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Early Permian carbonate shelf margin deposits: the type section of the Trogkofel Formation (Artinskian/Kungurian), Carnic Alps, Austria/Italy

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Abstract

Herein the type section of the Trogkofel Formation (Artinskian/Kungurian) in the Carnic Alps (Southern Alps) is described. The *locus typicus* is mount Trogkofel, where a succession up to ~500 m thick of reefal to peri-reefal limestones is exposed. In the pedestal of mount Trogkofel, a succession of shelf limestones (Zottachkopf Formation) is sharply overlain by the unbedded Trogkofel Formation. Farther north, at Zweikofel, the boundary between a package of shelf limestones (Zweikofel Formation), and the overlying, clino-bedded Trogkofel Formation is a disconformity. Deposition of the Trogkofel Formation started after a backstep from shelf deposition (Zottachkopf and Zweikofel Formations) to a carbonate shelf-margin setting with buildups. The backstep was associated with tectonism.

The lower to middle part of the Trogkofel type section is characterized by patch buildups grown in a foreslope to uppermost slope setting. Main buildup facies includes *Tubiphytes*-bryozoan-algal-cement boundstones, botryoidal-fibrous cementstones with *Archaeolithoporella*, and phylloid-algal bafflestones. The buildups are intercalated with intervals up to 10-15 m thick of bioclastic limestones. The upper ~100 m of the type section consist primarily of bioclastic grainstones rich in fusulinid tests and fragments of calcareous green algae; the bioclastic grainstone intervals episodically aggraded at least to near sea-level. The upper part of the section may result from (i) a shoaling because of moderate progradation-aggradation of the platform, or because of eustatic or tectonic sea-level lowering, and/or (ii) changed patterns of offbank sediment dispersal. In the Trogkofel Formation, soft-sediment to brittle deformation features record syn- to early post-depositional tectonism. Within paleokarstic caverns, 'intra-seismites' are represented by discrete, stacked packages of internal sediments with convolute lamination and/or intrabrecciation.

Deposition of the Trogkofel Formation was terminated by uplift and subaerial truncation. Karstic caverns filled with geopetally-laminated lime mudstones to wackestones (typically dolomitized), and with caymanitic layers, reach to the base of the formation. Syndepositional deformation, and the uplift that terminated deposition of the Trogkofel Formation, may be related to the 'Saalian tectonic phase'. The truncation surface that caps the Trogkofel Formation is onlapped by carbonate-lithic breccias (Tarvis Breccia) that, on mount Trogkofel, probably accumulated from hillslope colluvium. The entire Tarvis Breccia and the upper part of the Trogkofel Formation are replaced by epigenetic dolomite. Down-section, dolomitization is tied to fractures and adjacent host rock, and to paleokarstic cavities and their vicinity. Dolomitization tapers out towards the base of the formation. Late-stage fractures and dissolution pores are filled with saddle dolomite.

In dieser Arbeit wird das Typus-Profil der Trogkofel-Formation (Artinskium/Kungurium) in den Karnischen Alpen (Südalpen) beschrieben. Am *locus typicus*, dem Trogkofel, ist eine bis etwa 500 m mächtige Abfolge aus Riff- und Peri-Riffkalken aufgeschlossen. Am Fuße des Trogkofels wird eine Abfolge aus Schelfkarbonaten (Zottachkopf-Formation) mit scharfer Grenze vom ungebankten Trogkofelkalk überlagert. Weiter nördlich am Zweikofel ist die Grenze zwischen Kalken eines flachneritischen Schelf-Milieus (Zweikofel-Formation) und der aufliegenden, klinoform-geschichteten Trogkofel-Formation als Diskonformität ausgebildet. Die Ablagerung der Trogkofel-Formation setzte nach einem tektonisch mitbedingten Rückschreiten von flachneritischer Schelfablagerung (Zottachkopf- und Zweikofel-Formationen) zu einem karbonat-dominierten Schelfrand-Bereich mit Riffbildungen ein.

Der untere und mittlere Teil des Trogkofel Typ-Profils ist durch Flecken-Riffe eines 'foreslope' bis oberen Abhang-Milieus charakterisiert. Die Hauptfazies der Riffbildung beinhaltet *Tubiphytes*-Bryozoen-Algen-Zement boundstones, botryoidal-fibröse cementstones mit *Archaeolithoporella*, und bafflestones aus phylloiden Algen. Die Riffe wechsellagern mit Intervallen aus bioklastischen Kalken von bis zu 10-15 m Dicke. Die oberen ~ 100 m des Typ-Profils bestehen vorwiegend aus bioklastischen grainstones mit zahlreichen Fusulinengehäusen und Bruchstücken von Kalkgrünalgen; die Intervalle aus bioklastischen grainstones aggradierten immer wieder bis mindestens knapp unter den Meeresspiegel. Der obere Teil des Profils entstand wahrscheinlich durch (i) Verflachung aufgrund moderater Progradation-Aggradation der Plattform oder eustatische/tektonische Meeresspiegel-Absenkung, und/oder (ii) durch eine Änderung im Muster des ablandigen Sedimenttransports. Die Trogkofel-Formation führt ein Inventar an synsedimentär bis früh postsedimentär gebildetenn Strukturen, die Verformung vom Weichsediment bis hin zu Fraktur beinhalten. Sediment-Füllungen von Paläokarst-Höhlen im Trogkofelkalk zeigen örtlich mehrere Generationen von 'Intra-Seismiten' in Form vertikal gestapelter Pakete mit Wickelschichtung und/oder Intern-Brekziierung. Die Ablagerung der Trogkofel-Formation wurde

durch Hebung und subaerische Trunkation beendet. Paläokarst-Hohlräume, die mit geopetal laminierten – meist dolomitisierten – Lime Mudstones bis Wackestones und mit caymanitischen Lagen gefüllt sind, reichen bis an die Basis der Trogkofel-Formation hinab. Die synsedimentäre Verformung sowie die Hebung, die zur subaerischen Trunkation führte, könnten mit der „Saalischen tektonischen Phase" zusammenhängen. Die Trunkationsfläche am Dach der Trogkofel-Formation wird von karbonatlithischen Brekzien (Tarviser Brekzie) überlagert, die am Trogkofel wahrscheinlich aus Hangkolluvium hervorgingen.

Die gesamte Tarviser Breccie und der obere Teil der Trogkofel-Formation ist durch epigenetischen Dolomit ersetzt. Zum Liegenden hin ist die Dolomitisierung an Frakturen und deren angrenzendes Nebengestein, sowie an Füllungen von Paläokarst-Hohlräumen und deren nähere Umgebung gebunden. Gegen die Basis der Formation hin läuft die Dolomitisierung aus. Später gebildete Frakturen und Lösungsporositäten sind mit Satteldolomit gefüllt.

1. Introduction

After the Late Devonian extinction of coral-stromatoporoid reefs, buildups composed of newly-emerged reefal organisms slowly re-established during the Carboniferous. Aside from calcimicrobes, Permo-Carboniferous mounds to low-relief reefs were characterized by comparatively small organisms such as calcareous algae, calcisponges, bryozoans, and sessile foraminifera. According to Fagerstrom (1987), most Late Paleozoic reefs are composed of boundstone and bafflestone due to the abundance of algae which acted as binders and bafflers. The only metazoans that were important reef-building organisms were porifera, bryozoans and brachiopods (Fagerstrom, 1987). Whereas Early Permian mounds were do-

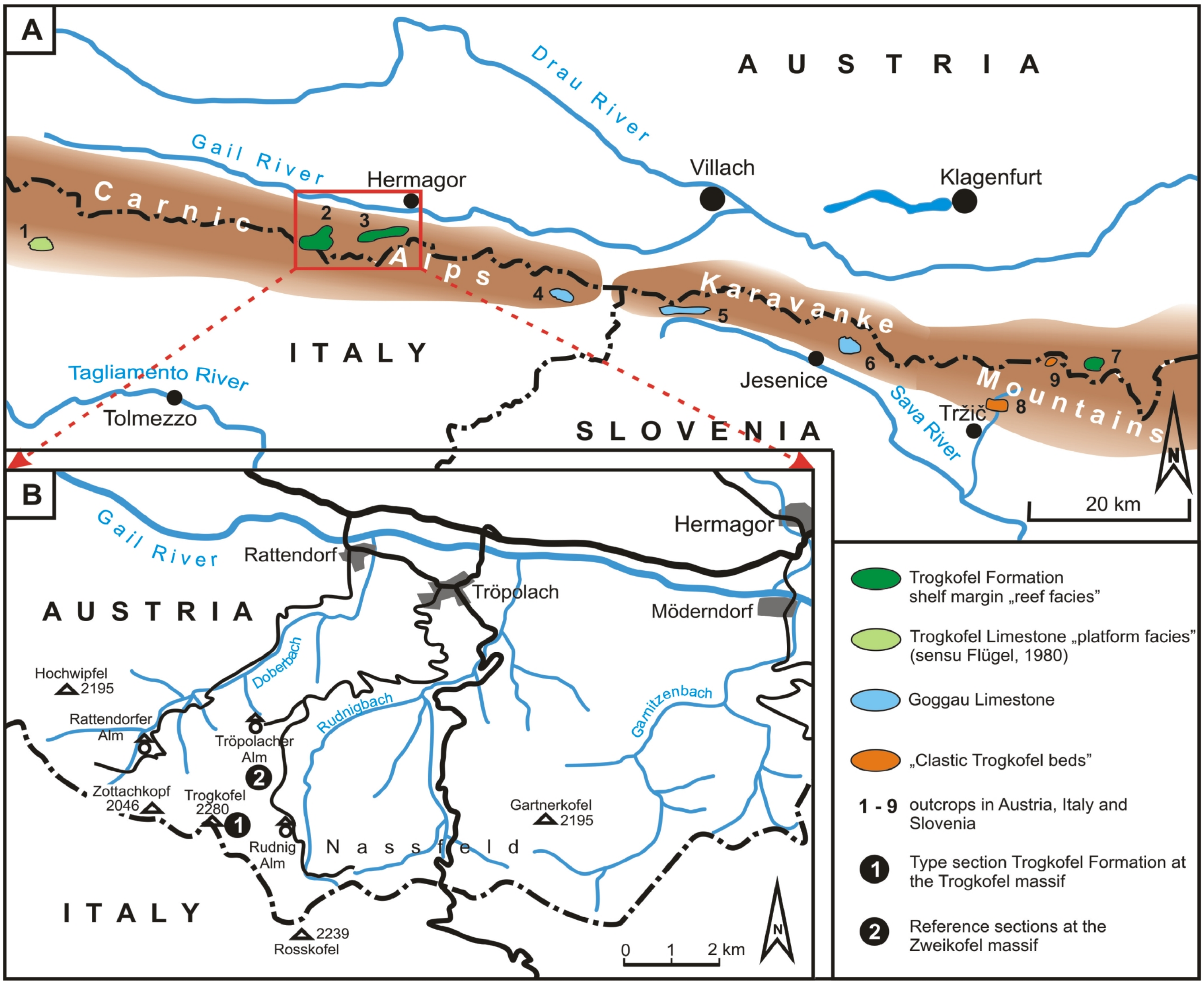


Figure 1: A: Map of the Carnic Alps and Karavanke Mountains in the border regions of Austria-Italy-Slovenia. The investigated area at the Trogkofel (marked with 2 in the red rectangle) is located in the Carnic Alps. Numbers 1- 9 show outcrops in the Carnic Alps and the Karavanke Mountains where "Trogkofel Limestone", "Goggau Limestone" or "clastic Trogkofel beds" are exposed. 1: Forni Avoltri, 2: Trogkofel-Zottachkopf massif, 3: Zweikofel – Granitzenbach area, 4: Coccau/Tarvisio, 5: Kranjska Gora, 6: Javorniski Rovt, 7: Trögern, 8: Dovzanova Soteska (Teufelsschlucht), 9: south of Kosuta mountain. B: Location of the study area. 1: Type section of the Trogkofel Formation at the Trogkofel, 2: Reference sections in the Zweikofel massif.

minated by calcareous algae, rugose corals and brachiopods prevailed in Middle to Upper Permian reefs (Wahlman, 2002; Weidlich, 2002a).

