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2nd International Congress on Stratigraphy
STRATI 2015
19. - 23. July 2015, Graz, Austria

Sylvain Richoz [ed.]

Field trips in the Eastern and Southern Alps (Austria, Italy)

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FT-2 Triassic/Jurassic							FT-9 Pre-Variscan Carnic Alps			

The Pre-Variscan sequence of the Carnic Alps

Carlo Corradini, Monica Pondrelli, Thomas J. Suttner & Hans Peter Schönlaub

with contributions from
Maria G. Corriga, Annalisa Ferretti, Erika Kido, Luca Simonetto & Claudia Spalletta

30 figures

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Contents

Abstract

The Pre-Variscan sequence of the Carnic Alps includes rocks deposited between the Middle Ordovician and the early Late Carboniferous, and represents one of the most continuous sequence of the world in that time interval. In a relatively small area it is possible to distinguish rocks deposited at various latitudes and climate (from cold in the Ordovician to tropical in the Devonian), and in different sedimentary environments (from shallow water, including reef deposition, to basin). The lithostratigraphy of the sequence has been recently revised and formalised, and 36 formations have been discriminated.

1. Topics and area of the Field Trip

The Carnic Alps are located along the Italian-Austrian border (Fig. 1). One of the better exposed and complete Palaeozoic sequences of the world, is here exposed.

Fig. 1. Location of the Carnic Alps.

Rocks deposited between the Middle Ordovician and the Upper Triassic crop out in the Carnic Alps. They are subdivided into three sequences: the Pre-Variscan, the Permo-Carboniferous and the Alpine sequences. The Pre-Variscan sequence includes rocks of Middle Ordovician to early Late Carboniferous age, which were affected by the Variscan orogeny during the late Bashkirian and Moscovian (SCHÖNLAUB, 1980; VENTURINI, 1990; SCHÖNLAUB & FORKE, 2007). The Variscan orogeny had its climax during the Moscovian and affected the Pre-Variscan sequence, producing different systems of asymmetric folds, faults and thrusts distributed along a N 120°-140°E direction (VENTURINI, 1990). The Permo-Carboniferous sequence ranges from the Late Carboniferous to the Middle Permian. The youngest Palaeozoic rocks of the Carnic Alps are Late Permian and Middle Triassic in age, and are part of the so-called ‘Alpine’ sequence (VENTURINI, 1990).

Fig. 2. Road map of the Carnic Alps, with indication of the areas visited during the field trip. Black rectangle: Day 1 (Fig. 7); red rectangle: Day 2 (Fig. 10); blue rectangle: Days 3-4 (Fig. 20). The yellow rectangle enhance the village of Dellach, where the Visitor Centre of the Carnic Alps Geopark is located.

The field trip focuses on the Pre-Variscan sequence, with special attention to the newly established lithostratigraphic subdivision (CORRADINI & SUTTNER, 2015). Several sections and outcrops in the central part of the Carnic Alps will be visited during the four days field trip (Fig. 2) and thus provide a chance to recognise the great majority of the 36 formations which were recently revised and newly defined in the area. All the localities will be reached by hiking on well-marked paths in a mountain environment. This will give also the opportunity to visit some military evidences (trenches, fortifications, cemeteries) of First World War: in fact, the Carnic Alps were theater of hard fighting in that period. A visit to the Visitor Centre of the Carnic Alps Geopark is also scheduled.

2. Geological overview

The Carnic Alps are located along the Italian-Austrian border. One of the better exposed and complete Palaeozoic sequences of the world, ranging from the Middle Ordovician to the Permian/Triassic boundary up to the Middle Triassic, is here exposed.

The "Palaeocarnic Chain" is considered as a part of the Variscan ancient core of the Eastern Alps in the Southalpine domain, and extends as a narrow strip for more than 100 km in a W-E direction, with a N-S width that rarely exceeds 15 km (Fig. 3). To the North it is bordered by the Gailtail Line, part of the Periadriatic Lineament, separating the Austroalpine domain from the Southalpine domain; towards the S it is unconformably covered by Upper Palaeozoic and Triassic successions (VENTURINI & SPALLETTA, 1998; SCHÖNLAUB & FORKE, 2007). The Palaeocarnic Chain can be subdivided into two parts (Fig. 3), separated by the Val Bordaglia thrust (BRIME et al., 2008), a prominent NE-SW trending fault: the western zone is made of greenschist facies metamorphic rocks, the eastern zone mainly consists of sedimentary successions (SCHÖNLAUB, 1980, 1985, 1997; VENTURINI & SPALLETTA, 1998; BRIME et al., 2008) except for the northernmost part where banded limestones occur.

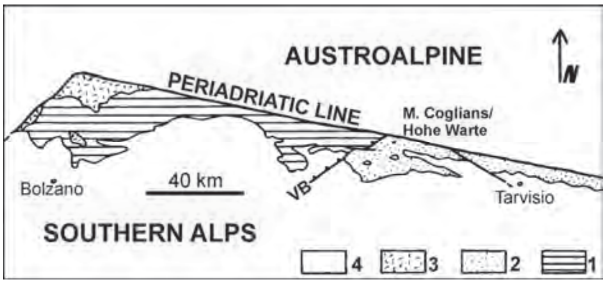

Fig. 3. Simplified geological map of the Southern Alps showing the partition of the Palaeocarnic Chain into a West and an East Zone (VENTURINI & SPALLETTA, 1998, modified). VB: Val Bordaglia thrust; 1: Low to middle grade metamorphic basement; 2: Non- to anchi-metamorphic units; 3: Variscan intrusive bodies; 4: Post-Palaeozoic units.

The Carnic Alps underwent compressional as well as extensional deformational events during Variscan and Alpine times, which originated a complex structural framework including some low metamorphic terrains of Variscan age (Fig. 4) (BRIME et al., 2008; BARTHEL et al., 2014).

According to VENTURINI (1990), Variscan compression originated roughly N120°E trending top to the south thrusts and folds. The first Alpine compression of Chattian-Burdigalian age is coaxial with the Variscan one, thus reactivating the older structures and enhancing their shortening (VENTURINI, 1990). The two more recent Alpine events (Tortonian-Serravallian and Plio-Pleistocene respectively) depict a strike-slip stress regime also with some compressional and extensional features (VENTURINI, 1990). These phases were very important to originate pluri-kilometer-scale vertical folding along the Gailtal and Bordaglia lines while in the rest of the Carnic Alps they fragmented the previously formed structural setting mostly by high angle strike-slip faults.

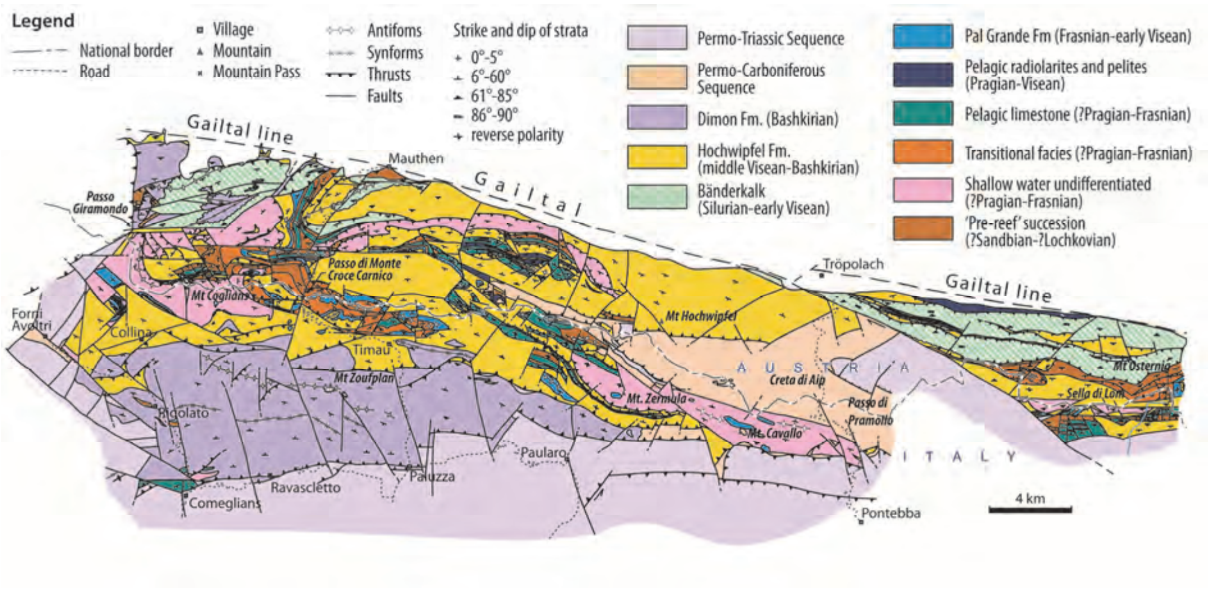

Fig. 4. Sketch of the geology of the Carnic Alps (after BRIME et al., 2008, simplified).

