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Early Permian Shelf Margin Retreat and Carbonate Deposition, Zweikofel Massif, Carnic Alps (Austria)

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Abstract

Along the southern margin of the Pramollo basin (Carnic Alps), an early Permian backstep of the shelf margin triggered carbonate deposition, from external platform to slope environments, above an underlying mixed siliciclastic-carbonate cyclothemic succession.

In the central Carnic Alps, following Variscan deformation and subaerial erosion, the vestige of the orogen became onlapped and overstepped during Kasimovian time. The Kasimovian to Sakmarian-?Artinskian succession is characterized by decameter-scale, mixed siliciclastic-carbonate cyclothems that accumulated from distal-fluvial and/or beachface to inner shelf environments. Cyclothemic deposition was mainly controlled by glacio-eustatic sea-level changes. In the Zweikofel massif, the cyclothemic succession is sharply overlain, along a surface of erosion, by a succession of: (a) interval 1, about 40 m thick, composed of bioclastic limestones, microbial boundstones, and carbonate-lithic rudites, sharply overlain by (b) interval 2, a succession of mudstones with intercalated beds of arenites to bouldery rudites of mixed carbonate-lithic/bioclastic composition, overlain by (c) interval 3, a succession about 50 m in preserved thickness of bioclastic limestones and *Archaeolithoporella-Tubiphytes* cementstones (Trogkofel Limestone). In the lower portion of interval 3, beds both thin and lap out towards the north. The facies of interval 3 are comparable to a pure carbonate succession, about 400 m in thickness, of the Trogkofel massif closely towards the south, but offset by a large fault from the Zweikofel massif.

Interval 1 records a minor backstep from terrigenous beachface to inner carbonate shelf environments (= upper part of cyclothemic succession) to an external carbonate shelf sheltered from terrigenous input. The transition from interval 1 to 2, in turn, records a significant backstep that led to 'basinal' conditions; the backstep was triggered by downfaulting of the shelf margin. The depositional water depth of the 'basinal' interval 2, however, can hardly be estimated. The intercalated beds of arenites to rudites were shed from a prograding carbonate shelf. Interval 3 records northward progradation of the Trogkofel Limestone platform. The vertical transition from the cyclothemic succession into the Trogkofel Limestone indicates a termination of clear-cut stratigraphic cyclicity. Glacio-eustatic sea-level changes yet persisted from Pennsylvanian into early Permian times. In the Trogkofel Limestone, sea-level changes most probably are recorded but in a different fashion, such as by multiple phases of subaerial exposure and karstification.

Am Südrand des Naßfeld-Beckens (Karnische Alpen) führte während des frühen Perms ein tektonisch verursachtes Rückschreiten des Schelfrandes zu Ablagerung von Schelfrand- bis Abhang-Karbonaten, über einer liegenden Folge von gemischt siliziklastisch-karbonatischen Zyklothemen.

Im Bereich der zentralen Karnischen Alpen begann die sedimentäre Eindeckung des variszischen Gebirgsrumpfes während des Kasimoviums. Die Abfolge von Kasimovium bis Sakmarium-?Artinskium ist durch Zehnermeter-dicke, gemischt siliziklastisch-karbonatische Zyklotheme gekennzeichnet. Diese Zyklotheme bildeten sich von distal-fluviatilen und/oder küstennahen Bereichen bis hin zum inneren Schelf. Die Zyklothem-Bildung wurde wesentlich von glazio-eustatischen Meeresspiegel-Schwankungen gesteuert. Im Zweikofel-Massiv wird die zyklothemische Folge entlang einer Erosionsfläche scharf von einer andersartigen Abfolge überlagert; von unten nach oben besteht diese Abfolge aus: (a) Intervall 1 (bis etwa 40 m dick) aus bioklastischen Kalken, mikrobiellen Boundstones und karbonat-lithischen Ruditen; scharf überlagert von (b) Intervall 2, ein Paket von Schiefertonen mit eingeschalteten Bänken von Areniten bis block-führenden Ruditen gemischt karbonat-lithischer/bioklastischer Zusammensetzung; überlagert von (c) Intervall 3, eine Folge bis etwa 50 Meter erhaltener Dicke aus bioklastischen Kalken und *Archaeolithoporella-Tubiphytes* Cementstones (Trogkofelkalk). Im unteren Teil des Intervalles 3 dünnen und flachen die Bänke nach Norden hin aus. Die Fazies des Intervalles 3 sind vergleichbar jener der etwa 400 m dicken, reinen Karbonat-Abfolge des knapp südlich davon gelegenen, durch eine Störung abgesetzten Trogkofel-Massives.

Das Intervall 1 zeigt ein geringes Rückschreiten der Faziesgürtel an, von terrigen-küstennah bis innerer Karbonatschelf (=oberer Teil der zyklothemischen Folge) zu einem äusseren Karbonatschelf ohne terrigenen Eintrag. Am Übergang von Intervall 1 zu 2 erfolgte eine markante Abtiefung, die zu 'becken-artigen' Ablagerungsbedingungen führte (Intervall 2). Die Abtiefung wurde durch ein tektonisches Rückschreiten des Schelfrandes verursacht. Die Ablagerungstiefe des beckenartigen Intervalles 2 ist jedoch kaum genauer abzuschätzen. Die im Intervall 2 eingeschalteten Bänke von Areniten bis Ruditen wurden von einem vorbauenden Karbonatschelf geschüttet. Intervall 3 schließlich entstand während einer nordgerichteten Progradation der Trogkofelkalk-Plattform. Der Übergang von der liegenden zyklothemischen Abfolge in den Trogkofelkalk zeigt ein Ende klar ersichtlicher stratigraphischer Zykli-

zität auf. Glazio-eustatische Meeresspiegel-Schwankungen dauerten jedoch vom Pennsylvanium bis in das frühe Perm hinein an. Im Trogkofelkalk werden Meeresspiegel-Schwankungen daher wahrscheinlich auf andere Arten aufgezeichnet, wie etwa durch wiederholte Phasen subaerischer Freilegung und Verkarstung.

1. Introduction

In the Carnic Alps of Austria and Italy a Palaeozoic succession comprising, with gaps, the Upper Ordovician to uppermost Permian interval is preserved (Schönlaub, 1979; Schönlaub and Histon, 1999). The Upper Carboniferous to Lower Permian post-Variscan portion of this succession is characterized by decameter-scale, mixed siliciclastic-carbonate cyclothems (Fig. 1); these cyclothems are interpreted as the distal-fluvial-to-inner shelf tracts of glacio-eustatic depositional sequences (Krainer, 1991, 1992; Massari et al., 1991; Samankassou, 1997, 2002). In the central Carnic Alps, in the area of Zweikofel to Trogkofel (Fig. 2), this cyclothemic succession is overlain by an approximately 400 m thick interval composed mainly of unbedded platform limestones and dolomitized limestones termed Trogkofel Limestone (Piller et al., 2004; Schönlaub and Forke, 2007).

In the central Carnic Alps the change from deposition, over roughly 23 Ma, of mixed siliciclastic-carbonate cyclothems to the thick platform succession of the Trogkofel Limestone represents a stratigraphic turning point. The development and potential causes for this turnover, however, were not described to date. In the present paper, we describe the early stage of development of the Trogkofel carbonate platform in the large, hitherto little documented key outcrop (see also Schönlaub and Forke, 2007) of the Zweikofel massif that also allows to investigate the relation to the underlying cyclothemic succession. We argue that the change from cyclothemic, mixed siliciclastic-carbonate to 'pure' carbonate platform deposition was caused by a tectonic retreat of the shelf margin.

2. Geological setting

The Carnic Alps are part of the Southern Alps, and are delimited along their northern margin by the Gailtal Line. The Gailtal Line is a dextral segment of the Periadriatic Lineament, a major fault zone that separates the Southern Alps from the Eastern and Western Alps, respectively. During the early Permian, the area of the Southern Alps was situated along the southern margin of a marine embayment (Fig. 3). The marine embayment, and similar basins elsewhere, formed within a dextral megashear zone between Gondwana and Laurasia. As a result, the lower Permian of the Southern Alps is characterized by transtensional graben formation, crustal thinning, high heat flow and magmatism (Arthaud and Matte, 1977; Venturini, 1991; Rantitsch, 1997; Muttoni et al., 2003; Vai, 2003; Schuster and Stüwe, 2008).

