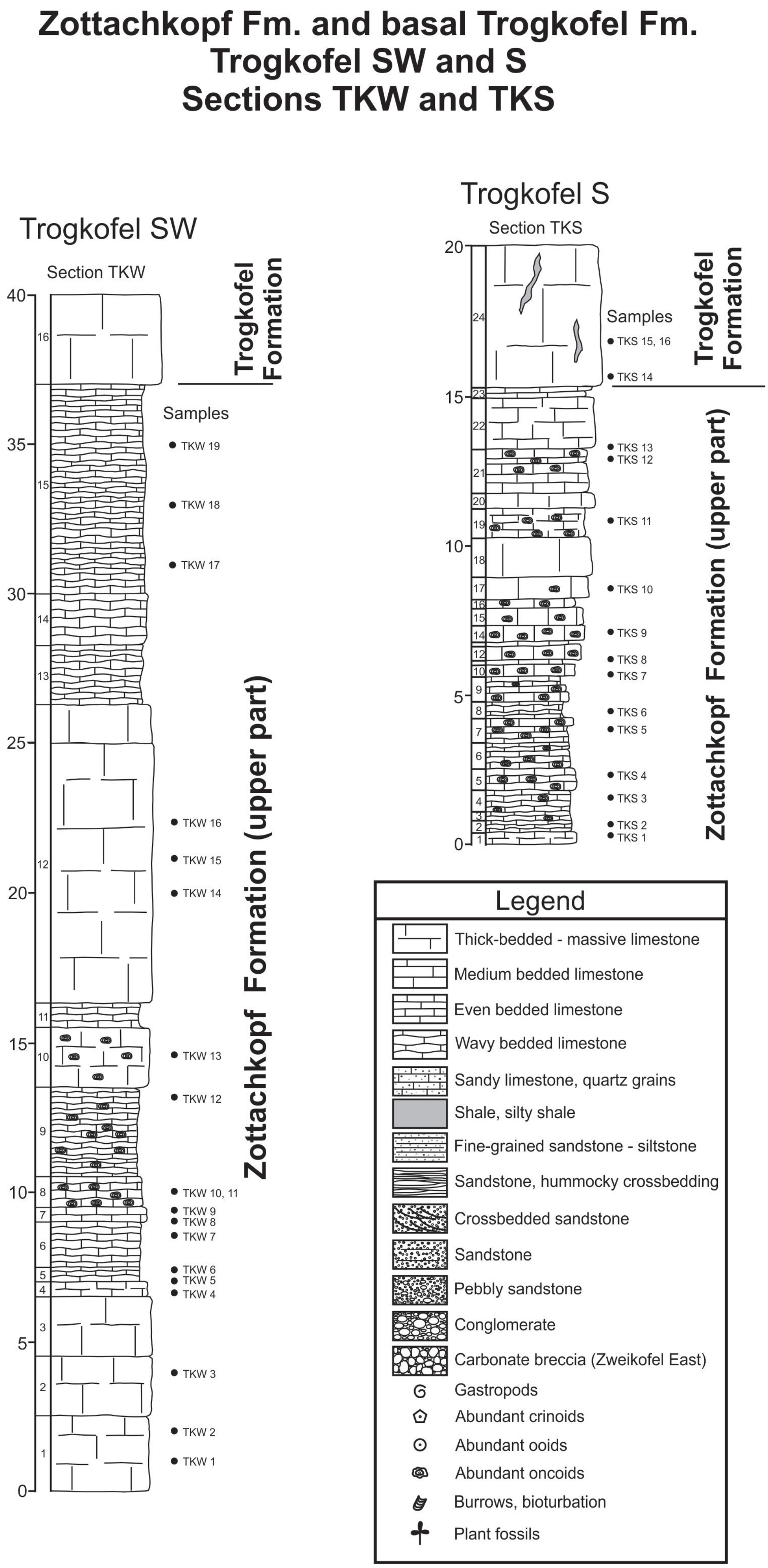
Text-Fig. 4.
Lithologic section through the Zottachkopf Formation at section TNA (Trogkofel North A; lower part), TNB (Trogkofel North B; middle–upper part) (type section). Location of the sections is shown in Text-Figure 3. Legend is shown in Text-Figure 7.



Text-Fig. 5.
Lithologic section through the upper part of the Zottachkopf Formation and basal Trogkofel Formation at section TNC (Trogkofel North C) (type section). Location of the section is shown in Text-Figure 3. Legend is shown in Text-Figure 7.



Text-Fig. 6.
Lithologic section through the Zottachkopf Formation (middle–upper part) and basal Trogkofel Formation at sections ZT (Trogkar) and Z (Zottachkopf). Locations of the sections are shown in Text-Figure 3. Legend is shown in Text-Figure 7.



Text-Fig. 7.
Lithologic sections (including legend) through the upper part of the Zottachkopf Formation and basal Trogkofel Formation at sections TKW (Trogkofel Southwest) and TKS (Trogkofel South). Locations of the sections are shown in Text-Figure 3.

Limestone that forms the top of interval A is composed of oolitic wackestone overlain by intraclast wackestone to floatstone (Pl. 1, Fig. G).

Oolitic wackestone contains abundant ooids, many detrital quartz grains and few intraclasts. Some of the quartz grains form the nuclei of ooids. Fossil are rare and include echinoderm fragments, shell fragments and recrystallized skeletons.

Intraclast wackestone to floatstone contains abundant micritic intraclasts, peloids, small quartz grains (0.05–0.2 mm) and few fossils (echinoderms, smaller foraminifers and ostracods).

Interval B is 2.9 m thick and composed of reddish limestone (grainstone to packstone and rudstone) that is cross-bedded and contains abundant crinoid fragments, fusulinids and brachiopods. The cross-bedded sets display an erosive base. The upper part is composed of up to 20 cm thick cross-bedded sets that display wavy tops (Text-Figs. 4, 8).

Microfacies: In the lower part (unit 13), grainstone contains abundant recrystallized spherical grains, oncoids, few detrital quartz grains (0.2–0.3 mm), peloids and rare fossils such as echinoderm fragments, shell debris and fusulinids (Pl. 1, Fig. H). Grainstone layers alternate with layers composed of wackestone that contains abundant ooids, peloids, some intraclasts, quartz grains and rare fusulinids.

Grainstone, packstone and rudstone of units 14 and 15 (Pl. 2, Fig. A) are composed of abundant echinoderm fragments (crinoids), shell fragments (brachiopods, bivalves), fusulinids, calcareous algae (*Anthracoporella*), bryozoans, smaller foraminifers, ostracods, gastropods, rare calcisponges and *Tubiphytes*. Locally, many fossils display thin micritic envelopes and in the upper part many fossils are encrusted by *Girvanella* and subordinately by *Claracrusta* to form oncoids with diameters up to 2 cm.

Interval C is 7.1 m thick and starts with grey, wavy-bedded to flasery limestone. Above follows thin-bedded (10 cm) oncoidal limestone with cm-thick limestone beds intercalated. The upper 3 m of this interval are composed of oncoidal limestone (Text-Fig. 4).

Microfacies: Dominant microfacies is packstone to rudstone including oncoidal rudstone, all containing a diverse assemblage of strongly fragmented fossils (Pl. 2, Fig. B).

In bioclastic packstone to rudstone, the most abundant fossils are echinoderm (crinoid) fragments, fusulinids and calcareous algae (*Anthracoporella, Epimastopora, Neoanchicodium*). In smaller amounts brachiopods, bryozoans, smaller foraminifers, gastropods and ostracods are present. Intraclasts are rare. In sample TNA 17 foraminifers, particularly fusulinids, are filled with micrite indicating that they have been reworked and transported. Many fossils display micritic envelopes. Some of the fossils, particularly crinoid fragments, algae and fusulinids, are encrusted by *Girvanella* and partly also by *Claracrusta* to form oncoids with diameters up to 2 cm (mostly < 1 cm). Locally, oncoids are abundant (oncoidal rudstone) (Pl. 2, Fig. C).

Interval D is 6.8 m thick and starts with reddish and grey limestone that contains up to 5 mm large quartz grains, subordinately black chert (lydite) grains and abundant crinoid fragments. The limestone is indistinctly laminated (Text-Fig. 4).

Above thin-bedded limestone is exposed that contains few small quartz grains. The next unit is thin-bedded, reddish

Text-Fig. 8.
Cross-bedded limestone (grainstone-packstone and rudstone) containing abundant quartz grains. Lower part of the Zottachkopf Formation, section TNA, Interval B.

and grey fossiliferous limestone with many quartz grains up to 1 cm in size. The limestone is partly wavy-bedded. The uppermost 2 m are composed of laminated and cross-bedded limestone containing many quartz grains up to 2 cm in diameter and black chert (lydite) grains near the top. The limestone consists of grainstone-packstone to rudstone.

Microfacies: Grainstone-packstone to rudstone (Pl. 2, Figs. D–F). All of them contain a diverse fossil assemblage and many fossils are strongly abraded. The microfacies is very similar to that of Interval C. Most abundant are echinoderm (crinoid) fragments and fusulinids, subordinately calcareous algae (*Anthracoporella, Epimastopora, Neoanchicodium*), smaller foraminifers, bryozoans, gastropods, *Tubiphytes*, ostracods and calcisponges are present. Individual beds contain detrital quartz grains (mainly polycrystalline quartz and chert, subordinately monocrystalline quartz) with diameters up to 5 mm. Fusulinids are locally filled with micrite indicating that they have been reworked and transported. Locally, some of the fossils display thin micritic envelopes.

Oncoids are present in varying amounts with diameters up to 1 cm (Pl. 2, Fig. E). Nuclei of the oncoids are mostly fragments of calcareous algae, also fusulinids, bryozoans, echinoderm fragments, rare calcisponges and shell fragments. The nuclei are encrusted by *Girvanella* and rarely by *Claracrusta*. Locally, the oncoids are abraded indicating that they have been transported.

Interval E measures 10.3 m and is composed of thin-bedded (10–30 cm), subordinately medium-bedded (40–50 cm) grey fossiliferous, oncoidal limestone (Text-Fig. 4).

Microfacies: Limestone is composed of bioclastic packstone to rudstone, and commonly of oncoidal rudstone. The fossil assemblage is dominated by echinoderm (crinoid) fragments, many fusulinids and calcareous algae *(Epimastopora, Neoanchicodium*). Subordinately smaller foraminifers, gastropods, bryozoans, rare calcisponges, ostracods and echinoid spines occur. Locally, abundant micritic intraclasts and peloids are present. Fusulinids are partly abraded and locally crinoids and algal fragments display thin micritic envelopes. Oncoids are present in small amounts.

In oncoidal rudstone the oncoids are commonly up to 5 cm in diameter, composed of *Girvanella* and *Claracrusta* (Pl. 2, Fig. G).

All limestones of intervals C, D and E contain abundant crinoid fragments that in interval C are up to 3 cm. Oncoids are present in most of the limestones with diameters of up to 2–3 cm, in interval E up to 5 cm. Fusulinids are observed in many limestone beds.

Interval F is 4.1 m thick and composed of thick-bedded (60–90 cm) grey limestone that is fault-bounded on the top (Text-Fig. 4).

Microfacies: The limestone is composed of wackestone to floatstone (Pl. 2, Fig. H) that contains abundant echinoderm (crinoid) fragments and fusulinids, calcareous algae (*Epimastopora*) and smaller foraminifers, few oncoids and many reworked micritic fragments that are partly probably derived from oncoids. Some of the fusulinids are filled with micrite and are abraded which indicates that they also have been reworked. Fossils, micritic intraclasts and oncoids are embedded in recrystallized, fine-bioclastic micrite.

Trogkofel north (section TNB)

Section TNB is approximately 91 m thick and composed of the following lithotypes (Text-Fig. 4):

- Thin (5–25 cm), wavy-bedded limestone, dark grey, fossiliferous (bioclastic wackestone).
- Thin (5–25 cm), wavy-bedded limestone, dark grey, containing abundant oncoids. This lithofacies is common in the lower part.
- Thin, even-bedded limestone, partly containing oncoids. This lithotype is rare.
- Thicker limestone beds (25–70 cm), grey, fossiliferous, partly containing oncoids.
- Medium-bedded limestone (25–50 cm), grey, commonly containing oncoids with diameters up to 5 cm.
- Indistinctly medium-bedded to massive limestone, light grey, fossiliferous, rarely containing oncoids. This lithofacies is up to several meters thick.

Approximately 16 m above the base a small mound is intercalated in the bedded facies (Text-Fig. 4). The massive mound facies is 50 cm thick and laterally extends over approximately 3 m. The mound contains small oncoids near the base and corals near the top.

Approximately 18 m above the base five mounds occur in a stratigraphic level. The mounds are composed of massive limestone and are embedded in thin-bedded intermound facies. The massive mound facies is up to 2 m thick and laterally extends over approximately 5 m. The mound facies contains calcareous algae, crinoid fragments, fusulinids and corals.

Microfacies: The most common microfacies of section TNB is wackestone to floatstone (Pl. 3, Fig. A) including oncoidal floatstone (Pl. 3, Fig. B). Less abundant are oncoidal rudstone and bioclastic rudstone. The mound in the lower part is composed of bindstone, bioclastic wackestone to floatstone, phylloid algal floatstone and grainstone on top.

All microfacies contain a diverse fossil assemblage. Abundant fossils are echinoderm (crinoid) fragments, fusulinids, calcareous algae and smaller foraminifers (Pl. 3, Fig. C) (in varying amounts). Less abundant are ostracods, *Tubiphytes*, gastropods, echinoid spines, bivalve shells, bryozoans and rare calcisponges and corals. Locally, limestone contains abundant algal spores. Many limestone beds contain intraclasts (partly derived from reworking of oncoids) and peloids (peloidal micritic matrix). Also present are undeterminable, recrystallized skeletal grains.

Oncoids are mainly formed by *Girvanella*, rarely also by *Claracrusta* and very rarely *Efluegelia* and *Tuberitina* are involved in the construction of oncoids (Pl. 3, Figs. A, B, G).

Bindstone is composed of *Claracrusta* and crusts of cyanobacteria, peloidal micrite and cement. Fossils are scarce and include fusulinids, echinoderm fragments, ostracods, bryozoans and *Tubiphytes* (Pl. 3, Fig. F).

Phylloid algal floatstone contains recrystallized fragments of phylloid algae (? *Neoanchicodium*), and few other fossils such as fusulinids, bryozoans, smaller foraminifers, ostracods and echinoderms that are embedded in peloidal micrite (Pl. 3, Fig. D).

Grainstone is poorly washed and is composed of recrystallized skeletons (mostly fragments of calcareous algae), echinoderms (crinoids), calcareous algae (mostly *Neoanchicodium*), fusulinids, smaller foraminifers, rare gastropods, bryozoans, and ostracods. Grainstone contains many intraclasts, peloids and small oncoids (formed by *Girvanella*) (Pl. 3, Figs. E–H).

Trogkofel north (section TNC)

This section represents the upper part of the Zottachkopf Formation (74 m) and the basal Trogkofel Formation (11 m) (Text-Fig. 5).

The section is composed of the following lithofacies and microfacies (in ascending order):

- 27 m indistinctly thick-bedded to massive limestone, light grey.
- **Microfacies:** *Archaeolithoporella-Tubiphytes* bindstone to cementstone, partly brecciated, with intercalated peloidal wackestone to grainstone. In the upper part phylloid algal bafflestone to bindstone, on top bioclastic wackestone.
- 1.5 m thin-bedded, greenish-grey limestone.
- **Microfacies:** Bioclastic wackestone to floatstone, diverse, containing few small oncoids.
- 2 m massive limestone.
- **Microfacies:** Bioclastic wackestone to floatstone, diverse (Pl. 4, Fig. D), and peloidal wackestone to bindstone (Pl. 5, Fig. H).
- 3 m indistinctly thin-bedded limestone.
- **Microfacies:** Bioclastic wackestone (Pl. 5, Fig. A), bindstone (Pl. 4, Fig. B) and algal floatstone.
- 29 m indistinctly thick-bedded to massive limestone, light grey, top reddish, containing small oncoids and fusulinids (including *Zellia*).
- **Microfacies:** Bioclastic wackestone-packstone-floatstone, grainstone-packstone (Pl. 5, Figs. C, F), grainstone-rudstone (Pl. 4, Fig. C), packstone-rudstone, oncoidal floatstone (Pl. 4, Fig. A), algal floatstone (Pl. 4, Fig. H; Pl. 5, Fig. B), bindstone including *Tubiphytes-Girvanella* bindstone (Pl. 5, Figs. D, E).
- 5 m greenish-grey, indistinctly thin-bedded (10–20 cm) limestone containing small oncoids, crinoidal debris and fusulinids (including *Zellia*).
- **Microfacies:** Bioclastic wackestone to packstone (Pl. 4, Figs. F, G), oncoidal floatstone to rudstone and bindstone.
- 5 m indistinctly bedded reddish limestone, which is overlain by massive limestone of the Trogkofel Formation. The contact between the bedded limestone (Zottachkopf Formation) and basal Trogkofel Formation is sharp.
- **Microfacies:** Bioclastic wackestone to packstone, rudstone. Basal Trogkofel Formation: Bioclastic wackestone to floatstone and bindstone (mound facies).

Common fossils are echinoderm (crinoid) fragments, fragments of calcareous algae (phylloid algae – *Neoanchicodium*, mostly recrystallized, subordinately *Anthracoporella, Epimastopora* and other algae), algal spores, smaller foraminifers, fusulinids, fragments of brachiopods, ostracods and *Tubiphytes*. Less common are bryozoans (Pl. 5, Fig. G), calcisponges, gastropods and trilobite fragments. Cyanobacteria (mainly *Girvanella*) are present in many samples encrusting skeletal grains (particularly calcareous algae) and forming oncoids or binding the sediment (forming bindstone; Pl. 4, Fig. E). All samples contain undeterminable, recrystallized skeletons. Non-skeletal grains include intraclasts (partly derived from reworking of oncoids) and peloids.

Trogkar (section ZT)

The Trogkar section is located in the cirque between Trogkofel and Zottachkopf at an elevation of 1,740–1,800 m (Text-Figs. 6, 9).

At the Trogkar section, approximately 82 m of the Zottachkopf Formation is exposed that is overlain by massive limestone of the Trogkofel Formation. The contact between the Zottachkopf and Trogkofel formations is not exposed (covered interval).

The dominant lithofacies is thin (10–20 cm), wavy-bedded, grey to dark grey limestone that occurs as 30 cm to 3.5 m thick intervals. Most of these intervals contain abundant oncoids, in a few intervals oncoids are rare to absent. Thin-bedded limestone with even-bedding is rare. Intercalated in the thin-bedded limestone facies are thicker limestone beds (40–80 cm), most of them also containing abundant oncoids. Indistinctly medium-bedded to massive limestone occurs as thicker intervals (up to 4.7 m). This lithotype is more abundant in the upper part of the section. In the lower part, thin-bedded limestone intervals alternate with thicker limestone beds. Oncoids are common throughout the section, most abundant in the thin- and wavy-bedded facies and less abundant in the indistinctly bedded to massive facies. Oncoids are a few mm up to 4 cm, rarely up to 5 cm large. Many limestone intervals contain abundant crinoid fragments. Individual limestone beds are rich in fusulinids.