According to BARTHEL et al. (2014) in a N-S profile along the axis of maximum shortening between the Drau Range and the Friuli Southalpine wedge five kinematic groups can be distinguished: (1) N-S compression; (2) NW-SE compression; (3) NE-SW compression, Ʊ3 changes gradually from subvertical to subhorizontal; 4) N-S compression; and (5) NW-SE compression. The authors concluded that the deformation sequence on either side of the PAF (Periadriatic Fault) is similar.

2.1 Palaeogeographic remarks

During the early Palaeozoic the Carnic Alps belong to those group of terrains that detached from the northern Gondwana margin within the Ordovician, and moved northward faster than the main continent (Fig. 5a). These terranes, often indicated as Galatian terrane assemblage (VON RAUMER & STAMPFLI, 2008), include among others the Pyrenees, Montagne Noire, Sardinia, the Graz Palaeozoic, Barrandian and Saxothuringian, beside the Carnic Alps (Fig. 5b). However, the mutual position of these areas, and their distance from the emerged continents is not completely clear.

Important is to note that the drift from about 50°S in the Late Ordovician, to 35°S in the Silurian and to tropical belt in the Devonian (SCHÖNLAUB, 1992) is reflected in clear evident differences in litho- and biofacies along the Carnic Alps.

2.2 The Pre-Variscan sequence

The oldest rocks of the Carnic Alps are Middle Ordovician in age (Fig. 6) and crop out west of the Val Bordaglia Line. They are represented by phyllitic schists and quartzites, with subordinate conglomeratic layers (Val Visdende Fm.), followed by porphyroids (Comelico Fm.) and volcano-clastic sediments (Fleons Fm.).

With the exception of local fossil occurrences in the Fleons Fm., the most ancient fossiliferous rocks of the Carnic Alps belong to the Valbertad Fm. (Katian). They are

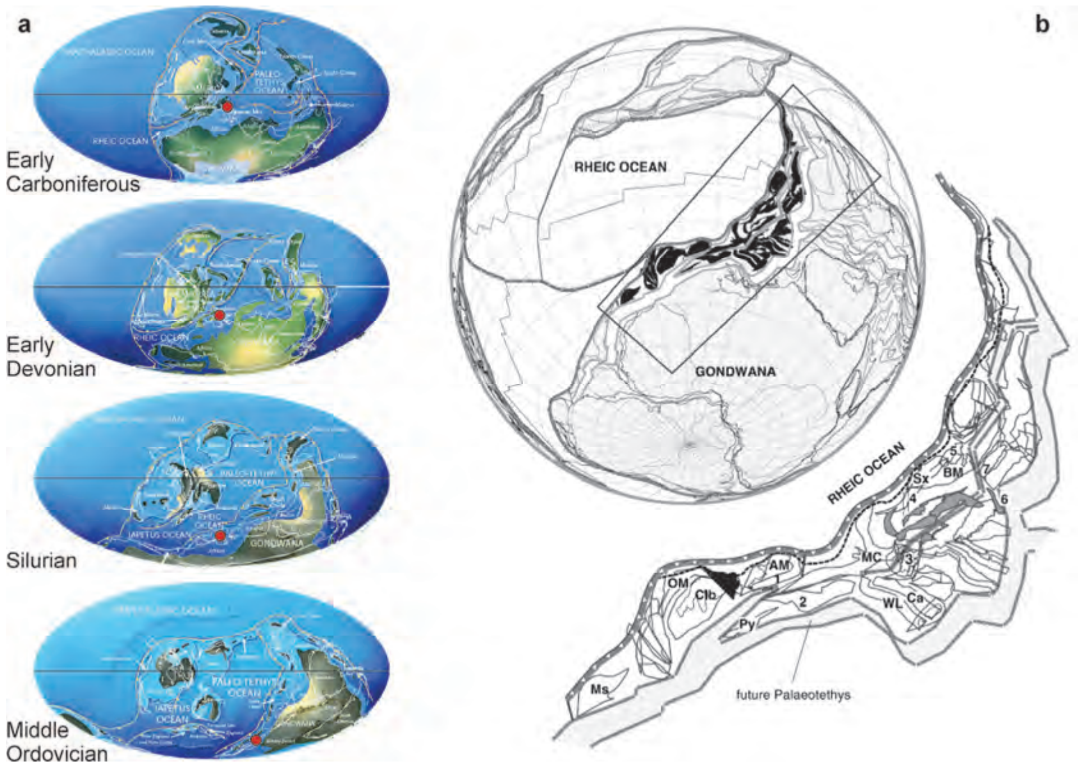

Fig. 5. Palaeogeography of the Carnic Alps. a) Position of the Carnic Alps (red circle) from the Ordovician to the Lower Carboniferous (maps after www.scotese.com). b) Global tectonic situation at the beginning of the Devonian (after von Raumer & Stampfli, 2008) and detail of the Galatian terrane assemblage. 1: Southern Brittany; 2: North Spain; 3: Sardinia; 4: S. Black Forest; 5: Barrandian; 6: Carnic Alps; 7: Graz Palaeozoic. AM: Armorican Massif; BM: Moldanubian part of the Bohemian Massif; Ca: Cantabrian Zone; Clb: Central Iberia; MC: French Massif Central; Ms: Meseta; OM: Ossa Morena Zone; Py: Pyrenees; Sx: Saxothuringian; WL: Westasturian Leonese Zone.

represented by up to 100 m of shallow-water pelites, sandstones and rare conglomerates deposited at medium-high southern latitudes. Fossils, mainly bryozoans, brachiopods, echinoderms, trilobites and gastropods, are abundant. In the central part of the basin a coarser grained sandstone unit (Himmelberg Fm.) crops out. The basal clastic sequence is followed by an encrinitic parautochthonous limestone (Wolayer Fm.) in the central part of the chain and by the coeval slightly-deeper-water limestones of the Uqua Fm. Both these units are late Katian in age, even so an extension to the basal Hirnantian cannot be excluded. The global glacially-induced regression of the Hirnantian is documented by the calcareous sandstone of the Plöcken Fm., providing evidence of the HICE $\delta^{13}C$ excursion (Schönlaub et al., 2011). It resulted in erosion and local non-deposition, as also indicated by Silurian strata resting disconformably upon the Upper Ordovician sequence (Schönlaub & Histon, 1999; Brett et al., 2009; Hammarlund et al., 2012; Pondrelli et al., 2015a).

Silurian deposits are irregularly distributed within the Carnic Chain, and range from shallow water bioclastic limestones to nautiloid-bearing limestones, interbedded shales and limestones to deep-shelf or basinal black graptolitic shales and cherts ("lydites"). The overall thickness does not exceed 60 m. The Silurian transgression started at the base of the Llandovery, and, due to the disconformity separating the Ordovician and the Silurian, an unknown thickness of sediments is locally missing, which corresponds to several conodont zones of Llandovery to Ludlow age (Schönlaub & Histon, 1999; Brett et al., 2009; Štorch & Schönlaub, 2012; Corradini et al., 2015a).

The Silurian of the Carnic Alps is subdivided into four lithological facies representing different depths of deposition and hydrodynamic conditions (SCHÖNLAUB, 1979, 1980; WENZEL, 1997). The Wolayer facies is characterised by proximal sediments, while the Bischofalm facies corresponds to deep water euxinic deposits. The Plöcken facies and the Findenig facies are intermediate between the ones mentioned above. In rough approximation, the four facies seem to be distributed north-west to south-east in the central sectors of the chain. The depositional features suggest an overall transgressional regime from Llandovery to Ludlow times. Uniform limestone sedimentation within the Prídoli suggests that more stable conditions developed (SCHÖNLAUB, 1997).

In terms of lithostratigraphy, three calcareous units are vertically developed in the proximal parts of the basin: the Kok Fm. (Telychian-lower Ludfordian), the Cardiola Fm. (Ludfordian) and the Alticola Fm. (upper Ludfordian-basal Lochkovian). These units mostly correspond to the "*Orthoceras* limestones" of earlier authors, and are represented by bioclastic wackestones-packstones. Nautiloid cephalopods are very abundant. Trilobites, bivalves and conodonts are common; crinoids, gastropods and more rare ostracods, brachiopods and chitinozoans are present as well (BRETT et al., 2009; CORRADINI et al., 2010, 2015a; HISTON, 2012).

In the deeper part of the basin, the Bischofalm Fm. was deposited. It is a tripartite succession, up to 60 m thick, of black siliceous shales, with cherts interbedded (1), clayish alum shales (2), and black graptolitic shales (3) which mainly were deposited in a euxinic environment. Graptolites are generally abundant (JAEGER, 1975; JAEGER & SCHÖNLAUB, 1977, 1994; SCHÖNLAUB, 1997). Intermediate sedimentary conditions between calcareous and shaley facies are represented by the Nölbling Fm., composed of alternating black graptolitic shales, marls and limestone beds (JAEGER & SCHÖNLAUB, 1980; SCHÖNLAUB, 1997).