Variations in reef forming biota were controlled by temperature, depth and chemistry of sea water, respectively (e.g. Stanley and Hardie, 1998; Stanley, 2006; Blättler et al., 2012). Deglaciation of Gondwana (Isbell et al., 2003; Fielding et al., 2008; Montañez and Poulsen, 2013) and the change from cold to warm global climate (Isbell et al., 2003; Korte et al., 2008)

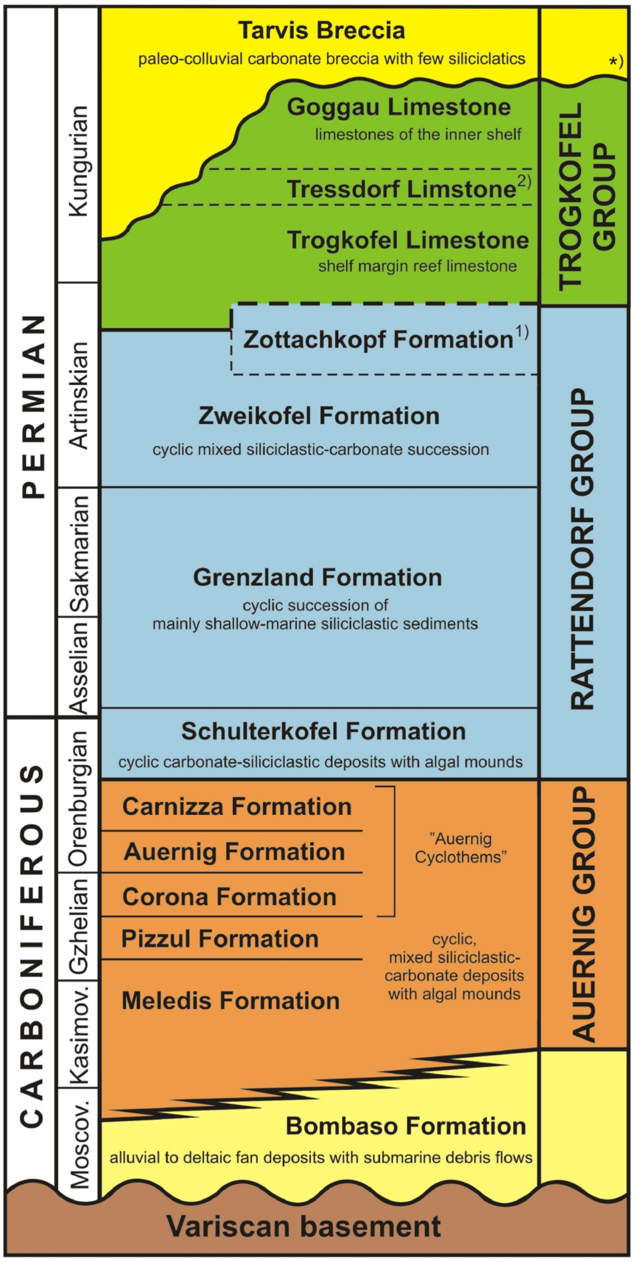


Figure 2: Lithostratigraphic chart of the post-Variscan succession (Carboniferous – Lower Permian) of the Carnic Alps. The Variscan Basement consists of Devonian limestones, cherts and Carboniferous flysch-type sediments; 1) well-bedded succession of mainly shallow neritic limestones, algal mounds and red silty carbonates; 2) polymict carbonate stylobreccia; *) hiatus of unknown duration between Trogkofel Limestone and Goggau Limestone and the overlying Tarvis Breccia. Modified after Krainer and Davydov (1998), Schönlaub and Forke (2007), Schaffhauser et al. (2010), and Davydov et al. (2013).

stimulated reef growth and culminated in a Late Permian reef acme that was terminated by the Permian/Triassic mass extinction (e.g. Hallam and Wignall, 1997; Weidlich, 2002b; Joachimski et al., 2012).

In western and central Europe, Lower Permian neritic carbonate successions are confined to the Southern Alps. These deposits accumulated at low latitude at the northwestern margin of the Paleotethys. Today, Lower Permian shallow-water carbonate rocks are preserved in an array of fault-bounded terrains in the Carnic Alps and in the Karavanke Mountains. In the Trogkofel-Zweikofel massif of the central Carnic Alps, reefal to peri-reefal carbonate rocks – termed Trogkofel Limestone – are very well preserved and excellently exposed. The Trogkofel Limestone is a well-known lithologic unit for more than 100 years that was studied by several authors, mainly by sampling of scree (e.g. Buggisch and Flügel, 1980; Flügel, 1980a, 1981). To date, however, the Trogkofel Limestone was not investigated by in-situ field documentation and sampling at its 'classic' type locality, and no type section was presented before. In this paper, we formally raise the Trogkofel Limestone to formation rank, define a type section at the type locality Trogkofel, describe the facies and fossil content, and discuss the age of the Trogkofel Formation following the recommendations of Steininger and Piller (1999) for the Austrian National Stratigraphic Code.

2. Study area and geological setting

We studied the Trogkofel Limestone at mount Trogkofel in the Carnic Alps. The summit of Trogkofel (2280 m a.s.l.) is located at the Austrian/Italian border west of Nassfeld Pass (Fig. 1A). Mount Trogkofel provides the type locality of the Trogkofel Formation (Fig. 1B).

The Carnic Alps are part of the Southern Alps that are separated by the dextral Gailtal fault zone from the Eastern Alps adjacent to the North. In the Carnic Alps, Variscan orogeny (Serpukhovian to Moscovian) resulted in epi- to anchimetamorphic overprint of sedimentary successions. The Variscan basement (Devonian limestones and cherts, or Lower Carboniferous flysch-type sediments of the Hochwipfel Formation) (Fig. 2) (Läufer et al., 2001; Brime et al., 2008; Krainer and Vachard, 2014) is unconformably overlain by a non-metamorphic Carboniferous to Triassic succession. Sedimentation of the preserved post-Variscan record started during late Moscovian to early Kasimovian time (Kahler 1983; 1985; Davydov and Krainer, 1999; Schönlaub and Forke, 2007). The post-Variscan successions – locally up to 2000 m in thickness – accumulated in three narrow transtensional basins mainly oriented WNW-ESE and NE-SW; towards the SE, these basins opened into the wider Paleotethys (Venturini, 1991; Massari et al., 1991; Schönlaub and Forke, 2007). Transtension was related to a dextral Pangean mega-shear zone (Arthaud and Matte, 1977; Vai, 2003), and was accompanied by a thermal event in the middle Permian (Schuster and Stüwe, 2008).

The Trogkofel Limestone is one of the most distinctive lithologic units in the central Carnic Alps; it comprises the topmost unit of the prevalently shallow-marine and partly cyclothemic post-Variscan succession. This post-Variscan succession includes the Bombaso Formation (Collendiaul Formation and Malinfier Formation in Schönlaub and Forke, 2007), the Auernig Group (Auernig Formation of Schönlaub and Forke, 2007), the Rattendorf Group, and the Trogkofel Limestone (Krainer and Davydov, 1998; Vachard and Krainer, 2001; summary in Schönlaub and Forke, 2007 with references therein).

3. Historical background

In the Carnic Alps, geological investigations started with von Buch (1824). Early researchers distinguished between: (i) Paleozoic deposits, synonymously termed "Gailtaler Schichten", "Kohlenkalk", "Kohlenschiefer" (Foetterle, 1855, 1856; Peters, 1855) or "Kohlenformation" (Stur, 1856), and (ii) Triassic sediments. The discovery of graptolites (Unger, 1869; Stache, 1872a) and fusulinids (Suess, 1870; Tietze, 1870; Stache, 1872a, 1872b, 1873) resulted in a refined stratigraphy of the Paleozoic succession (Stache, 1874). The fusulinids were correlated with faunas of similar successions in North America and Russia (Suess, 1870).

Stache (1888) dated unbedded limestones near Goggau/Coccau – Tarvisio as Permian, based on fusulinids and the brachiopod *Productus flemmingi* (SOWERBY). These limestones were later termed Trogkofelkalk and finally renamed as Goggauer Kalk (Goggau Limestone) by Kahler (1971, 1974) based on a fusulinid fauna which differs from that of the Trogkofel Limestone.

The unbedded limestone which forms the Trogkofel massif was assumed to be of Triassic age by Frech (1894). Based on the discovery of fusulinids, Geyer (1895) recognized a Permian age of the white and red „Fusulinenkalk" (fusulinid limestone) at Trogkofel. One year later, he stated that in the Trogkofel massif the unbedded Fusulinenkalk (=Trogkofel Limestone, see summary in Table 1) rests on the dark, bedded „Oberer Schwagerinenkalk" (upper *Schwagerina* limestone). The term „Trogkofelkalk" (Trogkofel Limestone) was introduced by Geyer (1898) with its type locality at Trogkofel. Schellwien (1898a) described fusulinids from reddish limestone at Trogkofel which he named „obere Trogkofelschichten" (upper Trogkofel beds) which are synonymous with Trogkofelkalk (Trogkofel Limestone).

Gortani (1902, 1903, 1906) reported the occurrence of Trogkofel Limestone from Col Mezzodi near Forni Avoltri (Italy).

Lithostratigraphic Name	Geographic distribution	Author
Trogkofelkalk (Trogkofel Limestone)	Trogkofel area, Gartnerkofel area, Goggau (Coccau)	Geyer (1895, 1896, 1903)
Trogkofelschichten (Trogkofel beds)	Trogkofel area, Teufelsschlucht/Neumarktl (Dovzanova Soteska, Slovenia)	Schellwien (1900)
Trogkofelkalk (Trogkofel Limestone)	Forni Avoltri (Italy)	Gortani (1906)
	Karavanke Mountains	Teller (1910)
Trogkofel Kalk weisser Trogkofelkalk (white Trogkofel Lmst) rosaroter Trogkofelkalk (pink Trogkofel Lmst) roter Trogkofelkalk (red Trogkofel Lmst)	Trogkofel area, Gartnerkofel area, Zottachkopf, Zweikofel area, Faak am See, Forni Avoltri, Coccau, Teufelsschlucht/Neumarktl (Dovzanova Soteska, Slovenia), Veldes and Wocheiner Vellach (Slovenia)	Heritsch (1933b, 1936,1943)
Roter Trogkofel Kalk (red Trogkofel Limestone of Höhe 2004)	Troghöhe	Kahler and Kahler (1938)
Klastische Trogkofel Schichten (Clastic Trogkofel beds)	Karavanke Mountains	Ramovs (1963)
Tressdorfer Kalk (Tressdorf Limestone)	Tressdorfer Alm	Homann (1969)
Goggauer Kalk (Goggau Limestone)	Coccau (Italy)	Kahler (1974)
Trogkofel Schichten: Trogkofel Kalk Tressdorfer Kalk Goggauer Kalk Tarviser Brekzie	 Forni Avoltri, Trogkofel area, Reppwand, Gartnerkofel area, Garnitzen Gorge Tressdorfer Alm Coccau area (Italy)	Flügel (1980b), Buggisch and Flügel (1980)
Trogkofel Formation	Trogkofel mountain	Flügel (1981), this study

Table 1: Historic evolution of the term "Trogkofel Limestone"

In the Karavanke Mountains Schellwien (1898a, b, c, 1900) described a rich fauna from the Trogkofelkalk (Trogkofel Limestone) at Teufelsschlucht/Dovzanova Soteska near Neumarktl/Trcic (Slovenia). This fauna contains foraminifers, gastropods, bivalves, corals, ammonites and abundant brachiopods which were revised by Heritsch (1938), see also Heritsch (1943). The Trogkofelkalk of Teufelsschlucht was studied in detail by Forke (2002) and Novak (2007a, b), who assigned the succession to the Dovzanova Soteska Formation which is dated as middle to late Asselian (summary in Novak and Skaberne, 2009). Trogkofelkalk was reported also from other localities in the Karavanke Mountains by Teller (1910) and Novak and Forke (2005, 2006) (see summary in Novak and Skaberne, 2009, for the Slovenian area of the Karavanke Mountains).

Heritsch (1940) proposed the term „Trogkofelstufe" (Trogkofel Stage) for the time span during which the Trogkofel Limestone was deposited. During the 1930s, biostratigraphy based on brachiopods and ammonoids was replaced by a more precise biochronostratigraphy with fusulinids, clearly indicating a Permian age of the Trogkofel Limestone (Kahler, 1934a, b; Kahler and Kahler, 1937, 1938, 1941).

After Kahler (1980), the Trogkofel Stage includes the Trogkofel Limestone, Treßdorf Limestone, Goggau Limestone and Tarvis Breccia. According to Kahler (1980), the Trogkofel Stage encompasses the Sakmarian (Trogkofel Limestone), Artinskian (Treßdorf and Goggau Limestone) and Cisjanskian (Tarvis Breccia).

In the Carnic Alps, Homann (1969) introduced the term Treßdorfer Kalk (Treßdorf Limestone) for a polymict limestone breccia which is exposed near Treßdorfer Alm NW of Nassfeld. The Treßdorf Limestone is either interpreted as a time-equivalent of the Trogkofel Limestone developed with a different facies (Flügel, 1968) or is assumed to rest on the Trogkofel Limestone and is interpreted as a lateral equivalent of the Goggau Limestone. Fusulinids indicate an Artinskian age (Kahler, 1973; see Schönlaub, 2014).

The last comprehensive study of the Trogkofel Limestone was published by Flügel (1980b, 1981) and includes data on the geographic distribution (Buggisch and Flügel, 1980), microfacies (Flügel, 1980a), geochemistry (Buggisch, 1980), calcareous algae (Flügel and Flügel-Kahler, 1980), fusulinids of the Trogkofel Limestone (Kahler and Kahler, 1980) and definition of the Trogkofel Stage (Kahler, 1980). Most of the samples studied by these authors are derived from the section at Forni Avoltri, from clasts of Trogkofel Limestone within the Tarvis Breccia near Sexten–Kreuzbergpass, from the Gartnerkofel-Reppwand area, and from Goggau–Tarvisio. Only a few samples were taken from the Trogkofel Limestone at the type locality (Trogkofel). For the limestones of the Trogkofel-Gartnerkofel area, Flügel (1980a) suggested a shelf marginal reef development. The reef was formed by *Tubiphytes-Archaeolithoporella* boundstones and marine cements (Flügel, 1981). According to Kahler and Kahler (1980), the Trogkofel Limestone at the type locality did not yield any determinable fusulinids, all the fusulinids he described from the Trogkofel Limestone are from other locations, mainly from Forni Avoltri and Goggau.

In the Stratigraphic Chart of Austria (2004), the invalid term „Trogkofelkalk" is still used, underlain by and laterally interfingering with the „Obere Pseudoschwagerinen-Formation"; the latter is another invalid unit that was formally renamed as Zweikofel Formation by Krainer (1995).