Microfacies: Characteristic microfacies types are oncoidal floatstone to rudstone (Pl. 6, Fig. A), fusulinid-oncoid floatstone to rudstone (Pl. 6, Fig. B), fusulinid rudstone (Pl. 6, Fig. C), algal rudstone (Pl. 6, Fig. D), bioclastic packstone to rudstone (Pl. 6, Fig. E), oolitic grainstone (rare; Pl. 6, Fig. F) and peloidal grainstone to packstone (rare; Pl. 6, Fig. G). The basal limestone of the overlying Trogkofel Formation is foraminiferal wackestone to floatstone.

Abundant fossils are fusulinids, calcareous algae and smaller foraminifers. Many of the fusulinid tests are abraded and fragmented, partly encrusted by *Girvanella*. Calcareous algae are dominantly recrystallized fragments of phylloid algae (*Neoanchicodium*), subordinately *Epimastopora* and other algae. Locally, algal spores are present. Other fossils include fragments of bivalves, gastropods, ostracods, rare trilobite fragments and *Tubiphytes*. Algal rudstone is composed of recrystallized fragments of phylloid algae and few *Epimastopora*. Also present are fusulinids, gastropods, smaller foraminifers, echinoderm fragments, ostracods and few oncoids. Peloidal grainstone to packstone is lami-

Text-Fig. 9.
Upper part of the bedded Zottachkopf Formation exposed at Trogkar, section ZT.

nated, contains small echinoderm fragments, smaller foraminifers, ostracods, recrystallized skeletons and few intraclasts. Oolithic grainstones contains recrystallized ooids that are 0.1–0.4 mm in diameter, few fossils (echinoderms, shell fragments, ostracods) and few intraclasts.

Oncoids are mainly formed by *Girvanella*, subordinately by *Claracrusta* and *Efluegelia, Palaeonubecularia* and rarely by other encrusting foraminifers (*Tuberitina*). The nuclei are commonly formed of fragments of calcareous algae, subordinately fusulinids and other skeletal grains. Some of the oncoids are abraded indicating that they have been reworked and transported (Pl. 6, Fig. H).

Zottachkopf (section Z)

Northnorthwest of Zottachkopf, at an elevation of approximately 1,710–1,740 m, approximately 33 m of the Zottachkopf Formation is exposed which is overlain by massive limestone of the Trogkofel Formation (Text-Figs. 6, 10). According to Flügel (1970) and Flügel et al. (1971) the section starts at an elevation of 1,780 m and ends at 1,855 m, with a thickness of 53 m (type section of the "Obere Pseudoschwagerinen-Kalk" = Zweikofel Formation of Kahler & Kahler (1937a, b).

The Zottachkopf Formation is dominantly composed of thin- and wavy-bedded (10–30 cm), dark grey limestone. Most of the limestone beds contain oncoids. Crinoidal debris is a common constituent of many limestone intervals. Individual limestone beds contain abundant fusulinids. Intercalated are a few thicker limestone beds (30–60 cm) that also contain oncoids. At the base of the succession, a massive limestone is exposed that contains abundant crinoid fragments and fusulinids.

Microfacies: Lithology and microfacies are very similar to the Trogkar section. Characteristic microfacies are bioclastic wackestone-grainstone-packstone-rudstone (Pl. 7, Figs. A, B, D), fusulinid floatstone (Pl. 7, Fig. E), floatstone-rudstone containing abundant algae (Pl. 7, Fig. C), packstone-rudstone and oncoid-fusulinid floatstone to rudstone (Pl. 7, Figs. F–H). All contain a diverse fossil assemblage that is identical to that of the Trogkar section: echinoderm (crinoid) fragments, fusulinids, calcareous algae (mostly phylloid algae, *Epimastopora*), smaller foraminifers, ostracods, bryozoans, gastropods, *Tubiphytes*, algal spores, brachiopods, bivalve shells, rare trilobites. Fusulinids are partly abraded and fragmented. Individual beds contain reworked fragments of oncoids. Some of the beds contain peloids (peloidal micrite) and subordinately intraclasts.

Trogkofel South (section TKS)

Southwest of the Trogkofel summit, along the trail at an elevation of approximately 1,930 to 1,950 m we measured a section through the uppermost 15 m of the Zottachkopf Formation, which is overlain by massive limestone of the Trogkofel Formation (Text-Figs. 7, 11).

There, the uppermost Zottachkopf Formation is developed in bedded facies with a sharp lithologic boundary to the overlying Trogkofel Formation (Text-Fig. 11).

The basal 5.6 m of the measured section is composed of thin- and wavy-bedded, dark grey limestone with bed thickness ranging from 5 to 20 cm. Oncoids (up to 3 cm in diameter) and crinoid fragments are common in this interval. Individual limestone beds contain fusulinids.

In the overlying interval from 5.6 to 10.2 m bed thickness ranges from 10 cm to 130 cm. Most of the limestone beds contain oncoids and crinoidal debris; locally fusulinids are present. The thick limestone bed on top of this interval is composed of wackestone that lacks oncoids.

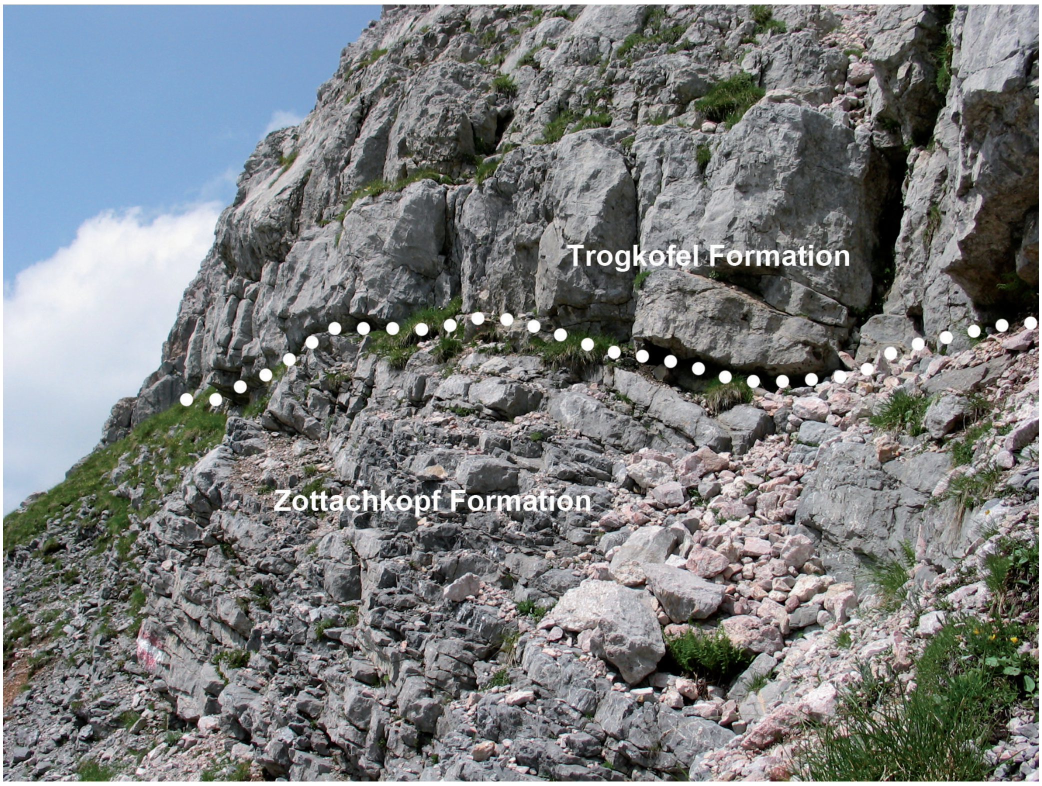
Text-Fig. 10.
Upper part of the bedded Zottachkopf Formation overlain by massive limestone of the Trogkofel Formation, exposed north of Mount Zottachkopf (section Z).

The uppermost 5 m is a thin- to medium-bedded (10–50 cm) succession of partly indistinctly bedded limestone with even-bedding. Oncoids are less abundant in this interval. All limestone beds contain crinoidal debris. Fusulinids occur in individual beds. Rarely corals are observed.

The overlying massive limestone of the Trogkofel Formation contains small karst cavities that are filled with red karst sediment.

Microfacies: The bedded limestones of the uppermost 15 m are composed of bioclastic packstone to rudstone and floatstone, oncoid floatstone to rudstone, grainstone and rare phylloid algal floatstone (Pl. 8, Figs. A–D). The microfacies types are very similar to those of the Trogkar and Zottachkopf sections.

Most common fossils are echinoderm (crinoid) fragments, calcareous algae (mostly recrystallized phylloid algae –



Text-Fig. 11.
Bedded limestone of the uppermost Zottachkopf Formation, overlain by thick-bedded and massive limestone of the Trogkofel Formation, exposed along the trail on the southern side of Mount Trogkofel (section TKS).

Text-Fig. 12.
Phylloid algal mound and bedded limestone in the upper part of the Zottachkopf Formation (section TKW), overlain by massiv limestone of the Trogkofel Formation. Southwestern side of Mount Trogkofel.

Neoanchicodium, less abundant *Epimastopora, Anthracoporella* and other algae). Recrystallized spherical grains are probably algal spores. Fusulinids are present in all studied samples, locally abundant. Fossils that are present in small amounts are smaller foraminifers, ostracods, bryozoans, gastropods, brachiopod and bivalve shells, *Tubiphytes* (locally abundant and partly reworked), rare calcisponges. All samples contain also undeterminable recrystallized skeletons. Many samples contain peloids (peloidal micrite) and intraclasts. Oncoids are present in many samples. Individual beds contain reworked fragments of oncoids.

Trogkofel Southwest (section TKW)

This section was measured along the trail on the southwestern side of the Trogkofel-Zottachkopf massif south of Zottachkopf at an elevation between approximately 1,880 and 1,920 m above sea level. The measured section starts a few m below the trail, is 40 m thick and includes the uppermost 37 m of the Zottachkopf Formation and the basal Trogkofel Formation (Text-Figs. 7, 12, for location see Text-Fig. 3).

The basal 6.5 m of the measured section are composed of thick-bedded to massive, light grey limestone, overlain by thin- and wavy-bedded, grey to dark grey limestone that in the lower three meters contains many fusulinids and in the upper 6 m oncoids, crinoidal debris and rare fusulinids. A small coral colony (10 cm high and 20 cm wide) is present about 10 m above the base.

This bedded limestone facies is overlain by indistinctly bedded to massive, light grey limestone (2 m) with oncoids and few fusulinids, and thin- and wavy-bedded grey limestone (0.8 m) containing crinoidal debris, calcareous algae, shell fragments and fusulinids. The next interval is composed of massive, light grey limestone that is partly dolomitized. The uppermost part of the Zottachkopf Formation is represented by a thin- and wavy-bedded (mostly 10–20 cm) interval that is 10.7 m thick. In the lower part, this bedded facies contains calcareous algae and few fusulinids. Approximately 2 m below the top of the thin-bedded interval a small coral colony is developed. With a sharp lithologic boundary, dark grey limestone of the bedded facies is overlain by light grey, massive limestone of the basal Trogkofel Formation.

Microfacies: The thin-bedded limestone facies, including the indistinctly bedded to massive limestone (2 m), is composed of bioclastic wackestone-packstone-floatstone-rudstone (Pl. 8, Fig. E), fusulinid packstone to rudstone (Pl. 8, Fig. F), and oncoid-fusulinid floatstone to rudstone (Pl. 8, Fig. G) all containing a diverse fossil assemblage of echinoderm fragments, fusulinids, calcareous algae, ostracods, smaller foraminifers, *Tubiphytes*, gastropods, brachiopods, bivalves, bryozoans, corals and very rare trilobites. Rarely small colonies of *Claracrusta* occur forming bindstone. Many oncoids display the following growth trend: the nucleus was first encrusted by *Girvanella*, later by *Claracrusta* and *Girvanella*, rarely *Efluegelia*, and during the latest stage by *Palaeonubecularia* and *Tubiphytes*.

The basal thick-bedded to massive limestone is composed of phylloid algal floatstone to bindstone (algal mound facies), composed of large, partly broken thalli of recrystallized phylloid algae and rare bryozoans that are encrusted by *Girvanella* and *Archaeolithoporella* (Pl. 8, Fig. H). The floatstone to bindstone contains cement and peloidal micrite that contains few *Tubiphytes*, smaller foraminifers and ostracods. Locally, the floatstone to bindstone is brecciated.

The upper massive, light grey limestone is composed of recrystallized phylloid algal mound facies that contains abundant cement (partly cementstone) and few fossils such as bryozoans, *Tubiphytes*, fusulinids and smaller foraminifers. This mound facies is partly brecciated.

Lower and upper boundaries

We draw the lower boundary of the Zottachkopf Formation on top of the greenish mudstone/shale that forms the top of the basal 2.4 m of section TNA (Text-Fig. 4). The basal massive limestone shows evidence of karstification (Permian karst) which indicates that this basal interval probably can be assigned to the Zweikofel Formation. In the Zweikofel massif, the top of the Zweikofel Formation is represented by a surface of erosion that is documented by a truncation surface and locally by up to more than 15 m thick, coarse carbonate breccia composed of reworked limestone clasts (Krainer et al., 2009). This suggests tectonic movements resulting in uplift and erosion of individual blocks. Locally, these uplifted blocks were probably subaerially exposed and karstified. Section TNA is the only location where the lower boundary of the Zottachkopf Formation can be drawn.

The upper boundary of the Zottachkopf Formation is drawn at the sharp lithologic contact between the uppermost thin-bedded, dark grey limestone of the Zottachkopf Formation and the conformably overlying thick-bedded and massive, light grey limestone of the Trogkofel Formation (Text-Fig. 13). This boundary is well exposed at sections TNC, Zottachkopf (section Z), Trogkofel South (section TKS) and Trogkofel Southwest (section TKW). At the Trogkar section (ZT) this contact is covered (see Text-Figs. 5–7).

A complete section of the Zottachkopf Formation is not exposed. The type section is a combination of sections TNA, TNB and TNC. Unfortunately, there is no overlap between sections TNA and TNB although field data indicate that only a small part is missing. Section TNB and TNC overlap, unit 71 of section TNB correlates to the basal part of unit 1 of section TNC. This results in a total thickness (minimum thickness) of approximately 184 m for the Zottachkopf Formation.

As far as known, the Zottachkopf Formation is only present in the Trogkofel-Zottachkopf massif that is separated from the Zweikofel massif in the north by a WNW–ESE oriented fault that is exposed on the saddle (Großer Sattel) between these two massifs. The Trogkofel-Zottachkopf massif probably represents an isolated, fault-bounded tectonic block. Outcrops at the base of the steep northern wall of the Trogkofel massif indicate that this tectonic block was overthrusted towards the north.

Fossils

All limestones of the Zottachkopf Formation contain a diverse fossil assemblage that includes brachiopods, bryozoans, echinoderms (mostly crinoids), smaller foraminifers, fusulinids, ostracods, trilobites, calcisponges, gastropods, bivalves, rare trilobites, corals, cyanobacteria, calcareous algae, and microproblematica.

Cyanobacteria and calcareous algae

Among the algae, phylloid algae (*Neoanchicodium*, *Eugonophyllum*, mostly recrystallized), and dasycladacean algae (*Anthracoporella, Epimastopora*) are most abundant. Oncoids are abundant in the Zottachkopf Formation and are mainly formed by *Girvanella*. Recently Krainer et al. (2019a) described and documented the following cyanobacteria and calcareous algae from the Zottachkopf Formation (Pl. 9):

Cyanobacteria

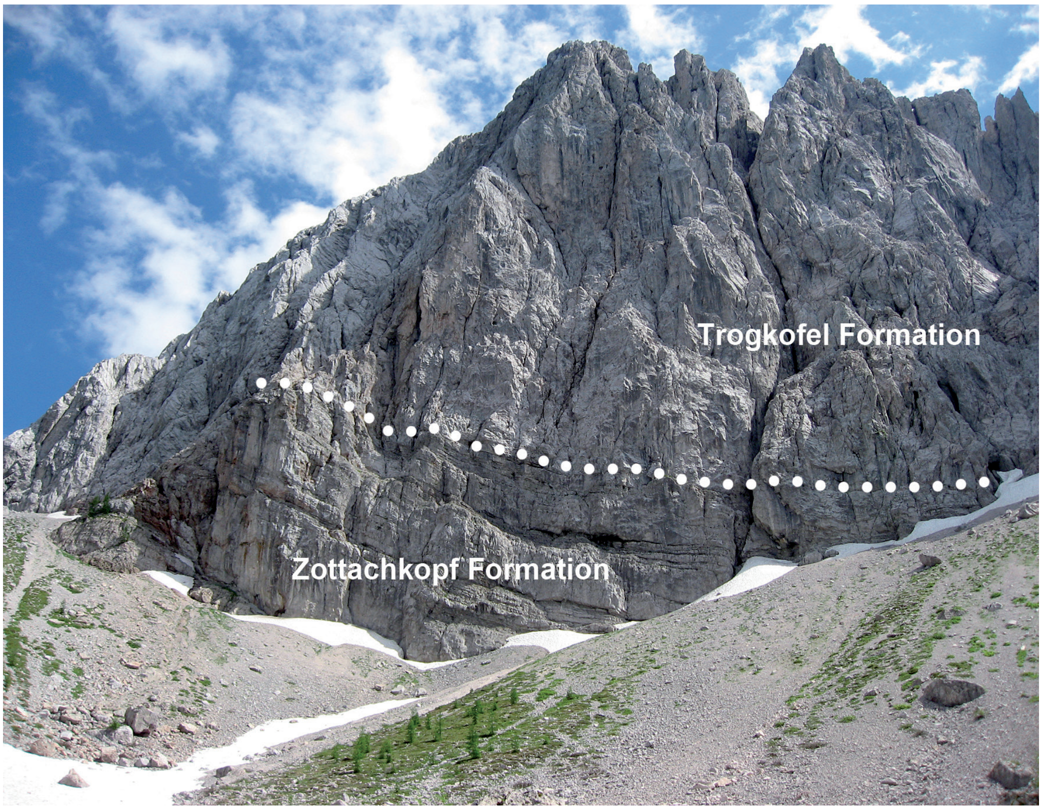
Stromatolites indet. (section TKW)
Girvanella sp. (TKS, TKW, TNA, TNC, Z)
Koivaella ex gr. *permiensis* (TNB, TNC)
Clinortonella cf. *goggauensis* (TNA)

Red algae

Parachaetetes ortonelloides (Z)

Bryopsidales

Homannisiphon morikawai (TNA, TNB, Z)
Anchicodium japonicum (TNA, TKS)
Ivanovia tenuissima (TNA, TNC)
Eugonophyllum magnum (TKS, TKW, Z)
Neoanchicodium catenoides (TKS, TKW, Z, TNC)
Calcipatera schoenlaubi (TNA)
Nanjinophycus? sp. (TNA)



Text-Fig. 13.
Steep northern wall of Mount Trogkofel with bedded Zottachkopf Formation overlain by massive limestone of the Trogkofel Formation.