During the Lochkovian (Lower Devonian) the Carnic basin started to differentiate (SCHÖNLAUB, 1992; KREUTZER, 1990, 1992; KREUTZER et al., 1997; HUBMANN et al., 2003; SUTTNER, 2007; CORRIGA et al., 2012). The Seekopf Fm. was deposited in moderately shallow water, and the Rauchkofel Fm. and La Valute Fm. on the outer platform. In the deeper parts of the basin the Nölbling Fm. and the Bischofalm Fm. continued up to the top of the stage (*M. hercynicus* graptolite Zone).

Starting from the upper Lochkovian, differences within the sedimentary basin increased: "the Devonian Period is characterised by abundant shelly fossils, varying carbonate thicknesses, reef development and interfingering facies ranging from near-shore sediments to carbonate buildups, lagoonal and slope deposits, condensed pelagic cephalopod limestones to deep oceanic off-shore shales" (SCHÖNLAUB & HISTON, 1999: 15). From the Pragian to the lower Frasnian, within short distances a strongly varying facies pattern developed, indicating highly diverse depths in the basin. More than 1000 m of reef and near-reef limestones (Hohe Warte Fm., Seewarte Fm., Lambertenghi Fm., Spinotti Fm., Kellergrat Fm.) and various intertidal lagoonal deposits (Polinik Fm.) are time equivalent to less than 100 m of pelagic limestones (Findenig Fm. and Valentin Fm.). In the intermediate fore-reef areas thick piles of mainly gravity-driven deposits accumulated (Kellerwand Fm., Vinz Fm., Cellon Fm., Freikofel Fm.). Pelites and cherts were deposited in the deeper part of the basin (Zollner Fm.). Between the fore-reef and the deeper part of the basin the gravity driven deposits alternated with pelagic limestone and black shales (Hoher Trieb Fm.).

Reefs reached their maximum extension during the Givetian and early Frasnian, when the present Carnic Alps were at a latitude of about 30° S (SCHÖNLAUB, 1992). Four major reef areas developed, now represented by the cliffs of Mt. Coglians/Hohe Warte, Mt. Zermula,

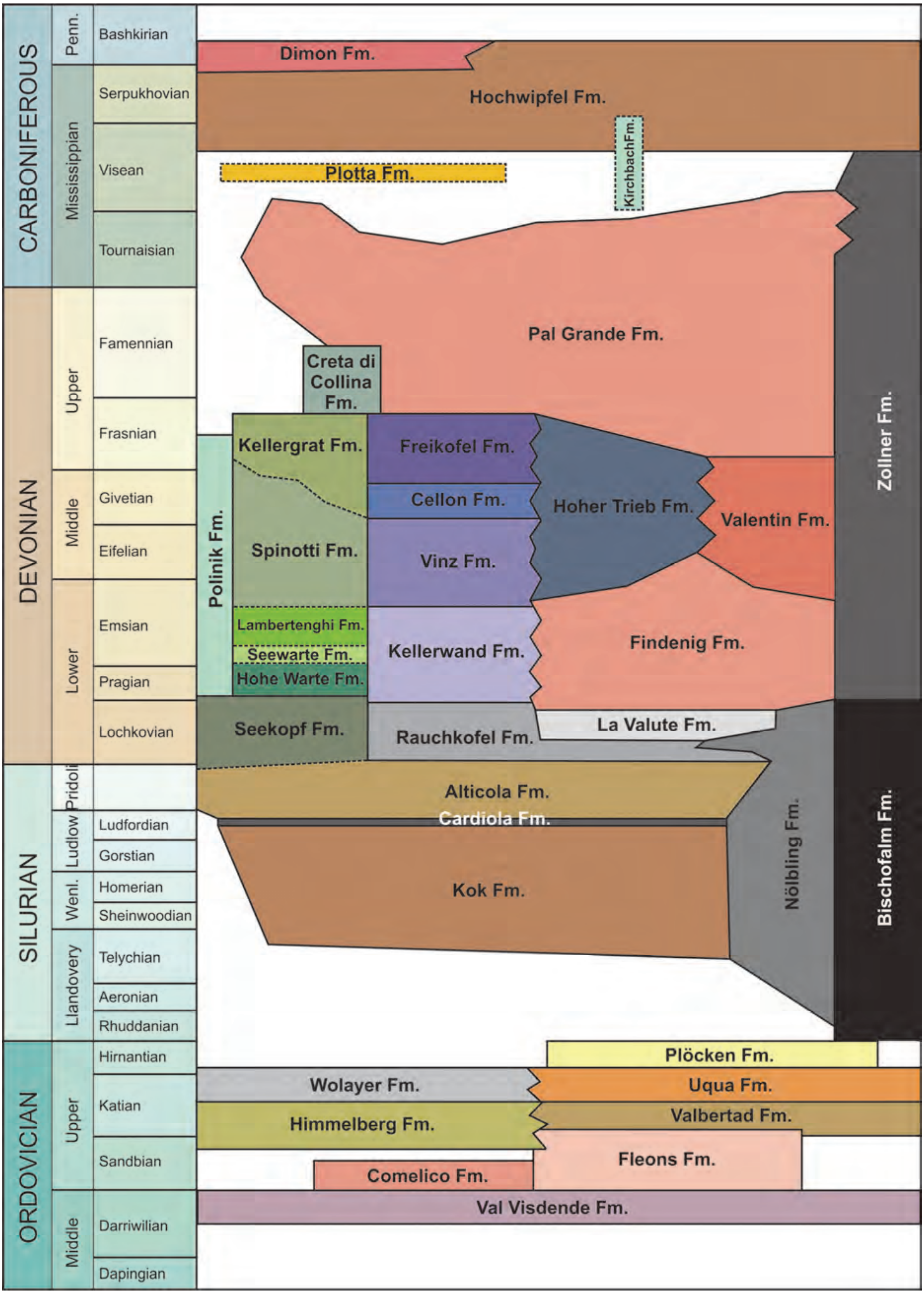

Fig. 6. General lithostratigraphic scheme of the Pre-Variscan sequence of the Carnic Alps (CORRADINI & SUTTNER, 2015).

Mt. Cavallo/Roßkofel and Mt. Oisternig, beside several minor buildups. The fossil content is always very high: stromatoporoids, tabulate and rugose corals, brachiopods, crinoids, gastropods, ostracods, bivalves, cephalopods, trilobites, algae, calcispheres, and foraminifers (KREUTZER, 1990, 1992; KREUTZER et al., 1997; SCHÖNLAUB, 1992; RANTITSCH, 1992).

During the early Frasnian, extensional tectonic activity caused collapse of the basin and consequently reefs rapidly drowned and reefal organisms disappeared. Starting from the upper Frasnian (Upper *rhenana* conodont Zone) a uniform pelagic environment developed, which continued up to the lowermost Visean (SCHÖNLAUB, 1969; SCHÖNLAUB & KREUTZER, 1993; PERRI & SPALLETTA, 1998): the Pal Grande Fm. is represented by a greyish, pinkish, reddish wackestone with cephalopods. At places cherty sediments (Plotta Fm.) unconformably capped the Pal Grande Fm. indicating a palaeokarstic event in the lowermost Carboniferous (SCHÖNLAUB et al., 1991).

Starting from the upper Visean, up to 1000 m of arenaceous pelitic turbidites of the Hochwipfel Fm. were deposited. It is interpreted as a Variscan Flysch sequence (VAI, 1963; AMEROM et al., 1984; SPALLETTA & VENTURINI, 1988 and references therein). These deposits indicate a Variscan active plate margin in a collisional regime following the extensional tectonics during the Devonian and the Early Carboniferous (SCHÖNLAUB & HISTON, 1999). The Hochwipfel Fm. consists of quartz-sandstones and greyish shales, turbidites, with intercalations of mudstones, chaotic debris flows and chert and limestone breccias. At place plant remains are present and rare trace fossils can be found (AMEROM et al., 1984; AMEROM & SCHÖNLAUB, 1992). Short local episodes of carbonatic deposition during the Lower Visean to the Serpukhovian boundary are represented by the Kirchbach Fm. In the upper part of the Early Carboniferous, the basic volcanites and volcanoclastic deposits of the Dimon Fm. occur. They are related to crustal thinning associated to a rifting episode (VAI, 1976; ROSSI & VAI, 1986; LÄUFER et al., 1993, 2001). These conditions continued up to the Late Bashkirian (Late Carboniferous), when the Hercynian orogeny in the Carnic area marked the end of the deposition of the Pre-Variscan sequence (VENTURINI, 1991).

2.3. Summary of the lithostratigraphic units

A complete description of the lithostratigraphic units of the Pre-Variscan sequence of the Carnic Alps (Fig. 6) is available in volume 69 of the *Abhandlungen der Geologischen Bundesanstalt* (CORRADINI & SUTTNER, 2015).