Subsequent to rapid exhumation of Variscan metamorphic rocks (Mader et al., 2007), the preserved Upper Palaeozoic record of the eastern Carnic Alps starts with terrestrial to shallow-marine deposits that onlap and overstep the erosional vestige of the Variscan orogen (Fig. 1). The Zweikofel-Trogkofel area was situated along the margin of the transtensional Naßfeld/Pramollo basin (Venturini, 1991). At least in its early stage of development, during the Kasimovian to Gzhelian, the Pramollo basin represented an intramontane basin, but the total basin fill comprises the Kasimovian to Capitanian interval (Venturini, 1991; cf. Schönlaub and Forke, 2007, their Fig. 3). From a maximum preserved thickness of more than 2000 meters, the filling of the Pramollo basin thins to about 100 meters near its margin (Venturini, 1991; Krainer, 1992; Schönlaub and Forke, 2007). The basin-fill may be subdivided into five superposed parts (compare Fig. 1): (1) a basal part (Bombaso Fm., and lower part of Auernig Group) dominated by siliciclastic cyclothems that show marked lateral changes in thickness and facies that may result from syndepositional tectonism (Massari et al., 1991) and/or from burial of an older erosional relief. (2) A thick succession of mixed siliciclastic-carbonate cyclothems that overall are of more 'regular' thickness and facies distribution relative to underlying cyclothems

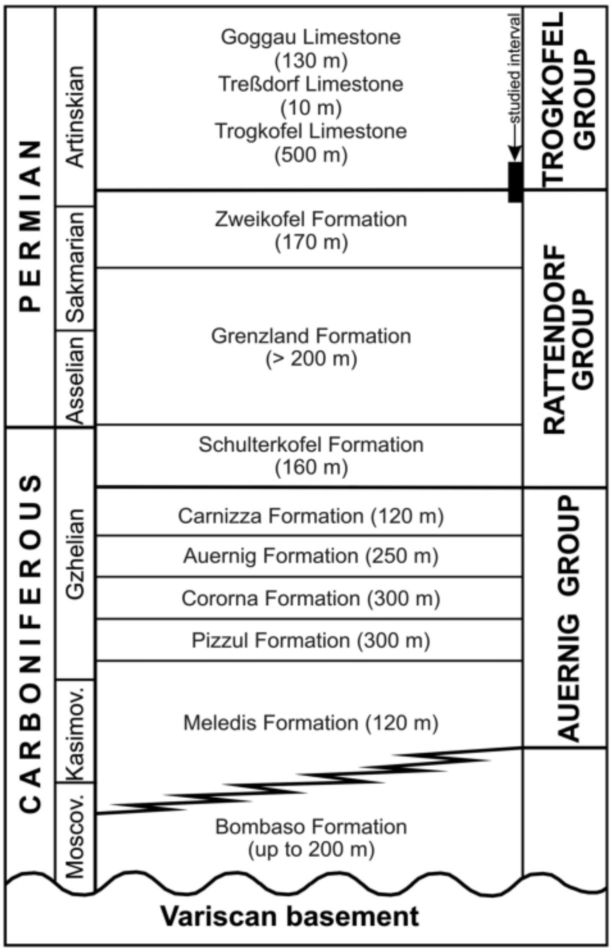


Figure 1: Chrono- and lithostratigraphy of the post-Variscan succession of the Carnic Alps. Heavy black bar indicates the interval described in the present paper (after Krainer and Davydov, 1998; Schönlaub and Forke, 2007).

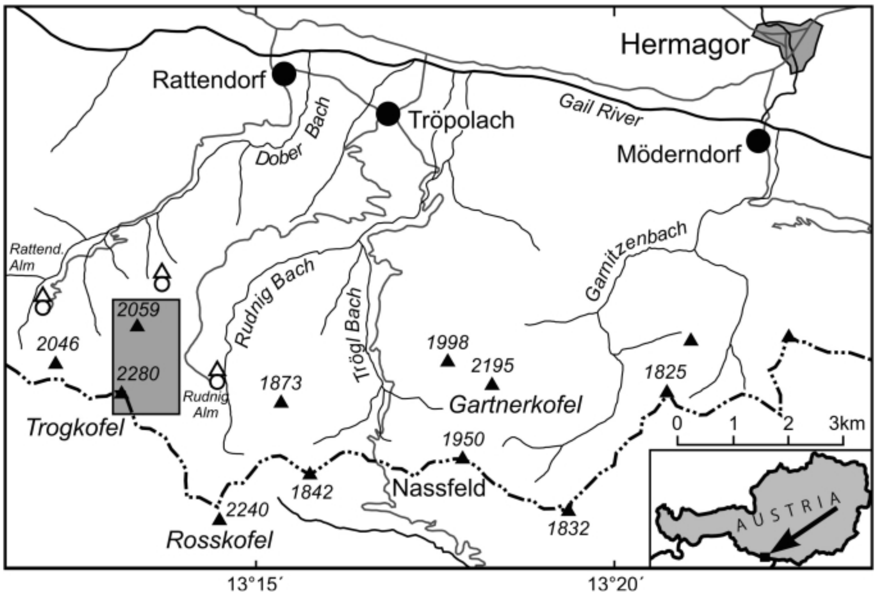


Figure 2: Geographic position of Zweikofel-Trogkofel area (grey shaded rectangle) in the Carnic Alps.

that probably accumulated in subaerial environments, overlain by the Val Gardena Formation, a succession mainly of fluvial sandstones and overbank deposits (cf. Venturini, 1991; Krainer, 1993).

In the present paper, the switch from cyclothemic deposition (part 1 to 3 of basin fill) to deposition of the carbonate succession (part 4) of the Trogkofel Limestone is described in more detail. Cyclothemic deposition persisted over roughly 23 Ma, from Kasimovian to Sakmarian times. From bottom to top of the cyclothemic succession, limestones progressively prevail over siliciclastics (Fig. 4). Near the top of the cyclothemic succession, siliciclastics are confined to beachface

(major part of Auernig Group). (3) A package of mixed siliciclastic-carbonate cyclothems that, up-section, become dominated by neritic limestones (lime mudstones, bioclastic limestones, oncolites, oolites, phylloid-algal limestones) with an intercalated interval dominated by siliciclastic sediments (Rattendorf Group). (4) The succession of the Trogkofel Group, mainly composed of a succession up to about 500 m in preserved thickness of shallow neritic limestones (Trogkofel Limestone) was deposited along the margin of the Pramollo basin. The Trogkofel Limestone is dominated by: (a) *Archaeolithoporella-Tubiphytes* boundstones with abundant fibrous cement, and (b) by shallow-water bioclastic limestones. (5) The Trogkofel Breccia (see Schönlaub and Forke, 2007, for term) and Tarvis Breccia, two intervals of carbonate-lithic breccias

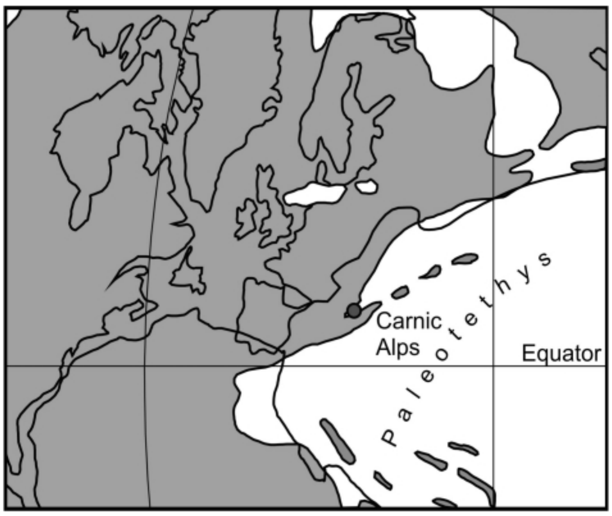


Figure 3: Approximate Early Permian palaeogeographic position of investigated succession (after Ziegler et al., 1996). The depositional area probably was located along a north-dipping shelf that fringed a large bay of Palaeo-Tethys. The surrounding mainland of the bay was represented by the erosional vestige of the Variscan orogen.

quartz conglomerates or to beds of sandstone to siltstone intercalated into neritic limestones. This trend is superposed by a lower-hierarchy arrangement into packages of siliciclastic-dominated and limestone-dominated cyclothems, respectively (Krainer, 1991; Massari et al., 1991). Aside of the vertical change from siliciclastic to limestone prevalence, no major change of cyclothem thickness and no major shift in prevalent depositional settings and palaeo-water depths is discerned; that is, all of the cyclothems accumulated mainly in shore zone to inner shelf environments. This suggests that the overall vertical shift in cyclothem composition was not caused by progressive deepening, but by a decrease of terrigenous input (e. g. because of climatic aridization, or by progressive burial of hinterland relief) and/or by hinged subsidence and widening of a slowly subsiding shelf (cf. Schuster and Stüwe, 2008; see also below). The cyclothems represent the shelfal tracts of glacio-eustatic depositional sequences (Krainer, 1991; Massari et al., 1991). Each or most cyclothems thus probably comprise solely a part of the transgressive systems tract as well as the highstand systems tract.

During the early Paleogene, the area of the Carnic Alps was subject to southwest-vergent thrusting (Doglioni, 1987), followed by southeast-vergent thrusting since the late Miocene (Venturini, 1991; Schönborn, 1999). In addition, southward along the Gailtal Line, the Carnic Alps are riddled by a transtensive fault set composed of: (a) synthetic, NW-trending dextral faults, (b) antithetic, NE-trending sinistral faults, and (c) normal faults that may have a vertical offset of hundreds of meters (Venturini, 1991; Rantitsch, 1997; Schönborn, 1999). As a result, adjacent fault-bounded blocks were not juxtaposed during deposition; this is also expressed in fault-related offset of metamorphic zonations in the post-Variscan cover succession (Rantitsch, 1997).