Dasycladales
Anthracoporella spectabilis (TNA, Z)
Anthracoporella vicina (TNA)
Epimastopora japonica (TKS, TKW, TNA, TNC, Z, ZT)
Epimastopora likana (TKS, TKW, TNA, TNC, Z, ZT)
Epimastopora alpina (TKW, TNA, TNC, Z)
Epimastopora fluegeli (TKW, TNA)
Globuliferoporella piae (TKS, TKW, Z, ZT)
Globuliferoporella angulata (TKW)
Gyroporella sp. (ZT)
Pseudoepimastopora carnica (Z, ZT)
Mizzia velebitana (TKS)
Mizzia yabei (TKS, Z)
Mizzia cornuta (Z)

Algospongia
Claracrusta catenoides (TKW, TNA, Z)
Ungdarella uralica (TNB, TNC)
Efluegelia johnsoni (TKW)
Efluegelia ex gr. *johnsoni* (TKW, Z)

Foraminifers

Limestones of the Zottachkopf Formation contain a rich and diverse assemblage of smaller foraminifers and fusulinids (details see Krainer et al., 2019b) (Pls. 10–15).

Tuberitinoidea
Eotuberitina reitlingerae (TKW, Z)
Tuberitina bulbacea (TKW)
Tuberitina collosa (TNC)

Earlandioidea
Earlandia dunningtoni (TNB, TKW, Z)

Lasiodiscoidea
Eolasiodiscus donbarcanus (TKW, TNB, Z)
Pseudovidalina damghanica (TKS)
Pseudovidalina modificata (TKS, TKW, TNA, TNB, TNC, Z, ZT)
Pseudovidalina media (TKW, TNC, Z)
Pseudovidalina multihelics (TKS, TKW, TNA, TNB, TNC, Z, ZT)

Endothyroidea
Endothyra cf. *rzhevica* (TKS, TKW, TNA, TNB, TNC)
Endothyra cf. *arctica* (TKS, TNA, TNB, TNC, Z)
Endothyra aff. *miriformis* (TNA, TNB, ZT)
Endothyra aff. *symmetrica* (TNA, TNB, TNC, Z, ZT)
Planoendothyra ultimata (TNA, Z)

Palaeotextularioidea
Palaeotextularia aff. *minutissima* (TKS, TNA, TNB)
Climacammina elegans (TKW, TNA, TNB)
Climacammina sphaerica (TNB)
Deckerella cf. *tenuissima* (TNA, TNB, TNC)
Deckerella bashkirica (TKS, TNB)
Cribrogenerina gigas (TNB)

Endoteboidea
Spireitlina ex gr. *conspecta* (TKW, TNA, TNB, TNC)
Spireitlina cf. *bashkirica* (TKS)
Rectoendoteba tieni (TKW)

Tetrataxoidea
Tetrataxis ex gr. *paraconica* (TKW, TNB, Z)
Tetrataxis ex gr. *parviconica* (TKW)
Polytaxis maxima (TKW, Z)
Abadehellopsis pauciseptata (TKS)

Globivalvulinoidea
Globivalvulina ex gr. *bulloides* (TKS, TKW, TNA, Z)
Globivalvulina donbassica (Z)
Globivalvulina cf. *ovata* (TKW)
Septoglobivalvulina cf. *guangxiensis* (TKS, TKW, TNB, Z, ZT)

Staffelloidea
Hayasakaina kawadai (ZT)
Hayasakaina kozakiensis (TKS)
Pseudoreichelina slovenica (TNB)

Schubertelloidea
Schubertella transitoria (TKS, TKW, TNC, Z, ZT)
Schubertella exilis (TKW, TNB, TNC)
Schubertella ex gr. *exilis* (TKS, TNB)
Schubertella paramelonica (TKS)
Zarodella? *nevadensis* (Z)
Toriyamaia? *zweikofelica* (TKW)
Oketaella shiroishiensis (TKS, TNC)
Biwaella europaea (Z)
Boultonia willsi (TKW, TNA, TNB)
Boultonia cheni (TNA, TNB)

Fusulinoidea
Quasifusulina div. sp. (TKS, TKW, TNA)

Schwagerinoidea
Alpites div. sp. (TNA, TNB, Z)
Zellia media (TKW, TNB, Z, ZT)
Zellia amedaei (Z)
Robustoschwagerina schellwieni (TKW, Z)
Robustoschwagerina aff. *psharti* (TKW, Z)
Darvasella cf. *praecox* (TKW, TNC, Z)
Darvasella cf. *compacta* (TNB)
Sakmarella aff. *devexa* (TKS, Z)
Sakmarella cf. *implicata* (TNA)
Grozdilovia ex gr. *sulcata* (TNB)
Kutkanella cf. *kutkanensis* (TNB)
Chalaroschwagerina aff. *obesa* (Z)
Chalaroschwagerina ex gr. *globularis* (TKS)
Paratriticites jesenicensis (TNB, TNC, TKS, TKW, Z)
Perigondwania forkei (TKS, TKW, TNB, TNC, Z, ZT)
Perigondwania sp.2 (TNB, TNC)
Leeina? div. sp. (TKW, TNB, TKS, Z)
Laxifusulina sp. (TKS, TNB)
Praeskinnerella formosa (TNB)

Calcivertellidae
Calcivertella div. sp. (TKS, TNA, TNB, TNC)
Calcitornella sp. (TNA, TNC)

Tubiphytidae
Latitubiphytes homanni (TKS, TNA)
Tubiphytes obscurus (TKS, TNA, TNC)
Tubiphytes carinthiacus (TKS)

Ellesmerellidae
Ellesmerella subparallela (TKS, TNB, ZT)

Cornuspiridae
Cornuspira div. sp. (TKW, TNB, Z, ZT)
Hemigordiellina regularis (TNB, TNC)

Hemigordiidae
Olgaorlovella dublicata (TNB)
Hemigordius div. sp. (TKS, TNB, Z, ZT)

Neodiscidae
Uralogordiopsis longus (TKS)
Uralogordiopsis? cf. *kungurensis* (TKW, TNB, ZT)

Syzraniidae
Syzrania cf. *pulchra* (TKW, Z, ZT)
Syzranella cf. *otadetsi* (Z)
Tezaquina carnica (TNA, Z, ZT)

Protonodosariidae
Protonodosaria aff. *praecursor* (ZK)
Protonodosaria aff. *rauserae* (TNC)
Paravervilleina farcimeniformis (TNB, Z)
Tauridiopsis venusta (TKS, TKW, TNC, Z, ZT)
Tauridiopsis kahlerorum (TKW)
Nodosinelloides potievskayae (TKS, TKW, TNB, TNC, Z, ZT)
Nodosinelloides aequiampla (TKW, TNB, TNC, Z)
Nodosinelloides cf. *ronda* (TNB)
Nodosinelloides netschajewi (TKW, TNC, Z, ZT)
Nodosinelloides mirabilis (TKS, TNA, TNB)
Nodosinelloides longa (TNB)
Nodosinelloides longissima (TKS, TKW, TNA, TNB, Z, ZT)
Nodosinelloides pinardae (TKW, TNC, ZT)

Geinitzinidae
Geinitzina cf. *spandeli* (TNB, TNA, Z)
Geinitzina bisulcata (TK)
Geinitzina cf. *ichnousa* (TKW)
Geinitzina cf. *longa* (TNB, TNC, Z)
Geinitzina cf. *multicamerata* (TKW, TNC, ZT)
Praerectoglandulina cf. *primitiva* (TNB, TNC, Z)
Praerectoglandulina miklukhomaklayorum (ZT)
Praerectoglandulina geinitzinaeformis (TKS, TKW, TNA, TNB, TNC, ZT)

Pachyphloiidae
Pachyphloia? div. sp. (TNC, Z, ZT)

Corals

Homann (1970) reported the occurrence of corals from the Zottachkopf Formation at the SW-flank of Trogkofel (?*Wentzellophyllum felseri* Minato & Kato, 1965). Most of the corals described by Homann (1970) are from the Lower Pseudoschwagerina Limestone (Schulterkofel Formation), rarely from the Upper Pseudoschwagerina Limestone (Zweikofel Formation) at Zweikofel.

Biostratigraphy

Biostratigraphy of the late Palaeozoic sedimentary succession of the Carnic Alps (Bombaso Formation, Auernig Group, Rattendorf Group, Trogkofel Formation) is mainly based on fusulinids that were first described by Tietze (1870), Stache (1872) and Schellwien (1892). Kahler (1931) started a systematic study of the fusulinids (summarised in Kahler, 1973, 1986a, b, 1987, 1989; Kahler & Kahler, 1980). Holger C. Forke (Forke 1995a–c, 2000, 2002, 2019; Forke et al., 1998, 2006, 2008; Schönlaub & Forke, 2007, 2021) and Vladimir I. Davydov (Davydov & Krainer, 1999; Krainer & Davydov, 1998; Davydov et al., 2013) continued the work of Franz Kahler (Text-Fig. 14).

Smaller foraminifers were intensively studied by Daniel Vachard (Vachard & Krainer, 2001a, b; Krainer et al., 2019b).

Forke (1995c) reported conodonts from the "Red Limestone" (basal Zottachkopf Formation) at Trogkar, including *Mesogondolella* cf. *bisselli*, *Aethotaxis advena*, *Hindeodus minutus*, *Diplognathodus expansus*, *Sweetognathus inornatus* and *Sweetognathus* aff. *whitei*.

Forke (2002) described *Sweetognathus* sp. aff. *S. whitei* from the lower part of the Zweikofel Formation at the type section (Zweikofel) and *Neostreptognathodus* sp. cf. *N. pequopensis* from the basal Trogkofel Formation at Zweikofel.

Sweetognathus aff. *S. whitei* was identified as *Sweetognathus anceps* (Davydov et al., 2013), a species that originally was described from the latest Sakmarian and early Artinskian in the Urals (Chernykh, 2006).

Calvo González et al. (2023a, b) reinterpreted *Sweetognathus* determined by Forke (2002) and Davydov et al. (2013) as *Sweetognathus binodosus* transitional to *Sw. anceps*.

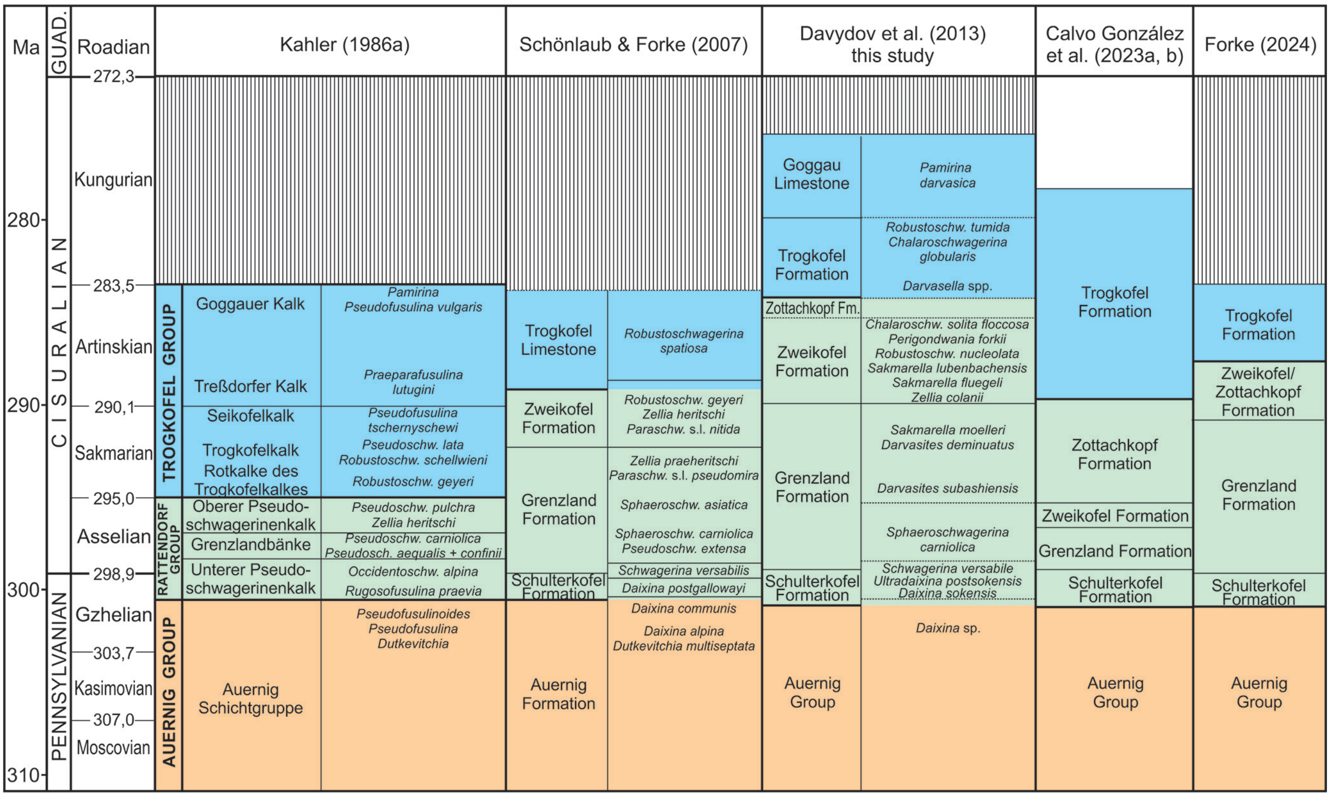
Davydov et al. (2013) intensively studied the fusulinid fauna of the Zweikofel Formation at the type section on the western side of Zweikofel. They determined five fusulinid zones (in ascending order):

1) *Sakmarella moelleri–Alpites deminuatis* Zone
2) *Sakmarella fluegeli–Zellia colaniae* Zone
3) *Sakmarella lubenbachensis–Robustoschwagerina nucleolata* Zone
4) *Leeina pseudodivulgata–Chalaroschwagerina incomparabilis* Zone
5) *Chalaroschwagerina solita floccosa* Zone

Fusulind Zone 1 occurs in the basal 2 m of the Zweikofel Formation and is assigned to the Sakmarian. Fusulinid Zones 2 and 3 indicate early Artinskian and Zones 4 and 5 are lower Yakhtashian (middle–late Artinskian).

Limestone of the basal Trogkofel Formation at Trogkar cirque contains fusulinids that are characteristic of the upper Yakhtashian in Darvaz (Tajikistan), including *Quasifusulina magnifica, Chalaroschwagerina globularis, Robustoschwagerina tumida, Perigondwania? sera, Perigondwania oingaronica* and *Praeskinerella pseudogruperaensis* (Davydov et al., 2013).

According to Calvo González (2022), "key foraminifera taxa" and reinterpretation of conodonts indicate that the Grenzland and Zweikofel formations are of Asselian age. The Asselian–Sakmarian boundary is placed within the



Text-Fig. 14.
Stratigraphic subdivision of the upper Pennsylvanian and Cisuralian in the Carnic Alps.

lowermost Zottachkopf Formation at locality "Höhe 2004". The Zottachkopf Formation is interpreted to be latest Asselian to late Sakmarian, and the overlying basal Trogkofel Formation as latest Sakmarian–earliest Artinskian (Text-Fig. 14).

This new biostratigraphic interpretation is based on the occurrence of *Boultonia willsi*, *Biwaella omiensis, Cribrogenerina gigas, Amphoratheca* sp. and *Tezaquina* cf. *clivuli*.

However, these foraminifers have a long temporal range: *Biwaella willsi* occurs from the late Gzhelian to the early and middle Permian (Krainer et al., 2019b). *Biwaella omiensis* ranges from the Gzhelain to the Cisuralian (Davydov, 2011), *Cribrogenerina gigas* from the middle Asselian to the Sakmarian (Krainer et al., 2019b), *Amphoratheca* sp. from the Gzhelian to the Sakmarian, and *Tezaquina* cf. *clivuli* from the Gzhelian to the Artinskian (see Krainer et al., 2019b).

Recently, Forke (2024) discussed the conodont and fusulinid biostratigraphy of the Rattendorf Group in detail and dated the Grenzland Formation as Asselian–Sakmarian, the overlying Zweikofel Formation as latest Sakmarian to early Artinskian, and the Trogkofel Formation as middle–late Artinskian (Text-Fig. 14). He considers the Zottachkopf Formation to be time-equivalent to the Zweikofel Formation (Forke, 2024; Text-Fig. 4).

Forke (2024) concluded that the proposed conodont biostratigraphy (late Asselian age for the Zweikofel Formation) of Calvo Gonzáles (2022) and Calvo González et al. (2023a, b) is unsubstantiated and that the well-established fusulinid biostratigraphy of Forke (1995c, 2002), Schönlaub & Forke (2007, 2021) and Davydov et al. (2013) has been completely ignored.

As in the Zweikofel Formation, fusulinids are abundant also in limestones of the Zottachkopf Formation, although less well studied. Krainer et al. (2019b) listed fusulinids from the Zweikofel Formation that were also identified from limestones of the Zottachkopf Formation in thin sections prepared for microfacies analysis. The list includes *Boultonia willsi*, *Quasifusulina* div. sp., *Alpites* div. sp., *Zellia media*, *Zellia amedaei*, *Robustoschwagerina schellwieni*, *Robustoschwagerina* aff. *psharti*, *Darvasella* cf. *praecox*, *Darvasella* cf. *compacta*, *Sakmarella* aff. *devexa*, *Sakmarella* cf. *implicata*, *Grozdilovia* ex gr. *sulcata*, *Kutkanella* cf. *kutkanensis*, *Chalaroschwagerina* aff. *obesa*, *Chalaroschwagerina* ex gr. *globularis*, *Paratriticites jesenicensis*, *Perigondwania forkei*, *Leeina*? div. sp., *Laxifusulina* sp., and *Praeskinnerella formosa.* Some of the fusulinids from the Zottachkopf Formation are shown on Plates 14 and 15.

The fusulinid assemblage of the Zottachkopf Formation is very similar to that of the Zweikofel Formation, and, at present, it is not clear if the Zottachkopf Formation is time equivalent to or younger than the Zweikofel Formation based on fusulinids. A precise biostratigraphic classification requires a detailed investigation of the fusulinid fauna of the Zottachkopf Formation (and overlying Trogkofel Formation).

In summary, the biostratigraphic age of the Zottachkopf Formation is still unclear. The biostratigraphy of the Lower Permian (Cisuralian) succession, including the Grenzland, Zweikofel, Zottachkopf and Trogkofel formations, presented by Calvo González (2022) and Calvo González et al. (2023a, b) is based on the reinterpretation of conodonts documented by Forke (1995c, 2002) and Davydov et al. (2013) and on a few long-ranging foraminifers (mostly smaller foraminifers). Calvo González (2022) and Calvo González et al. (2023a, b) completely ignored the well-established fusulinid biostratigraphy, particularly of the Zweikofel Formation (Forke, 1995c, 2002; Schönlaub & Forke, 2007, 2021; Davydov et al., 2013). We thus agree with the critical comments of Forke (2024) and reject the biostratigraphy proposed by Calvo González (2022) and Calvo González et al. (2023a, b). The absence of glacioeustatic cycles in the Zottachkopf Formation indicates that the sediments of this formation are younger than the cyclic Zweikofel Formation and accumulated during a period when glacioeustatic sea-level fluctuations did not occur. We conclude that the Zottachkopf Formation is younger than the Zweikofel Formation, and most probably, the sedimentary succession of the Zottachkopf Formation was deposited during the late Artinskian.

Depositional Environment

Zweikofel Formation

Limestones of the basal 2.4 m that are ascribed to the Zweikofel Formation are composed of bindstone, wackestone, floatstone and grainstone with a diverse fossil assemblage indicating deposition in a shallow, normal marine, low- to high-energy shelf environment. Karst sediments within the basal massive limestone bed probably indicate subaerial exposure and karstification of the Zweikofel Formation prior to deposition of the overlying Zottachkopf Formation.