3. The Field Trip

3.1. Mt. Cellon area (Day 1)

We will leave Graz moving westward on the highway A2 up to Villach, and we will continue along the Gail Valley to Dellach where we will stop at the Visitor Centre of the Geopark of the Carnic Alps. Then, we will proceed through Kötschach-Mauthen to Plöckenpass/Passo di Monte Croce Carnico (1360 m). We will park close to the Austrian/Italian border, and we will continue by foot in a narrow mountain path up the Cellon section.

3.1.1. Stop 1 – Cellon section

The Cellon section is located in a narrow avalanche gorge on the eastern flank of Mt. Cellon, at an altitude of about 1500 m, at coordinates 46°36'32" N, 12°56'31" E, close to the Austrian/Italian border. It is reachable by a short walk from Plöcken Pass/Passo di Monte Croce Carnico (Fig. 7).

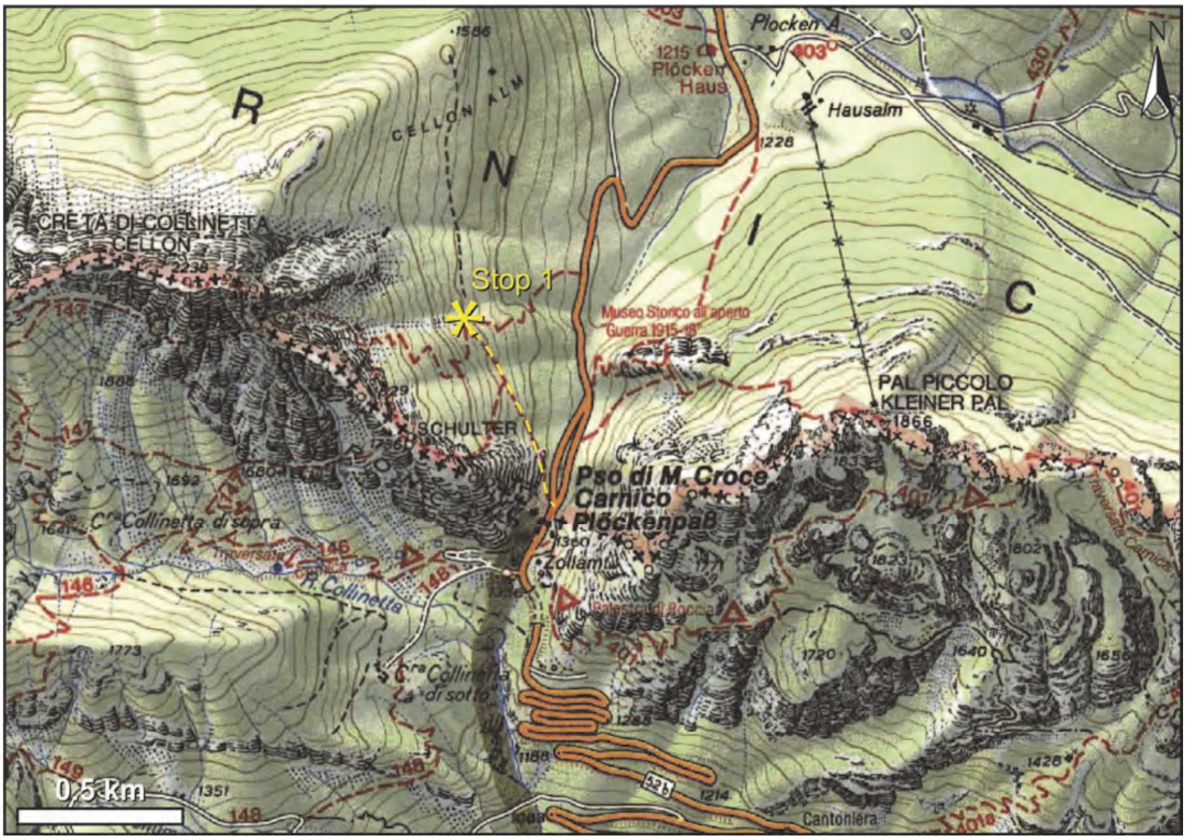

Fig. 7. Topographic map with indication of the itinerary of Day 1 and location of the Cellon section (stop 1).

It probably represents the most famous Silurian section in the world, and is the reference section for many Silurian studies. The conodont fauna from the section was studied and described by WALLISER (1964), whose pioneering work on the section included the first proposed Silurian conodont zonation. Subsequent studies on the Cellon section have documented the composition and distribution of several fossil groups, microfacies, isotope signatures, taphonomic and palaeoenvironmental indicators and eustatic sea-level changes (SCHÖNLAUB & LAMMERHUBER, 2009). For a complete review of the previous studies on the Cellon section, and a revision of the Silurian conodont biostratigraphy, refer to CORRADINI et al. (2015a).

The section exposes rocks from the Upper Ordovician to the Lower Devonian and represents the classical exposure of the Silurian "Plöcken facies". However, although the conformable sequence suggests continuity of sedimentation, several small gaps have been recognised, reflecting eustatic sea level changes in an overall shelf water environment (SCHÖNLAUB et al., 1994).

The following lithostratigraphic units can be recognised (from base to top) (Figs. 8–9):

1) Valbertad Formation. Lithology: greenish and greyish siltstones and shales. Thickness: More than 100 m. Age: Katian based on the occurrence of the deep-water *Foliomena* brachiopod fauna (HARPER et al., 2009).

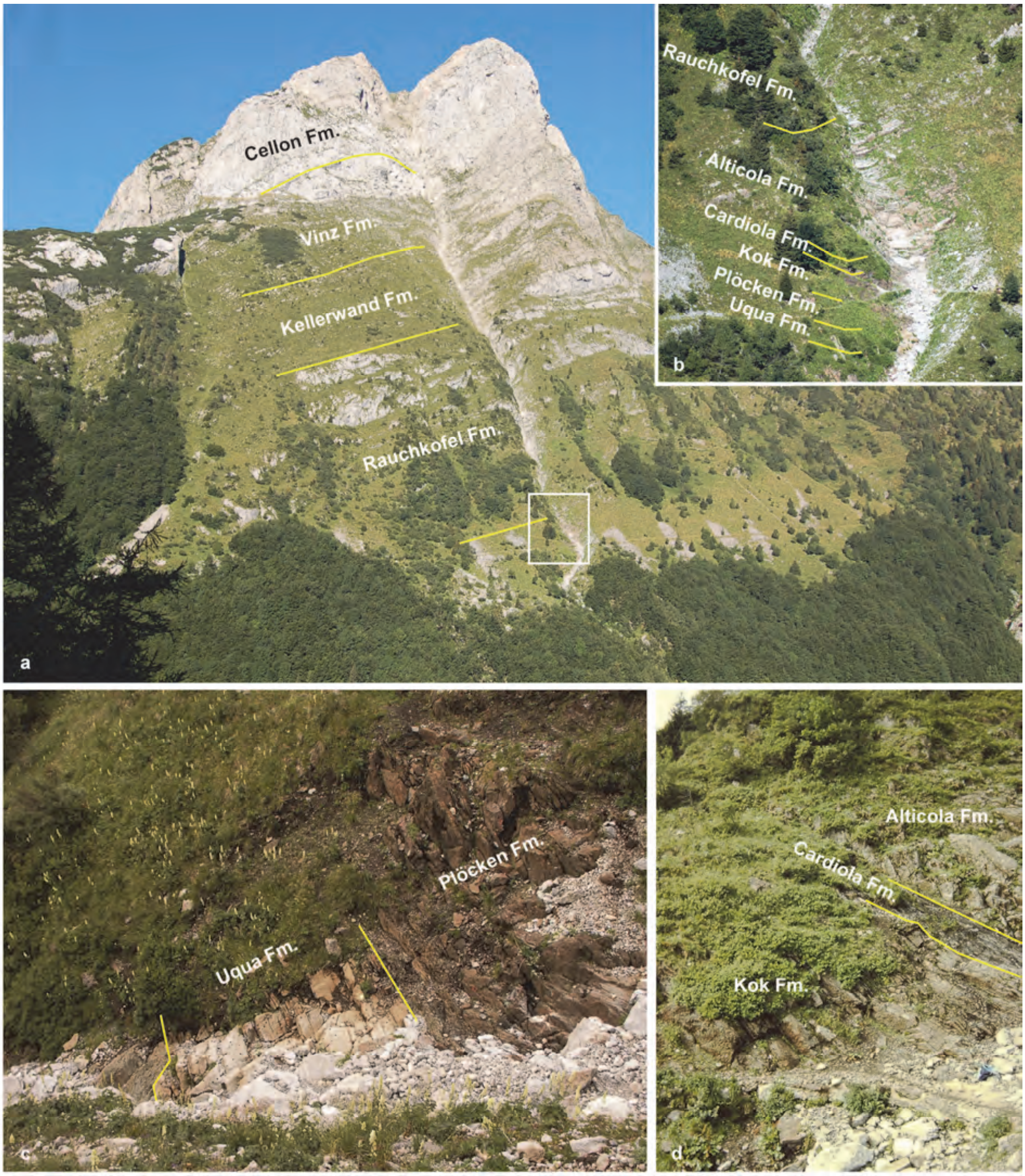

Fig. 8. General views of the Cellon section. a) Panoramic view to the west of Mt. Cellon/Creta di Collinetta, with indication of the lithostratigraphic units; b) Detail of the units of the Cellon section (box in fig.a); c) The Ordovician part of the Cellon section; d) The lower part of the Silurian sequence at Cellon section.