A type section of the Trogkofelkalk has never been presented. In the description of the lithostratigraphic units of the Austrian Stratigraphic Chart 2004,

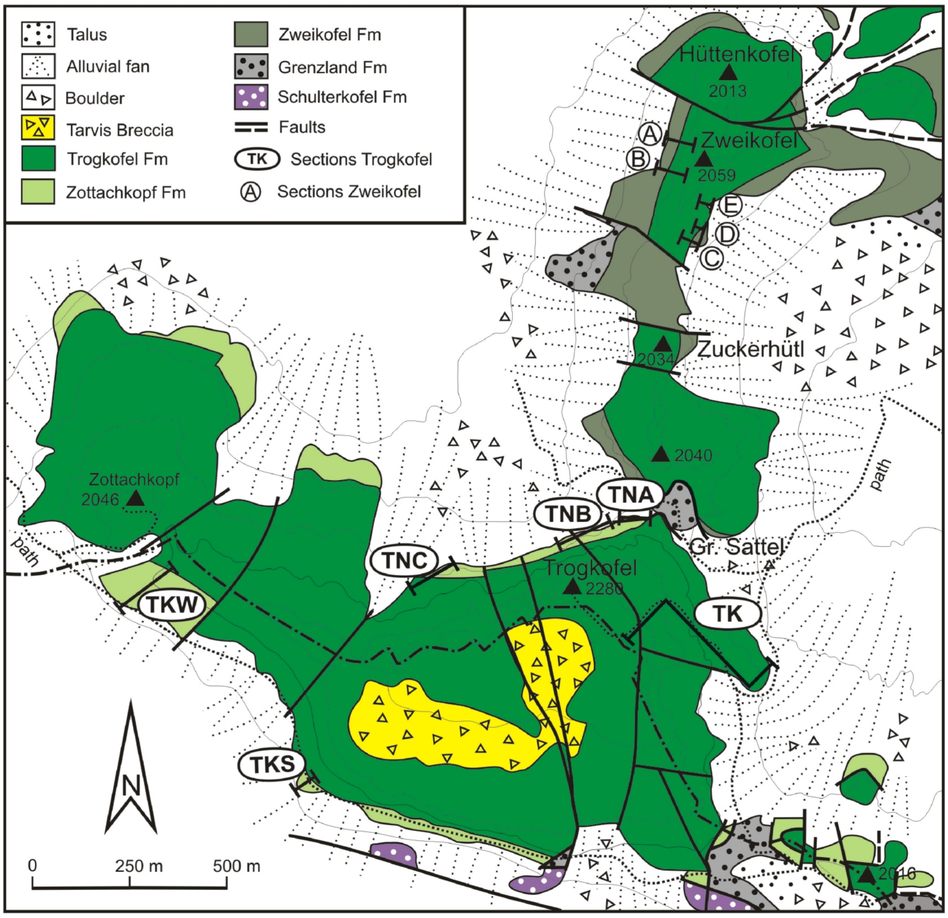
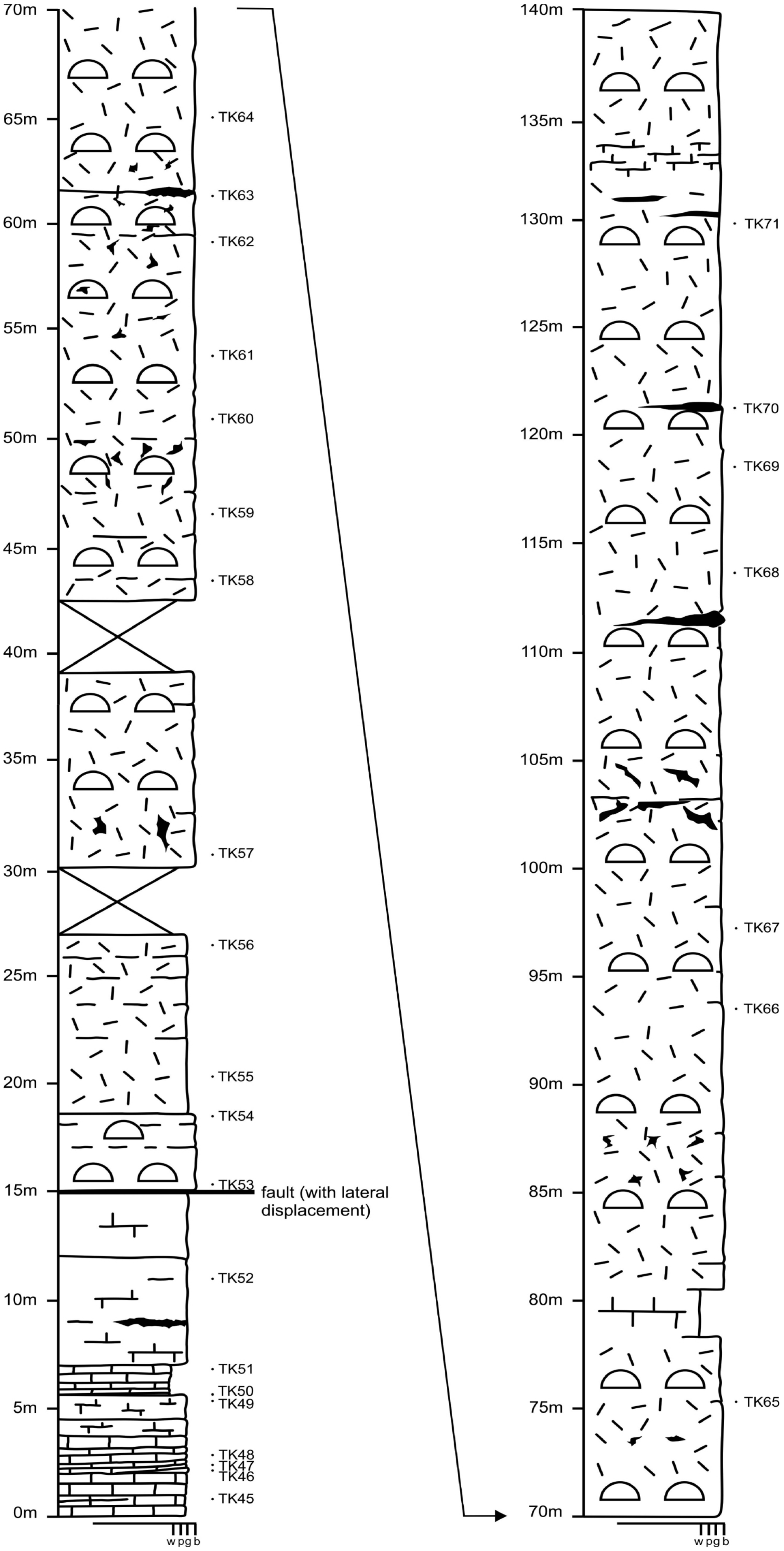


Figure 3: Geologic map of the Trogkofel–Zweikofel area, showing the positions of the type section (TK, TNC) and reference sections (A-E). Additionally, sections TKW and TKS represent the transition between the Zottachkopf Formation and the Trogkofel Formation. Section TNA and TNB were measured in the Zottachkopf Formation.



the Trogkofelkalk is described as *„mainly composed of massive, light-colored, partly reddish carbonates. Large parts correspond to a Tubiphytes/Archaeolithoporella-cement boundstone"* (Schönlaub, 2014, p. 87; see also Kahler in Kühn, 1962, p 483-484). The Trogkofel Limestone is dated as Late Artinskian (see also Schönlaub and Forke, 2007).

In the Italian literature, the Zweikofel Formation (Obere Pseudoschwagerinen-Formation) is named Formazione superiore a *Pseudoschwagerina* (Selli, 1963a; Venturini, 1990a, b), the Trogkofel Limestone is named Calcare del Trogkofel (Venturini, 1990a, b) or Formazione del Trogkofel (Selli, 1963a), and the overlying Tarvis Breccia is designated as Breccia di Tarvisio (Venturini, 1990a, b) or Breccia a cemento rosso di Tarvisio (Selli, 1963a).

4. Methods and samples

The Trogkofel Limestone was studied from field to thin section. Stratigraphic type sections were logged along the toes of cliffs and along trails through the cliffs of mount Trogkofel (type section TK and TNC; TNA, TNB, TKS, TKW; locations see Fig. 3). Another section was studied at Garnitzenbach stream. Rock specimens were collected from all measured sections for microfacies and geochemical analyses. To document facies inventory, a few samples were additionally handpicked from scree slopes. Approximately 250 thin sections (5 x 8 cm in size) were prepared for microfacies analyses. The classification schemes of Dunham (1962), Embry and Klovan (1971) and Wright (1992) were applied. Dolomite rock textures were designated

Figure 4: Basal part of the stratotype of the Trogkofel Formation (informal "lower member").

according to the classification of Sibley and Gregg (1987). Microfacies types were established according to Wilson (1975) and Flügel (2004).

5. Lithostratigraphic unit

The name Trogkofel refers to the most prominent outcrops of the Trogkofel Limestone at the mount Trogkofel (Creta di Aip) in the Carnic Alps, located at the Austrian – Italian border, west of Nassfeld Pass (Figs. 1B, 3).

5.1 Stratotype

The stratotype of the Trogkofel Formation is formed by a combination of two lithologic intervals (composite stratotype). Section TK is defined as the holostratotype that represents the characteristic features within the lithostratigraphic unit (Figs. 4, 5). Section TNC, in turn, is designated as a parastratotype to illustrate the boundary between the Trogkofel Formation and the underlying Zottachkopf Formation (Fig. 6).

Section TK was measured at the east-facing cliff of the Trogkofel along the trail ("Überlacher Steig") to Trogkofel summit (Fig. 3). The coordinates at the base of the holostratotype section are: 46° 34′ 11″N/13° 13′ 22″E. Section TNC was measured along the steep wall on the northern side of Trogkofel (see Figs. 3, 7). The coordinates at the base of ‚section TNC are: 46° 34′ 18″N/13° 12′ 55″. The geographic position of holostratotype and parastratotype are both located in the Austrian Map (ÖK), sheet 198 (Weissbriach), scale 1:50.000.

5.2 Reference Sections

Reference sections of the Trogkofel Formation are located on the eastern and western sides of the Zweikofel (Fig. 3) and their geographic positions can be found on the Austrian Map, sheet 198 (Weissbriach), scale: 1:50.000. At Zweikofel, the Trogkofel Formation rests on the Zweikofel Formation with a disconformable contact; the Zottachkopf Formation is absent, probably due to erosion. The Trogkofel Formation consists of a lower interval 40 m in thickness composed of bioclastic limestones, microbial boundstones and carbonate-lithic rudites. This lower interval is followed up-section by a proximal-basinal facies composed of argillaceous mudstones with intercalated beds of carbonate-lithic arenites to rudites. This basinal facies is overlain by approximately 50 m of faintly clinobedded Trogkofel Limestone composed of bioclastic limestones and *Archaeolithoporella-Tubiphytes*-cementstones (details in Krainer et al., 2009). A comparison of the Trogkofel Formation at the type locality and the reference sections at Zweikofel is shown in Table 2.

5.3 Description of type section

5.3.1 Lower boundary

In the north-facing cliff of mount Trogkofel, the unbedded

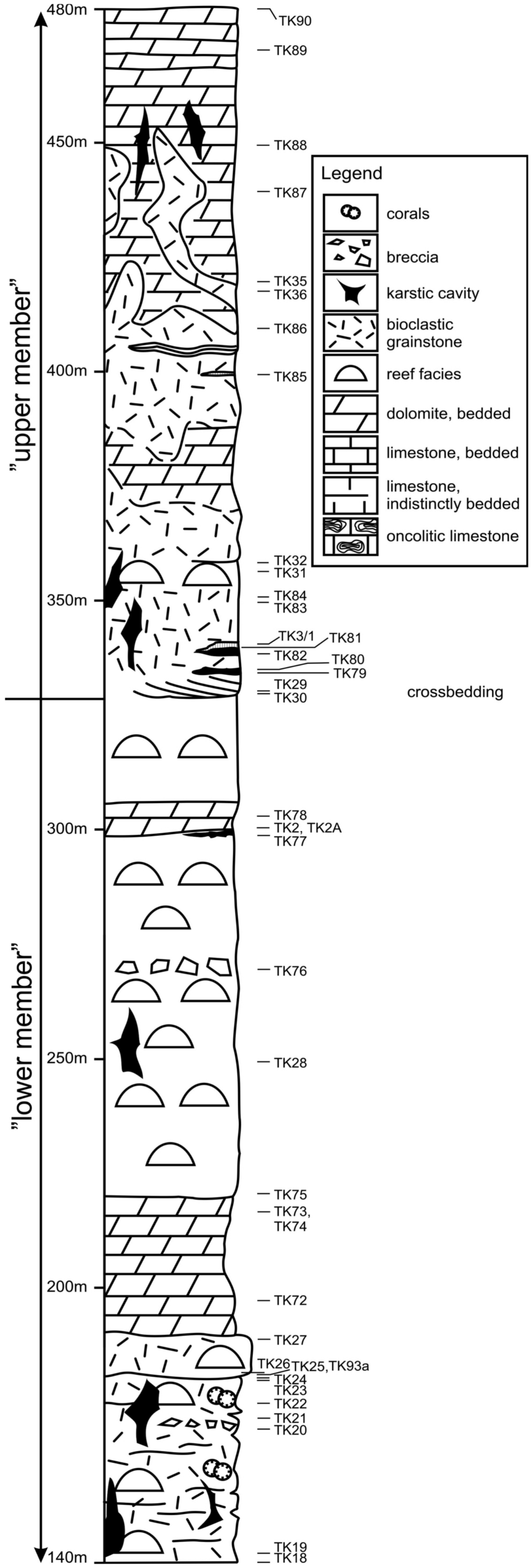


Figure 5: Continuation of the stratotype section (middle and upper part) to the Trogkofel summit.

limestone of the Trogkofel Formation sharply but conformably overlies the well-bedded limestone succession of the Zottachkopf Formation (Fig. 7). Section TNC which is proposed as parastratotype, exhibits the lower boundary between the Trogkofel Formation and the underlying Zottachkopf Formation. A sequence of red, medium-bedded bioclastic wacke- to packstones, locally rich in oncoids, represents the upper part of the Zottachkopf Formation. The boundary to the overlying Trogkofel Formation is placed on top of this red bedded limestone succession. A layer, a few centimeters thick of red mudstone marks the boundary to the overlying unbeddded Trogkofel Formation. The lowermost part of the unbedded Trogkofel Limestone is an oncolitic limestone approximately 20 cm thick, overlain by a *Tubiphytes*-bryozoan-*Archaeolithoporella* boundstone; the latter represents the typical facies of the unbedded Trogkofel Formation.