Zottachkopf Formation

Fragments of calcareous algae, echinoderms (crinoids) and foraminifers (including fusulinids) are the most abundant fossils of limestones of the Zottachkopf Formation. Additionally, oncoids are present in almost all the limestone beds. Limestones of the Zottachkopf Formation are composed of a photozoan grain association due to the high amounts of light-dependent organisms, and most samples can be ascribed to the chloroforam grain association type of Beauchamp (1994), which is a common warm-water association of Permian carbonate successions (Flügel, 2004).

Oncoids are present in most limestone beds except in the lowermost part (in Interval A of section TNA) and in the mound facies. Oncoids are up to 5 cm in diameter, mostly < 1 cm. The nuclei are mostly formed of calcareous algae, less abundant of fusulinids, bryzoans, echinoderms, and rarely of calcisponges, shell fragments and other fossil fragments. Skeletons are mainly encrusted by *Girvanella*, by dark micrite, subordinately by *Claracrusta*, and rarely by *Efluegelia*, *Tuberitina, Palaeonubecularia* and *Tubiphytes*. Many limestone beds contain abraded and also broken fragments of oncoids indicating reworking and transportation by currents. The oncoids belong to the *Girvanella* and *Claracrusta* oncoids of early Permian limestones in the Carnic Alps of Flügel (2004) that indicate formation in an open-marine, inner platform setting with minor siliciclastic input. Toomey et al. (1989) described similar oncoids from the lower Permian Winfield Limestone of southern Kansas and northern Oklahoma, which they termed “osagid grains”. These osagid grains are composed of a nucleus that is encrusted by laminae of dark micrite, *Girvanella* and encrusting foraminifers. According to Toomey et al. (1989), these osagid grains formed in shallow, well-agitated water on a carbonate shelf.

Lower part of the Zottachkopf Formation (Section TNA)

At section TNA, the Zottachkopf Formation starts with fine-grained wackestone of a low-energy shelf setting, overlain by mixed siliciclastic-carbonate sandstone and limestone containing abundant detrital quartz grains (Interval A). Individual beds display small-scale cross-bedding and wavy-bedding (ripples). Grainstone, packstone and rudstone of Interval B containing detrital quartz grains and displaying cross-bedding and wavy-bedding indicate a high-energy depositional setting, probably shoreface deposits formed by dunes migrating up the shoreface caused by shoaling waves or by longshore currents. Interval A and B form a shoaling-upward succession starting with low- to high-energy shelf deposits and grading into shoreface deposits.

Packstone and rudstone of Interval C (including oncoidal rudstone) containing reworked fusulinids and oncoids but lacking quartz point to high-energy shelf deposits that formed above the storm wave base. Interval D is composed of packstone and rudstone containing abundant crinoids, fusulinids and oncoids. The presence of detrital quartz grains indicates siliciclastic influx from the hinterland. Cross-bedding in the upper part probably indicates shoreface deposits. Intervals C and D indicate a shallowing upward trend from quartz-free high-energy, shelf deposits to high-energy shelf deposits containing quartz and finally to shoreface deposits with detrital quartz grains up to 5 mm.

The shoreface deposits of Interval D are overlain by bedded limestones composed of oncoidal packstone to rudstone that are free of detrital quartz grains and that point to deposition in a high-energy, normal marine shelf environment. The overlying Interval F is composed of diverse wackestone to floatstone that formed in a shallow marine environment of low to moderate turbulence. Sea-level increased from the upper part of Interval D (shoreface) to Interval F.

Middle part of the Zottachkopf Formation (Section TNB)

Thin- to medium-bedded limestone is dominantly composed of wackestone to floatstone including oncoidal floatstone. Less abundant are oncoidal rudstone and bioclastic rudstone. The mound in the lower part is composed of bindstone, bioclastic wackestone to floatstone, phylloid algal floatstone and grainstone on top.

All microfacies contain a diverse fossil assemblage, with echinoderm (crinoid) fragments, fusulinids, calcareous algae and smaller foraminifers being most abundant. Microfacies and the fossil assemblage indicate deposition on a shallow, normal marine open shelf above the storm wave base under dominantly low to moderate water turbulence (wackestone, floatstone), interrupted by periods of higher water turbulence (rudstone).

Upper part of the Zottachkopf Formation (Sections TNC, ZT, Z, TKW, TKS)

The upper part of the Zottachkopf Formation is well exposed at sections Trogkofel N (TNC), Trogkar (ZT), Zottachkopf (Z), Trogkofel SW (TKW) and Trogkofel S (TKS).

The bedded limestone facies is very similar at all sections and composed of different types of wackestone, packstone, floatstone and rudstone. Common types are oncoidal floatstone to rudstone, fusulinid floatstone, and oncoid-fusulinid floatstone to rudstone. Less common are phylloid algal floatstone to rudstone. Grainstone is rare and includes peloidal and oolitic grainstone. All microfacies contain a diverse fossil assemblage. Fusulinids and oncoids are partly reworked. Locally, at sections Trogkofel N and SW, massive mound facies is intercalated in the bedded facies. The mound facies is composed of *Archaeolithoporella-Tubiphytes* bindstone to cementstone and phylloid algal bafflestone, and intercalated peloidal wackestone and grainstone (Trogkofel N). At Trogkofel SW the mound facies is composed of phylloid algal bafflestone to bindstone. The mound facies is absent at sections Trogkar and Zottachkopf.

Due to the similar microfacies and fossil content, the bedded facies was deposited in a depositional setting similar to that of the middle part of the Zottachkopf Formation. During periods of low water turbulence, locally mounds formed in water depths just below the storm wave base, but within the photic zone.

In the Late Palaeozoic sedimentary succession of the Carnic Alps, skeletal mounds occur at different stratigraphic levels. The oldest mounds are built by auloporid corals and occur in the lower part of the Meledis Formation of the Auernig Group (Flügel & Krainer, 1992). Algal mounds are developed within the Auernig Formation of the Auernig Group (Krainer, 1995b) and within the Schulterkofel Formation of the Rattendorf Group (Flügel, 1987; Krainer et al., 2003; Samankassou, 1999). The Trogkofel Formation is composed of bedded shelf limestones and thick massive limestones (mounds) composed of *Tubiphytes*-bryozoan-algal-cement boundstone, botryoidal fibrous cementstones with *Archaeolithoporella*, and phylloid algal bafflestone (Flügel, 1980, 1981; Schaffhauser, 2013; Schaffhauser et al., 2015; see also Krainer, 2007; Samankassou, 2003).

The phylloid algal thalli in the mounds of the upper part of the Zottachkopf Formation are strongly or completely recrystallized and not in life position, but mostly are broken, toppled in situ or have been transported over very short distances. The abundance of algal skeletons in the mound facies indicates that the in-situ density of the algae during life was so high that they nearly excluded all other organisms. A subdivision into core facies, flanking bed facies and capping bed facies is not observed. According to Wilson (1975), algal bafflestone that often forms the core facies, generally formed below wave base in quiet water as much as 25 m deep, where the phylloid algae trapped lime mud. According to the guild concept of Fagerstrom (1987, 1988, 1991) phylloid algae are members of the baffler guild, which originally trapped lime mud but rapidly broke, toppled in-situ and were transported. Members of the binder guild are, particularly, *Archaeolithoporella* and *Tubiphytes*. Fishes, gastropods and echinoderms were significant members of the destroyer guild that bored into, rasped or bit the members of the baffler guild. The dweller guild includes organisms that are neither actively building nor destroying the mound framework. In particular, foraminifers, distinct fishes, brachiopods, gastropods, and bivalves were members of the dweller guild.

Flügel et al. (1971) presented a palaeoecological interpretation of the upper part of the Zottachkopf Formation at Zottachkopf, based on the study of smaller foraminifers and microfacies. They concluded that the limestones were deposited in a shallow marine shelf setting with water depths of approximately 10–20 m, normal marine salinity with mostly firm ground, and locally sandy soft ground, under low to moderate water turbulence in the outer part of an inner shelf environment ("küstenferner Innen-Schelf-Bereich").

Cycles and the late Paleozoic ice age

According to Calvo González et al. (2023a, b), the contrast in the amplitude of glacioeustatic sea-level fluctuations from the Schulterkofel Formation (approximately 100 m) to the Zweikofel Formation (a few tens of metres), and the absence of cycles in the Zottachkopf Formation, are interpreted to result from a gradual decrease in the amount of water contained in Gondwanan ice sheets during the Glacial III/P1 interval. Absence of glacioeustatic fluctuations in the Zottachkopf and Trogkofel formations may indicate the absence of widespread ice sheets postdating the Asselian–Sakmarian boundary (Calvo González et al., 2023a, b).

However, Montañez (2022) pointed out that the apex of the late Palaeozoic glaciation started in the Gzhelian and continued into the Sakmarian. A return to glacial conditions occurred in west-central Gondwana in the Sakmarian. The third and terminal deglaciation for this region occurred at ~283–282 Ma, i.e. near the Artinskian–Kungurian boundary. Restricted ice sheets existed in parts of central and eastern Gondwana until about 255 Ma (Lopingian).

According to Montañez (2022), a widespread loss of cyclicity in post-mid Sakmarian sedimentary successions is observed in lower-latitude successions.

Thus, ice sheets decreased during the Artinskian but existed locally until the Lopingian.

This is in good agreement with the Cisuralian sedimentary succession of the Carnic Alps (following the biostratigraphy proposed by of Davydov et al., 2013) that is characterized by cyclic successions caused by glacioeustatic sea-level fluctuations until the middle Artinskian (Grenzland and Zweikofel formations). The non-cyclic Zottachkopf Formation of probable late Artinskian age indicates that glacioeustatic sea-level changes did not occur during the late Artinskian and Kungurian (Trogkofel Formation). There is no evidence that the Gondwana ice sheets collapsed at the Asselian–Sakmarian boundary and that glacioeustatic sea-level fluctuations did not occur during the Sakmarian as argued by Calvo González et al. (2023a, b).

Discussion

In the past the bedded limestone facies that underlies the Trogkofel Formation in the Trogkofel-Zottachkopf massif was assigned to the "Upper *Pseudoschwagerina* Limestone" (= Zweikofel Formation) with the type section located at the northern side of Zottachkopf (Kahler & Kahler, 1937a, b; Flügel et al., 1971; Homann, 1972; Flügel, 1974). Detailed sedimentological investigations showed that this bedded limestone facies differs significantly from the Zweikofel Formation, which justified the definition of a new lithostratigraphic unit of formation rank, the Zottachkopf Formation (as proposed by Schaffhauser et al., 2010). The original "type section" for the Upper *Pseudoschwagerina* Limestone (Kahler & Kahler, 1937a, b; Flügel et al., 1971) refers to section Z of this study and represents only the upper part of the Zottachkopf Formation.

The most striking differences between the Zweikofel Formation and Zottachkopf Formation are listed below:

1) Oncoids: In the Zweikofel Formation, oncoids are much less abundant and concentrated in distinct horizons. Oncoids are up to 14 cm in diameter and composed of *Girvanella* and *Claracrusta*, and also *Archaeolithophyllum lamellosum* (Krainer & Schaffhauser, 2012). In the Zottachkopf Formation, oncoids are present almost through the entire succession. Oncoids are up to a few cm in size. Oncoid floatstone to rudstone and oncoid-fusulinid floatstone to rudstone are common microfacies of the Zottachkopf Formation.

2) Siliciclastic horizons: In the Zweikofel Formation five thin (0.6–4.5 m) siliciclastic horizons are intercalated that are composed of siltstone to fine-grained sandstone, sandstone and fine-grained conglomerate. These siliciclastic horizons allow a subdivision of the Zweikofel Formation into six depositional sequences (Krainer & Schaffhauser, 2012). Such distinct siliciclastic horizons are absent in the Zottachkopf Formation, where mixed siliciclastic sediments occur in the lowermost part.

3) Cycles: The Zweikofel Formation is a cyclic succession composed of well-developed parasequences that are 2–10 m thick and are interpreted as high-frequency cycles caused by glacioeustatic sea-level fluctuations related to the Gondwana Glaciation (Krainer & Schaffhauser, 2012; Calvo González et al., 2023a, b). Such cycles are absent in the Zottachkopf Formation. The only cycles occur near the base of the formation (lower part of section TNA) where two shallowing-upward cycles are developed.

4) Mounds intercalated in the upper part of the Zottachkopf Formation are very similar in composition to the mounds of the overlying Trogkofel Formation. Such mounds are absent in the Zweikofel Formation.

5) In the Zweikofel massif, the Zweikofel Formation is overlain by a carbonate breccia that probably is composed of reworked clasts derived from the Zottachkopf Formation. The Zottachkopf Formation is not exposed in the Zweikofel massif (see Krainer et al., 2009). At Garnitzenbach the Zweikofel Formation is overlain by the Trogkofel Formation, probably with a tectonic contact.

Faunal and floral changes observed at about 287 Ma in nonmarine successions of the Southern Alps are probably driven by a global climatic event, the "Artinskian Warming Event" (Marchetti et al., 2022). This distinct warming event that is also observed in low palaeolatitudes of Pangaea is probably related to the eruptions of the Tarim Large Igneous Province of NW China and Panjal Traps of NW India that may have caused the final melting of the Gondwanan ice sheets (Marchetti et al., 2022).

The period of maximum expansion of ice sheets in Gondwana coincides with the occurrence of cyclic sediments in the Carnic Alps (late Moscovian to Gzhelian Auernig Group, Gzhelian Schulterkofel Formation, Asselian–Sakmarian Grenzland Formation, early–middle Artinskian Zweikofel Formation).

Sediments of the Zottachkopf Formation most probably were deposited during the late Artinskian, after the "Artinskian Warming Event". The late Artinskian and Kungurian were almost ice-free, indicating that glacioeustatic sea-level changes did not occur during that time when the Zottachkopf and Trogkofel formations accumulated.

Conclusion

Bedded limestone facies that underlies the Trogkofel Formation in the Trogkofel-Zottachkopf massif displays significant differences in facies compared to the Zweikofel Formation. This justified the introduction of a new lithostratigraphic unit of formation rank and to define this succession as Zottachkopf Formation.

A complete section of the Zottachkopf Formation is not exposed. The type section includes sections TNA, TNB and TNC, all located at the northern side of Trogkofel. The total thickness of the Zottachkopf Formation is approximately 184 m.

The Zottachkopf Formation is a succession of thin- to medium-bedded (mostly 10–40 cm) limestone with some siliciclastic influx in the lower part. Locally, algal mounds are intercalated in the upper part.

Limestones of the Zottachkopf Formation contain a diverse fossil assemblage with calcareous algae, echinoderms (crinoids) and foraminifers (including fusulinids) being the most abundant fossils. Almost all limestone beds contain oncoids.

The lower part is interpreted in the way to have been deposited in a low- to high-energy shelf environment.

Bedded limestones of the middle and upper part are deposits of a shallow, normal marine, open shelf environment above storm wave base under dominantly low to moderate water turbulence, interrupted by periods of high water turbulence.

Intercalated mounds in the upper part are composed of phylloid algae, *Archaeolithoporella* and *Tubiphytes*, and are similar to the mounds of the overlying Trogkofel Formation.

The fusulinid assemblage of the Zottachkopf Formation is very similar to that of the Zweikofel Formation but is less well studied. Thus, the biostratigraphic age of the Zottachkopf Formation is still unclear. The absence of glacioeustatic cycles in the Zottachkopf Formation indicates that the sediments accumulated during a period when glacioeustatic sea-level fluctuations did not occur. This indicates that the Zottachkopf Formation is younger than the Zweikofel Formation. Most probably, the Zottachkopf Formation is of late Artinskian age.

So far, the Zottachkopf Formation is only known from the Trogkofel-Zottachkopf massif.

We conclude that the absence of glacioeustatic cycles and abundance of oncoids in the Zottachkopf Formation are possibly a consequence of the end of the Gondwana glaciation and a major increase of pCO_2 and Na_2O.

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Plates

Plate 1

Thin section photographs of characteristic microfacies types of the uppermost Zweikofel Formation and lower Zottachkopf Formation at section TNA (Trogkofel North A). All under plane light.

Fig. A: Bioclastic wackestone, partly bindstone, composed of micritic matrix, cyanobacteria colonies (dark grey to black) and *Claracrusta*. The matrix contains peloids, small intraclasts and small, recrystallized skeletons. Sample TNA 1, Zweikofel Formation.

Fig. B: *Anthracoporella* floatstone to rudstone containing large fragments of *Anthracoporella* embedded in pelmicritic matrix. Sample TNA 2, Zweikofel Formation.

Fig. C: Bioclastic wackestone to poorly washed grainstone containing a diverse fossil assemblage, peloids, micritic matrix and cement. Sample TNA 3, Zweikofel Formation.

Fig. D: Grainstone to packstone composed of dominantly echinoderm fragments, subordinately of fusulinids and other fossils, and intraclasts. Sample TNA 4, Zweikofel Formation.

Fig. E: Bioclastic wackestone containing echinoderm fragments, fusulinids, recrystallized skeletons, intraclasts and many small detrital quartz grains. Sample TNA 6, Zottachkopf Formation.

Fig. F: Mixed siliciclastic-carbonate sandstone composed of abundant detrital quartz grains, carbonate grains, few echinoderm fragments and peloids embedded in micritic matrix. Sample TNA 8, Zottachkopf Formation.

Fig. G: Oolitic wackestone composed of abundant recrystallized ooids, many detrital quartz grains, few intraclasts and rare fossil fragments, embedded in micrite. Sample TNA 11, Zottachkopf Formation.

Fig. H: Grainstone composed of abundant sphaerical grains (partly ooids), few detrital quartz grains, peloids, and rare fossils. Sample TNA 14, Zottachkopf Formation.