The outcrops described in the present paper comprise the west- and east slopes of the Zweikofel massif (2059 m a.s.l.), directly north of Trogkofel (2280 m a.s.l., type section of Trogkofel Limestone) (Fig. 5). The Zweikofel massif is offset from the succession of Trogkofel by a fault zone with significant lateral and vertical displacement. At Zweikofel, the cyclothemic succession is capped by a surface of erosion. Up-section, the erosional surface is overlain by: (a) an interval about 40 m thick of Trogkofel limestone with microbial boundstones and carbonate-lithic breccias (Lower Trogkofel Interval, LTI), (b) a package of argillaceous mudstones and intercalated beds of carbonate-lithic rudstones (dubbed 'basinal interval' hereunder), and (c) an interval about 50 m in thickness of Trogkofel Limestone (Upper Trogkofel Interval, UTI). This stratigraphic development is exposed only in the Zweikofel massif. At other locations such as Reppwand, Garnitzenklamm, and Trogkofel (see Fig. 2), the cyclothemic succession is overlain by a single, pure carbonate succession of Trogkofel Limestone. In the cliff along the western face of Zweikofel, sampling of lithologies and documentation of lateral facies relationships were done by roping down from pitches placed at different locations. The other sections were logged in hiking. Cut and polished rock slabs and 150 thin sections were used for documentation of microfacies.

3. Age

The age of the Zweikofel Formation has been tentatively determined by fusulinids and conodonts as late Sakmarian to early Artinskian (see Forke, 2002; Schönlaub and Forke, 2007, p. 54, for discussion). For the overlying package of marls and lithic rudstones, *Neostreptognathodus* cf. *pequopensis* and *Robustoschwagerina spatiosa* suggest a late Artinskian age (Forke, 2002; Schönlaub and Forke, 2007, p. 57). These tentative age data, and our observation of an unconformable contact between the top of the Zweikofel Formation and the interval of unbedded Trogkofel Limestone above suggest the presence of a hiatus, or hiatuses, in the transitional interval from the Zweikofel Formation into the Trogkofel Group (see below for description).

Because of an apparent scarcity in index fossils, the age assignment of the Trogkofel Limestone of the type section to date rests on hypothetical correlations with similar, age-dated sediments in other areas (see discussion in Schönlaub and Forke, 2007, p. 56 f.). In the Trogkofel type section, a low-diverse fauna of fusulinids ("*Pseudofusulina*" ex gr. *fusiformis*, *Biwaella* aff. *americana*) suggests a Sakmarian to Artinskian age (Schönlaub and Forke, 2007, p. 57). Because the limestone succession that comprises the summit of Zweikofel consists of Trogkofel Limestone, this may imply that the Trogkofel Limestone of the type section is partly or entirely of (late) Artinskian age (Schönlaub and Forke, 2007, their Fig. 4). In any case, more biochronostratigaphic data are required to arrive at a better age assignment of the Trogkofel Limestone.

4. Sedimentary facies

Six groups of facies are distinguished (Table 1): (1) Microbial boundstones, composed mainly of a tangled meshwork of tubes of *Girvanella* and similar forms, such as *Koivaella* (Figs. 6A-B). In addition, a few *Tubiphytes*, *Pseudovermiporella* and fenestrate bryozoans may contribute to frame building. Locally, bioclasts (e. g. fusulinids, echinoderm fragments, fragments of calcareous algae) are interspersed within the boundstone fabric. The microbial boundstones are intercalated with lenses and beds of shallow-water bioclastic grainstones to packstones (cf. Flügel, 1980, 1981).

(2) Reefal cementstones: These are composed of an initial framework of interpreted foliose-encrusting red algae (*Archaeolithophyllum*, *Archaeolithoporella*), locally overgrown by scattered *Tubiphytes* and fenestrate bryozoans. The red algal-*Tubiphytes*-bryozoan framework, in turn, is filled by thick botryoidal fringes of fibrous cement, such that the final fabric is dominated by cement (up to more than 50% by volume) (Fig. 6C). In detail, encrustation-to-cementation successions may be repetitive. Intrinsic pores between cement fringes typically contain geopetal infillings of lime mudstone, and/or of micropeloidal grainstone to packstone that may contain a few bioclasts (e. g., fusulinids and smaller benthic foraminifera). This

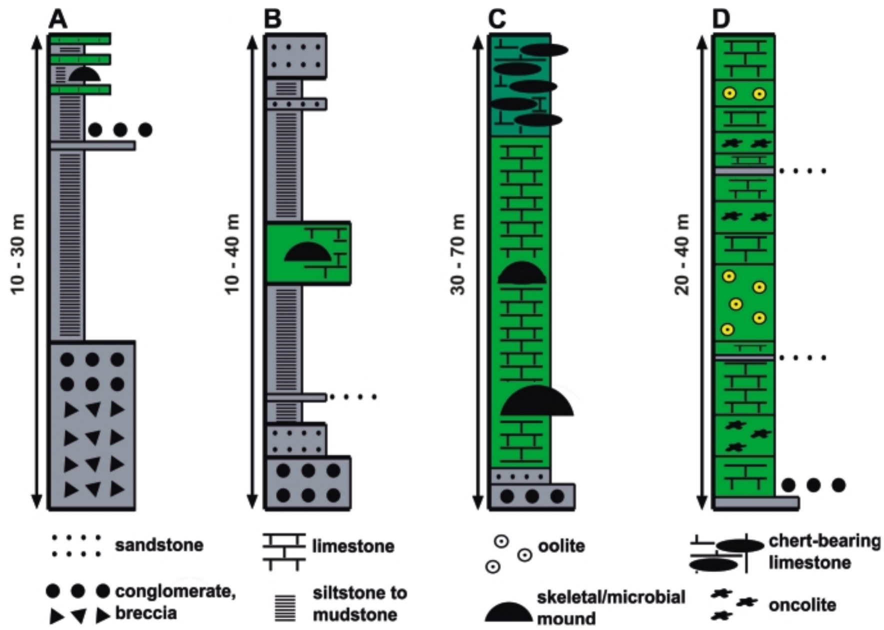


Figure 4: Cartoon to illustrate vertical change of cyclothem composition in the Kasimovian to Sakmarian p. p. succession of the Carnic Alps. Up-section, from the lowest part of the cyclothemic succession (column A) to its top (column D), siliciclastics (grey colour) decrease in abundance whereas neritic limestones (green colour) increase in relative proportion. Throughout the cyclothemic succession, however, no major shift of depositional palaeowater depths and no major change of cyclothem thickness is discerned. See text for further discussion.

facies resembles the *Tubiphytes-Archaeolithoporella* boundstone of Flügel (1980, 1981). Karstic cavities in the reefal cementstones are filled with light red to dark red lime mudstone to carbonate siltstone.

(3) Bioclastic limestones: These comprise: (3a) Bioclastic grainstones rich in fusulinids, smaller benthic foraminifera (*Tetrataxis*, *Tuberitina*), and fragments of molluscs, calcareous green algae and phylloid algae. The bioclasts typically are well-rounded with a micrite envelope. A few bioclasts may show a thin oncoidal coating. These grainstones typically are faintly thick-bedded or unbedded; in polished slabs, they are characterized by indistinct lamination subparallel to bedding. Bioclastic grainstones from the Lower Trogkofel Interval may show well-developed micritic meniscus cements (Fig. 6D). (3b) Bioturbated bioclastic wackestones to packstones to grainstones with abundant fragments of the phylloid alga *Neoanchicodium*, echinoderms, green algae, and rare *Tubiphytes*. Grain rounding and micritization of bioclasts is highly variable both among and within individual samples. In the Lower Trogkofel Interval, bioclastic wacke- to packstones may show: (i) circumgranular cracking, (ii) short extensional cracks with a geopetal infilling of lime mudstone, micropeloidal grainstone, or carbonate siltstone, and (iii) biomoulds (e. g. after molluscs) with a geopetal fill of lime sediment.

(4) Carbonate-lithic breccias to arenites: These include a wide spectrum of (stylo-)rudstones to floatstones to (stylo-)grainstones and packstones of angular to rounded clasts. According to their field presence, two types are distinguished: (4a) Litho-bioclastic rudstones to floatstones in the basal part of and intercalated into the Lower Trogkofel Interval. These consist of clasts of shallow neritic limestones with a facies inventory typical for the Zweikofel Formation (e. g., dasycladacean fragment packstones, bioclastic limestones with fusulinids and fragments of phylloid algae, phylloid-algal limestones). Within some of the clasts, in turn, rounded lithoclasts of similar lithologies were observed that may be coated by a thin oncoidal crust. In addition to lithoclasts, isolated bioclasts (e. g. echinoderms, bryozoans) are present (Figs. 6E-F). (4b) Beds and bedsets of bouldery breccias to breccias to arenites (grainstones, packstones) above the Lower Trogkofel Interval, vertically associated with argillaceous mudstones (see below). Most lithoclasts are derived from erosion of lithologies with a similar facies inventory as the Trogkofel Limestone of the type section. Other clasts, however, are of different facies and may stem from unpreserved, inner-shelf facies belts of the 'Trogkofel platform' or, again, from the underlying cyclothemic succession. Many clasts had undergone dolomitization and/or karstification prior to erosion. The bouldery breccias to arenites comprise sharp- or erosive-based beds up to about 2 meters in thickness. The breccias are clast- to matrix-supported, and may be present in graded or non-graded beds. A few of the breccia beds are slumped. The breccias consist mainly of lithoclasts derived from erosion of *Archaeolithoporella-Tubiphytes* reefal cementstones (Fig. 6G). In addition, lithoclasts of fenestral *Girvanella-Tubiphytes* boundstones are present that are similar to the boundstones of the Lower Trogkofel Interval. Vertically across clast-supported beds of breccias, coarse-tail grading typically is conspicuous only in the uppermost part of beds. Similarly, beds of arenites may be ungra-