2) Uqua Formation. Lithology: Greyish to brownish flaser limestone with layer of bioclastic debris. Thickness: 4.96 m. Age: Katian (Upper Ordovician), *Amorphognathus ordovicicus* conodont Zone (beds 1–5).

3) Plöcken Formation. Lithology: Greyish siltstone intercalating with impure bioclastic limestone at the very base and grading into calcareous pyritic limestone and sandstone higher in the section. The lowermost strata of the formation are evidently of diamictite origin, the upper strata display contorted deformation structures, slumping, channel fillings and interbeds of fossil debris. Thickness: 6.17 m. Age: Hirnantian (Upper Ordovician), *Normalograptus persculptus* graptolite Zone (beds 6–8).

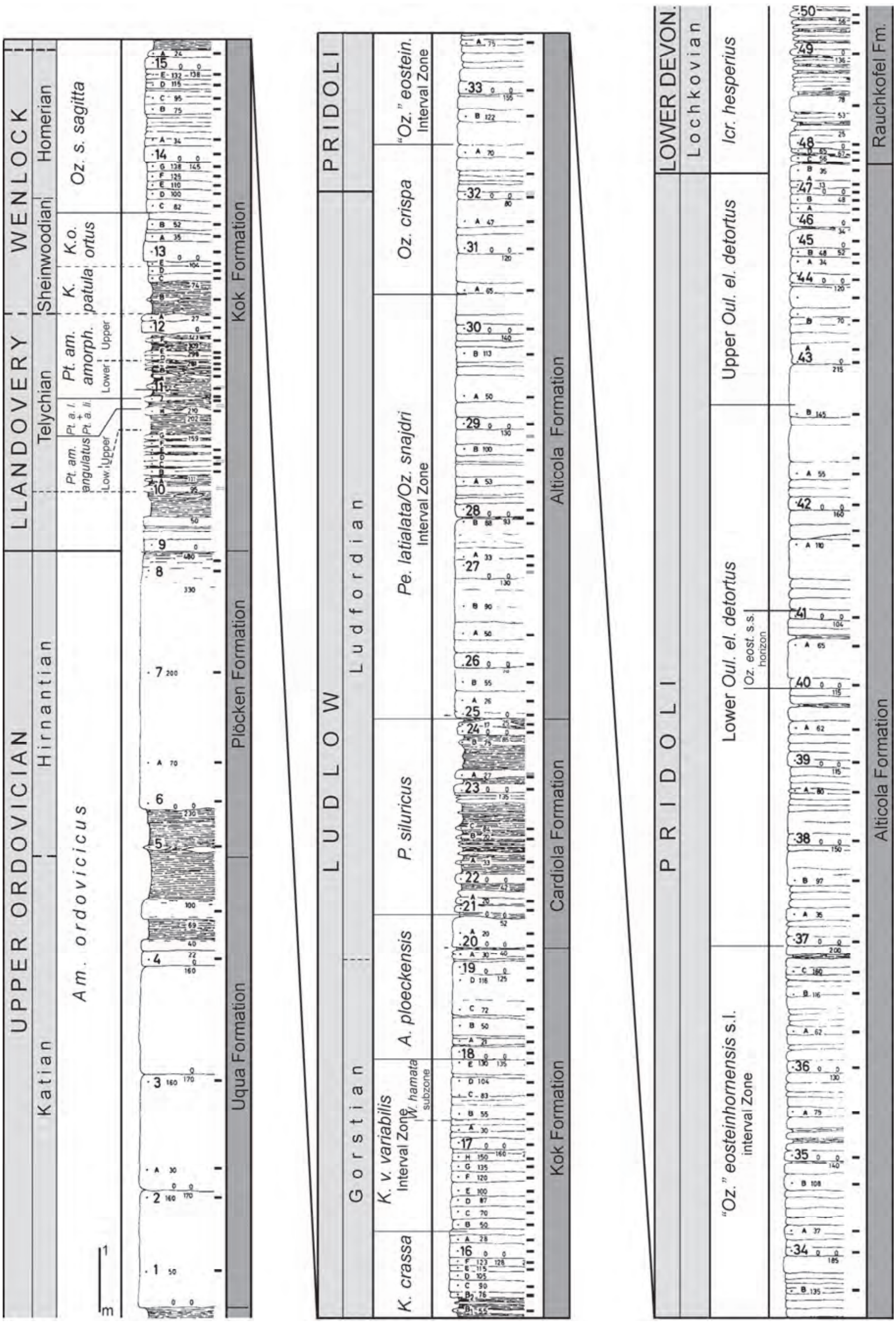

Fig. 9. Stratigraphic log of the Cellon section (after WALLISER, 1964) with indication of sample position, chronostratigraphy, biostratigraphy (after FERRETTI & SCHÖNLAUB, 2001 and CORRADINI et al., 2015a) and lithostratigraphy.

4) Kok Formation. Lithology: Well bedded brownish ferruginous nautiloid limestone, at the base alternating with black shale and marly interbeds. Thickness: 13.5 m. Age: Llandovery to Ludlow, *Pterospathodus celloni* SZ to *Ancoradella ploeckensis* conodont Zone (beds 9–19).
5) Cardiola Formation. Lithology: Dark grey to black limestone with marly and shaly interbeds. Thickness: 3.5 m. Age: Ludlow, *A. ploeckensis* to *Polygnathoides siluricus* conodont zones (beds 20–24A).
6) Alticola Formation. Lithology: Grey to reddish nautiloid limestone with some marly layers and coarse bioclastic interbeds. Thickness: 28 m. Age: Ludlow to Pridoli, *Pedavis latialata–Ozarkodina snajdri* IZ to *Icriodus hesperius* conodont Zone (beds 25–47B).
7) Rauchkofel Formation: Lithology: Blackish platy limestone with black marly interbeds. Thickness: 80 to 120 m. Only the lowermost part of the unit has been studied for conodonts and graptolites (WALLISER, 1964; JAEGER, 1975); a study of conodont biostratigraphy and revision of this part of the section is in progress (CORRIGA & CORRADINI, pers. comm. 2015). Age: Lochkovian (Lower Devonian), *Icriodus hesperius* conodont Zone (bed 47C and above).

Higher in the mountain, the Kellerwand, Vinz and Cellon Fm. are exposed.
The Cellon section is the type section for five lithostratigraphic units: Uqua Fm. (SCHÖNLAUB & FERRETTI, 2015b), Plöcken Fm. (SCHÖNLAUB & FERRETTI, 2015c), Kok Fm. (FERRETTI et al., 2015a), Cardiola Fm. (FERRETTI et al., 2015b) and Alticola Fm. (FERRETTI et al., 2015c).

In terms of chronostratigraphy, several boundaries can be traced along the section (SCHÖNLAUB & KREUTZER, 1994, CORRADINI et al. 2015a):
- the Katian/Hirnantian boundary can be tentatively traced at the transition between the Uqua Fm and the Plöcken Fm., even if an earliest Hirnantian age cannot be excluded for the uppermost part of the Uqua Fm.
- the Ordovician/Silurian boundary is drawn between the Plöcken and the Kok Fm. It should be noted that a large hiatus is present, since most of the Llandovery, up to the Lower *Pt. am. angulatus* Zone (*Pt. celloni* Superzone), is not present.
- the Llandovery/Wenlock boundary (= Telychian/Sheinwoodian boundary) is located within the short black shale interval between samples 12A–12B. Most of the Sheinwoodian is missing, since the graptolite *M. rigidus* was collected from this interval (JAEGER, 1975) and many conodont zones are not represented (sample 12B already belongs to the *K. patula* Zone).
- the Sheinwoodian/Homerian boundary cannot be precisely located. It occurs in the lowermost part of the *Oz. s. sagitta* Zone, tentatively around bed 13E.
- the Wenlock/Ludlow boundary (= Homerian/Gorstian boundary) cannot be precisely located because most of the upper Homerian is missing. However, it can be traced within the black shale level between samples 15A and 15B1 by the occurrence of *K. crassa* in the latter.
- the Gorstian/Ludfordian boundary can be traced only approximatively within the *A. ploeckensis* conodont Zone.
- the Ludlow/Pridoli boundary is located in the narrow black shale level just above sample 32, by the occurrence of *M. parultimus* (JAEGER, 1975). In terms of conodont stratigraphy it occurs in the upper part of the *Oz. crispa* Zone, since the index taxon is present up to sample 32A (CORRADINI et al., 2015a).
- the Silurian/Devonian boundary is placed in the uppermost part of the Alticola Fm., at the bedding plane between sample 47A and 47B, at which the first representatives of the index conodont *Icr. hesperius* occur.
References: WALLISER (1964), SCHÖNLAUB (1980), SCHÖNLAUB et al. (1994), HISTON et al. (1999a), BRETT et al. (2009), CORRADINI et al. (2015a).