At the southern flank of mount Trogkofel, the boundary between the well-bedded succession of the Zottachkopf Formation and the medium- to thick-bedded limestones of the Trogkofel Formation is not as sharp as in the northern cliff (section TKS, Fig. 3). The boundary was placed into the upper part of the bedded succession; there, a change in facies to prevalence of boundstones indicates the base of the Trogkofel Formation.

Trogkofel Formation		
Features	**Trogkofel (type section)**	**Zweikofel (reference section)**
Thickness	Approximately 500 m (type section), ~200 m (in the south) and 300 m (in the north)	Approximately 110 m
Underlying strata	Zottachkopf Formation	Zweikofel Formation
Lower boundary	Concordant with Zottachkopf Formation; sharp lithologic contact (paraconformity?)	Disconformity
Lithologic subdivisions and characteristics	<u>“Lower member“:</u> Gray and red, unbedded (TK-north) and indistinctly bedded limestones (TK-south) in its basal part; up-section, unbedded limestones with intercalations of bedded limestones <u>”Upper member“:</u> limestones with indistinct bedding and cross-stratification in the lower part; medium-bedded, dolomitized limestones in topmost part	<u>‘Lower Trogkofel interval’ (LTI):</u> not stratified limestone with intercalated carbonate breccias (internal and sedimentary breccias), locally basal breccias; limonitic crust on top <u>‘Basinal interval’ (BI):</u> Mudstones with intercalated beds of breccias composed of boulder- to sand-sized grains <u>‘Upper Trogkofel Interval’ (UPI):</u> reefal limestones with clinobeds dipping towards NNE to N
Sedimentary facies	<u>”Lower member” (reefal facies):</u> *Tubiphytes*-bryozoan-algal–boundstones associated with microbial carbonates and *Tubiphytes*-bryozoan-cementstones, phylloid algal bafflestones; intercalations of bioclastic grainstones <u>“Upper member” (sand shoal facies):</u> bioclastic grainstones with intercalations of laminated bindstones	<u>LTI:</u> unbedded succession of microbial boundstones, bioclastic pack/grainstones and bioturbated wacke/pack/grainstones; sedimentary breccias composed of litho-bioclastic rud- to floatstones; lithoclasts of shallow-neritic limestone with facies known from Zweikofel Formation; internal breccias: poorly sorted, angular boulders to sand-sized grains, lithoclasts with facies of adjacent limestones, matrix: yellow or light red dolostones <u>BI:</u> argillaceous mudstones to marly mud/wackestones; clast- to matrix supported breccias, lithoclasts mainly of *Archaeolithoporella-Tubiphytes*-cementstones (Trogkofel Limestone) <u>UPI:</u> reefal *Archaeolithoporella-Tubiphytes*-bryozoans-cementstones; bioclastic grainstones rich in fusulinids, benthic foraminifera
Upper boundary	Truncation surface	Eroded
Overlying strata	Tarvis Breccia	Eroded

Table 2: Comparative characteristics of the Trogkofel Formation at the type locality (Trogkofel) and at Zweikofel.

At the southwestern side of Trogkofel, the boundary to the Trogkofel Formation was observed on top of a thin-bedded, dark gray limestone succession of the Zottachkopf Formation (section TKW, Fig. 3). The basal part of the Trogkofel Formation is represented by an interval approximately 10 – 20 m in thickness of thick- to medium-bedded limestones, overlain by unbedded 'reef' limestone.

5.3.2 Thickness and lithology of the Trogkofel Formation

Due to erosional truncation prior to deposition of the Tarvis Breccia, in the type area, the thickness of the Trogkofel Formation varies laterally from nearly 500 m at the northeastern edge of the massif to approximately 300 m exposed in the north-facing cliff, and to 200 m along the southern side.

The Trogkofel Formation consists of gray and pink limestones. At the type locality, two members of the Trogkofel Formation are suggested: a) "lower member" representing the reef facies and b) "upper member" characterized by the bedded sand shoal facies (Fig. 5). Here, we use the term reef following the definition of James and Wood (2010).

The "lower member" is characterized by unbedded limestone (in the north-facing cliff) or faintly-bedded limestone (in the south-facing cliff) at its base, overlain by unbedded limestone. Locally, bedded grainstones are intercalated within the mainly unbedded limestone near the base base of the type section. The *Tubiphytes*-bryozoan-*Archaeolithoporella*-boundstone facies is closely associated with cementstones of calcified bo-

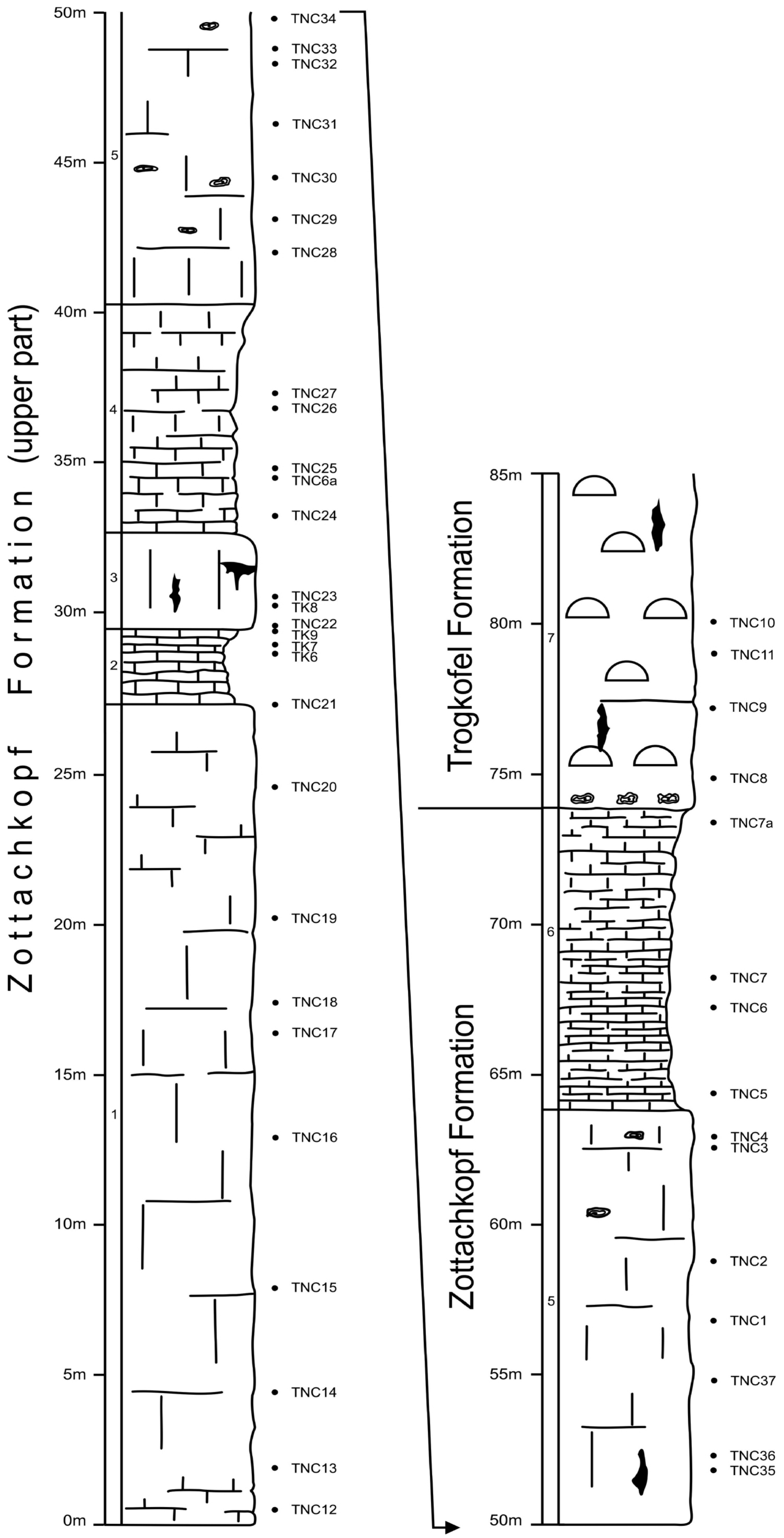


Figure 6: Section TNC, basal part of the type section.

tryoids formerly composed of fibrous marine cements, and cement crusts. Additionally, the boundstones contain a variable amount of constructors like phylloid algae and calcareous sponges. Locally, stromatactoid pores are present.

The "upper member" is composed of faintly bedded limestones with local cross-stratification, vertically passing into bedded epigenetic dolostones near Trogkofel summit. Bioclastic grainstones, rich in fusulinids and calcareous green algae, dominate the "upper member". Locally, fenestral microbialites formed by *Girvanella* and other microbial fabrics of presumed cyanobacterial affinity are intercalated. This facies is known from rockfall boulders spalled off the cliffs. In the bedded succession at Trogkofel summit, epigenetic dolomitization had overprinted and partly obliterated primary depositional features of former limestones.

At Trogkofel, the entire Formation down to the upper part of the Zottachkopf Formation is riddled with paleokarstic dikes and cavities that range in size from caverns to vugs. The paleokarstic cavities are variably filled with internal breccias, geopetally-laminted silty to argillaceous red lime mudstones (commonly dolomitized), and cements. Paleokarst features in the Trogkofel massif were described by Schönlaub and Forke (2007).

Both, the Tarvis Breccia and the topmost ~50 m of the Trogkofel Formation are pervasively dolomitized. Down-section, dolomitization is confined to the fillings of paleokarstic cavities (dikes, caverns and vugs) and to haloes adjacent to the cavities. In the lower part of the Trogkofel Formation, dolomitization is confined to local, selective replacement of bioclasts and micritic limestones. The downward tapering of dolomitization and the association of epigenetic dolomite with paleokarstic cavities suggests that the dolomitizing fluids descended downward into the succession.

5.3.3 Upper boundary

The upper boundary of the Trogkofel Formation is a truncation surface with a distinct paleorelief, overlain by the Tarvis Breccia. Approximately 100 m south of Trogkofel summit the unconformity between the Trogkofel Formation and the Tarvis Breccia is well exposed (Fig. 8). The Tarvis Breccia consists of stacked, thick-bedded, clast-supported and rarely matrix-supported carbonate-lithic breccias. Both, the Tarvis Breccia and the upper part of the Trogkofel Formation are dolomitized.

5.4 Type area

The Carnic Alps are the geographic area with the stratotype of the Trogkofel Formation. The type section is located on mount Trogkofel, but Trogkofel Formation is also exposed in the Zweikofel massif and in the Gartnerkofel–Reppwand–Garnitzenbach area. Additionally, Trogkofel Formation is exposed in the Austrian and Slovenian part of the Karavanke Mountains. Geological maps of the type area were edited by Selli (1963b), Geological Survey of Austria sheet 198 (1987), Venturini (1990c), and Schönlaub (2006).

6. Lithologies and diagenesis

At the type locality, the Trogkofel Formation shows eight lithologies (Tab. 3) and corresponding facies groups.

(1) *Bioclastic limestones*: These are typically unbedded and consist of moderately to poorly sorted rud-/grain-/packstones that may contain interstitial fillings of micropeloidal matrix (Tab. 3, Fig. 9A). Bioclastic limestones of the 'upper member' are either unbedded or poorly-bedded, or faintly cross-bedded. Most common bioclasts include *Tubiphytes*, crinoids, bryozoans, calcareous algae, calcisponges, and benthic foraminifera. Fusulinids are abundant in some grainstones. The first cement of the grainstones is, either, a me-

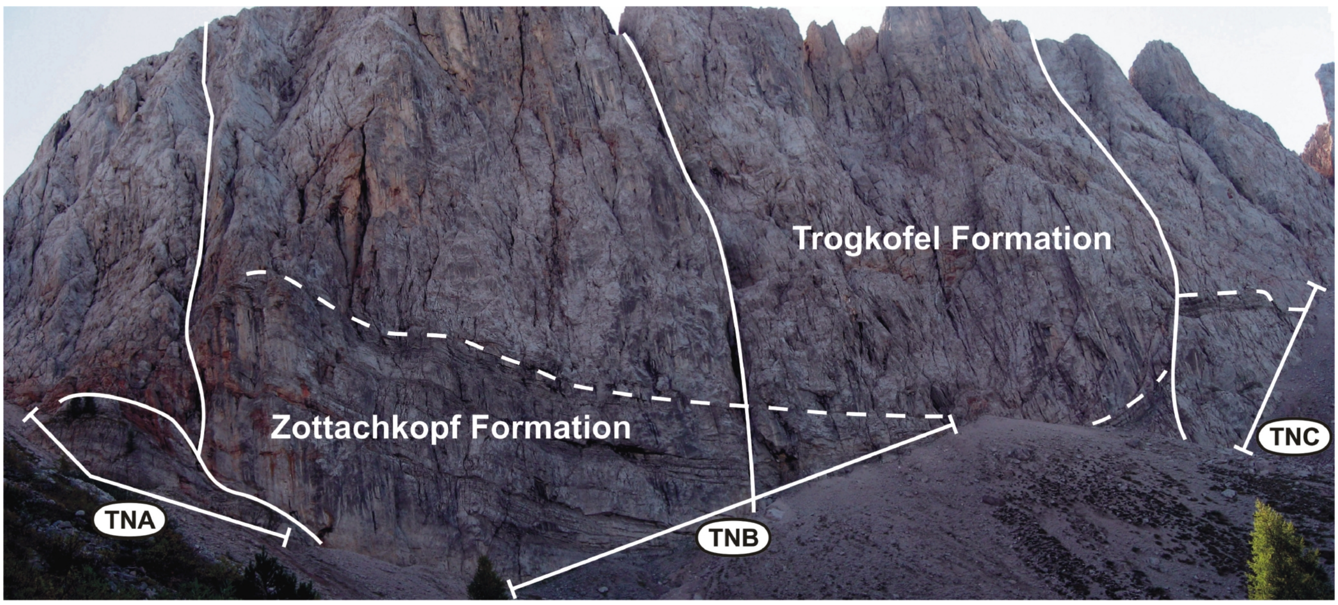


Figure 7: The lower boundary (white dashed line) of the Trogkofel Formation and the underlying Zottachkopf Formation exposed at the Trogkofel northface. Section TNC represents the basal part of the type section. Sections TNA and TNB are reference sections of the Zottachkopf Formation. White lines illustrate faults with vertical and horizontal displacement.