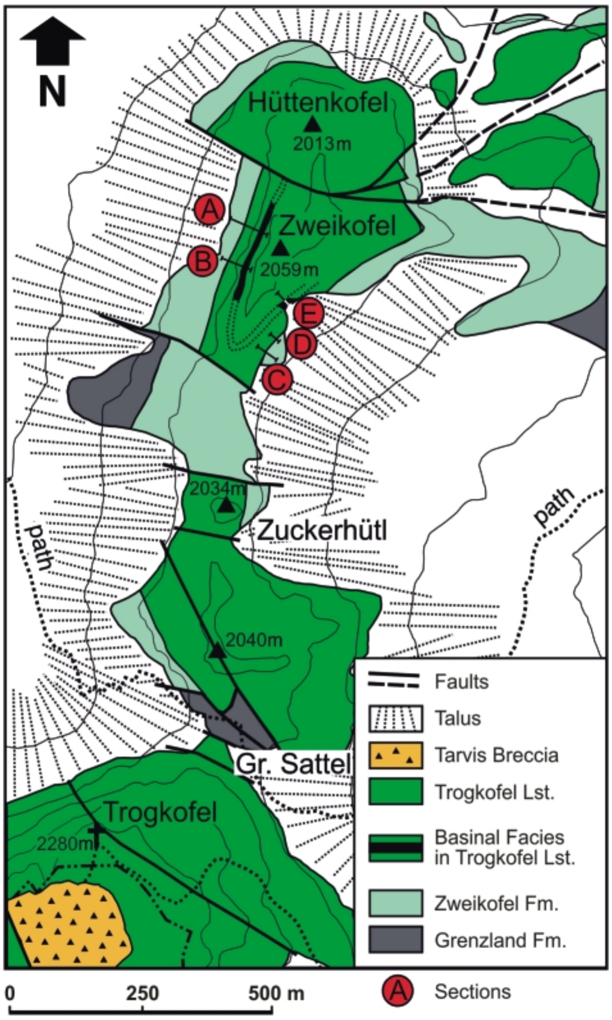
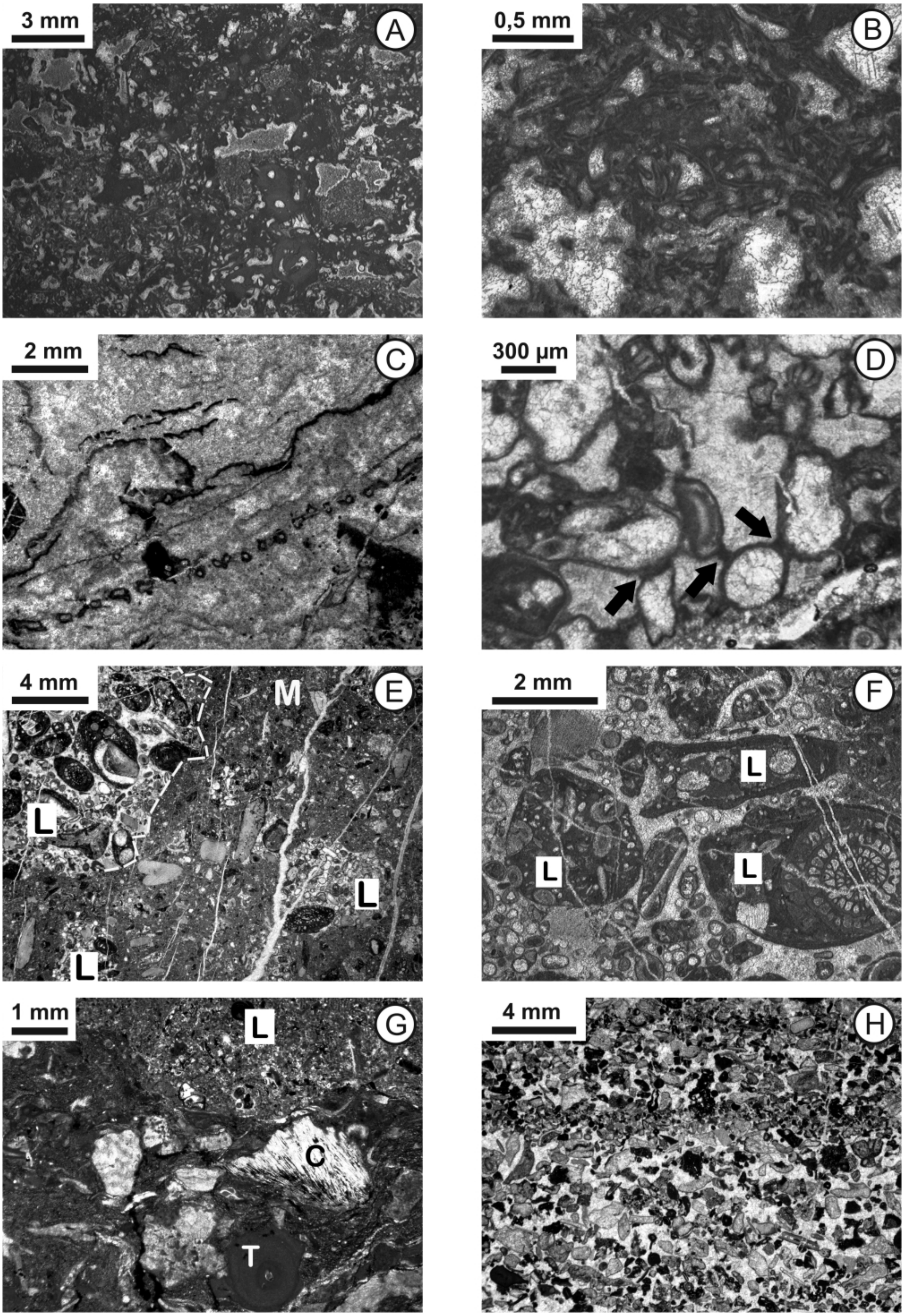


Figure 5: Geological map of Trogkofel - Zweikofel area (modified from Schönlaub and Forke, 2007). At Großer Sattel, the Trogkofel massif in the South is separated from the Zweikofel massif in the North by a fault zone of unknown but presumably large offset.

Figure 6: Thin section photomicrographs of limestone microfacies of Zweikofel massif (see also Table 1). A: Fenestral boundstone composed of tangled meshwork of Girvanella and Koivaella, locally with interspersed Tubiphytes. B: Detail of microbial boundstone. Tangled meshwork of tubes of Koivaella. C: Reefal cementstone, composed of primary framework of fenestrate bryozoans and Tubiphytes, overgrown by thick fringes of cement (light grey areas) with intercalated crusts of Archaeolithoporella (blackish streaks). D: Grainstone composed of cement-filled biomoulds after bioclasts with a micrite envelope. Note micritic meniscus cements at grain contacts. E: Very poorly sorted lithoclastic floatstone with a matrix (M) of litho-bioclastic wackestone. Lithoclasts (L) are derived from limestones similar to those of the Zweikofel Formation. F: Detail from within a lithoclast of floatstone facies as shown in Fig. 6E. Note rounded lithoclasts (L) that bear a thin oncoidic coating. G: Detail from bed of litho-bioclastic rudstone. Note lithoclast (L) of limestone, clast (C) of fibrous cement, and isolated bioclast of Tubiphytes (T). H: Thin section of graded bed of litho-bioclastic arenite. Note rounding and thin micrite envelopes on many grains.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ded or show coarse-tail grading (Fig. 6H). Where present, the lime mudstone matrix of arenites to rudstones is locally replaced by a small-crystalline, anhedral dolomite of xenotopic fabric. Many of the lithoclasts of the rudstone beds show features of meteoric-vadose diagenesis, such as micritic meniscus cements, and/or (micro)karstic cavities filled by yellow to reddish lime mudstone (locally replaced by small-crystalline anhedral dolomite).

(5) Mudstones to marly limestones: Argillaceous mudstones to marly lime mudstones-wackestones are confined to a single interval of the Zweikofel massif. The mudstones are of blackish tint upon fracture, and may contain a few bioclasts (echinoderm fragments, foraminifera, small brachiopods), pyritized bioclasts and pyrite framboids. The marly lime mudstones to bioclastic wackestones are characterized by shallow-water bioclasts (echinoderms, molluscs, *Tubiphytes*, bryozoans, fusulinids).

(6) Internal breccias: Discordant dykes of highly irregular shape and width, and filled by carbonate-lithic breccias, were observed within the LTI and the UTI, as well as within facies 4B. The internal breccias consist of an extremely poorly sorted, unordered mix of boulders to sand-sized grains of carbonate rocks; the fabric ranges from clast- or matrix-supported. The margins of breccia dykes may be sharply defined, or the breccia 'grades' into the adjacent limestone via a stylolitization zone typically a few centimeters in width. Many breccia clasts of gravel- to sand size are extremely angular with acute edges and deep pits. The matrix is a yellow to light red weathering dolostone with a xenotopic fabric of small-sized, anhedral crystals (Fig. 7). The clasts of the breccias comprise the same facies spectrum as the adjacent limestones. In a few clasts, veins and vugs filled by red marly lime mudstone to siltstone identical to the karstic infills within the adjacent, unbrecciated limestones were observed.