3.2. Mt. Freikofel area (Day 2)

On the second day we will partly drive and walk to Mt. Freikofel, spanning the state boundary between Austria and Italy, mainly to observe the Devonian transitional facies. We will leave the minibus near Passo Cavallo/Rossbodentörl (1580 m). From there we will descend on the Italian side and move to the West flanking the southern part of the Mt. Freikofel from where we climb to the top (1756 m). This will allow to observe all the formations of the so called Devonian transitional sequence. From there we will descend on the western side and continue back to the Plöckenhaus (Fig. 10).

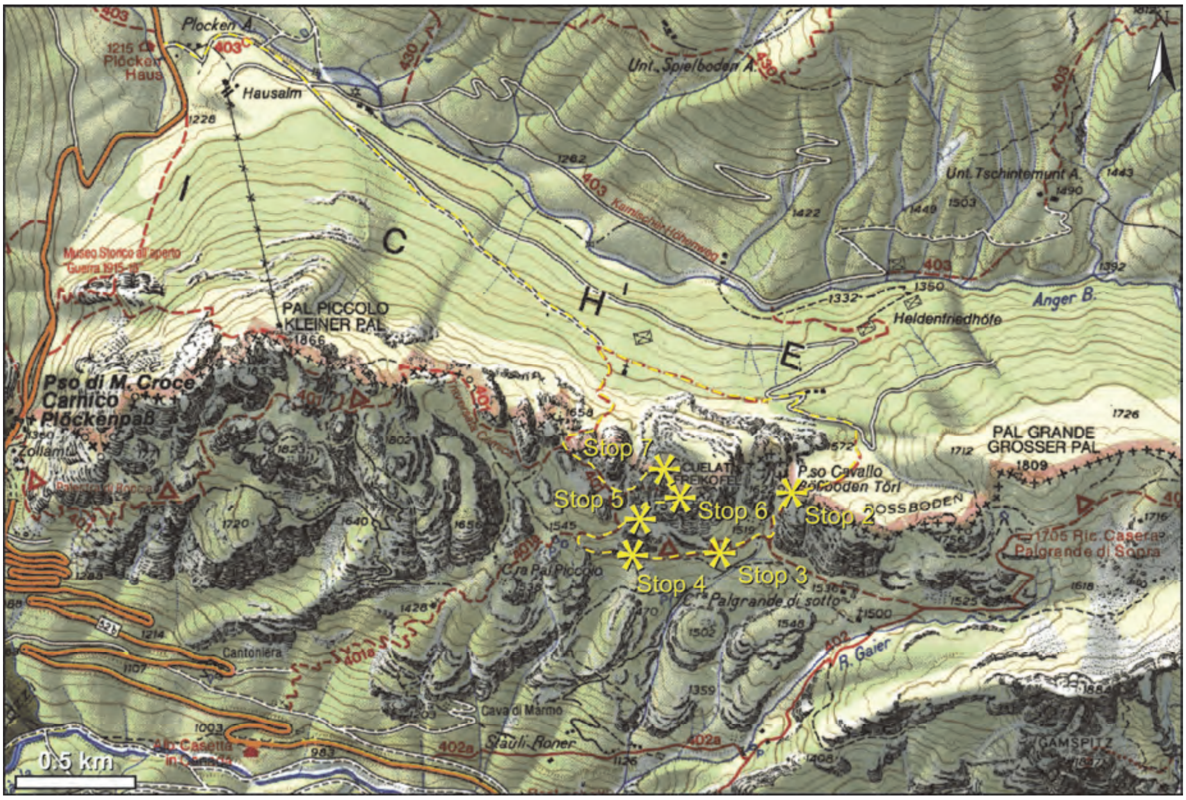

Fig. 10. Topographic map with indication of the itinerary and location of the stops of the second field trip day.

3.2.1. Stop 2 – Geological overview at Passo Cavallo/Rossbodentörl

The Angerbach valley is cut into siliciclastic rocks of the Hochwipfel Fm. which represents a syncline following the north-trending Kleiner Pal (Pal Piccolo) anticline to the south. The latter is mostly characterised by pelagic Devonian strata while in the core of the folded structure even Upper Silurian limestones are exposed between Plöckenpass and the summit of Kleiner Pal (Pal Piccolo). Farther to the North the prominent E-W trending dextral strike-slip fault located right in front of the Mt. Polinik bounds the Devonian peritidal deposits of the Polinik Fm.

We will walk along the northern flank of the huge anticline (Fig. 11). In the core that roughly corresponds to the valley south of the Mt. Freikofel, the oldest parts of the succession, including Upper Ordovician deposits of the Valbertad and Uqua Fms. and Silurian of the Kok and Alticola Fms., crop out, while the younger strata are exposed progressively (with some minor deformations) towards the top of the surrounding mountains. The Devonian starts with the Rauchkofel Fm. (Lochkovian) at its base followed by the whole succession of the transitional units: Kellerwand (Pragian-Emsian), Vinz (Emsian-lower Givetian), Cellon

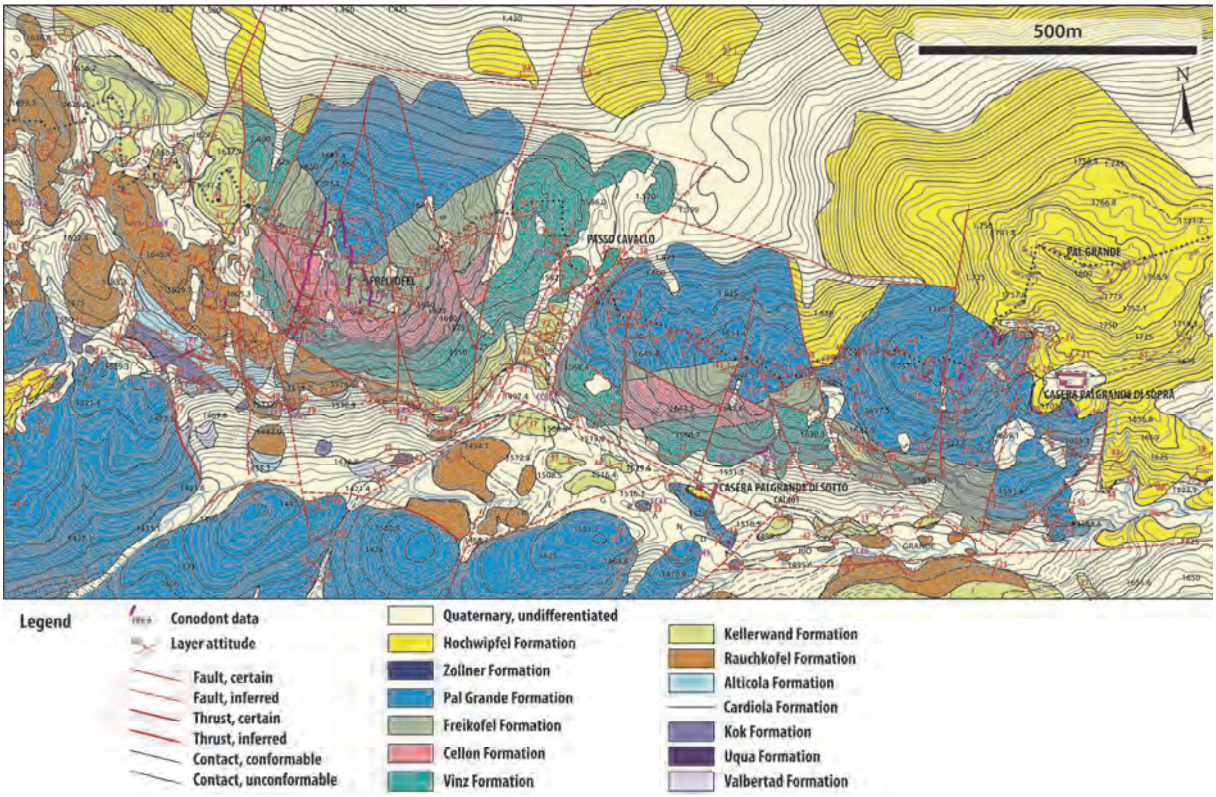

Fig. 11. Geological map of Mt. Freikofel and surroundings.