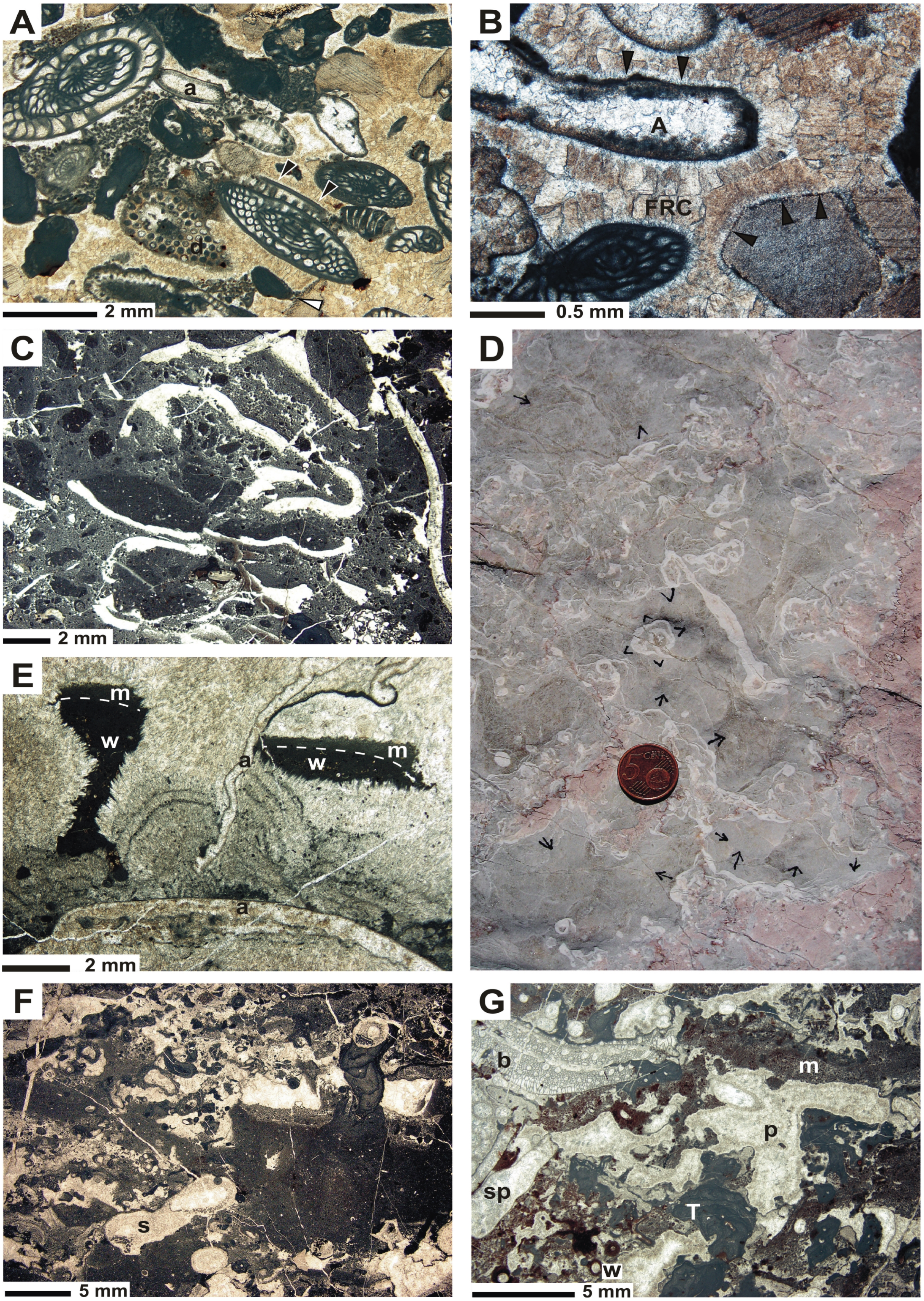
Figure 8: Erosional contact between dolomitized limestone of the Trogkofel Formation and the overlying Tarvis Breccia.

niscus cement or, more commonly, a fringe of fibrous calcite (Fig. 9A, B).

Bioclastic grain/packstones of the 'lower member' of the Trogkofel Formation typically are well- to moderately sorted, and characterized by fragments of *Tubiphytes*, bryozoans, phylloid algae, brachiopods, crinoids, calcareous sponges, worm tubes (microconchids), and rare clasts of calcareous green algae; in addition, a variable amount of angular fragments of boundstones and cementstones derived from the reef is present. In the lower member of the type section, bioclastic grainstones locally alternate with poorly sorted bioclastic wacke/pack/floatstones rich in fragments of phylloid algae, bryozoans and benthic foraminifera (Fig. 9C). Algal blades may be encrusted by *Tubiphytes*, sessile foraminifera, or bryozoans. Fabrics produced by bioturbation range from 'swirly' disorientation of bioclasts (indicative of softground burrowing) to partially open firmground burrows filled with micropeloidal wacke/pack/grainstone, and/or by calcite spar.

(2) *'Reef limestone'*: The unbedded, light gray to pink reefal limestone consists of *Tubiphytes*-bryozoan-algal boundstones associated with cementstones, microbialites and, locally, phylloid algal bafflestones. Most of the reefal limestones are characterized by an irregular three-dimensional network of intrinsic framework megapores, centimeters to tens of decimeters in width; the pores are filled with botryoidal cement, now calcified (Fig. 9D), or, less common, with bioclastic debris. The cavities were formed by phylloid algae, calcareous sponges and few rugose corals, and bound by fenestrate bryozoans and *Archaeolithoporella* and marine botryoidal cement. Towards the center of megapores, the amount of marine cement increases while *Archaeolithoporella* crusts decrease in thickness. Locally, the fibrous shape of the calcified crystals that comprise the botryoids is preserved by overlying infillings of wackestone (Fig. 9E). The boundstone is dominated by encrusting bryozoans, *Tubiphytes* and *Archaeolithoporella* (Fig. 9F). Phylloid algae, calcareous sponges, microconchids, and rugose corals are less common (Fig. 9G). In many cases, the fringes of fibrous cement that provide the botryoids in reef megapores are interspersed with layers of *Archaeolithoporella* (Figure 10A). In the middle and upper part of the 'lower member' of the type section, phylloid algal limestones were observed intercalated into intervals of reefal limestones as described; locally, phylloid algal limestones are also associated with red-coloured packstones rich in crinoid fragments. Phylloid algal bafflestones to cementstones consist of algal blades, some of them probably in life position (Fig. 10B). A few algal blades may bear thin crusts of *Archaeolithoporella* or *Tubiphytes*.

(3) *Stromatolite*: Rockfall boulders in the cirque north of Trogkofel summit indicate that an interval, or intervals, of light gray stromatolitic limestones (Tab. 3) attain a thickness of 8 m at least. In thin section, samples of this limestone consist of boundstones of tangled, micrite-walled tubes broadly reminiscent of *Girvanella* (Fig. 10C). Rare small *Tubiphytes* contribute to the fabric of these boundstones. Single skeletal grains or small accumulations of bioclasts, such as crinoid fragments, fusulinids, benthic foraminifera, *Pseudovermiporella* and fragments of calcareous algae may be interspersed. Dissolution pores fringed with fibrous cement which, in turn, is overlain by microbialite and/or red lime mudstone are common. The described interval of stromatolitic microbialite is vertically associated with bioclastic grainstones.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The stratigraphic downcut and exposure along the northern cliff of Trogkofel indicates that the described microbialitic stromatolite must stem from the Trogkofel Limestone. Unfortunately, we could not localize this interval in our type section; the overall good quality of outcrop along the type section suggests that this interval is not contained within, but in another portion of the Trogkofel Limestone.

(4) *Replacement dolomite and dolomite cement*: In the field, dolomitized Trogkofel Limestone can be easily identified by its brownish colour. Along the type section, the uppermost ~50 m of the Trogkofel Limestone are completely dolomitized. There, replacement dolomitization (Tab. 3) obliterated most of the intrinsic depositional fabrics. Down-section, dolomitized portions of the Trogkofel Limestone comprise fringes and haloes along fractures and around paleokarstic cavities. Selective dolomitization of micritic matrix or micritic skeletal grains (Fig. 10D) prevails. The dolomite fabrics range from optically-zoned dolomite crystals to aggregates of anhedral dolomite. Late diagenetic fractures are filled with a cement of saddle dolomite (Fig. 10E).

(5) *Carbonate breccia*: Carbonate-lithic breccias (Tab. 3) in the Trogkofel Limestone are of multiple origins. (i) Stratiform, poorly sorted, clast-supported breccias of pebbles to small boulders are intercalated in the unbedded reef limestone; the matrix is a reddish bioclastic wackestone (Fig. 10F). In total, the clast spectrum comprises the entire range of microfacies of the Trogkofel reefal limestone. Individual clasts display dissolution pores filled with reddish lime mudstone. The described carbonate breccias were observed only in boulders in scree slopes along the toe of the Trogkofel massif. (ii) Attrition breccias associated with syndepositional faulting comprise a wide spectrum of fabrics, from single-phase microbreccias to breccias, to multi-phase brecciated fabrics, with matrices including crystal silt, lime mudstone, and bio-lithoclastic wackestone to packstone; locally, clast interstitials are also filled with calcite spar. Internal breccia-tion associated with karstification is described farther below.

(6) *Internal sediments*: Dissolution cavities and vugs may be millimeter- to decimeter-sized, and are filled with gray, white or pink to red lime mudstone or with calcite cement (Fig. 10G). In larger paleokarstic cavities, different generations of infilling can be identified locally by discordant contacts between different generations of infilling and convolute/distorted lamination of internal sediments (Fig. 10H).

(7) *Fissure fills*: Fissures were filled with white to pink lime mud and/or with calcite cement (Figs. 11A, B). Locally, the walls of a fissure are lined with cement and intercalated layers of *Archaeolithoporella*. In some cases, later fracture of fissure fills formed internal breccias. Locally, fissure breccias were subject to subsequent karstification and infilling of red, now dolomitized, paleokarstic sediment in dissolution-widenes fracture and interstitial pores (Fig. 11C).

(8) *Paleokarstic sediments and cements*: Paleokarstic breccias consist of boulders up to a meter in size of reefal limestone, embedded in a matrix of red silty to argillaceous to fine-grained bioclastic wackestone to packstone. The matrix typically is dolomitized. Siliciclastic grains are rare, and represented by tiny grains of quartz and, more commonly, small flakes of mica (mainly muscovite). Some paleokarstic cavities, or parts thereof, are filled by speleothem calcite that may be partly dolomitized along fractures within the crystal fabric.

Figure 9: Litho- and microfacies of the Trogkofel Formation. A: Fusulinid grainstone with dasycladacean algae (d), phylloid algae (a), *Tubiphytes*, crinoid fragments and micropeloidal matrix. Micropeloids between bioclasts display meniscus cement (white arrow). Subsequently, thin isopachous fibrous cement (black arrows) and thick radiaxial fibrous calcite were precipitated. The central part of the pores are filled with coarse calcite spar. Sample TK36/1, plane-polarized light. B: Bioclastic grainstone of a sand shoal composed of phylloid algae (A), fusulinid and crinoid fragments showing two cement generations. First generation of thin fibrous calcite cement (black arrow tips) followed by the second cement generation of thick brownish RFC (radiaxial fibrous calcite). Sample TK36/1, plane-polarized light. C: Disruption of a semi-lithified algal float- to wackestone by strong bioturbation. Sample TK 47, plane-polarized light. D: Primary cavity in pink coloured Trogkofel boundstone. Arrows indicate growth direction of *Archaeolithoporella* crusts (white). The vast bulk of the cavity is filled with cement (gray). E: Bioclastic wackestone (w) preserved the needle-,like terminations of individual crystals of the botryoid. Single micropeloids are enclosed in the botryoid. Sample TK25/2, plane-polarized light. F: Boundstone composed of *Tubiphytes* (T) encrusting a calcareous sponge (sp), bryozoans, microbialite and synsedimentary cement. *Archaeolithoporella* is encrusting organic and inorganic material (black arrows). On the right side of the picture a bioclastic wackestone is embedded within the boundstone showing bioturbation and a remaining open burrow filled with calcite cement. Sample TK61, plane-polarized light. G: The *Tubiphytes*-bryozoan boundstone with calcisponges (sp) and agglutinated worm tubes (w) is associated with autochthonous microbialite and botryoidal cement. Remaining pores (p) were lined with radiaxial fibrous cement (RFC) and filled with calcite spar. Sample TNC11, plane-polarized light.

7. Fossil content

Numerous macro- and microfossils have been reported from the "Trogkofel Limestone" or "Trogkofel beds" of the Carnic Alps and Karavanke Mountains: brachiopods (Schellwien, 1900; Heritsch, 1938, 1943), smaller foraminifera and fusulinids (Schellwien, 1898b; Kahler and Kahler, 1938, 1941; Kochansky-Devidé, 1970; Kahler and Kahler, 1980; Kahler, 1983; 1985), algae (Pia, 1937; Homann, 1972; Kochansky-Devidé, 1970; Flügel, 1966; Flügel and Flügel-Kahler, 1980), corals (Heritsch, 1933a, 1943; Homann, 1971). Most fossils originated, either, from other localities (Forni Avoltri, Coccau, Karavanke Mountains), or they came from limestones that were assigned to other lithostratigraphic units (red limestones of "Höhe 2004", carbonate and clastic Trogkofel beds), only few were studied from the type locality, the Trogkofel massif.