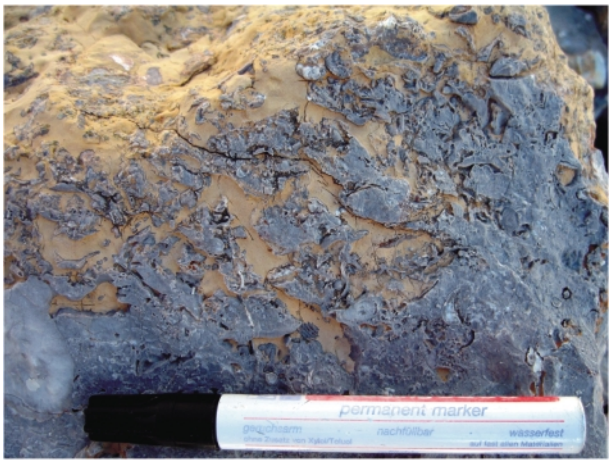

Figure 7: Detail from the margin of a discordant dyke of intraclastic breccia. The adjacent limestone (grey) grades into the dyke via a zone wherein the host limestone becomes progressively replaced by dolomitized lime mudstone (weathering with ocre tint), along a sharp contact of extremely irregular shape. Farther inside the dyke, the host limestone is represented only by extremely angular, lithoclasts floating toppled within the dolomitized matrix. Pen is 14 cm in length.

5. Succession and depositional geometries

5.1 Cyclothems of Zweikofel Formation:

In the western face of Zweikofel, the upper part of the Zweikofel Formation is exposed (Fig. 9). There, the cyclothems record facies shifts from sharp-based, quartz-gravelly beachface conglomerates to carbonate inner-shelf environments; the inner shelf record is characterized by oolites, oncolites, and shallow-water bioclastic limestones (see also Sanders and Krainer, 2005). In between the marker intervals of quartzose shore zone deposits, however, no clear-cut pattern of facies superposition is seen: oolites, oncolites and bioclastic limestones overlie each other without obvious order. Several of the intervals of quartz conglomerates start with a distinct erosive base. Up-section from the base, in a few intervals of quartz conglomerates, mean grain size decreases and the content in bioclasts and lime-muddy matrix increases; this suggests that the 'genetic' cycle boundary is situated at the top of the underlying limestones (=base of intervals of quartz conglomerates). The quartz conglomerates thus are interpreted as transgressive deposits. In the eastern face of Zweiko-

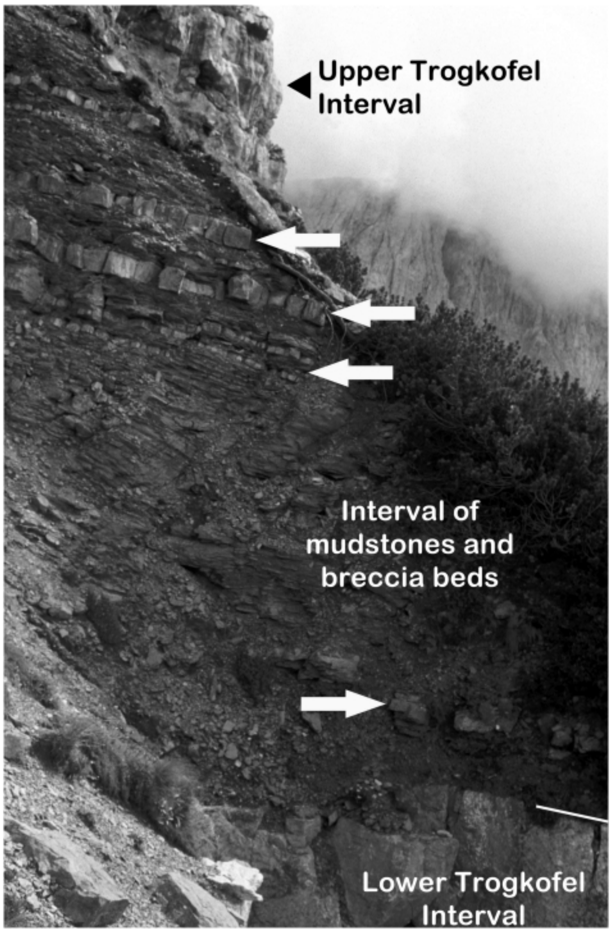

Figure 8: The top of the Lower Trogkofel Interval is a sharply defined surface (indicated by white line). The surface is overlain by an interval of argillaceous mudstones with sharply intercalated beds of carbonate-lithic breccias to arenites (=basinal interval of text). A few of the intercalated beds are labelled by white arrows. Higher up in photo, the basal part of the Upper Trogkofel Interval is visible.

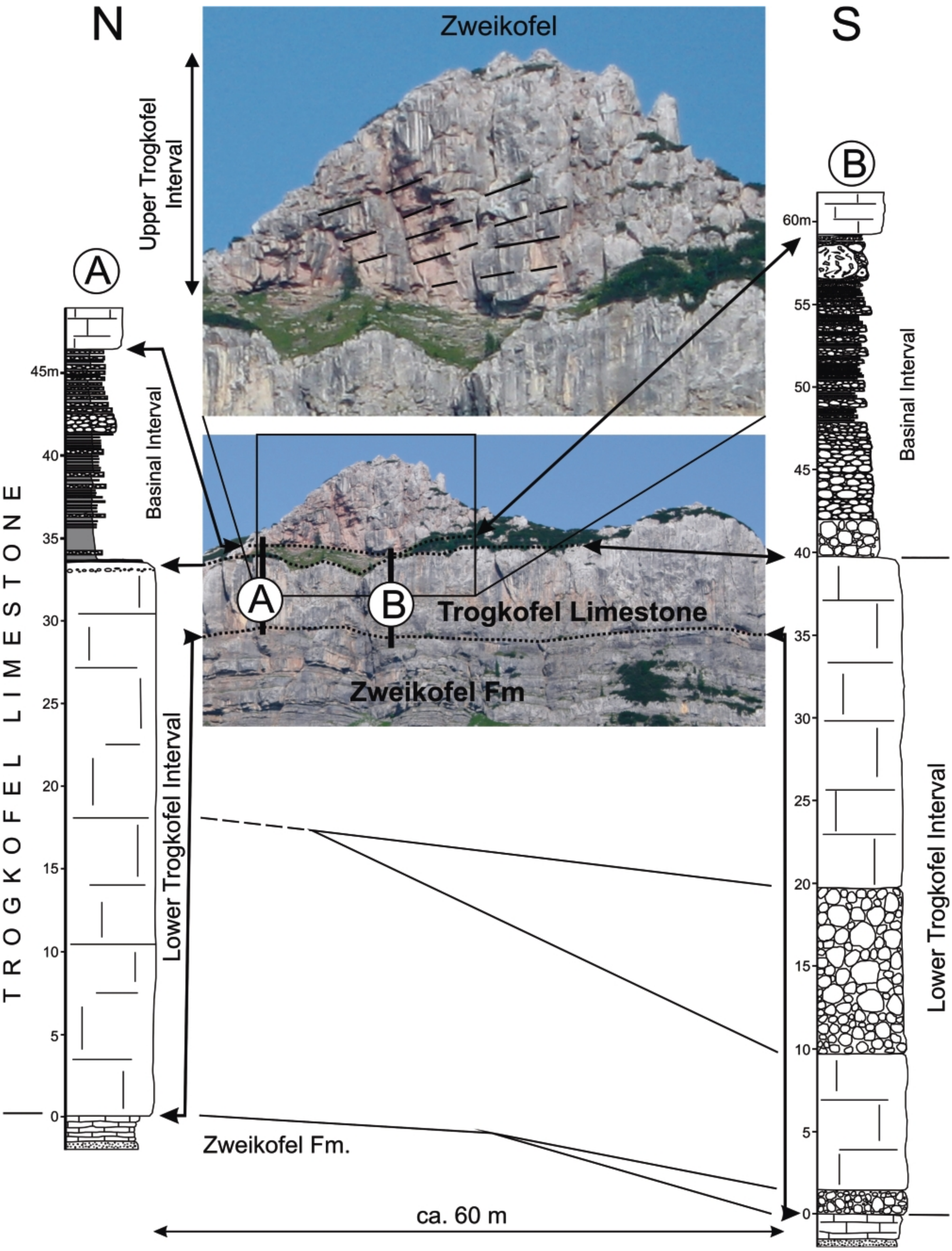

Figure 9: Western cliff of Zweikofel massif, with sections A and B. In section A, the Zweikofel Formation is overlain by a lower interval of Trogkofel Limestone (Lower Trogkofel Interval, LTI, see text). In section B, the Zweikofel Formation is unconformably overlain by breccias at the base of the LTI. The LTI, in turn, consists of bioclastic limestone, microbialites, and of intercalated intervals of breccias that pinch out laterally. LTI is sharply overlain by an interval of mudstones with intercalated beds of breccias to arenites (see Fig. 7B). Above, up to the summit of Zweikofel, the Upper Trogkofel Interval (UTI) consists of bioclastic limestones and reefal cementstones identical to that observed in the type section of the Trogkofel Limestone (cf. Fig. 5). In the UTI, gently-dipping bedding surfaces are present that suggest progradation of a carbonate slope with an apparent component towards present NNE to N.

fel, the topmost terrigenous deposit is a bedset of bioturbated sandstone (Fig. 10). The difference between the topmost terrigenous deposits in the eastern and western face of Zweikofel, respectively, may be related to proximal-distal gradients of facies over a lateral distance of about 200 meters (cf. Fig. 5) and/or to erosional truncation at the base of the Lower Trogkofel Interval (see below).