Fig. 12. View of the Mt. Freikofel from the East with the litostratigraphic subdivisions.

(Givetian) and Freikofel (Givetian-Frasnian) Fms (Fig. 12). The transitional units provide an insight into the development of the entire platform, reflecting the depositional evolution of the moderately shallow water part of the basin, with the advantage of an almost complete sedimentary record, also datable by conodonts.

This sequence is covered by the Pal Grande Fm. (Frasnian-Famennian and locally Tournaisian in this area) and, in disconformity, by patches of Plotta Fm. The Variscan sequence in this area terminates with the mostly turbiditic Hochwipfel Fm. (Visean-Bashkirian).

3.2.2. Stop 3 – Rauchkofel-Kellerwand formations transition

The limit between the Rauchkofel and Kellerwand Fms is exposed in correspondence of the FRKS section (Fig. 13), at the altitude of 1525 m and coordinates N 46°35'55.7" E 12°58'46.7".

Here the very dark grey packstone/grainstone to locally coral-bearing rudstone of the Rauchkofel Fm. are covered by medium dark grey mudstone and wackestone of the

Kellerwand Fm. This transition has been dated by scarce conodont data roughly referable to the Lochkovian-Pragian boundary (the index taxon *Icr. steinachensis* beta has been collected at the base of the Kellerwand Fm.).

Few tens of meters ahead along the path, the Kellerwand Fm. is better exposed and has been dated as lower part of the Pragian Stage (PERRI & SPALLETTA, 1998). Moving upward in the stratigraphic column, some lithoclastic horizons composed of grainstone and packstone become increasingly abundant. These levels might represent tempestites suggesting that the Kellerwand Fm. formed in the medium to distal part of a ramp-type margin (VAI, 1980).

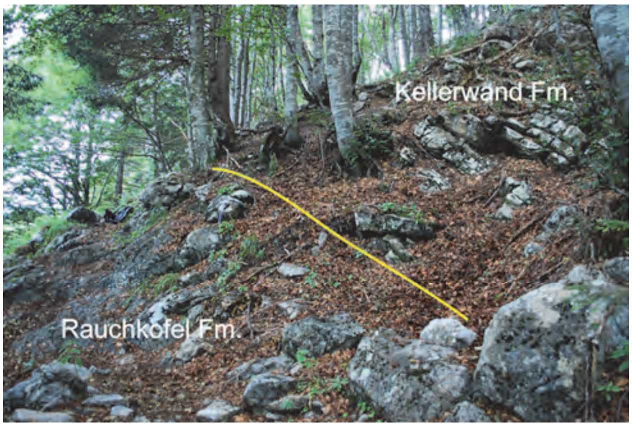

Fig. 13. Boundary between Rauchkofel Fm. and Kellerwand Fm. at the FRKS section.

3.2.3. Stop 4 – Alticola-Rauchkofel formations transition

The limit between the Alticola and Rauchkofel Fms is exposed in the FRS section (Fig. 14) at the altitude of 1552 m (coordinates N 46°35'54.9" E 12°58'32.3").

The grey pelagic *Orthoceras* bearing limestone of the Alticola Fm. pass into dark grey wackestone to grainstone of the Rauchkofel Fm. roughly corresponding to the Silurian-Devonian boundary.

The Rauchkofel Fm. consists of pack-stones to grainstones showing hummocky-cross stratification sometimes passing to wave ripples and interlayered with shales, which suggest deposition within the off-shore transition. Immediately above in the section, a coarser grained very thick bed suggests a transition to shoreface conditions. This succession suggests that the basin profile at the base of the Devonian corresponded to a ramp-type margin.

Fig. 14. Boundary between Alticola Fm. and Rauchkofel Fm. at the FRS section.

Walking forward along the track, we will move down in the succession, reaching the Silurian Kok Fm. and then the Alticola Fm. In this area the Cardiola Fm. is covered by detritus and vegetation, although sometimes can be inferred by the dark color of the terrains. Starting to climb towards the top of Mt. Freikofel, the Rauchkofel Fm. is exposed. In particular, the breccia facies crops out widely. It consists of angular clast-supported cm-large clasts that suggest a limited sedimentary transport.

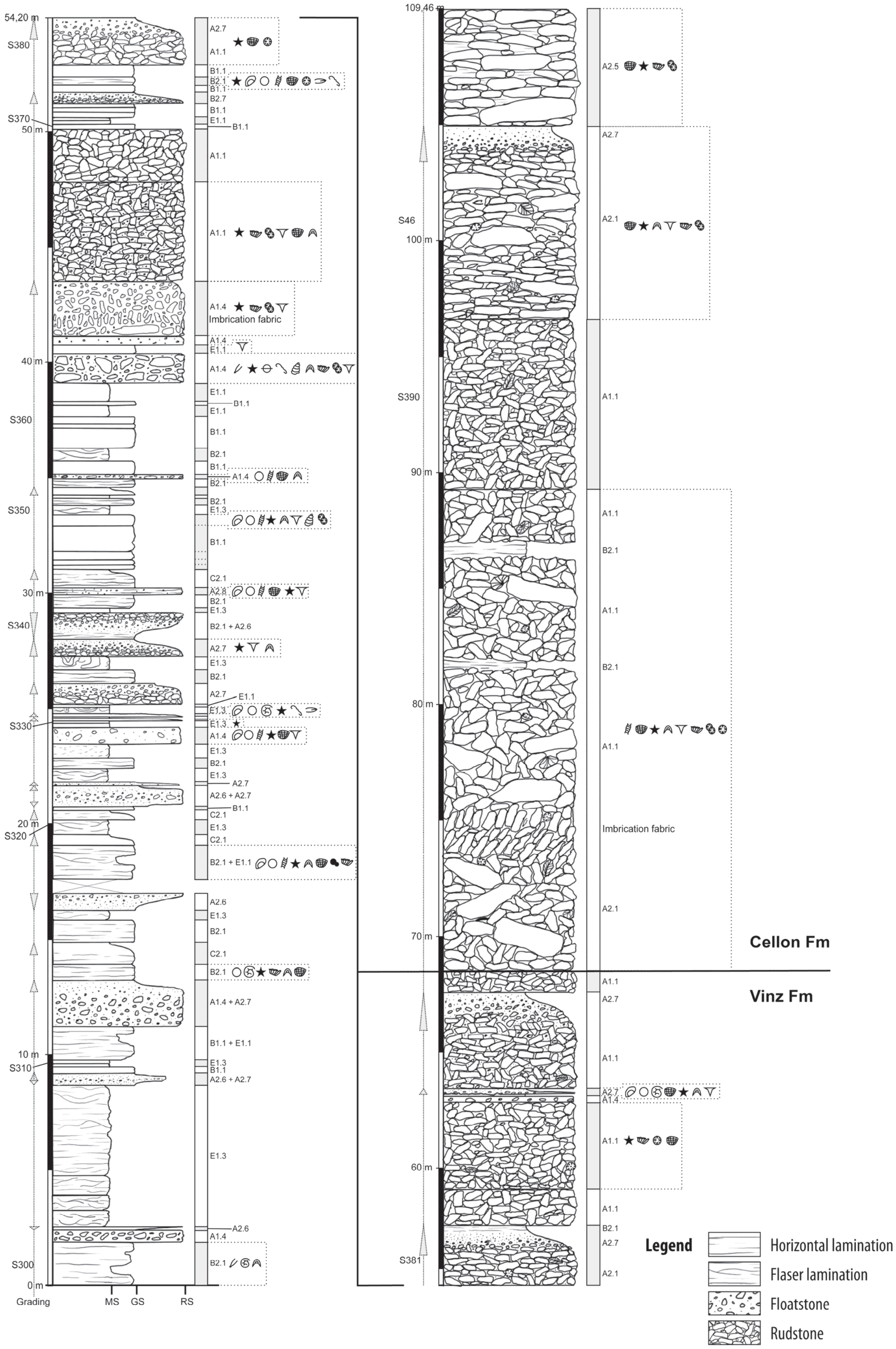

Fig. 15. Stratigraphic log of the lower part of the Freikofel section, correspondent to the upper part of the Vinz Fm. and the lower part of the Cellon Fm. (after SCHNELLBÄCHER, 2010).

3.2.4. Stop 5 – Vinz and Cellon formations

The ascent to Mt. Freikofel starts along a NW-SE trending fault, which marks the transition from the Rauchkofel Fm. to the Vinz Fm. After the fault, at an elevation of 1642 m and coordinates N 46°36'00.3" E 12 58'31.3", the upper part of the Vinz Fm. is exposed (Fig. 15). This unit consists of two interlayered facies (BANDEL, 1972; SCHÖNLAUB, 1985; KREUTZER, 1992; SCHNELLBÄCHER, 2010; PONDRELLI et al., 2015b): (1) medium dark grey, thin to medium bedded, wackestones to packstones and (2) medium dark grey, medium to thick bedded, poorly sorted coral- and stromatoporoid-bearing rudstones (more rarely floatstones) and grainstone matrix; sometimes rudstones shows a fining upward trend up to grainstones. The base of this succession, right after the fault, belongs to the Eifelian Stage (PERRI & SPALLETTA, 1998), but the base of the Vinz Fm., dated elsewhere as Emsian (PONDRELLI et al., 2015b), is not exposed here.