Therefore, macro- and microfossils of the Trogkofel Formation in the Trogkofel area are still poorly known. Heritsch (1933b) determined *Medlicottia artiensis* var. *carnica* (HERITSCH), an ammonoid from the white limestone of the Trogkofel. The coral species *Tachylasma aster* (GRABAU) was identified from the lower part of the Trogkofel Formation (Homann, 1971), and *Amplexocarinia muralis* var. *biseptata* (SOSHKINA) and *Parafusalina carnica* (GORTANI) were described from the white

Lithology	**Facies types**	**Characterisation**	**Diagenetic features**	**Interpretation**	**Remarks**
Bioclastic limestone	Bioclastic rud-/grain-/packst.	Unbedded limestone, moderately to well sorted, composed of fusulinids, *Tubiphytes*, bryozoans, echinoderm fragments, sponges and varying amounts of calcareous algae; locally micropeloidal matrix	Isopachous fibrous cements, syntaxial overgrowth cements, meniscus cements and vadose dissolution in "upper member"; selective dolo-mitisation of bioclasts is common	Shelf margin sand shoal	Associated with reef bound-stones and stromatolites; rare intercalations of algal packstone (storm layer), Fig. 9A, 9B
		Mainly composed of *Tubiphytes* and varying amounts of bryozoans, phylloid algae. Locally bedded limestones occur.	Drusy calcite cement, selective dolomitisation of micritic matrix and bioclasts	?off reef debris or sand body within the reef	Associated with wackestones of the basal reef, lenses of bedded limestone in the lower part of the Trogkofel section, Fig. 10D
	Bioturbated wackestone	Composed of bryozoans, phylloid algae and brachiopod shells; strong bioturbation			Associated with bioclastic grainstones, Fig. 9C
Reef limestone	Algal bafflestone, *Tubiphytes*-bryozoan-algal-microbial boundstone, Cementstone, Bioclastic wacke/packstone, calcarenite	Bafflestone of branching phylloid algae often encru-sted by *Archaeolithoporella*. Boundstone composed of *Tubiphytes*, bryozoans, *Archaeolithoporella*, phylloid algae, sponges and varying amounts of bioclastic wackestone, microbialite and synsedimentary cement. Common intercalations of bioclastic grainstone.	Synsedimentary cementation by botryoidal cements; stromatactis and stromatactoid fabric; vadose dissolution; cm- to m-sized karstic cavities filled with sediment and/or cement.	Reef on seaward side of the shelf margin, upper slope	In-situ brecciation by syn- to early postdepositional tectonics; locally catalasite Fig. 9DFG, 10AB
Stromatolite	Cyanobacterial boundstone	Planar stromatolite with slightly wavy lamination	Vadose dissolution vugs filled with cement and/or siltite.	?intertidal stromatolite leeward of the shelf margin sand shoal	Associated with bioclastic grainstones, Fig. 9C
Dolomite	Dolostone	Mainly selective, rarely pervasive dolomitization of an- to subhedral dolomite crystals and xenotopic to hypidiotopic fabric Large euhedral to subhedral crystals in veins	Secondary porosity: vugs lined with zoned saddle dolomite.	a) Replacement dolomite b) Dolomite cement	Fig. 10D Fig. 10E
Carbonate breccia	Calcarenites to calcirudites	Poorly sorted, clast-supported breccia of angular intraclasts, pebbly to small-bouldery in size; matrix of red bioclastic wackestone with varying amounts of bioclasts	Karstification of single lithoclasts	Sedimentary reef breccia	Fig. 10F
Internal sediment	Mudstone, siltite	Silite or white/grey/red mudstone, often laminated and deposited in mm to dm-sized dissolution cavities	Locally, cement precipitation prior to sediment infill.	Dissolution cavities filled with sediment	Dewatering structures and soft sediment deformation, Fig. 10G Fig. 11AC
Fissure fill	Mudstone Carbonate breccia - arenites	Small cracks filled with light pink mudstone, dikes filled with calcarentites to breccias, pinkt to red matrix, lithoclast spectrum originates from the surrounding limestone		Shear fractures	
Red karst breccias and silt- to mudstones		Clast- to matrix-supported, very poorly sorted breccia of up to boulder-sized, very angular to subangular lithoclasts in a red, commonly dolomitized matrix; local lamination of matrix. Red argillaceous to silty dolostone or mudstone, commonly laminated; sucrosic rock surface; very few bioclasts (echinoderm fragments)	Pre- and postsedimentary calcite precipitation, replacement dolomiti-zation of matrix, single lithoclasts, sediments and cements. Corrosion of bioclasts	Paleokarst sediments or chemical precipitation	Multiple sediment infills, extremely rare siliciclastic input (quartz, mica), dewatering structures, soft sediment deformation (seismite), Fig. 10H

Table 3: Lithologies and diagenetic features of the Trogkofel Formation at the type locality.

Trogkofel Limestone at Trogkofel (Heritsch, 1943). Ernst (2000) determined the following bryozoan taxa from the Trogkofel Formation of the Trogkofel: *Streblascopora germana* (BASSLER), *Rhombopora* sp., *Penniretepora trapezoida* (NIKIFOROVA), *Penniretepora* sp., *Alternifenestella subquadratopora* (SCHULGA-NESTERENKO).

Our investigations showed that macrofossils, such as brachiopods, crinoid stems, calcareous sponges, rugose corals and cephalopods occur. Diversity is low in the reef facies, therein most common taxa are: *Tubiphytes obscurus* (MASLOV) and *Tubiphytes carinthiacus* (FLÜGEL) (Figs. 12R, T), bryozoans (fenestrate and biofoliate; Fig. 12K), phylloid algae, *Archaeolithoporella hidensis* (ENDO) (Fig. 12P), calcareous sponges (Fig. 12G), cyanobacteria (*Koivaella*; Fig. 12A), agglutinated worm tubes (Fig. 12L), and few echinoderm fragments and fusulinids. Flügel (1981) also reported ostracods, gastropods and *Connexia*. Bioclastic grainstones of the sand shoal facies provided a more diverse fauna and flora consisting of: *Tubiphytes*, phylloid algae (e.g. *Neoanchicodium*; Fig. 12O), calcareous green algae (*Connexia*, *Epimastopora*, *Globuliferoporella*, *Gyroporella*, *Mizzia*; Figures 12H-J,M,N), fusulinids (*Nankinella* sp., *Perigondwania tersa* (ROSS), *Pseudoreichelina darvasica* (LEVEN), *Robustoschwagerina tumida* (LIKHAREV); (Figs. 12F, S, U, V), echinoderm fragments (crinoid fragments), other benthic foraminifera (*Tuberitina*, *Tetrataxis* sp., *Lasiodiscus tenuis* (REICHEL), *Spireitlina tokmovensis* (PINARD and MAMET); Figures 12B-E), cyanophyta , gastropods, microproblematica (*Pseudovermiporella* sp., Fig. 12Q), ostracods, bivalve fragments, and few trilobites.

8. Biostratigraphy of the Trogkofel Formation

Geyer (1895) correlated the Trogkofel Limestone with the Artinskian Stage of Russia. The biostratigraphy of the Trogkofel Limestone is discussed in detail by Heritsch (1943), mainly based on fusulinids, brachiopods and rare ammonoids, gastropods and one trilobite.

According to Heritsch (1943), the fauna of the Trogkofelkalk shows the strongest relationship to the *Schwagerina* Limestone of the Ural Mountains and the Artinskian Stage. Strong relationships exist also to Sosio (Sicily, Italy) and to the Productus Limestone of the Salt Range (Pakistan).

Most fossils considered by Heritsch (1943), however, are from the Trogkofel Limestone at Teufelsschlucht, now ascribed to the Zweikofel Formation, and from Forni Avoltri, a succession which is developed in a different facies and not included in the Trogkofel Formation as defined herein. Kahler studied the fusulinids of the Upper Paleozoic succession (including the Trogkofel Limestone) in the Carnic Alps over decades, and proposed a biostratigraphic chart (Kahler and Kahler, 1980; Kahler, 1986).

Kahler (1986) included in his Trogkofel Stage, which is subdivided into Sakmar(ian), Artinsk(ian) and Cisjansk(ian), the following lithologic and biostratigraphic units:

a) „Rotkalk des Trogkofels“ characterized by the occurrence of *Robustoschwagerina geyeri*

b) Trogkofelkalk with *Robustoschwagerina schellwieni* and *Pseudoschwagerina lata* (mainly based on samples from Forni Avoltri)

c) „Seikofelkalk“ (reworked limestone clasts in the Tarvis Breccia near Seikofel) with *Pseudofusulina tschernyschewi*

d) Treßdorfer Kalk containing the index fossil *Praeparafusulina lutugini*

e) Goggauer Kalk characterized by *Pamirina* and *Pseudofusulina vulgaris*

f) Tarviser Breccie

According to Kahler and Kahler (1980), Kahler (1986), Rotkalke des Trogkofels, Trogkofelkalk and Seikofelkalk are Sakmarian, Treßdorfer Kalk and Goggauer Kalk of Artinskian and Tarviser Breccie of Cisjanskian age. The biostratigraphic age of the Trogkofelkalk is mainly based on fusulinids from Forni Avoltri as according to Kahler and Kahler (1980). The Trogkofel Limestone at the type locality contains only few fusulinids which are not determinable due to dolomitization.

Forke (1995) noted the problem of dating the Trogkofel Limestone; because no fusulinid fauna has been described from the type locality at mount Trogkofel, in his discussion, he referred to the fusulinids of the "Trogkofelkalk" of Forni Avoltri. Further confusion resulted from misinterpretation of the stratigraphic position of the fusulinid-bearing Red Limestone (Rotkalk der Höhe 2004, Figure 13). The red limestones from locality “Höhe 2004” yielded a fusulinid fauna including *Pseudoschwagerina geyeri*, first recognized by Kahler and Kahler (1938), indicating a younger age than that of the Upper *Pseudoschwagerina* Limestone. Kahler (1983, 1986, 1992) dated these red limestones as Sakmarian and therefore ascribed them to the Trogkofel Limestone. Forke (1995, 2002) placed the red limestone into the Upper *Pseudoschwagerina* Limestone = Zweikofel Formation and dated the entire Zweikofel Formation as Sakmarian. Schönlaub and Forke (2007) dated the Zweikofel Formation as late Sakmarian to early Artinskian. The stratigraphic position of the red limestone is also briefly discussed by Heritsch et al. (1933), Heritsch (1936, 1938) and Kahler and Prey (1963).

Detailed field studies at Zweikofel, Trogkofel and Zottachkopf showed that the red limestone and gray well-bedded limestones which underlie the massive Trogkofel Limestone at Trogkofel and Zottachkopf differ significantly from the deposits of the Zweikofel Formation at Zweikofel and Garnitzenbach. Outcrops along the toe of the northern cliff of Trogkofel show that these red limestones are present near the base of a succession ~12 m thick mainly of thin-bedded limestones. For this succession, which differs from the Zweikofel Formation, Schaffhauser et al. (2010) proposed the term Zottachkopf Formation (see Krainer and Schaffhauser, 2012). Davydov et al. (2013) studied the fusulinid fauna of the red limestone of Höhe 2004. The fauna includes fusulinids which are characteristic of the fifth assemblage at the top of the Zweikofel