5.2 Boundary Zweikofel Formation-Trogkofel Group:

In the western face of Zweikofel, the boundary between the cyclothemic Zweikofel Formation and the overlying Trogkofel Group is a surface of erosion that locally is obvious by truncation of underlying strata (Fig. 11). In addition, the boundary is locally overlain by carbonate-lithic breccias. Within these breccias, as mentioned, clasts of limestones of facies comparable to the Zweikofel Formation are present. Over most of its extent, however, the boundary is just a sharp, subconcordant vertical transition. Similarly, in the eastern face of Zweikofel, the boundary seems to be concordant, but locally also is overlain by carbonate-lithic breccias (see description of facies above) that appear to show a northward lapout, with a few degrees, relative to their base.

5.3 Lower Trogkofel Interval (LTI):

The Lower Trogkofel Interval is characterized by unbedded limestone with intercalated carbonate-lithic breccias. A few of the breccias unequivocally are internal breccias as seen in the outcrops of the eastern face of Zweikofel. As far as lateral facies relations could be unraveled by roping down in the western cliff, however, and in view of the accessible outcrop in the eastern face of Zweikofel, some intervals of breccias are clearly of sedimentary origin (facies 4a). In these breccias to stylobreccias, many lithoclasts contain microkarstic cavities with infillings of red, argillaceous lime mudstone. In addition, crystal aggregates reminiscent of Microcodium were observed in a few of the clasts.

The western, unbedded face of the LTI yields a spectrum of facies, mainly microbial boundstones (facies 1) and bioclastic grainstones to packstones (facies 3). In a few samples of microbial boundstones and bioclastic limestones, a micritic crust up to

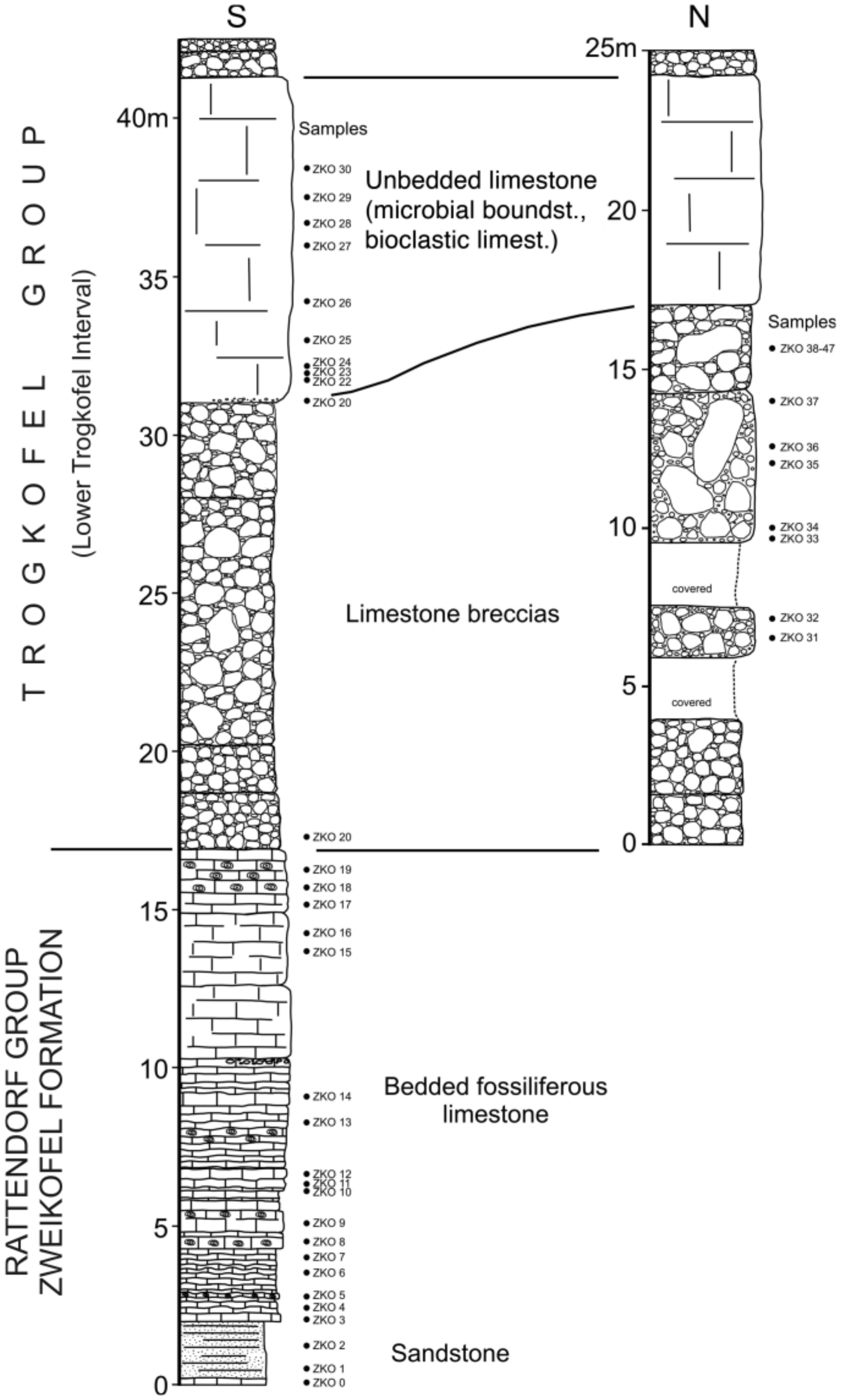

Figure 10: Sections along eastern side of Zweikofel (cf. Fig. 5). Here, the Zweikofel Formation is overlain by a bedset of litho-bioclastic rudstones to floatstones (cf. Fig. 6E-F). Above, an interval of unbedded limestones is present that consists of microbial boundstones and, near its top, of bioclastic limestones. Together, the interval of rudstones to floatstones and the overlying limestones comprise the Lower Trogkofel Interval.

a few millimeters thick is present. The crusts are of slightly irregular, undulating shape; they extend roughly subparallel to bedding across entire thin sections. Along the lower side of these crusts, fossils are truncated.

5.4 Top of Lower Trogkofel Interval:

The vertical transition from the LTI into the overlying mudstones is sharply defined (Fig. 8). The top surface of the LTI is locally offset by post-depositional normal faults. Consideration of the top surface between normal faults, however, suggests that it has a comparatively gentle undulating relief along the contact with the overlying mudstones. In addition, the top surface at least locally (where outcrops allow for) is coated by a porous, limonitic crust up to about 2 cm in thickness. In the ravine along the western face of Zweikofel, where the contact is exposed and accessible, the limonitic crust is directly overlain by a bed composed of laminae of bioturbated bioclastic calcisiltite interlaminated with lime mudstone.

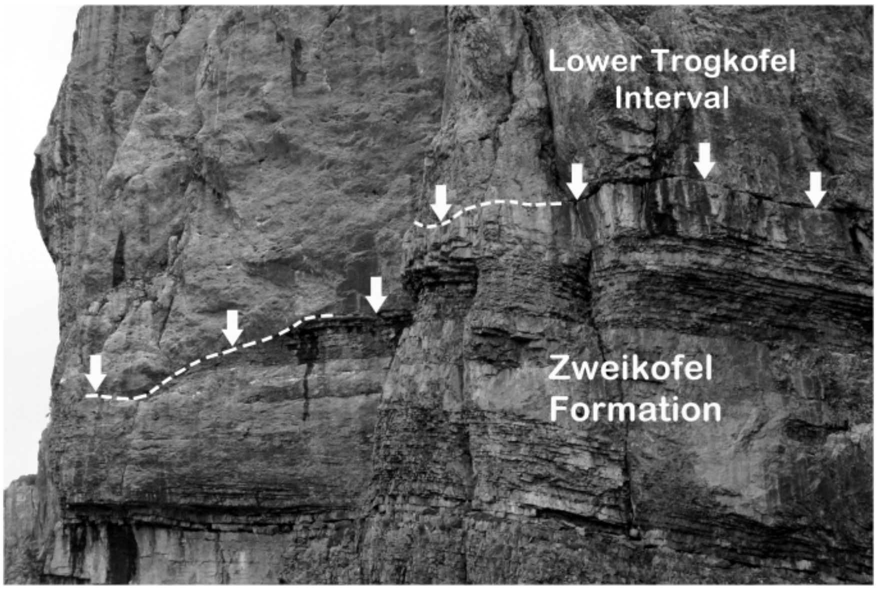

Figure 11: Detail of western cliff of Zweikofel. The succession of parallel-bedded limestones of the Zweikofel Formation is truncated and overlain by the Lower Trogkofel Interval. Height of view in foreground about 7 meters.