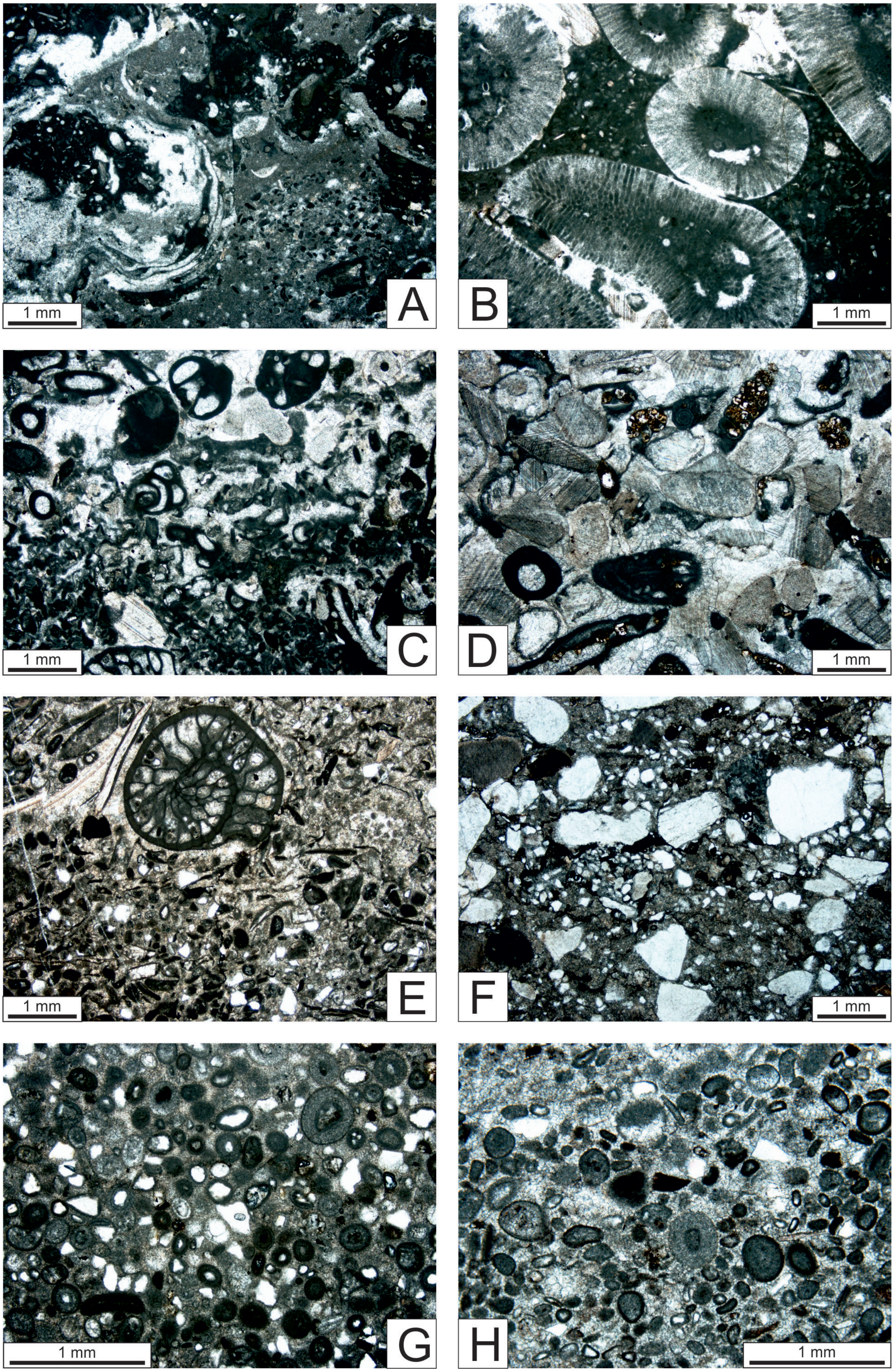
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Plate 2

Thin section photographs of characteristic microfacies types of the lower part of the Zottachkopf Formation at section TNA (Trogkofel North A). All under plane light.

Fig. A: Grainstone to packstone composed of abundant echinoderm (crinoid) fragments, fusulinids, and few other fossils. Some of the fossils display micritic envelopes. Sample TNA 15.

Fig. B: Bioclastic packstone to rudstone containing abundant echinoderm fragments, shell debris, bryozoans, calcareous algae, smaller foraminifers, ostracods and gastropods. Sample TNA 16.

Fig. C: Oncoid rudstone composed of abundant echinoderm fragments and oncoids, and few other fossil fragments. Sample TNA 19.

Fig. D: Rudstone composed of abundant echinoderm (crinoid) fragments, quartz grains and few other fossil fragments. Sample TNA 21.

Fig. E: Packstone to rudstone containing a diverse fossil assemblage and few oncoids. The sediment is poorly washed and contains micrite and cement. Sample TNA 23.

Fig. F: Rudstone containing a diverse fossil assemblage including echinoderm fragments, fusulinids, bryozoans and few quartz grains and intraclasts. Sample TNA 24.

Fig. G: Large oncoid composed of a phylloid algal fragment that is encrusted by *Girvanella* and *Claracrusta*. Sample TNA 27.

Fig. H: Bioclastic wackestone to floatstone containing echinoderm fragments, fusulinids, smaller foraminifers and few other fossil fragments. Sample TNA 30.

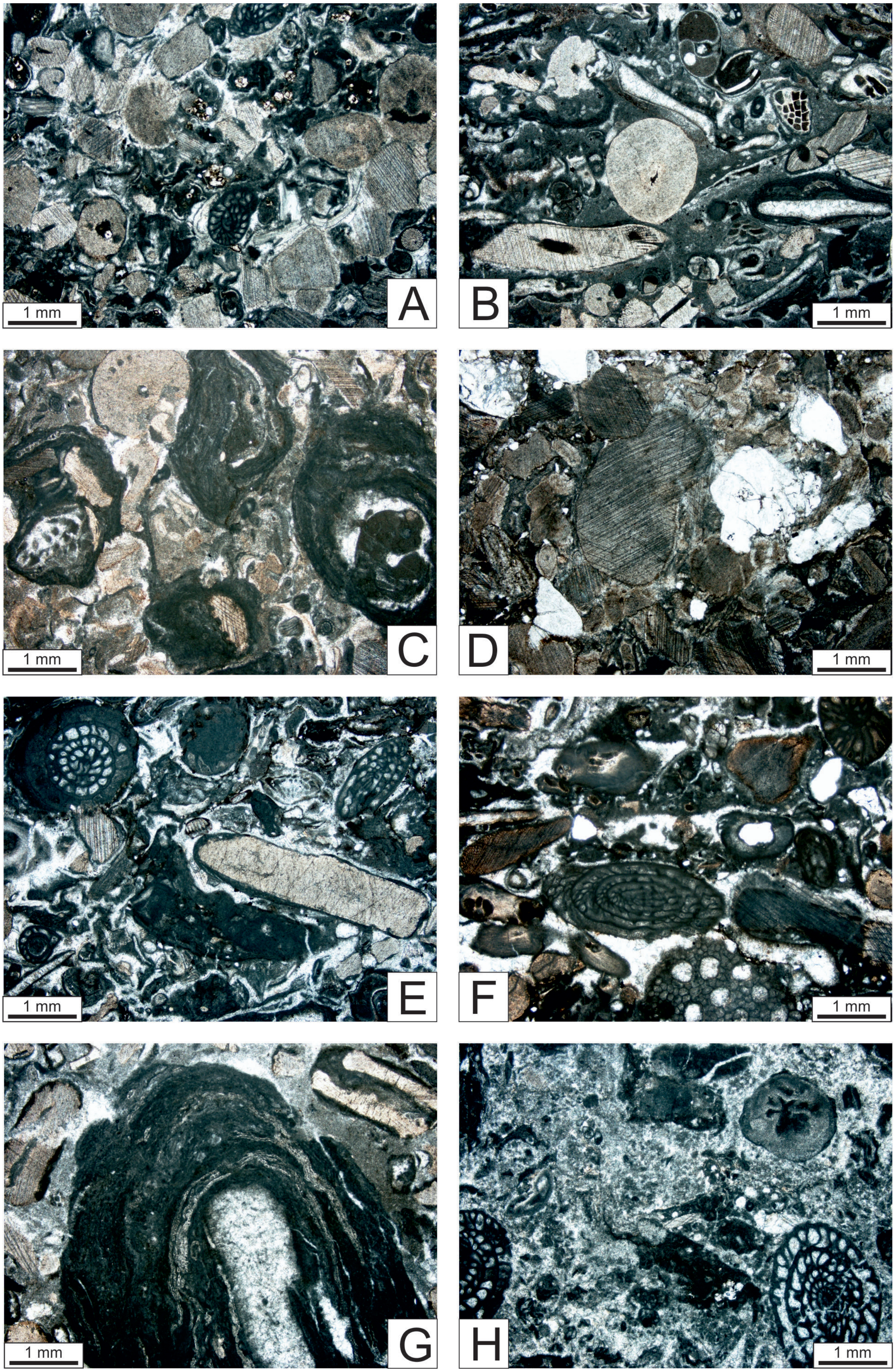
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Plate 3

Thin section photographs of characteristic microfacies types from the middle part of the Zottachkopf Formation at section TNB (Trogkofel North B). All under plane light.

Fig. A: Bioclastic wackestone to floatstone containing many fusulinids and oncoids, and subordinately other fossil fragments. Sample TNB 2.

Fig. B: Oncoidal floatstone composed of oncoids that float in bioclastic wackestone containing a diverse fossil assemblage. Sample TNB 5.

Fig. C: Bioclastic wackestone, poorly washed, fine-grained, containing abundant smaller foraminifers and subordinately other fossils. Sample TNB 7.

Fig. D: Algal floatstone containing recrystallized fragments of phylloid algae, micritic matrix and cement. Sample TNB 8.

Fig. E: Grainstone to rudstone containing calcareous algae, echinoderm fragments, bryozoans, smaller foraminifers, fusulinids, other skeletal grains, oncoids and intraclasts. Sample TNB 10.

Fig. F: Mound facies (bindstone to cementstone) containing *Archaeolithophyllum lamellosum*, cyanobacteria crusts, *Tubiphytes*, some micrite and much cement. The rock is brecciated in-situ. Sample TNB 11.

Fig. G: Oncoidal floatstone composed of large oncoids that float in bioclastic wackestone with a diverse fossil assemblage. Sample TNB 14.

Fig. H: Bioclastic grainstone to packstone, poorly washed, containing a diverse fossil assemblage, intraclasts and few peloids. Sample TNB 15.

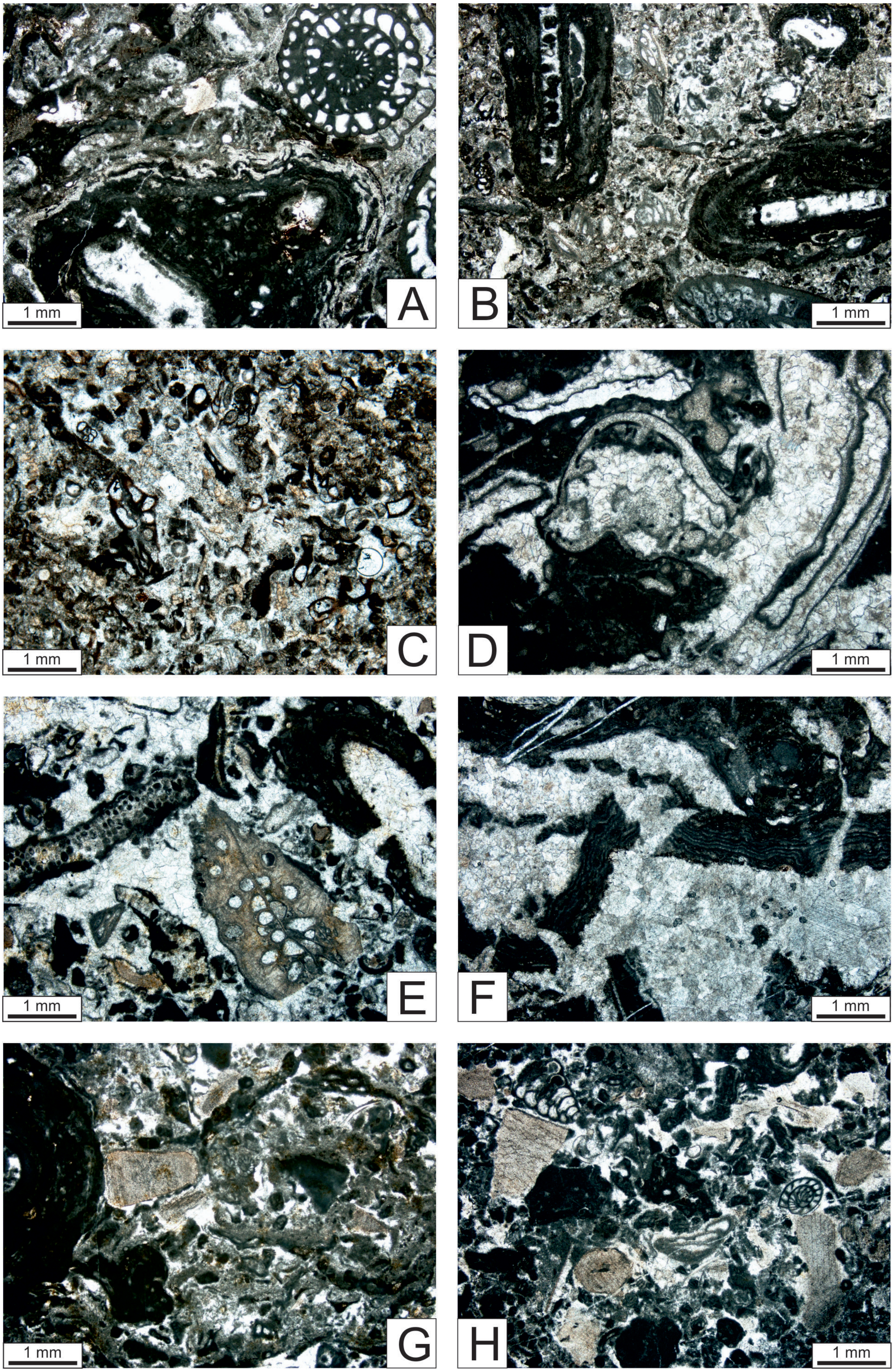

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Plate 4

Thin section photographs of characteristic microfacies types from the middle to upper part of the Zottachkopf Formation at section TNC (Trogkofel North C). All under plane light.

Fig. A: Oncoidal floatstone containing oncoids, *Tubiphytes*, echinoderm fragments, other fossils and small intraclasts. Sample TNC 1.

Fig. B: *Girvanella* bindstone. Sample TNC 1.

Fig. C: Grainstone to rudstone containing abundant recrystallized fragments of calcareous algae, shell debris, smaller foraminifers and few intraclasts. Sample TNC 2.

Fig. D: Bioclastic wackestone containing a diverse fossil assemblage, some intraclasts and peloids. Sample TNC 3.

Fig. E: Bindstone composed of larger fossil fragments that are encrusted by cyanobacteria (*Girvanella*). Sample TNC 5.

Figs. F, G: Bioclastic wackestone to packstone containing a diverse fossil assemblage, some small intraclasts and peloids. Sample TNC 6.

Fig. H: Phylloid algal floatstone, partly bindstone. Large fragments of recrystallized phylloid algae (probably *Neoanchicodium*) are partly encrusted by cyanobacteria (*Girvanella*) and are embedded in micrite and peloidal micrite. Pore space is filled with cement. Sample TNC 20.

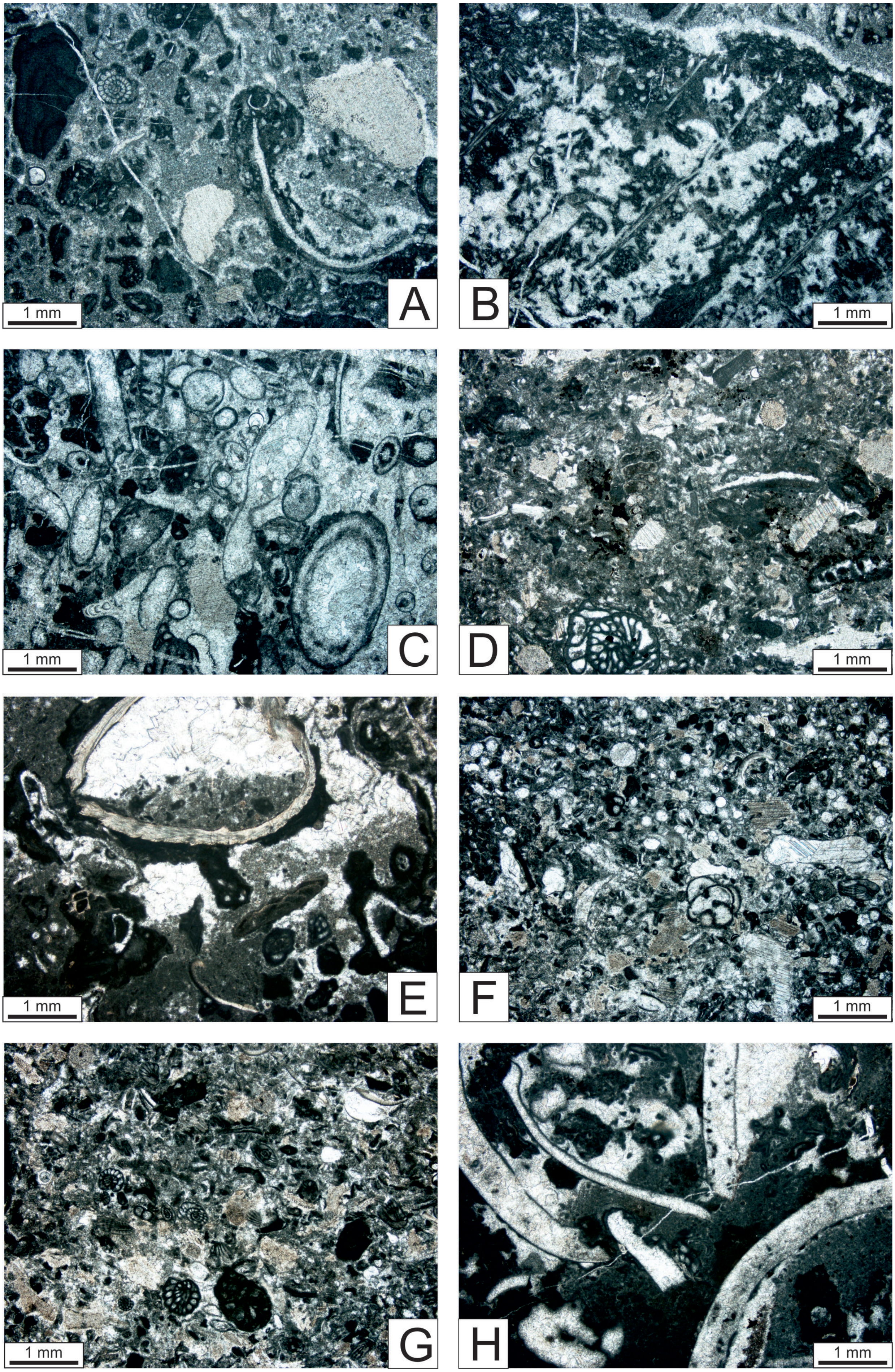
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Plate 5

Thin section photographs of characteristic microfacies types from the upper part of the Zottachkopf Formation at section TNC (Trogkofel North C). All under plane light.

Fig. A: Fine-grained bioclastic wackestone containing few larger fossils (calcareous algae, *Tubiphytes*). Sample TNC 21.

Fig. B: Phylloid algal floatstone. Large fragments of recrystallized phylloid algae are embedded in micritic matrix that contains few small skeletons. Sample TNC 26.

Fig. C: Bioclastic grainstone containing a diverse fossil assemblage, intraclasts (including reworked fragments of oncoids). Sample TNC 30.

Figs. D, E: *Tubiphytes–Girvanella* bindstone with a few small fossils, peloidal micrite and cement. Sample TNC 33.

Fig. F: Grainstone containing a diverse fossil assemblage, intraclasts and a few oncoids. Sample TNC 34.

Fig. G: Floatstone with a large bryozoan fragment that is encrusted by *Girvanella*. Sample TNC 35.

Fig. H: Indistinctly laminated peloidal wackestone to grainstone. Sample TNC 37.