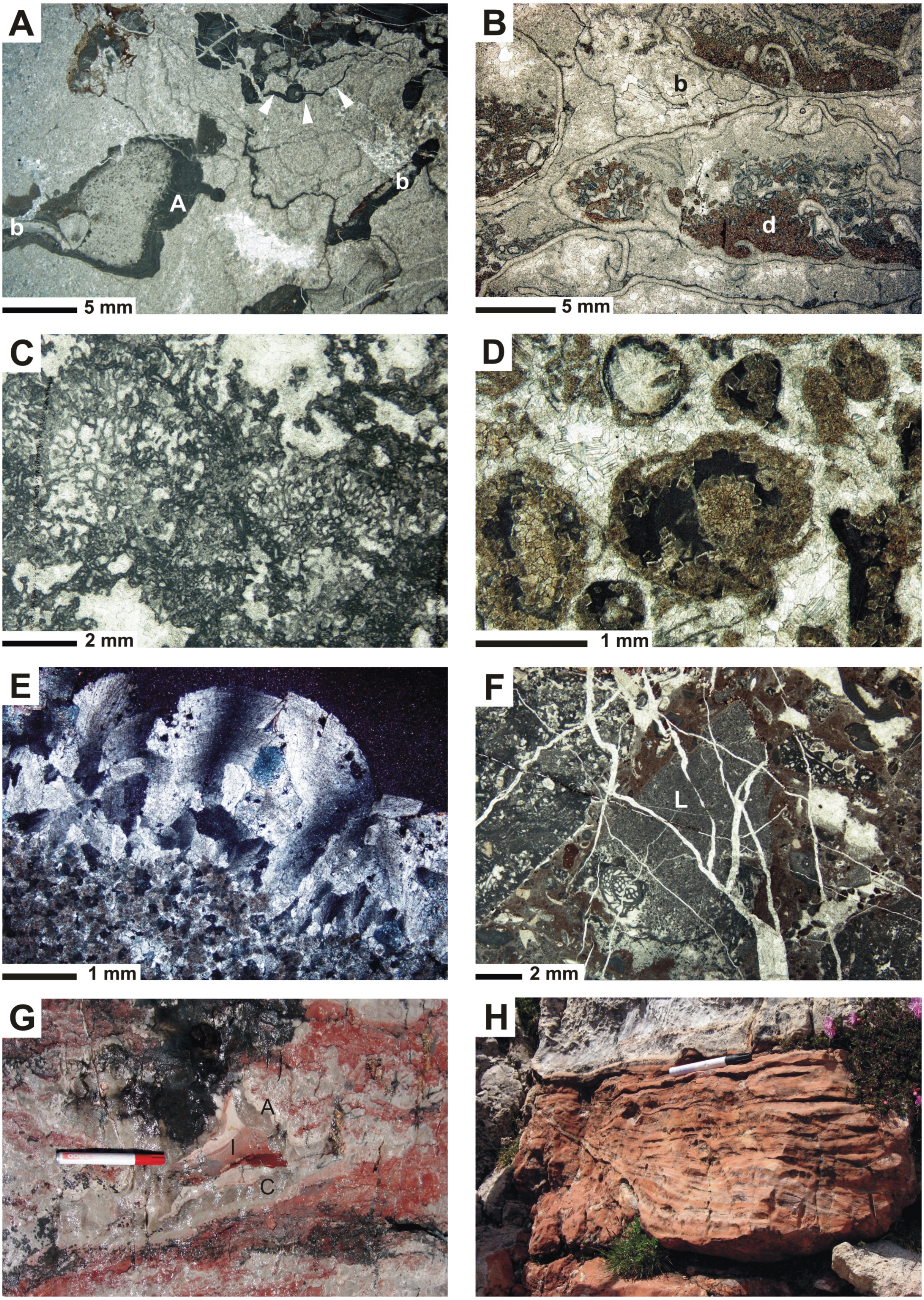
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Figure 10: Litho- and microfacies of the Trogkofel Formation A: Cementstone composed of *Tubiphytes* and bryozoans (b) encrusted by *Archaeolithoporella* (A) and large calcified botryoids. The syndepositonal cement is encrusted by *Archaeolithoporella* (arrows) and bioclastic wackestone was deposited on the cements in the remaining pore space. Sample TK57, plane-polarized light. B: Phylloid algal bafflestone with red bioclastic packstone deposited on algal blades. Cement botryoids (b) filled the pores. Replacement dolomitization (d) affected mainly micritic components of the packstone. Sample TB11, plane-polarized light. C: *Girvanella* tubes enclosing branching plants (?algae) in a *Girvanella*-boundstone. Sample TB33, plane-polarized light. D: Selective dolomitization of skeletal grains (e.g. *Tubiphytes*). Sample TK45, plane-polarized light. E: Large crystals of saddle dolomite with curved crystal faces and sweeping extinction. Smaller crystals of brownish coloured dolomite in the lower left of the image are replacement dolomite. Sample TK2A, crossed polars. F: Sedimentary breccia with a red bio- to fine lithoclastic matrix. The lithoclasts (L) are composed of a range of different facies types including cyanobacterial boundstone, microbial packstone, *Archaeolithoporella*-cementstone. Sample TB25A, plane-polarized light. G: Roof and walls of the cavity encrusted by *Archaeolithoporella* (A), subsequent precipitation of cement (C) and infill of white to pink to red lime mud (I). H: Trough-shaped infill of red laminated paleokarst sediment in a paleocave. Cements precipitated on top of the sediment infill.

Formation (Artinskian). Additionally, the assemblage contains abundant *Darvasella*, including *D. praecox* (LEVEN), and *Laxifusulina* as well as advanced *Robustoschwagerina* species which in Darvas characterize the upper Yakhtashian and Bolorian (Figure 14) thus suggesting a slightly younger age compared to the Zweikofel Formation (Davydov et al., 2013).

The Trogkofel Limestone of Forni Avoltri yielded a fusulinid fauna suggesting a Sakmarian age (Kahler and Kahler, 1980). Only *Boultonia willsi* (LEE), *Pseudofusulinoides regularis* (SCHELLWIEN) and *Pseudofusulina fusiformis* (SCHELLWIEN) were identified from the Trogkofel Limestone at the Trogkofel (Kahler and Kahler, 1980).

The fusulinid species *Robustoschwagerina spatiosa* (LIN) and the conodont species *Neostreptognathodus* cf. *pequopensis* were determined from the Trogkofel Limestone of the 'basinal interval' (= "Sonderfazies" of Forke, 2002) at the Zweikofel massif (Forke, 2002). These species indicate an upper Artinskian age (Schönlaub and Forke, 2007).

The basal Trogkofel Limestone at Trogkar contains fusulinids

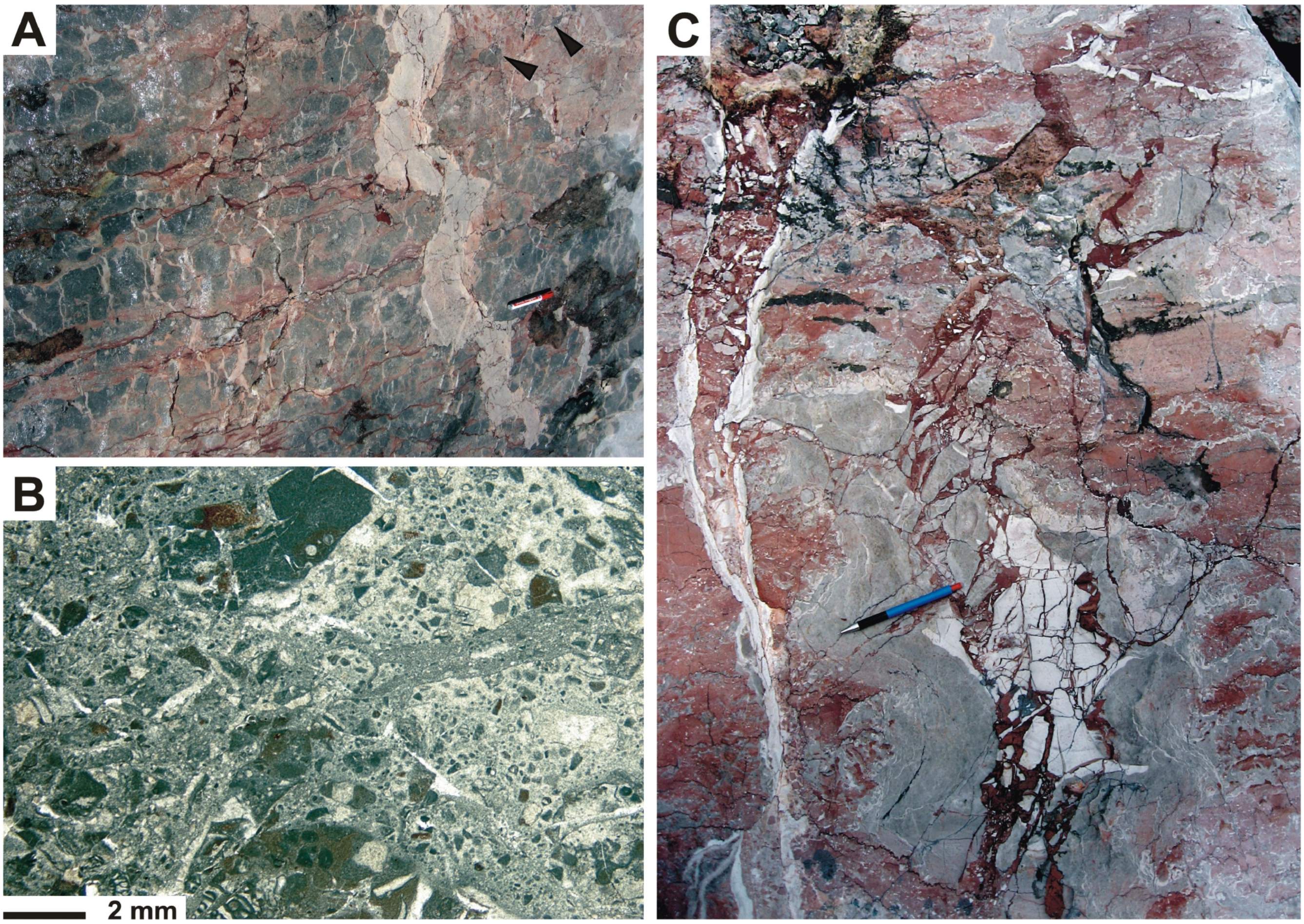

Figure 11: A: The package of gray fossiliferous limestones shows disintegration into lithoclasts in its upper part (arrows) which indicates a lateral displacement of unkown distance. The whole sediment package is pervaded by subvertical cracks and subsequently crosscut by a dike, both filled with light pink sediment. B: Fracturing of a carbonate breccia. The fracture pores are filled with a fine-grained lithoclastic wackestone. Open fractures are cemented by calcite spar. Sample TK18, plane-polarized light. C: Highlights in the historic evolution of the Trogkofel Limestone at a glance: 1) Cavity of presumed polygenetic origin which was first colonized by *Archaeolithoporella* (white crusts), followed by cement precipitation and sediment infill, shown in the lower part of the photograph. 2) Vertical dike with a poly-phase sediment infill of a) a white mudstone to lithic arenite and after reopening of the dike b) a poorly sorted carbonate breccia with red matrix, which contains lithoclasts from the previous dike infill. 3) Karstic cavities and fractures crosscut the reef limestone, the cavity infill and the vertical dike. Both, karstic cavites and fracture pores are filled with red karst sediments.

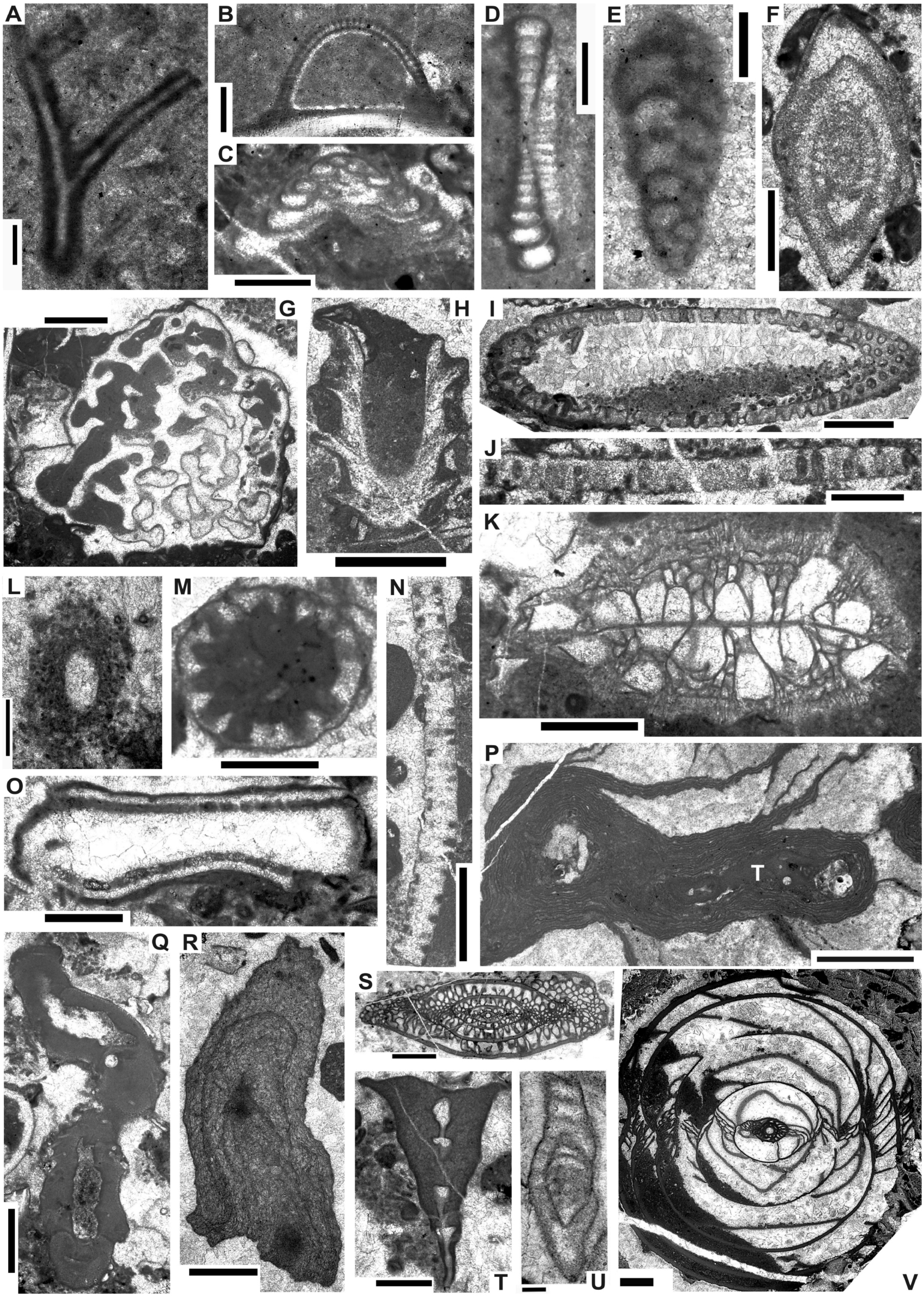
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Figure 12: Microfossils from the Trogkofel Formation. A: *Koivaella* sp., sample TK50_1, scale bar 0.1 mm. B: *Tuberitina*, sample TK50_1, scale bar 0.1 mm. C: *Tetrataxis* sp., sample TK26, scale bar 0.5 mm. D: *Lasiodiscus tenuis* (REICHEL), sample TK23, scale bar 0.1 mm. E: *Spireitlina tokmovensis* (PINARD and MAMET), sample TK24, scale bar 0.1 mm. F: *Nankinella* sp., sample TK36/1, scale bar 0.5 mm. G: Calcareous sponge, sample TK51A, scale bar 1 mm. H: *Connexia* sp., oblique cross section, sample TM5, scale bar 1 mm. I: *Gyroporella* sp., sample TK36/1, scale bar 1 mm. J: *Epimastopora* sp., sample TK36/2, Trogkofel Formation, scale bar 0.5 mm. K: Bifoliate cyclostomid bryozoan. Sample TK50/1, scale bar 0.5 mm. L: Agglutinated worm tube, *Thartharella* sp. Sample TK66A, scale bar 0.5 mm. M: *Mizzia* sp., sample TK36/1, scale bar 0.5 mm. N: *Globuliferoporella* sp., sample TM5, scale bar 1 mm. O: *Neoanchicodium* sp., sample TK51A, scale bar 1 mm. P: *Archaeolithoporella* encrusting *Tubiphytes* and bryozoan and spreading over rapidly growing cement botryoids and cement crusts. Sample TB1B, scale bar 2 mm. Q: *Pseudovermiporella* sp., sample TK31/1, scale bar 1 mm. R: *Tubiphytes* cf. *carinthiacus* (FLÜGEL), sample TM3, scale bar 1 mm. S: *Perigondwania tersa* (ROSS) sensu LEVEN, scale bar 1 mm. T: *Tubiphytes obscurus* (MASLOV), sample TK58/1, scale bar 1 mm. U: *Pseudoreichelina darvasica* (LEVEN), scale bar 0.1 mm. V: *Robustoschwagerina tumida* (LIKHAREV), scale bar 1 mm.

which are typical for the upper Yakhtashian in Darvaz, including *Quasifusulina magnifica* (LEVEN), *Chalaroschwagerina globularis* (SKINNER and WILDE), *Robustoschwagerina tumida* (LICHAREW), *Perigondwania*? *sera*, *P.*? *zigarica*, *P.*? *oingaronica*, and *Leeina pseudogruperaensis*. (Davydov et al., 2013). According to Davydov et al. (2013), the Trogkofel Limestone is of late Artinskian to early Kungurian (upper Yakhtashian) age. The Goggau Limestone which contains *Pamirina darvasica* (LEVEN), is younger than the Trogkofel Limestone (upper Yakhtashian, Fig. 14) (Davydov et al., 2013), but it should be considered that fusulinids from the middle and upper part of the Trogkofel Limestone have not yet been studied.