5.5 Interval of mudstones with intercalated beds:

(='Sonderfazies' of Schönlaub and Forke, 2007, p. 56-58)

As described, the breccias consist mainly of clasts of Trogkofel Limestone and, subordinately, of carbonate rock clasts of unknown derivation (?Zweikofel Formation). Up-section, overall, intervals of mudstones become thinner; concomitantly beds/bedsets of breccias and arenites become more densely-spaced and, overall, more coarse-grained up-section (Fig. 9). From bottom to top of the interval, no major change in prevalent microfacies of breccia clasts was identified. In addition, the overall content of lime mud seems to increase up-section through the interval, giving rise to beds of marl. The vertical distribution of mudstones versus breccias does not indicate a clear-cut pattern. While bedsets of breccias become more densely-spaced up-section, this is not accompanied by a comparable increase in grain size and bed thickness; for sake of brevity, this pattern is hereunder designated as 'upward-frequencing'.

5.6 Upper Trogkofel Interval (UTI):

As far as accessible to rock sampling, the UTI consist of reefal cementstones (facies 2) and bioclastic limestones (facies group 3). In the western face of Zweikofel, the UTI is riddled by surfaces with a distinct northward component of dip, and that show a tangential lapout relative to their base (Fig. 9). As far as well-accessible in outcrop, tracing of these surfaces in outcrop shows that they represent genuine bedding surfaces (not shear faults related to compaction of underlying sediments), that is, beds thin and pinch out towards the north. On the eastern side of Zweikofel, due to defacement of a mass of boulders along faults and joints into a slow mass movement, the mentioned bedding planes are hardly to trace in outcrop. Also the Upper Trogkofel Interval is riddled by karstic veins and dykes filled by internal breccias as described.

6. Interpretation

The Zweikofel Formation accumulated from quartz-gravelly beachface to shallow subtidal, inner carbonate shelf environments with ooid bars (Sanders and Krainer, 2005). At Zweikofel, the Zweikofel Formation is capped by a surface of erosion that is locally overlain by carbonate-lithic rudstones to floatstones. As outlined (section Age), the hiatus across this erosional surface may comprise part of the Artinskian stage. In the overlying LTI, the microbial boundstones with Tubiphytes and fenestrate bryozoans probably accumulated from carbonate mounds; this interpretation is further supported by sampling of microbial boundstones at several locations in the rock cliff on the western face of Zweikofel. Lateral to the mounds, level-bottoms of bioclastic sand to lime-muddy bioclastic sand were present. The fine-grained fenestral grainstones in the LTI may have accumulated under wave surf (cf. Inden and Moore, 1983), possibly in the topmost part of carbonate mounds. In the bioclastic limestones of the LTI, the micritic meniscus cements, the circumgranular cracking, and the geopetal infill of lime mud into biomoulds (e. g. after mollusc shells) record meteoric-vadose diagenesis. Unfortunately, in our rock samples we could not unequivocally identify an emersion surface, that is, a limestone/limestone-contact within the LTI separated by an exposure surface (cf. James, 1972; Fouke et al., 1996). The faintly bedded to unbedded, carbonate-lithic rudstones to floatstones intercalated into the LTI accumulated during marine transgression and reworking onto subaerially exposed limestone. The prevalent angular to subrounded shapes of the clasts, and their presence in very poorly sorted rudstone to floatstone texture records relatively low mean water energy during reworking; if these deposits had formed in a transgressive shore zone of high energy, carbonate-lithic conglomerates may be expected (cf. Sanders, 1997, 1998; Sanders and Höfling, 2000). The observed 'second-cycle clasts' with oncoidic coating record repeated phases of transgressive erosion of older limestones, separated by episodes of marine flooding and sedimentation. The entire LTI may be viewed as a composite mound consisting of microbial boundstones, bioclastic limestones and intercalated lithic rudstones to floatstones. Together, the evidence from facies and diagenesis of the LTI do not indicate a major deepening relative to the Zweikofel Formation, but record carbonate deposition sheltered from coarse-grained siliciclastic input. Shelter from terrigenous input may result from a more distal, but not significantly deeper position on a carbonate shelf (minor backstep in Fig. 12), or from a change of nearshore transport regime (cf. Roberts et al., 1977; Bush, 1991). The sharp, gently undulating surface on top of the LTI perhaps had formed during subaerial erosion. This surface may encompass another hiatus within the Artinskian.

Above the LTI, the interval of mudstones with intercalated beds of carbonate-lithic breccias to arenites accumulated in a deep neritic to, perhaps, upper bathyal environment. The sharp vertical transition from LTI into the mudstones thus records a significant deepening and backstep of facies (Fig. 12). The few bioclasts (echinoderm fragments, small brachiopods) found within the mudstones are of little palaeobathymetric indication. Unfortunately, the small size of preservation of the

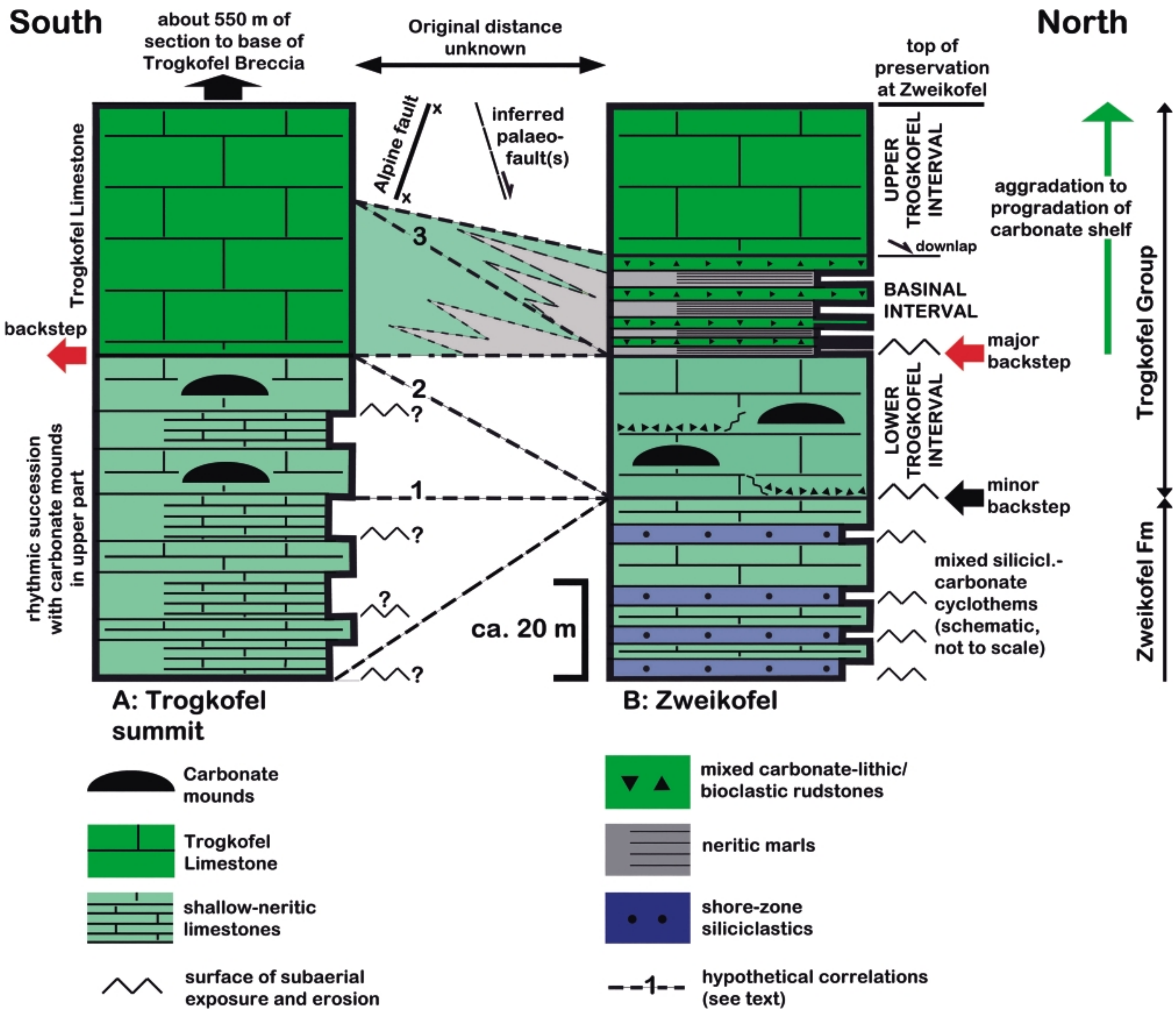

FIGURE 12: Cartoon showing main characteristics of sedimentary successions at Zweikofel and Trogkofel. A: At Trogkofel, the lower part of succession consists of decameter-scale rhythms composed of (a) medium-bedded limestones changing vertically with (b) very thick-bedded limestones that contain carbonate mounds; this succession is overlain by the unbedded Trogkofel Limestone. B: At Zweikofel, a package of mixed siliciclastic-carbonate cyclothems (Zweikofel Formation) is overlain by a succession as described in the text. The 'basinal interval' at Zweikofel correlates in time with deposition of Trogkofel Limestone, probably farther towards the present south. None of the possible correlation lines 1 to 3, however, can at present be proven or discarded. For the lower part of the successions, time correlation is highly uncertain (correlation lines labelled by question tags). See text for further description and discussion.