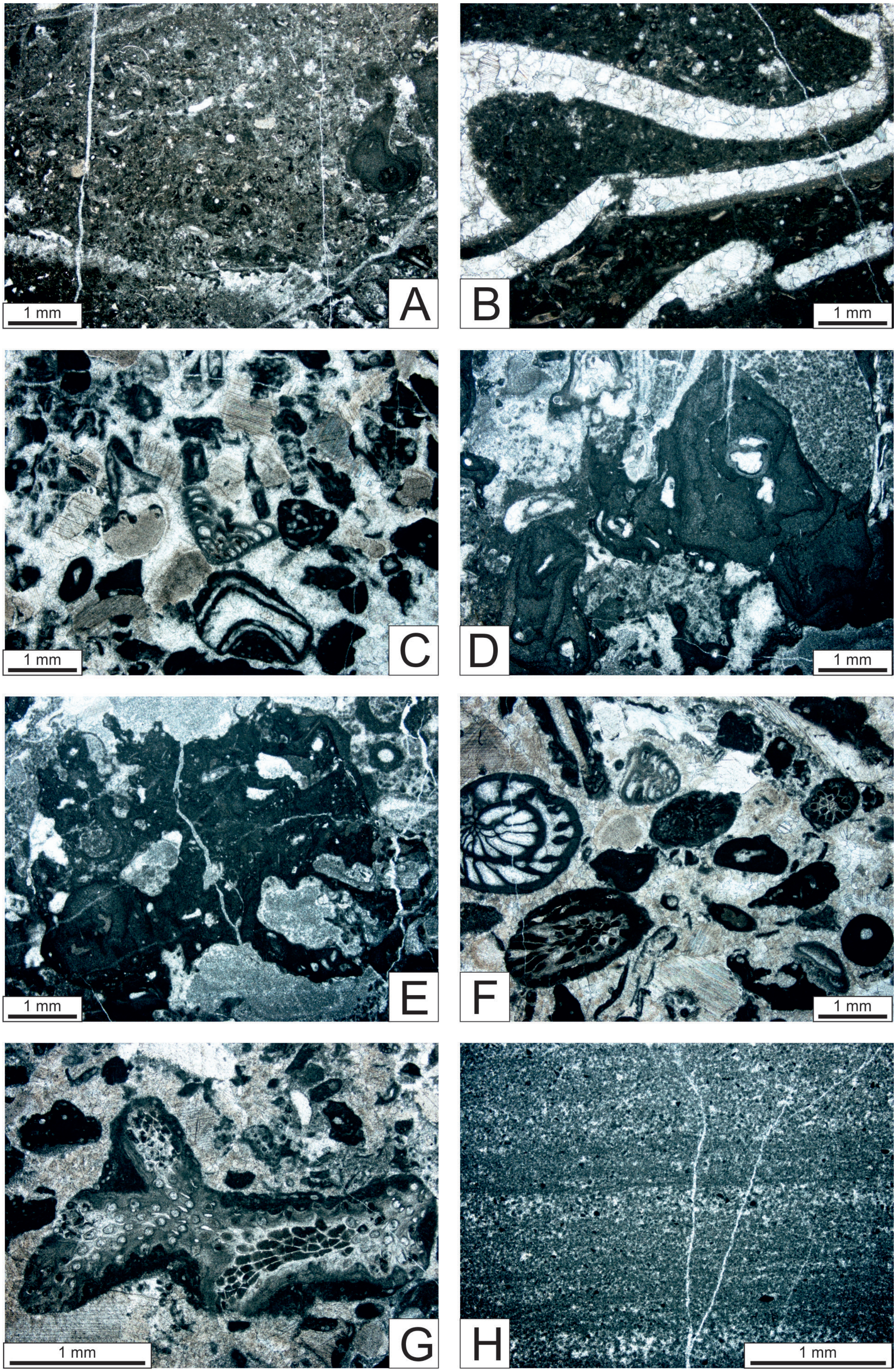
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Plate 6

Thin section photographs of characteristic microfacies types from the middle-upper part of the Zottachkopf Formation at section ZT (Trogkar). All under plane light.

Fig. A: Rudstone to oncoidal rudstone composed of a diverse fossil assemblage of fusulinids, calcareous algae, echinoderms, smaller foraminifers, ostracods, and oncoids. Some of the fusulinid tests are abraded. Sample ZT 4.

Fig. B: Fusulinid-oncoid rudstone composed of large fusulinids (partly abraded) and many large oncoids. The rudstone also contains algal fragments, smaller foraminifers, echinoderm fragments and ostracods. Sample ZT 15.

Fig. C: Fusulinid rudstone composed of abundant, partly abraded and fragmented fusulinid tests that are embedded in fine-grained bioclastic matrix containing echinoderm fragments, smaller foraminifers, ostracods, algal fragments and peloids. Sample ZT 10.

Fig. D: Algal rudstone composed of abundant fragments of recrystallized phylloid algae (*Neoanchicodium*), few *Epimastopora*, fusulinids, smaller foraminifers, ostracods and echinoderm fragments. Some of the skeletons are encrusted by *Girvanella* forming oncoids. Sample ZT 12.

Fig. E: Packstone to rudstone composed of a diverse fossil assemblage of strongly fragmented skeletons including abundant calcareous algae. Few intraclasts are present too. Sample ZT 1.

Fig. F: Recrystallized oolitic grainstone with few fossil fragments such as echinoderm and algal fragments. Sample ZT 13.

Fig. G: Peloidal grainstone containing abundant peloids, subordinately intraclasts, smaller foraminifers and echinoderm fragments. Sample ZT 7.

Fig. H: Oncoid composed of alternating crusts of *Girvanella* and *Claracrusta*. Sample ZT 15.

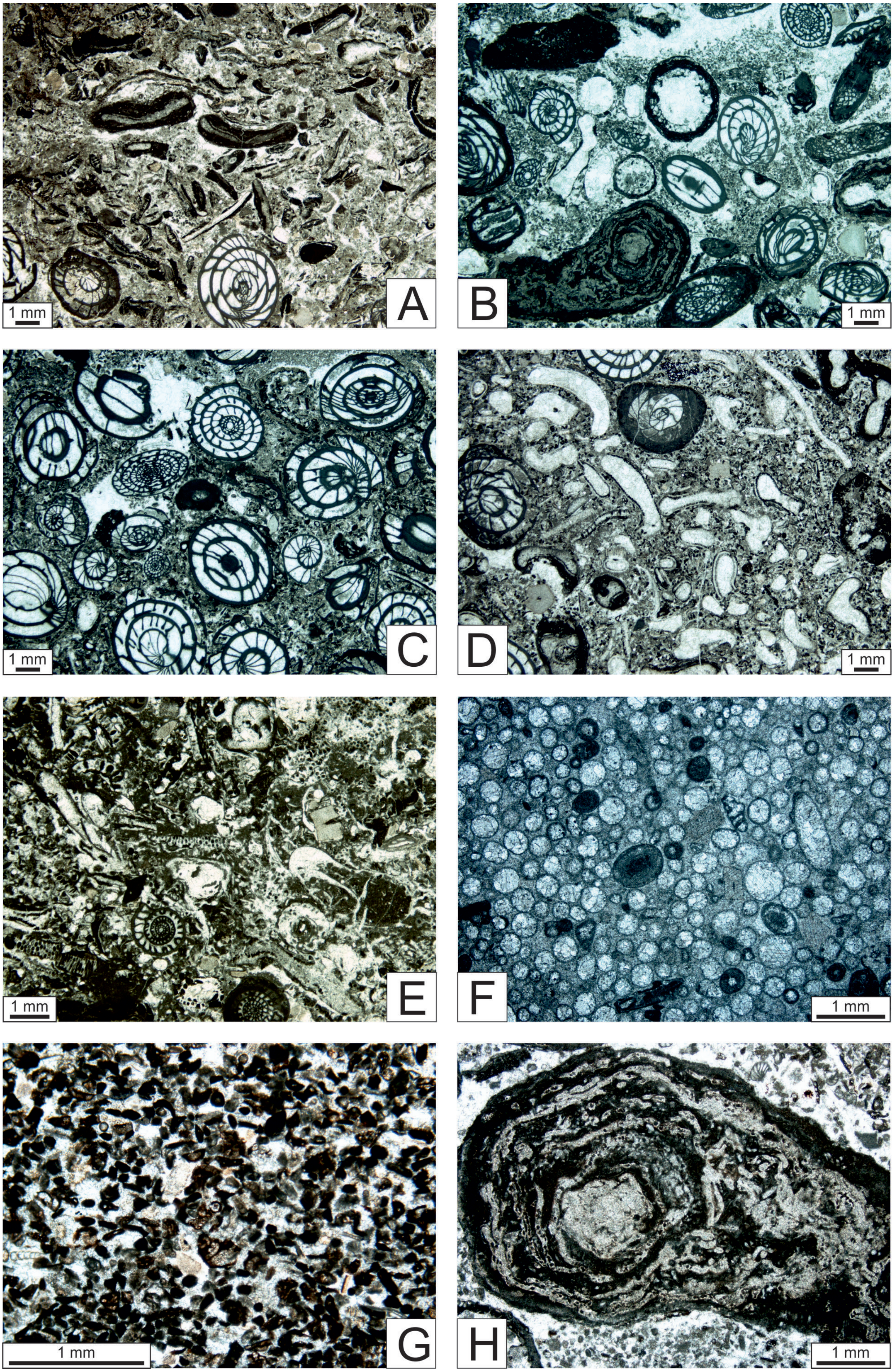
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Plate 7

Thin section photographs of characteristic microfacies types of limestones from the upper part of the Zottachkopf Formation at section Z (Zottachkopf). All under plane light.

Fig. A: Bioclastic packstone to rudstone with a diverse fossil assemblage including echinoderm fragments, calcareous algae, smaller foraminifers, bryozoans and recrystallized skeletons. A few oncoids are present. Sample Z 1.

Fig. B: Bioclastic packstone to rudstone with a diverse fossil assemblage. Sample Z 3.

Fig. C: Floatstone to rudstone containing abundant fragments of calcareous algae (*Epimastopora*, phylloid algae). Also present are fusulinids, smaller foraminifers, gastropods, echinoderms and oncoids. Sample Z 6.

Fig. D: Bioclastic wackestone to packstone containing many fragments of calcareous algae and sphaerical grains (?algal spores), few fusulinids, smaller foraminifers, echinoderms and few oncoids. Sample Z 7.

Fig. E: Floatstone to rudstone. Most abundant are fusulinids, algal fragments and oncoids that are embedded in fine-grained bioclastic matrix. Sample Z 9.

Fig. F: Fusulinid-oncoid floatstone to rudstone. Fusulinids and oncoids are embedded in fine-grained bioclastic matrix. Sample Z 10.

Fig. G: Oncoid-fusulinid floatstone. Large oncoids (up to 2 cm) and few fusulinids are embedded in fine-grained bioclastic, partly peloidal matrix. Oncoids are composed of phylloid algae that form the nucelus and are encrusted by *Girvanella* and *Claracrusta*. Sample Z 11.

Fig. H: Detail of an oncoid composed of *Girvanella* and *Claracrusta*. Sample Z 2.

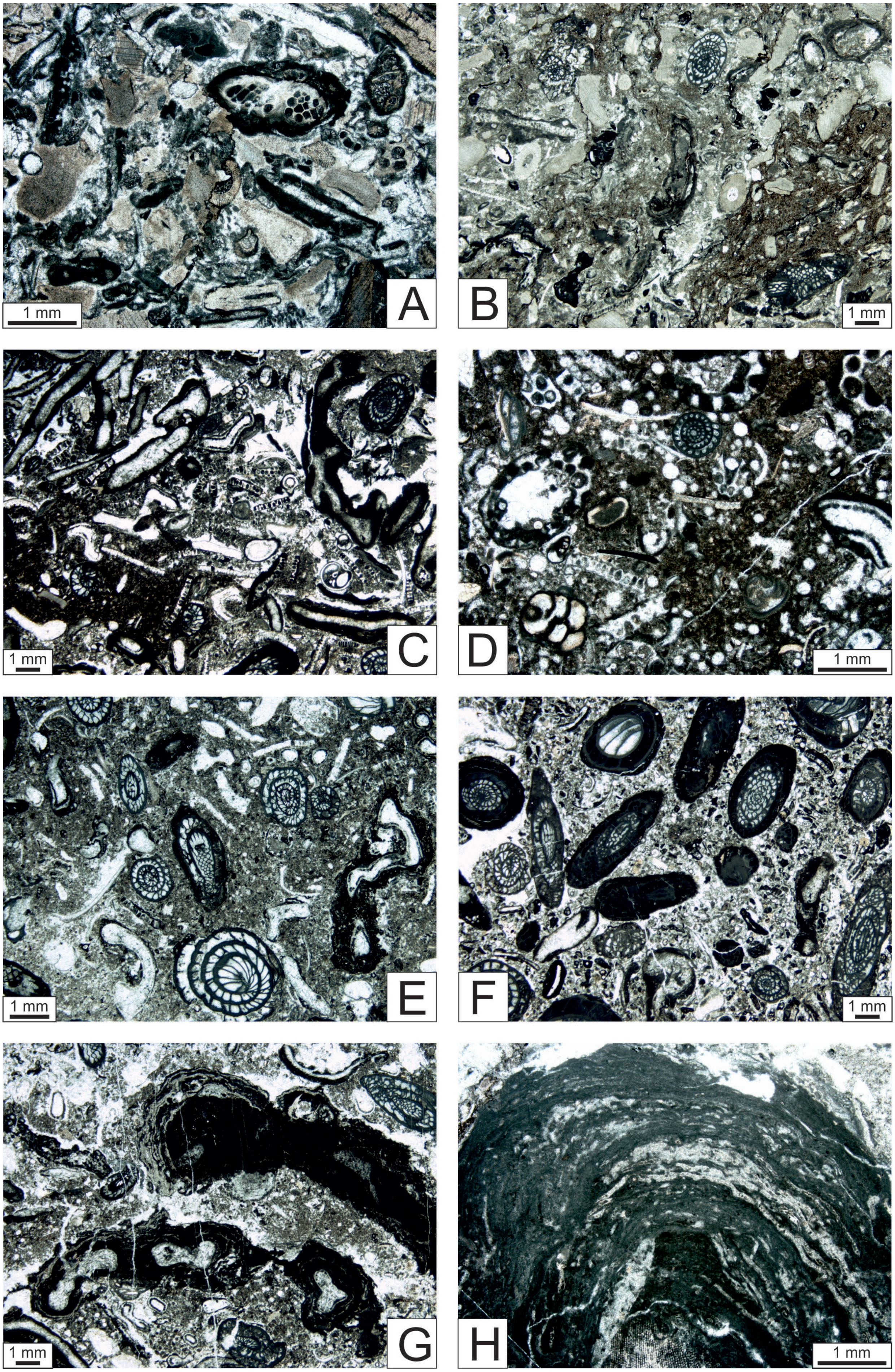
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Plate 8

Thin section photographs of characteristic microfacies types of limestones from the uppermost part of the Zottachkopf Formation at sections TKS (Trogkofel South) and TKW (Trogkofel Southwest). All under plane light.

Fig. A: Rudstone containing oncoids, many echinoderm fragments, calcareous algae, smaller foraminifers and few other fossil fragments. Sample TKS 4.

Fig. B: Oncoidal floatstone to rudstone containing oncoids, echinoderm fragments, *Tubiphytes*, smaller foraminifers, calcareous algae, ostracods and few other fossil fragments. Sample TKS 12.

Fig. C: Phylloid algal floatstone containing large thalli of recrystallized calcareous algae (mostly *Neoanchicodium*), subordinately echinoderm fragments, fusulinids, smaller foraminifers and few other fossils embedded in micritic matrix. Sample TKS 6.

Fig. D: Grainstone containing intraclasts including fragments of oncoids, many recrystallized skeletons, smaller foraminifers, fusulinids, echinoderm fragments and other fossils. Sample TKS 19 (basal Trogkofel Formation).

Fig. E: Rudstone composed of abundant recrystallized skeletons, echinoderm (crinoid) fragments, fusulinids, smaller foraminifers, calcareous algae, ostracods and few other fossils. Sample TKW 9.

Fig. F: Fusulinid packstone to rudstone composed of abundant fusulinid tests, echinoderm fragments, smaller foraminifers, calcareous algae, ostracods and peloids. Sample TKW 5.

Fig. G: Oncoidal rudstone to floatstone composed of oncoids up to 1 cm in diameter and few larger fossils embedded in fine-grained bioclastic matrix. Sample TKW 10.

Fig. H: Bindstone/cementstone (mound facies) composed of *Archaeolithoporella*-crusts and cement, brecciated in-situ. Sample TKW 1.

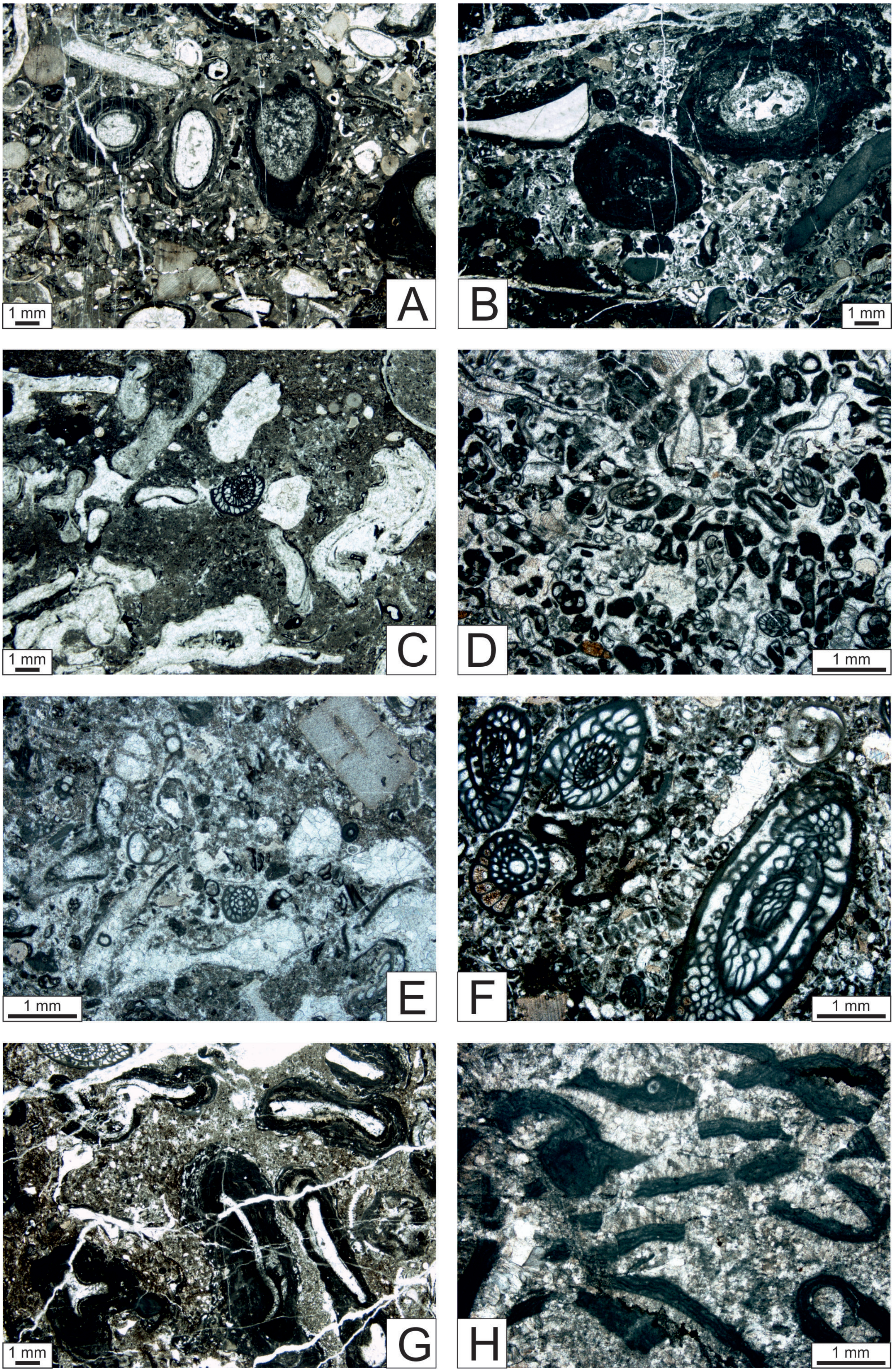
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Plate 9

Characteristic algae of the Zottachkopf Formation

1, 2 *Koivaella* ex gr. *permiensis* (1: sample TNB 3, 2: sample TNB 8), **3** *Parachaetetes ortonelloides* (sample Z 9B), **4, 5** *Homannisiphon morikawai* (both from sample Z 1), **6, 9** *Eugonophyllum magnum* (6: sample TKS 13, 9: sample TKS 14), **7** *Anchicodium japonicum* (sample TKS 3), **8** *Ivanovia tenuissima* (sample TNA 2), **10, 11** *Calcipatera schoenlaubi* (10: sample TNA 16, 11: sample TNA 18), **12, 13** *Neoanchicodium catenoides* (12: sample TNC 2, 13: sample TKW 9), **14** *Nanjinophycus*? sp. (sample TNA 16), **15** *Anthracoporella spectabilis* (sample Z 3), **16, 17** *Epimastopora japonica* (16: sample TNA 18, 17: sample Z 6), **18, 19** *Epimastopora likana* (18: sample TKW 9B, 19: sample TNC 5), **20** *Epimastopora alpina* (sample Z 10), **21, 23** *Globuliferoporella piae* (21: sample TKW 10, 23: sample TKW 12B), **22** *Epimastopora fluegeli* (sample TKW 13B), **24, 25** *Globuliferoporella angulata* (24: sample TKW 9B, 25: sample TKW 12), **26, 27** *Pseudoepimastopora carnica* (26: sample Z 5, 27: sample Z 7), **28** *Mizzia velebitana* (sample TKS 12), **29, 30** *Mizzia yabei* (sample TKS 12), **31** *Efluegelia johnsoni* (sample Z 17B), **32** *Ungdarella uralica* (sample TNB 15).