9. Discussion

9.1 Syndepositional tectonism

In the pedestal of mount Trogkofel, bedded shelfal limestones of the Zottachkopf Formation are sharply, but apparently conformably overlain by massive limestone of the Trogkofel Formation. This stratigraphic contact thus may represent a paraconformity or, more probably, a conformable sector of a disconformity. Farther north, at Zweikofel, the boundary between the underlying Zweikofel Formation and the overlying Trogkofel Formation is a clear-cut disconformity (Krainer et al., 2009). In any case, the vertical change across the boundary from shallow-shelfal deposition (Zottachkopf and Zweikofel Formation) to reefal/peri-reefal deposition above (Trogkofel Formation) records a backstep of the shelf margin. The backstep was associated with syndepositional faulting and localized deposition of breccias (Krainer et al., 2009). The described evidence for soft-sediment to brittle deformation (intraplasticlastic seismites to brittle attrition breccias), and the discrete 'intraseismitic' packages of convolute laminasets within paleokarstic cavities indicate that syndepositional tectonism and co-seismic deformation persisted during deposition of the Trogkofel Formation. The truncation surface that caps the Trogkofel Formation probably was caused by surface uplift that may be related to the "Saalian tectonic phase", or "Saalian movements" (e.g. Kahler, 1980; cf. McCann et al., 2008).

For the depositional breccias that are conformably associated with other Trogkofel facies types, their composition of clasts only of Trogkofel Limestone, and mainly of reefal limestones, an interpretation is impeded by the fact that these breccias were observed only in large boulders on scree slopes along the eastern and northern flank of Trogkofel. On mount Trogkofel, the absence of large and high clinobeds suggests that the breccias did not originate by gravitational instability on a steep slope; furthermore, this is precluded by their vertical association with reefal- to perireefal limestones. The breccias may have originated along and accumulated chiefly on the hangingwall of normal faults of comparatively small throw, or from fragmentation in monoclines above blind ends of normal faults. Assuming that the reefs accumulated in a gently-dipping foreslope/upper slope setting, fragmentation of limestones may also have been imparted by seismic shaking and

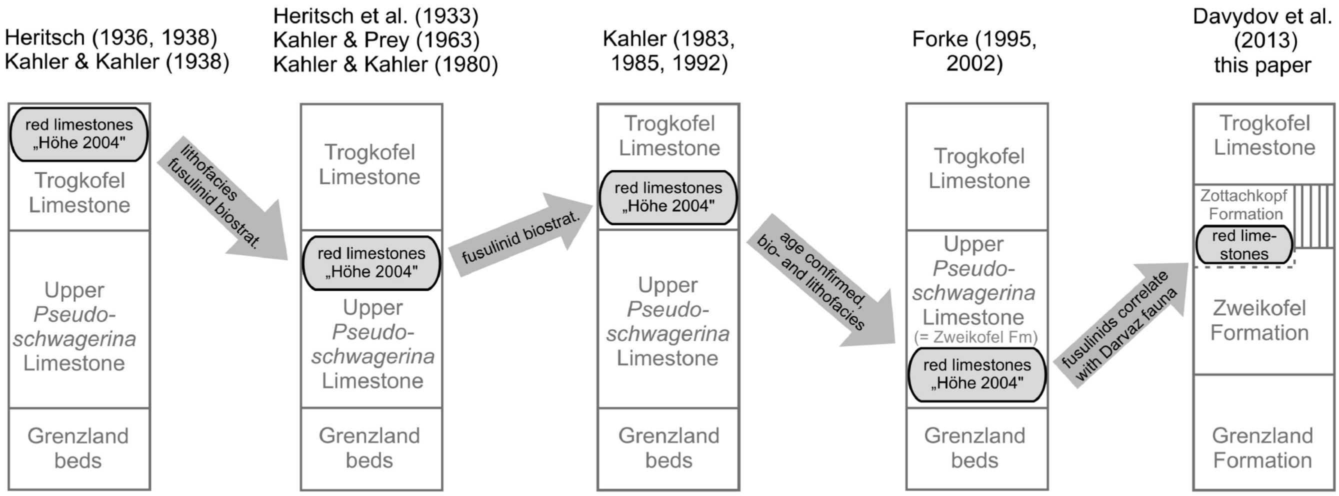

Figure 13: Shift in stratigraphic position of the red limestones of "Höhe 2004" within the Lower Permian lithostratigraphic succession of the Carnic Alps during the last decades.

associated gravitational instability of limestone tongues (cf. Hopkins, 1977); this hypothesis does not preclude fragmentation on low fault scarps or in monoclinal bends.

9.2 Water depth and sea-level changes

For the *Tubiphytes/Archaeolithoporella* buildups, their content in calcifying algae and, perhaps, also the fusulinids suggest depositional water depths of a few meters to a few tens of meters, in the photic zone below fair weather wave base (Flügel, 2004). We assume that the buildups accumulated in depths of more than 10 m, below the reach of most fairweather waves. Bioclastic grainstones rich in calcareous green algae and fusulinids from the upper part of the Trogkofel section were interpreted as platform deposits (Flügel, 1980a; Schönlaub and Forke, 2007). We suggest that these grainstones represent shelf margin sand shoals accumulated in shallower waters than the skeletal-microbial-cement reefs, under influence of episodic high-energy events.

In the entire Trogkofel massif, a distinct cyclicity of facies was recognized neither in the Trogkofel Formation nor in the underlying Zottachkopf Formation. Although different levels with vadose dissolution pores within the Trogkofel succession point to subaerial exposure and sea-level fluctuations, clear-cut emersion surfaces were not identified. In pure carbonate rock successions, emersion surfaces are difficult to identify in the field. The carbonate-siliciclastic cyclothems of the Upper Carboniferous to Lower Permian in the Carnic Alps were related to glacio-eustatic sea-level fluctuations (Massari and Venturini, 1990; Krainer, 1992). For the mid-Sakmarian to Kungurian, including the time range of Trogkofel Limestone deposition, sea-level changes in the range of 30–70 m are suggested, and 10–60 m in the Middle to Late Permian (Rygel et al., 2008). The probable range of depositional depth of the Trogkofel buildups combined with the amplitude of late Paleozoic sea-level changes thus strongly suggest that the preserved part of the shelf margin should have been intermittently exposed. The paleokarstic cavities and their multi-phase infillings, including caymanitic levels, probably provide the most direct record of sea-level changes and subaerial exposure.

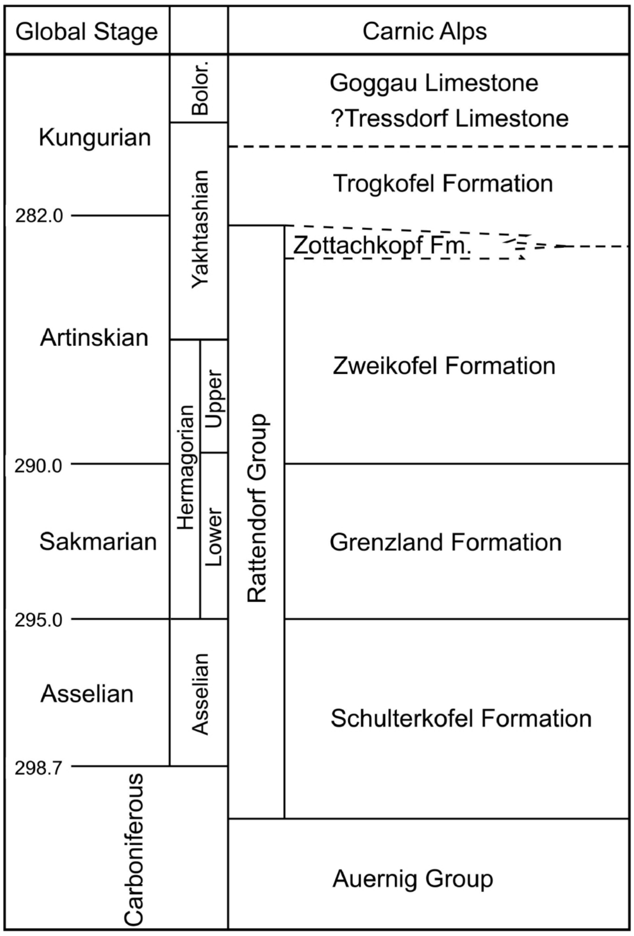

Figure 14: Stratigraphic chart of the Lower Permian of the Carnic Alps. After Davydov et al. (2013).

9.3 Correlations

Previous work on successions thought to be time-correlative to our Trogkofel Formation mainly focussed on outcrops near Forni Avoltri (Flügel, 1980a, 1981; Buggisch and Flügel, 1980). The deposits at Forni Avoltri comprise a mixed siliciclastic-carbonate succession hardly comparable to the Trogkofel type section. In addition, new fusulinid biostratigraphic data from the lower Trogkofel Formation suggest upper Artinskian (Davydov et al., 2013), whereas the fusulinid fauna of Forni Avoltri indicated a Sakmarian age (Kahler and Kahler, 1980); a modern revision of the latter fauna is required. We propose to confine the term Trogkofel Formation, or Trogkofel Limestone, to time-correlative successions of reefal and bioclastic limestones as present at the type locality. Conversely, microfacies similar to those of Forni Avoltri were observed in the Zottachkopf Formation (Schaffhauser et al., 2010), and also in the Zweikofel Formation, i.e., in formations underlying the Trogkofel Limestone. This confirms that restudy of the Forni Avoltri section is needed to resolve its chronostratigraphic position.

Correlation of the Trogkofel type section with other outcrops in the Nassfeld/Pramollo area (Zweikofel, Garnitzenbach Gorge) shows an initial shelf margin backstep at the base of each section. In the Trogkofel section, reefal limestones represent two-thirds of the succession, capped by sand shoal deposits. Contrary to that, a carbonate mound differing in facies from the typical Trogkofel reef, and local limestone breccias, accumulated at Zweikofel (see Krainer et al., 2009, for details). Although presently located close to each other, Trogkofel and Zweikofel are separated by transfer faults that may have splayed off from the nearby Periadriatic Line.

10. Conclusions

(1) At Trogkofel, a package of well-bedded inner shelfal limestones (Zottachkopf Formation) is conformably overlain by the unbedded carbonate shelf-margin succession ~500 m in preserved thickness of the Trogkofel Formation. The vertical transition Zottachkopf/Trogkofel Formation records a backstep of the shelf margin caused by syndepositional tec-

tonism (Krainer et al., 2009). The Trogkofel Formation is capped by a truncation surface which, in turn, is overlain by carbonate-lithic deposits of the Tarvis Breccia.

(2) Up-section, most of the Trogkofel Formation consists of 'reefal to peri-reefal' limestones of skeletal-microbial-cement reefs, mainly of *Tubiphytes*-bryozoan-algal-cement boundstones, cementstones, and phylloid-algal bafflestones. The buildups are intercalated with bioclastic limestones. Thicker packages of bioclastic grainstones record comparatively persistent higher-energy conditions, perhaps related to minor (or early) falls of relative sea-level. Throughout the Trogkofel Formation, however, no major lateral shift of facies belts is identified; the formation thus records a stationary carbonate shelf margin comprising fore-reef to platform-margin sand shoal deposits.

(3) Active tectonism during to early after deposition of the Trogkofel Formation is recorded by a spectrum of soft-sediment to brittle deformation features. Within karstic caverns in the Trogkofel Formation, discrete packages of internal sediment with convolute lamination and/or brecciation record events of co-seismic deformation.

(4) Deposition of the Trogkofel Formation was terminated by uplift, resulting in subaerial truncation and karstification. Karstic caverns filled mainly with dark-red, geopetally-laminated lime mudstones, dolostones, and caymanitic layers reach down to the base of the formation, albeit in decreasing abundance. Karstification probably was multi-phase.

(5) The subaerial erosional paleorelief on top of the Trogkofel Formation was onlapped by a package of carbonate-lithic breccias (Tarvis Breccia). At Trogkofel, the characteristics of the Tarvis Breccia suggest that it accumulated from hillslope colluvial mantles.

(6) The Tarvis Breccia and the entire upper part of the Trogkofel Formation are dolomitized. Downward within the Trogkofel Formation, dolomitized domains are confined to the vicinity of paleokarstic cavities and/or fractures. Dolomitization tapers out towards the base of the formation.

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