Upper Trogkofel Interval also does not allow for a good estimate of depositional water depth of the mudstones (see below). The composition of the breccias mainly of clasts of (karstified) Trogkofel Limestone records penecontemporaneous erosion, at unknown locations. The clasts may originally stem from fan deltas on subaerially exposed limestone terrain, or from a transgressive marine shore zone, or from submarine fault scarps; because of the limited preservation of the Trogkofel Limestone and its lateral equivalents, none of these possibilities can be definitely excluded. Within some of the rudstone clasts, the karstic cavities filled by yellow to red weathering lime mudstone (that subsequently became dolomitized) strongly suggest that these limestones had been subject to subaerial exposure and karstification prior to final deposition; the time of dolomitization, however, is not established. The presence of the breccias to arenites in sharp-based beds, intercalated into the succession of mudstones, indicates that they represent event deposits. The normal grading of some beds of breccias and arenites indicates that they were deposited from waning flows with suspended sediment load, probably turbidity currents. Clasts of gravel to boulder size may be transported by several processes, such as low-density turbidity currents, debris flows, and storm-induced fluid flows. The ungraded, chaotic beds with cobbles to boulders probably deposited from debris flows, or were transported by a low-density turbidity current that passed a debris-flow stage during waning of flow (Mutti et al., 2009). Low-density turbidity currents and debris flows may have been triggered by modified storm-fluid flows ('storm turbidites'), earthquakes near site, tsunamis, or heavy storms. The upward-frequencing of the breccias may have been caused by a change in the main trajectory of transport and/or by approach of their source area.

In the Upper Trogkofel Interval, the beds with a northward component of apparent dip and a tangential lapout relative to their base are interpreted as slope clinoforms. Because the surfaces of the clinobeds could not be measured, their true dip may be steeper than that seen in Figure 8. Both the upward-frequencing of breccia beds in the 'basinal' interval and the clinoforms in the UTI reflect progradation of the Trogkofel Limestone platform over the bathymetrically deeper area of the basinal interval. Because of the limited preservation of the UTI, however, the total height of the carbonate slope can not be estimated. Shedding even of megabreccia beds not necessarily requires slopes hundreds of meters or more in vertical height (Hine et al., 1992). We interpret the UTI as a record of highstand progradation of the Trogkofel Limestone platform over the 'basinal' succession of mudstones plus breccias. The interpretation of the Upper Trogkofel Interval as a highstand deposit is consistent with the succession of the type section of the Trogkofel Limestone (cf. Schaffhauser et al., 2009).

In the Zweikofel massif, the discordant dykes and pods filled by internal breccias formed during later subaerial exposure and karstification. Similarly, the type section of the Trogkofel Limestone is riddled down to its base by karstic veins, dykes and caverns with multiple infillings of internal sediments (e. g. breccias, lime mudstone, dolomitized lime mudstone; see also Schönlaub and Forke, 2007).

7. Discussion

The backstep of facies that caused the vertical change from

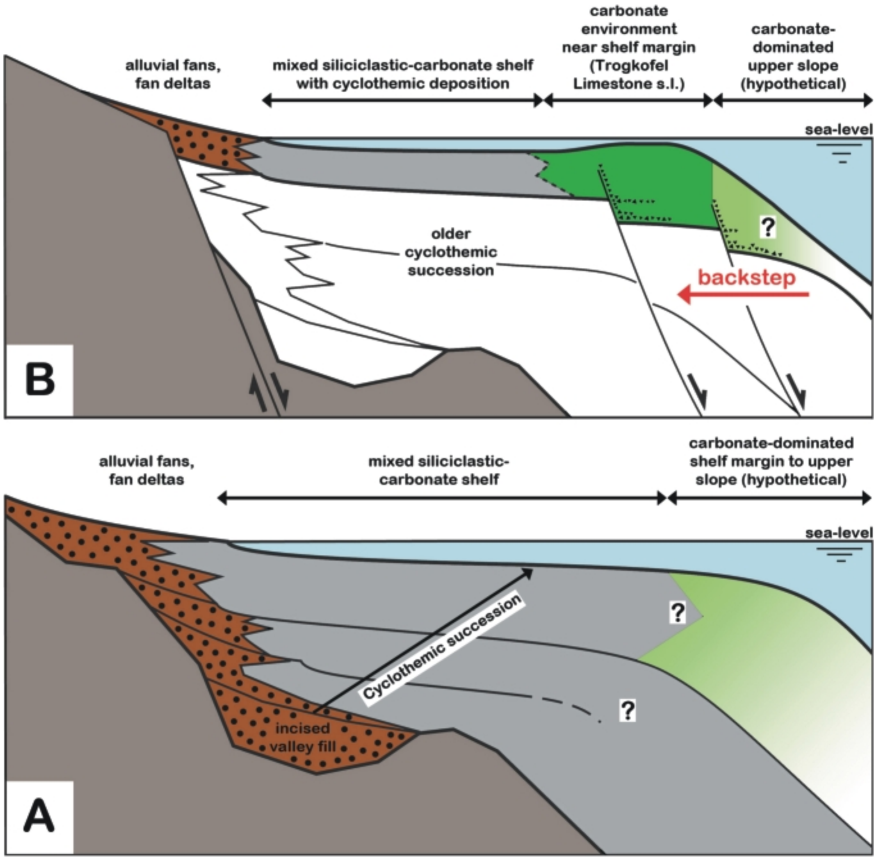

Figure 13: Scheme to illustrate major depositional phases. A (Kasimovian to Sakmarian): As a result of base-level rise ahead of marine transgression, incised valleys and fault-bounded grabens were filled by local-sourced clastics. Upon continued marine encroachment a slowly subsiding, mixed siliciclastic-carbonate shelf established that persisted for roughly 23 Ma. Near the shelf edge, a more-or-less pure carbonate environment possibly had established during the ?late Carboniferous to earliest Permian, but is not preserved. B (?Sakmarian pro parte, Artinskian): Upon downfaulting, the shelf margin stepped back. Near the shelf edge, a shallow neritic carbonate environment characterized by bioclastic sands and reefal mounds established (Trogkofel Limestone). Landward of the carbonate facies belt, mixed siliciclastic-carbonate deposition may have persisted. Faulting, differential subsidence and formation of internal breccias remained active during deposition of the carbonate shelf-edge succession.

mixed siliciclastic-carbonate cyclothemic deposition into the basinal succession (mudstones + breccias) and, higher up, into the Trogkofel Limestone results from downfaulting and foundering of the shelf margin (Fig. 13). A backstep of facies is indicated not only in the Zweikofel massif. In the type section of the Trogkofel Limestone, a backstep is recorded by a vertical change from a succession of well-bedded shallow neritic Trogkofel limestones with intercalated carbonate mounds below to unbedded Trogkofel Limestone above (unpubl. data). At Trogkofel, faulting and seismic activity concomitant to closely subsequent to deposition of the Trogkofel Limestone are also indicated by: (a) dykes of multi-phase cataclastic breccias sealed by geopetally-infilled lime mudstones, and (b) karstic caverns with multiple generations of geopetal infillings with convolute lamination (internal seismites) (Schönlaub and Forke, 2007; Schaffhauser et al., 2009).

As outlined above (section Geological Setting), during the late Pennsylvanian to early Permian the area of the Carnic Alps was characterized by development of slowly subsiding, fault-bounded basins. An overall low rate of subsidence is supported by the persistence, over about 20 Ma, of a shelf with mixed siliciclastic-carbonate cyclothemic deposition. Massari et al. (1991) had pointed out that with respect to their overall facies architecture and typical thickness, the cyclothems of the Carnic Alps are not radically different to those from stable epicratonic settings. For the early Permian of the Alps, Schuster and Stüwe (2008) had tested a model of heterogeneous lithospheric stretching to combine high-temperature/low-pressure metamorphism with magmatism, slow subsidence and graben formation.

The Pennsylvanian and early Permian were characterized by glacio-eustatic sea-level changes. For the cyclothemic succession of the Carnic Alps, a long-standing interpretation is that cyclicity was steered by glacio-eustasy (Krainer, 1991; Massari et al., 1991; Samankassou, 1997). Yet the vertical transition from the cyclothemic succession into the Trogkofel Limestone seems to indicate a termination of cyclicity. In the Trogkofel Limestone, however, sea-level changes most probably are recorded but in a different fashion, such as by multiple phases of karstification and subaerial exposure surfaces. 'Limestone/limestone' contacts, along sequence boundaries produced by glacio-eustasy, are well-known from Quaternary carbonate shelves (Enos and Perkins, 1977; Alexander et al., 2001). More detailed investigations into the Trogkofel Limestone will however be necessary to decipher its more subtle records of sea-level changes. In the Carnic Alps the first tectonic movements of the early Permian deformation phase (referred to the “Saalian orogenic phase” by many authors), which culminated during the Kungurian, started already during the early Artinskian and influenced the depositional processes of the Trogkofel Limestone.

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