Scale bar: 1, 2 = 0.1 mm; 3 = 0.2 mm; 8, 13–15, 17, 23–31 = 0.5 mm; 4–7, 9–12, 16, 18–22, 32 = 1 mm.

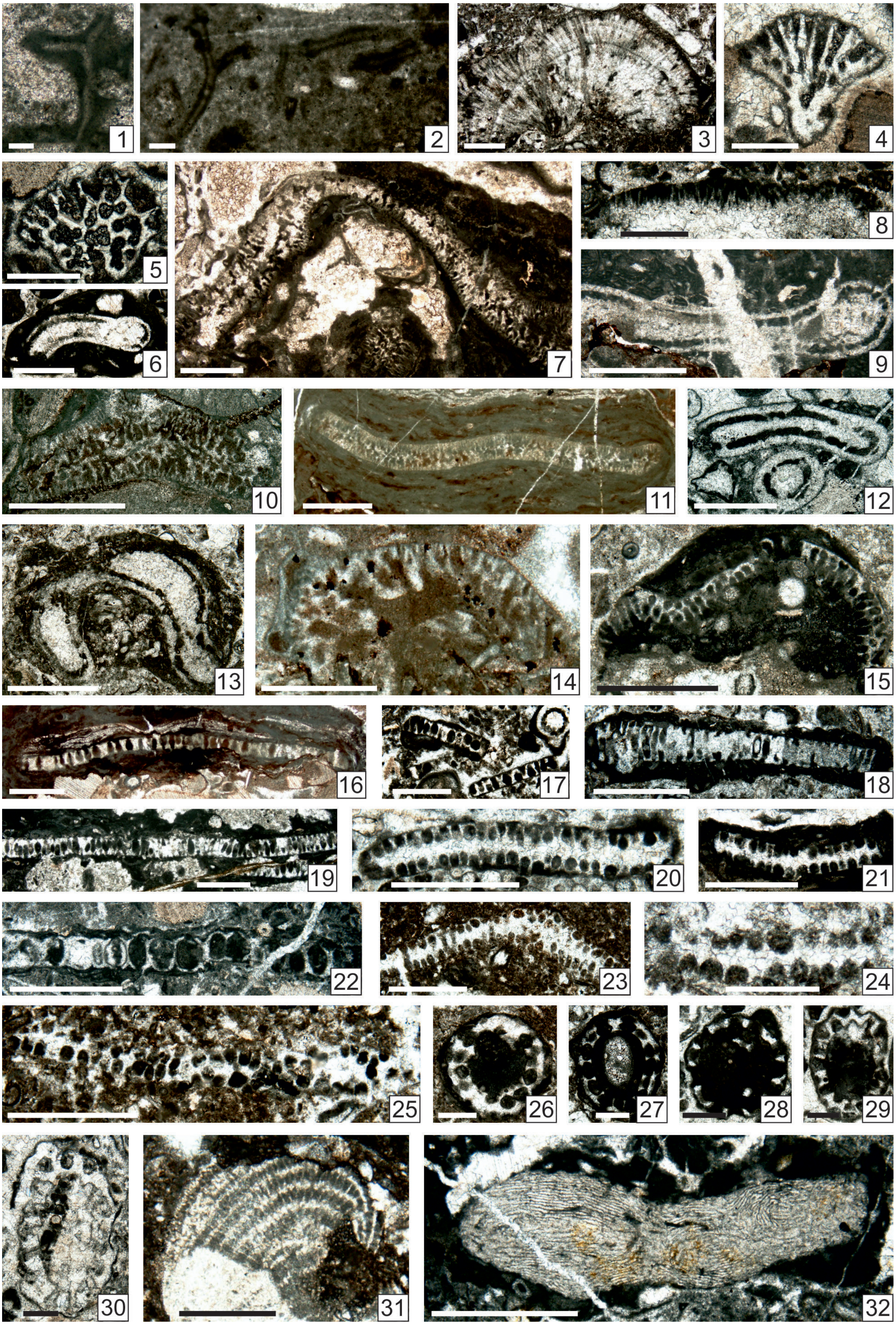
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Plate 10

Characteristic foraminifers of the Zottachkopf Formation (from Krainer et al., 2019b)

1 *Tuberitina bulbacea* (TNC 1), **2, 3** *Earlandia dunningtoni* (2: TKW 12, 3: Z 9), **4, 5** *Eolasiodiscus donbarcanus* (4: TKW 5B, 5: TNB 8), **6–8** *Pseudovidalina multihelics* (6: ZT 7, 7: Z 15, 8: TNA 1), **9** *Pseudovidalina media* (TNC 6), **10, 11** *Pseudovidalina modificata* (10: TKS 4, 11: Z 16B), **12–14** *Endothyra* cf. *rzhevica* (12: TKS 3, 13: TNC 7, 14: ZT 9), **15, 16** *Endothyra* cf. *arctica* (15: Z 15, 16: TKS 6), **17** *Planoendothyra ultimata* (TNA 15), **18** *Endothyra* aff. *miriformis* (ZT 2), **19, 20** *Endothyra* aff. *symmetrica* (19: ZT 10, 20: TNC 4), **21** *Globivalvulina* ex gr. *bulloides* (Z 11), **22** *Globivalvulina donbassica*, transitional to *G. graeca* (Z 13B), **23** *Globivalvulina* cf. *ovata* (TKW 9), **24** *Deckerella* cf. *tenuissima* (TNC 6), **25** *Climacammina elegans* (Z 11B), **26** *Palaeotextularia* aff. *minutissima* (TNB 3), **27** *Climacammina* cf. *tenuis* (TNB 3), **28** *Spireitlina* ex gr. *conspecta* (TNB 3), **29, 30** *Deckerella bashkirica* (29: TNB 13, 30: TNB 18), **31** *Deckerella* cf. *tenuissima* (TNA 19), **32** *Climacammina elegans* (TKW 13), **33** *Spireitlina* ex gr. *conspecta* (TKW 9).

Scale bar: 1–21 = 0.1 mm; 26, 28 = 0.2 mm; 22–25, 27, 29–33 = 0.5 mm.

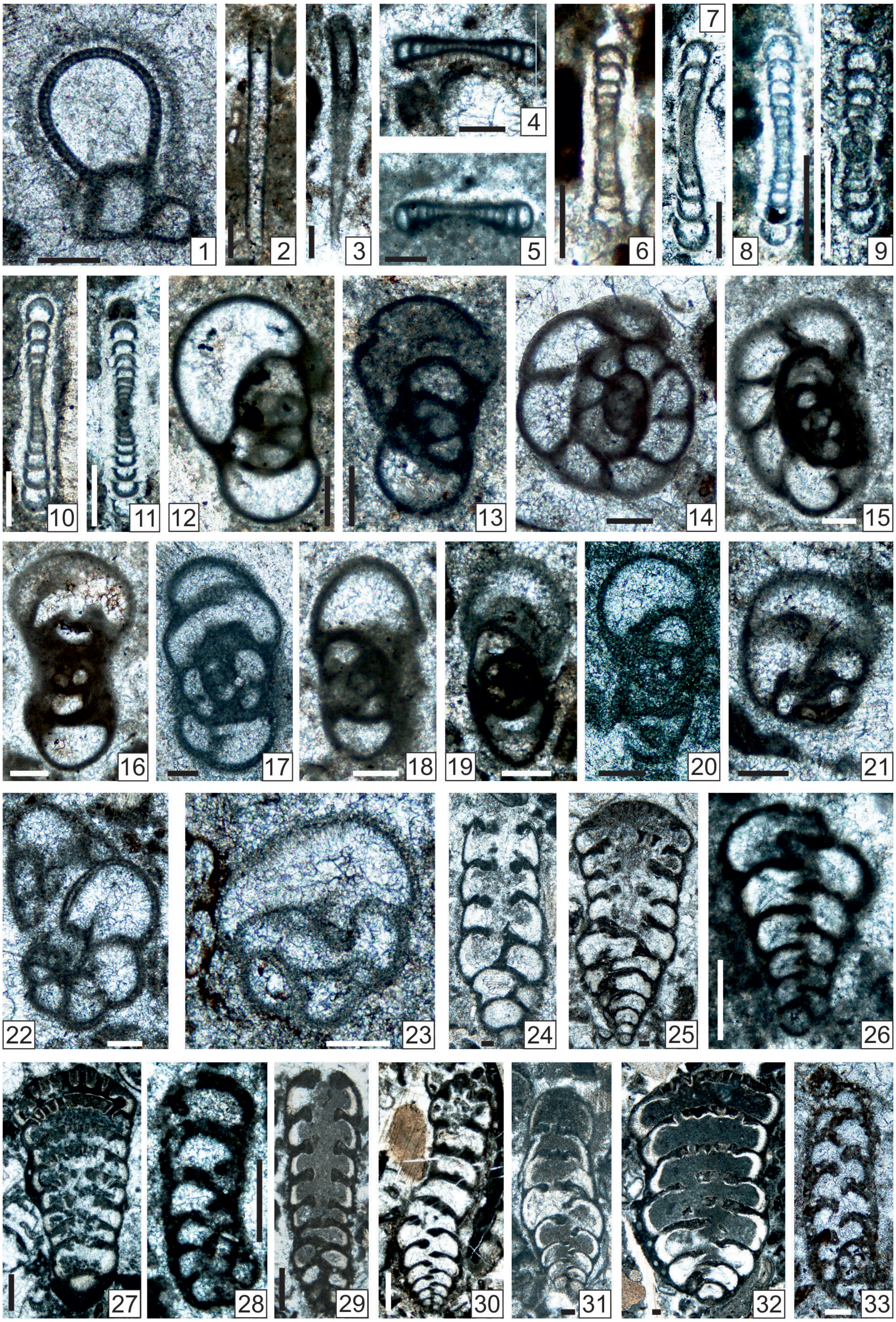
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Plate 11

Characteristic foraminifers of the Zottachkopf Formation (from Krainer et al., 2019b)

1 *Climacammina elegans* (TNB 2), **2** *Climacammina sphaerica* (TNB 1), **3** *Climacammina longissimoides* (ZT 18), **4** *Deckerella* cf. *tenuissima* (TNC 7A), **5, 6** *Spireitlina* ex gr. *conspecta* (5: TNA 2, 6: TNB 15), **7–9** *Rectoendoteba tieni* (7: TSK 18, 8: TKW 5B, 9: TKW 8B), **10** *Rectoendoteba*? sp. (TNB 13), **11** *Endothyra* cf. *arctica* (TNB 1), **12, 13** *Endothyra* cf. *rzhevica* (12: TNB 13, 13: TNB 18), **14** Atypical *Pseudovidalina damghanica* (TNB 19), **15, 16** *Pseudovidalina modificata* (15: TNB 13, 16: TNB 15), **17** *Pseudovidalina media* (TNB 19), **18** *Eolasiodiscus donbacanus* (Z 15), **19** *Palaeotextularia* aff. *minutissima* (right) and *Deckerella* cf. *tenuissima* (TNB 3), **20** *Pseudovidalina media* (TNB 21), **21** *Eolasiodiscus*? *donbacanus* (TNB 22), **22, 23** *Pseudovidalina modificata* (22: TNB 3, 23: TNB 22), **24** *Rectoendoteba tieni* (TNB 14), **25** *Spireitlina tokmovensis* (TNB 5), **26** *Endothyra* cf. *arctica* (TNB 3), **27** *Endothyra* aff. *miriformis* (TNB 21), **28** *Endothyra* aff. *symmetrica* (TNB 7), **29, 30** *Septoglobivalvulina* cf. *guangxiensis* (29: TNB 7, 30: TNB 19), **31** *Globivalvulina* cf. *ovata* (ZT 14).

Scale bar: 6, 10–14, 16–18, 20–31 = 0.1 mm; 3, 15 = 0.2 mm; 1, 2, 4, 5, 7–9 = 0.5 mm; 19 = 1 mm.

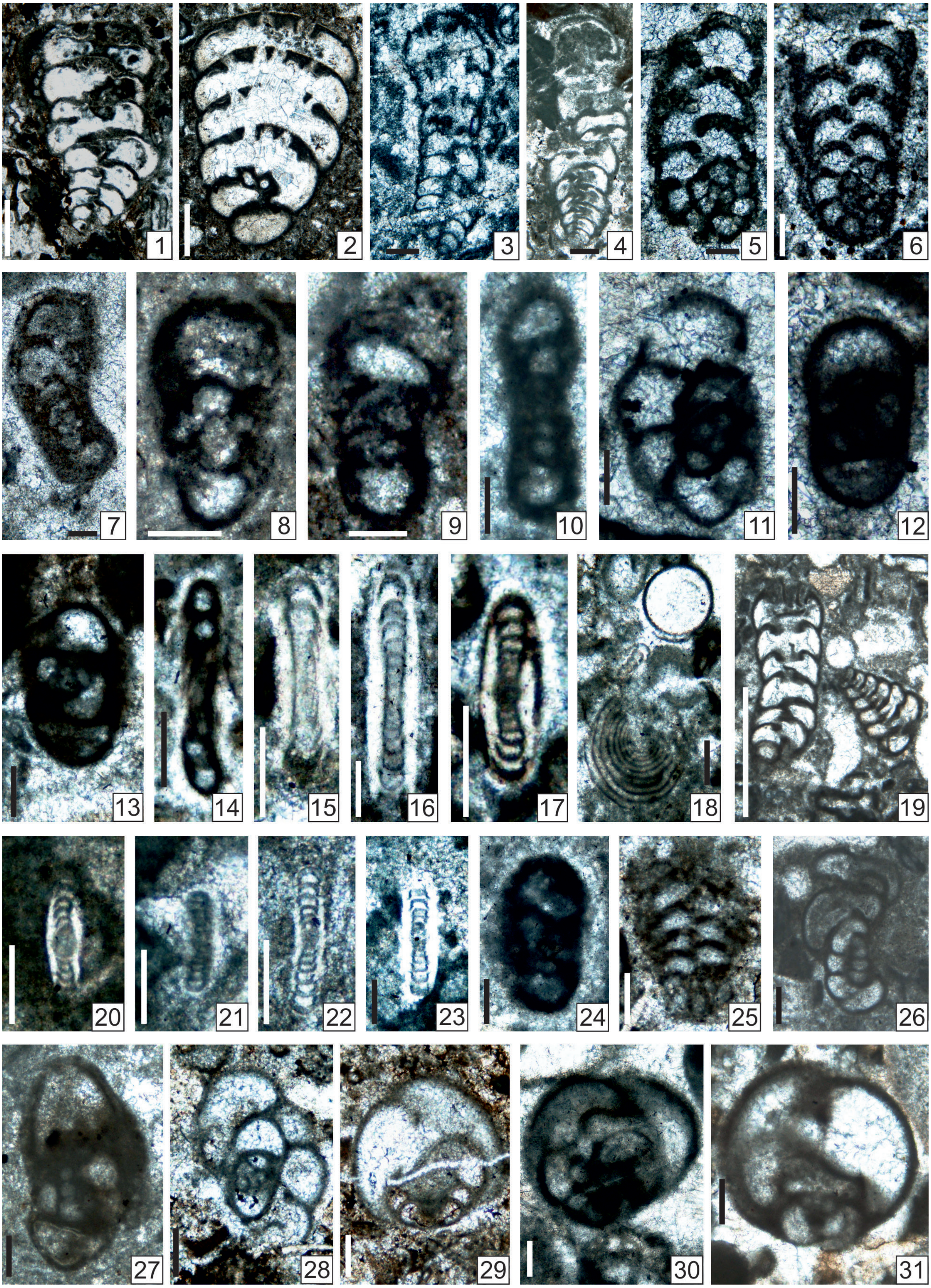
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Plate 12

Characteristic foraminifers of the Zottachkopf Formation (from Krainer et al., 2019b)

1, 2 *Calcivertella* sp. (1: TKS 19, 2: TNA 4), **3, 4** *Hemigordius* sp. (3: TNB 2, 4: TKS 1), **5, 6** *Hemigordiellina regularis* (5: TNB 21, 6: TNB 13), **7** *Tubiphytes obscurus* (TKS 8), **8** *Calcivertella* sp. (TNB 13), **9** *Tubiphytes carinthiacus* (TKS 9), **10** *Calcivertella* sp. (TKS 19), **11** *Hemigordius* sp. (TNB 10), **12** *Hemigordiellina regularis* (TNB 10), **13** *Uralogordiopsis* cf. *kungurensis* (TNB 13), **14** *Olgaorlovella dublicata* (TNB 19), **15** *Cornuspira* sp. (TKW 9), **16** *Olgaorlovella dublicata* (TNB 7), **17** *Hemigordius* sp. (ZT 11), **18** *Cornuspira* sp. (ZT 11), **19, 20** *Uralogordiopsis longus* (19: TKS 19, 20: TNB 5), **21, 22** *Nodosinelloides potievskayae* (21: TNB 2, 22: TNB 15), **23** *Paravervilleina farcimeniformis* (TNB 1), **24** *Tezaquina carnica* (ZT 5), **25** *Nodosinelloides netschajewi* (TKW 5), **26** *Nodosinelloides aequiampla* (TNB 15), **27** *Praerectoglandulina geinitzinaeformis* (TNB 15), **28** *Nodosinelloides* cf. *ronda* (TNB 5), **29** *Syzrania* cf. *pulchra* (Z 15), **30** *Nodosinelloides longa* (TNB 14), **31** *Nodosinelloides longissima* (TNB 12).

Scale bar: 2–6, 10–31 = 0.1 mm; 1, 7–9 = 0.5 mm.

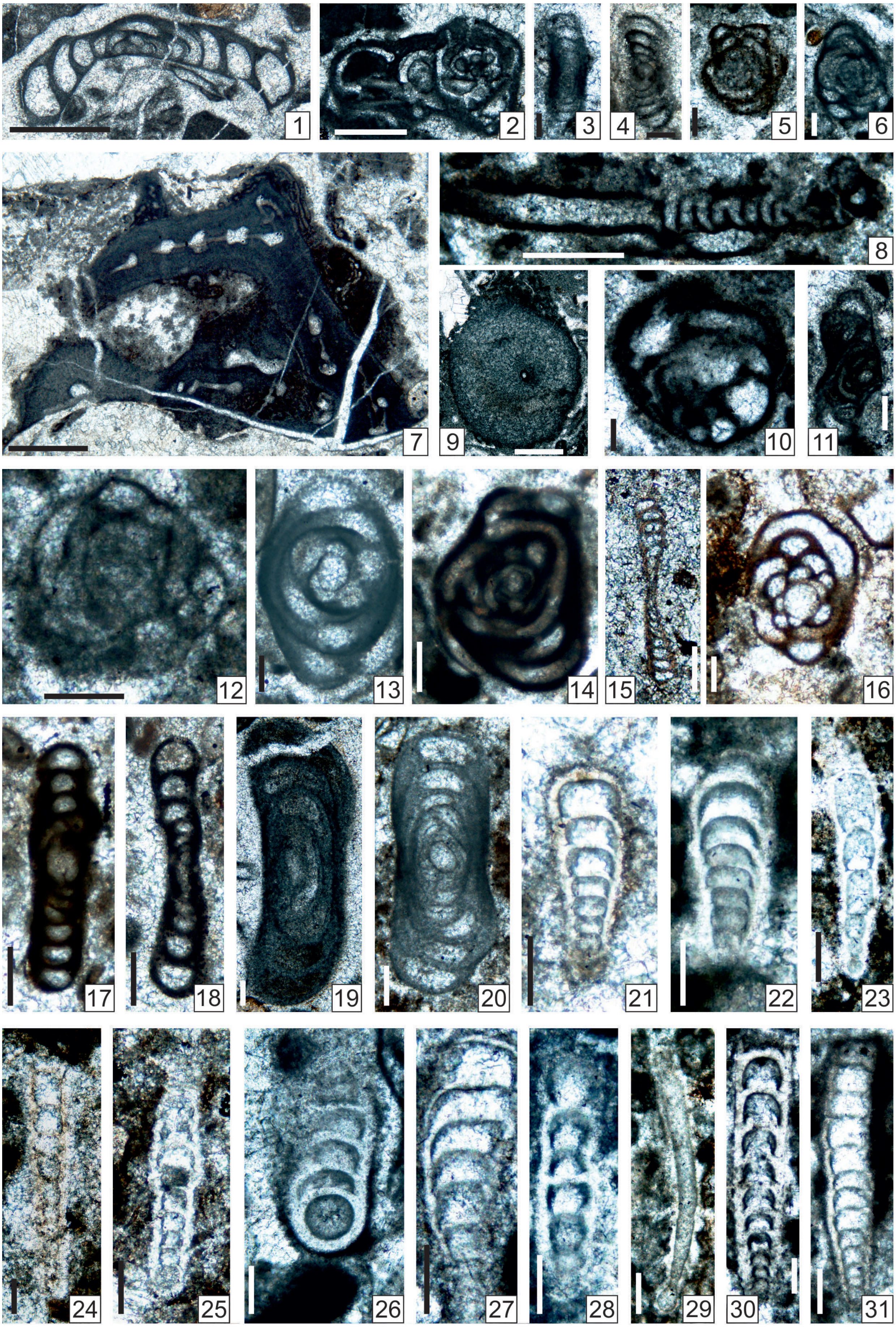
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Plate 13

Characteristic foraminifers of the Zottachkopf Formation (from Krainer et al., 2019b)

1 *Praerectoglandulina geinitzinaeformis* (Z 13B), **2** *Geinitzina spandeli* (TNA 16), **3, 4** *Geinitzina* cf. *ichnousa* (3: TKW 8B, 4: Z 15), **5–10** *Praerectoglandulina miklukhomaklayorum* (5: TKS 2, 6: TNB 13, 7: TNB 15, 8: ZT 10, 9: TKS 2, 10: ZT 15), **11** *Geinitzina* cf. *longa* (Z 16B), **12, 13** *Praerectoglandulina* cf. *primitiva* (12: TNC 6, 13: Z 15), **14–17** *Nodosinelloides pinardae* (14: TKS 10, 15: TNC 3, 16: TNC 6, 17: TKW 5B), **18** *Geinitzina* cf. *longa* (Z 5B), **19, 20** *Geinitzina* cf. *multicamerata* (19: TNC 2, 20: TKW 13B), **21** *Nodosinelloides longissima* (Z 9), **22** *Nodosinelloides mirabilis* (TKS 10), **23, 24** *Pachyphloia*? sp. (23: ZT 2, 24: Z 7), **25, 26** *Tauridiopsis venusta* (25: Z 16B, 26: TKW 13), **27** *Nodosinelloides longissima* (ZT 14).

Scale bar: 0.1 mm.

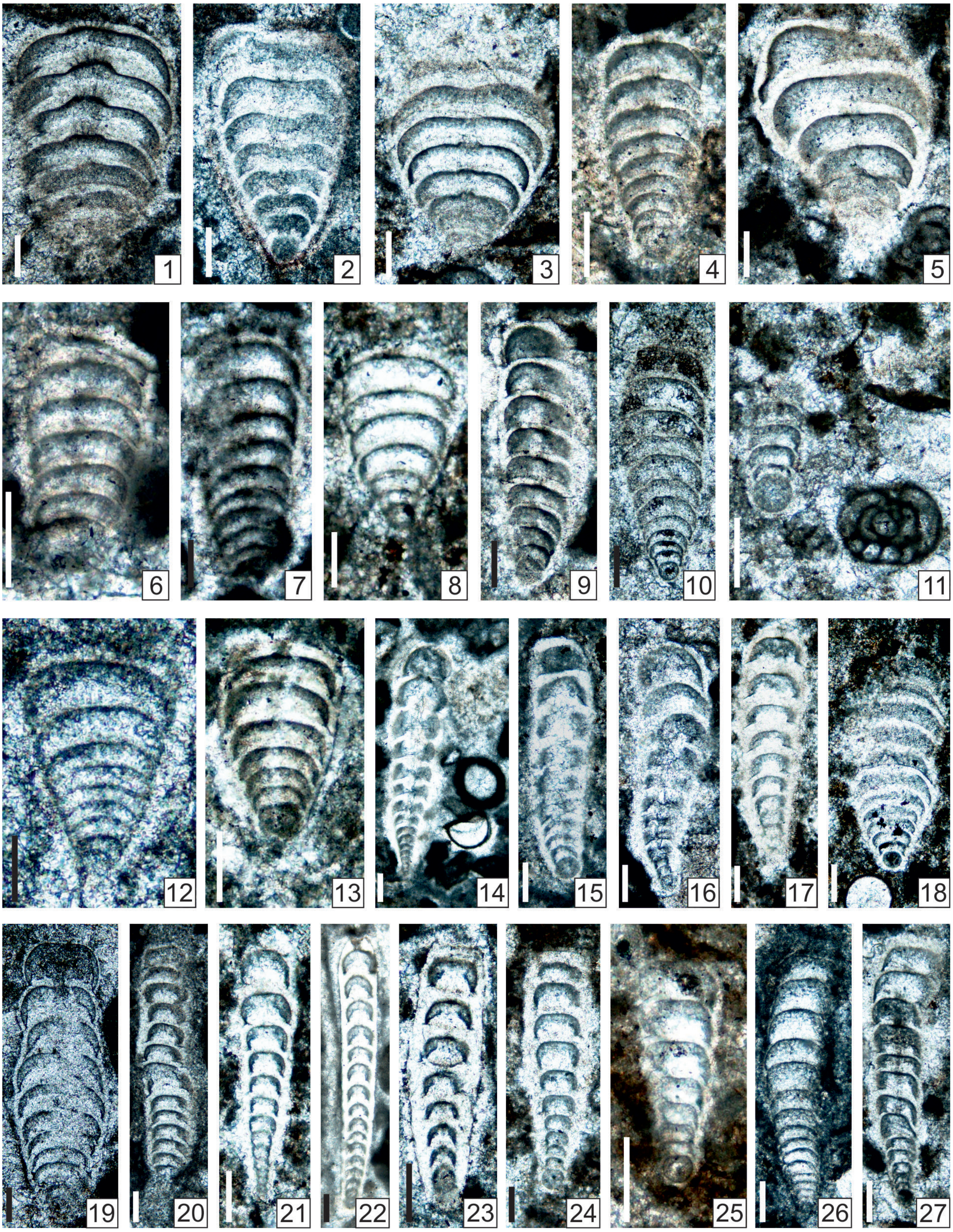

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Plate 14

Fusulinids of the Zottachkopf Formation (from Krainer et al., 2019b)

1 *Chalaroschwagerina* ex gr. *globularis* Skinner & Wilde, 1966. Subtransverse section. Sample TKS 3.
2 *Alpites parvus* (Chen, 1934) sensu Kahler (1988: Figs. 11a, b). Transverse section. Sample TNB 3.
3 *Zellia media* Kahler & Kahler, 1937a. Subaxial section. Sample ZT 8.
4 *Laxifusulina* sp. Subaxial section. Sample TNB 12A.
5 *Paraskinnerella* ex gr. *lutugini* (Schellwien, 1908). Axial section. Sample TKS 7.
6 *Praeskinnerella formosa* (Kochansky-Devidé, 1969). Axial section. Sample TNB 3.
7 *Perigondwania forkei* Davydov in Davydov, Krainer & Chernykh, 2013. Subaxial section. Sample TKW 6.
8 *Praeskinnerella pseudogruperaensis* Leven in Leven, Leonova & Dimitriev, 1992. Axial section. Sample TKW 13.
9 *Grodzdilova* ex gr. *sulcata* (Korzhenevskiy, 1940). Subtransverse section. Sample TNB 10.
10 *Perigondwania forkei* Davydov in Davydov, Krainer & Cherykh, 2013. Subaxial section. Sample TNB 3.
11 *Alpites eocontractus* (Leven & Shcherbovich, 1980). Subaxial section. Sample Z 1.

Scale bar: 1 mm.

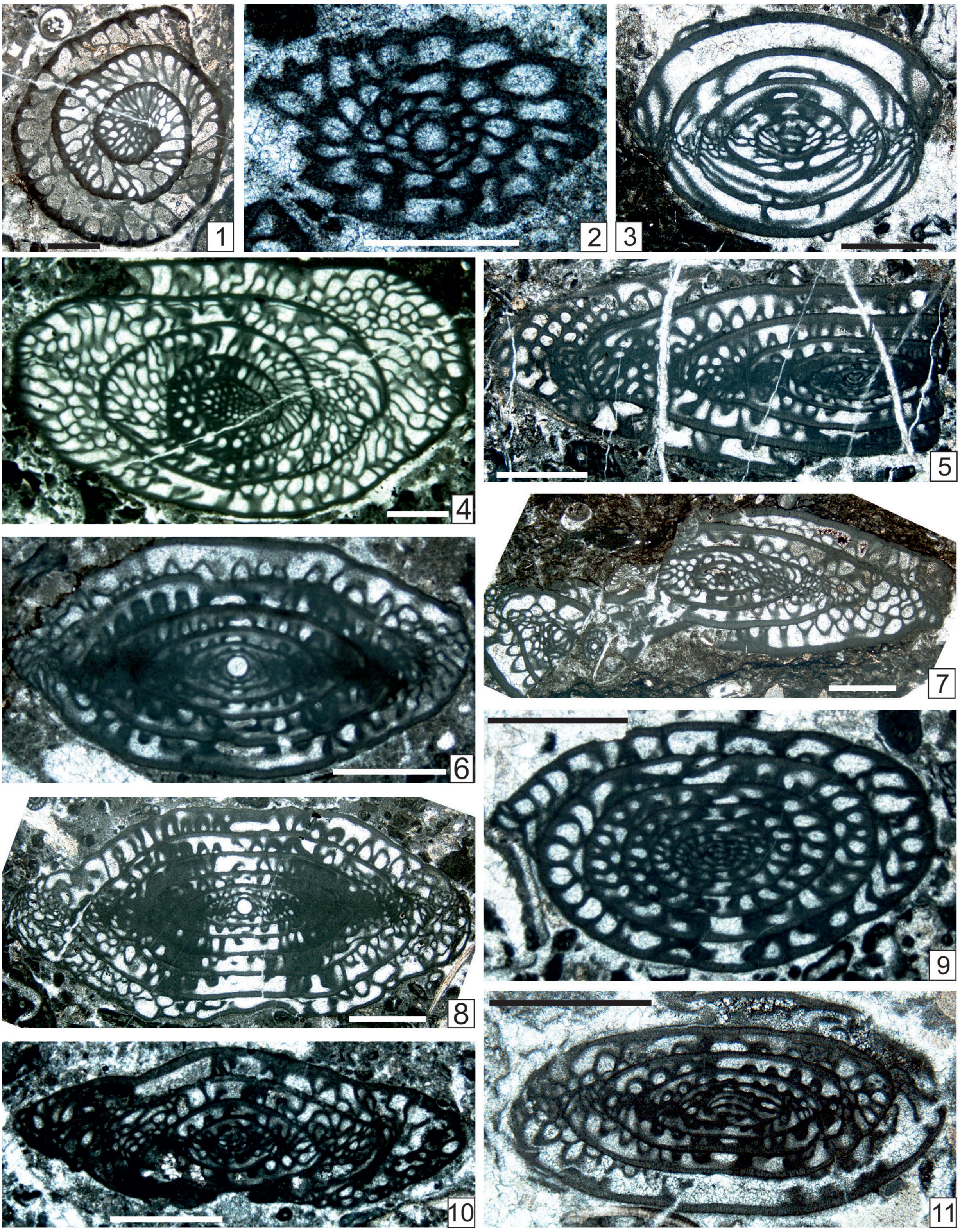
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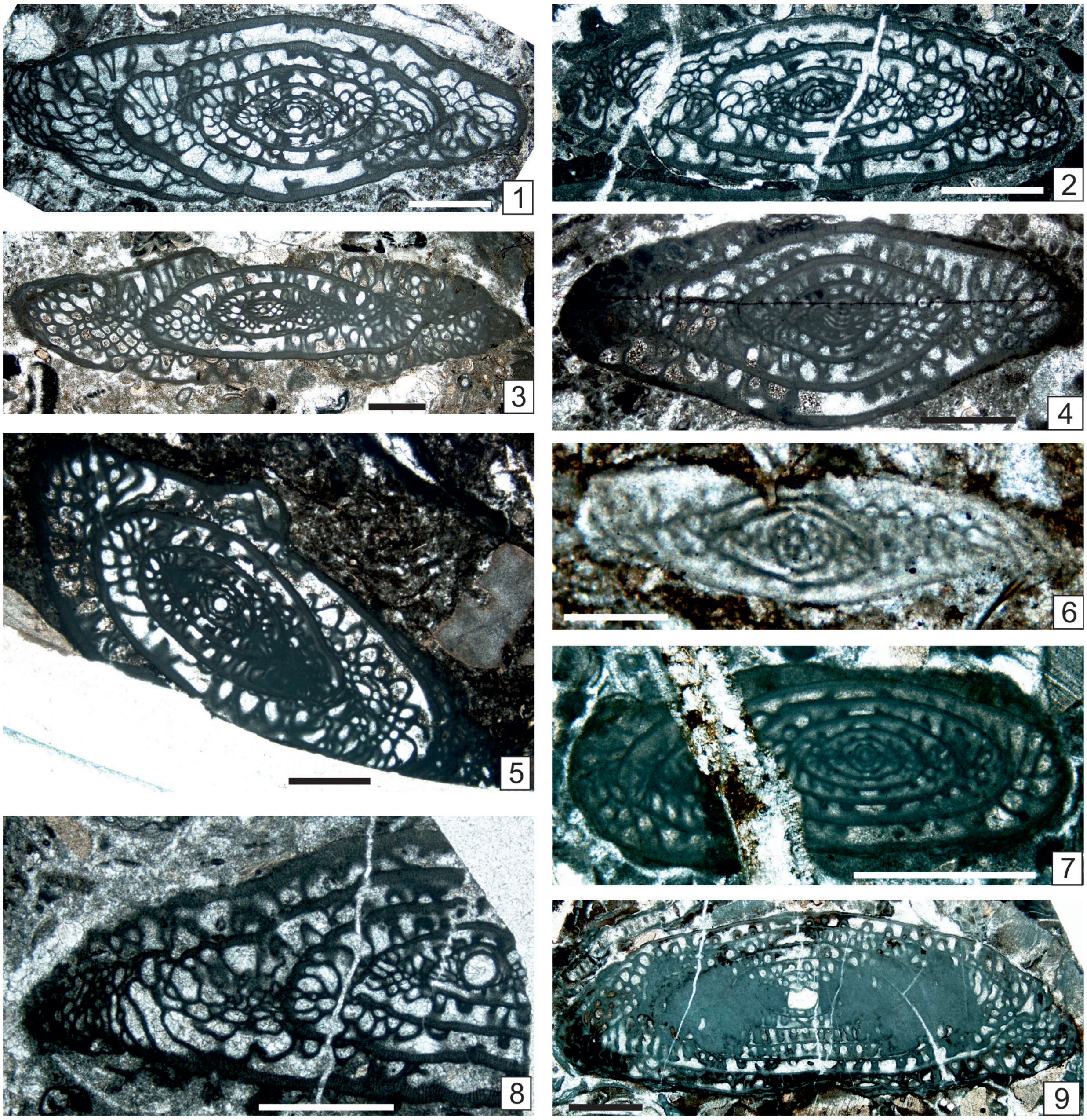
Plate 15

Fusulinids of the Zottachkopf Formation (from KRAINER et al., 2019b)

1 *Paratriticites jesenicensis* KOCHANSKY-DEVIDÉ, 1969. Axial section. Sample Z 9B.
2 *Perigondwania forkei* DAVYDOV in DAVYDOV, KRAINER & CHERNYKH, 2013. Axial section. Sample TKW 13B.
3 *Sakmarella* cf. *implicata* (SCHELLWIEN, 1908). Subaxial section. Sample TNA 28.
4 *Sakmarella* cf. *implicata* (SCHELLWIEN, 1908). Subaxial section. Sample Z 6.
5 *Kutkanella* cf. *kutkanensis* (RAUZER-CHERNOUSOVA, 1940). Axial section. Sample TNB 6.
6 *Boultonia willsi* LEE, 1927. Axial section. Sample TKW 8.
7 *Alpites deminuatis* DAVYDOV in DAVYDOV, KRAINER & CHERNYKH, 2013. Axial section. Sample TNA 17.
8 *Darvasella* cf. *praecox* LEVEN in LEVEN, LEONOVA & DIMITRIEV, 1992. Axial section. Sample Z 8.
9 *Quasifusulina* sp. Axial section. Sample TNA 18.

Scale bar: 1 mm, except 6 = 0.2 mm.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