The succession shows a thickening and coarsening upward trend which characterises the transition to the following Cellon Fm. (Figs. 11, 12, 15), which has been dated as lower Givetian. The Cellon Fm. consists of medium dark grey, very thick bedded, poorly sorted, coral- and stromatoporoid-bearing rudstones and subordinate floatstones with clasts up to ~40 cm of diameter and grainstone matrix; sometimes rudstones show a fining upward trend up to grainstones. Locally the base of the bed shows inverse grading with laminated grainstones passing to floatstone/rudstones. However, the deposits are mostly disorganised. The Cellon Fm. deposed in correspondence of the maximum extension of the reefal facies (BANDEL, 1972; SCHÖNLAUB, 1985; KREUTZER, 1992; SCHNELLBÄCHER, 2010).

The wackestone to packstone facies represent a pelagic depositional setting, while the breccia deposits represent gravitative-driven flows reworking shallow water, mostly reef-derived materials. This in turn implies the establishment of a reef and a slope connecting the shallow water environment with the basin. The base of the Vinz Fm. probably corresponds to a physiographic change of the basin from ramp-type to a rimmed shelf margin (BANDEL, 1972).

3.2.5. Stop 6 – Top of Mt. Freikofel

Walking along the path to the summit of the mountain, we will cross the Cellon Fm. up to the Freikofel Fm (Figs. 11, 12, 16). The transition has been dated as lower Givetian (PONDRELLI et al., 2015c).

A phosphorite-rich horizon (BANDEL, 1972) is present about 9 meters below the top of Cellon Fm. The transition to the Freikofel Fm. is marked by a progressive decrease, although with some fluctuations, of the breccia facies. The Freikofel Fm. consists of three well-bedded facies: (1) medium dark grey, medium to thick bedded, lithoclastic rudstones (subordinately floatstones) sometimes showing fining upward grading; matrix consists of grainstone (subordinately wacke-/packstone); (2) medium dark grey, thin to medium bedded grainstones and subordinate packstones locally showing fining upward grading; planar and subordinate cross lamination is present; (3) very thin to thin bedded, moderate pink to grey mud-/wackestones (BANDEL, 1972; SPALLETTA & VAI, 1984; SCHÖNLAUB, 1985; KREUTZER, 1992; SCHNELLBÄCHER, 2010; PAS et al., 2014).

The Freikofel Fm. was formed at the slope of a carbonate apron (SCHNELLBÄCHER, 2010; PAS et al., 2014). Deposits of hyperconcentrated and concentrated density flows and turbidity flows predominate. Thin interbeds of pelagic sediments are rarely preserved.

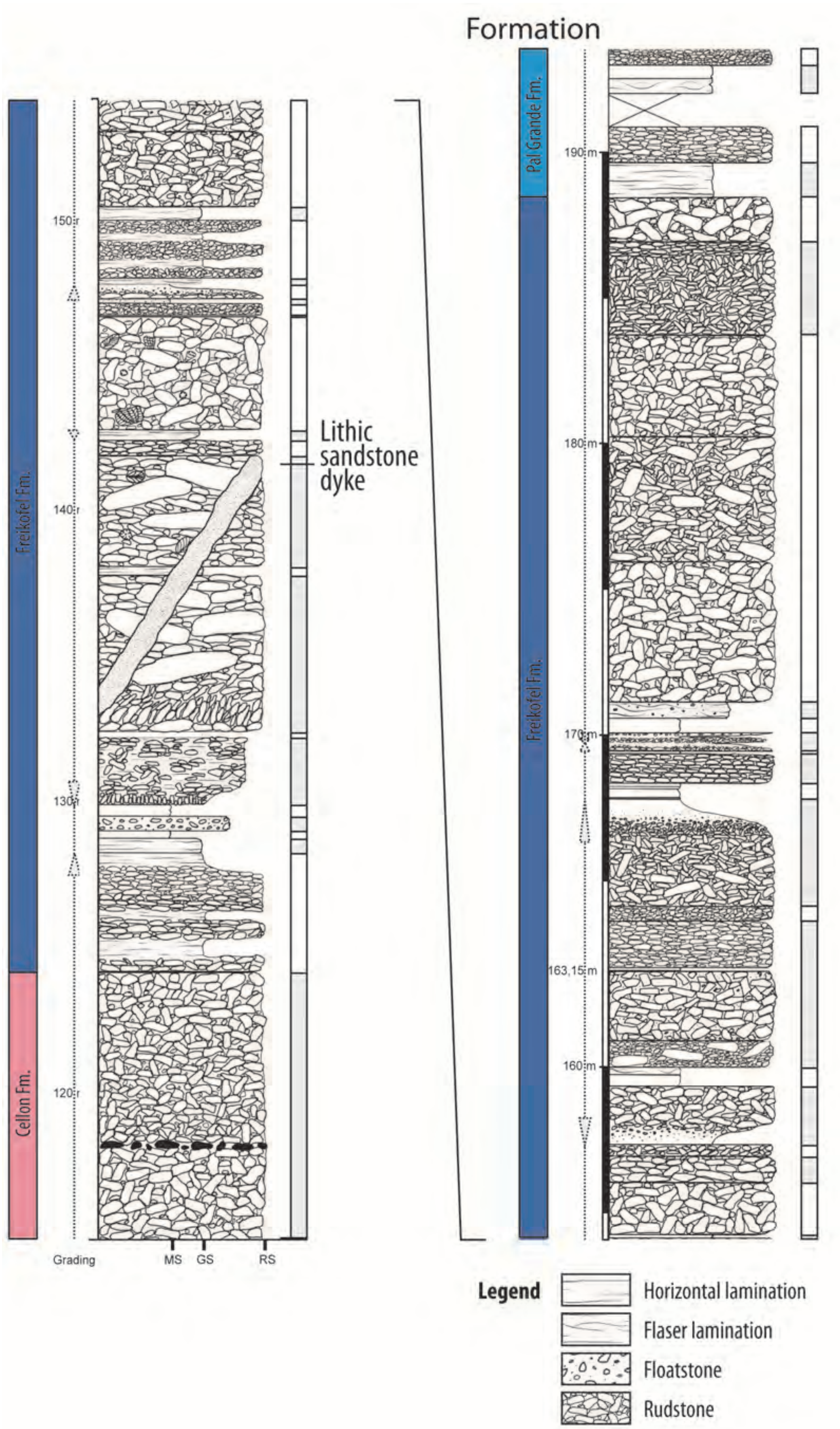

Fig. 16. Stratigraphic log of the upper part of the Freikofel section, correspondent to the upper part of the Cellon Fm., the Freikofel Fm. and the lower part of the Pal Grande Fm. (after SCHNELLBÄCHER, 2010).

Fig. 17. Panoramic view of the Creta di Timau area, with simplified stratigraphy and tectonic. The westward part of the complex shows the sharp boundary between the Rauchkofel and Kellerwand formations.

The top of Mt. Freikofel offers a spectacular panoramic view of the geology of this part of the Carnic Alps. To the southeast, the southern part of the anticlinal structure can be seen (Fig. 17), showing south-dipping beds of the Rauchkofel Fm. and the sharp transition to the Kellerwand Fm. The Rauchkofel Fm shows a clear thickening upward succession which reflects a shallowing upward trend abruptly interrupted at the base of the Kellerwand Fm. On the Eastern end of the cliff, the fault-bounded Creta di Timau represents part of the north-dipping flank of the anticline.

Toward the West (Fig. 18), the same succession of the Mt. Freikofel crops out in the Pal Piccolo and Cellon mountains. Instead in the Pizzo Collina, Mooskofel, Gamskofel and Polinik, the Devonian consists of shallow water facies.

Fig. 18. Panoramic view to the west from the Mt. Freikofel top. The Pal Piccolo and Cellon mountains consists of the same succession as the Mt. Freikofel. More to the west, the transition to the Devonian shallow water platform occurs.

3.2.6. Stop 7 – Freikofel and Pal Grande formations

Starting the descent from Mt. Freikofel in western direction, we will observe the gradual increase of thin-bedded grey and pink mud- and wackestones that will pass to the Pal Grande Fm. (Figs. 11, 12, 19). The formation boundary is assigned to the Frasnian according to conodont data (SPALLETTA et al., 2015a).

From the Lower Frasnian, the succession records low occurrences of reef-builder debris and/or shallow water-derived allochems compared to the high proportion of fore-reef-slope-derived lithoclasts (PAS et al., 2014). These data suggest a deposition during a period of low carbonate productivity within the shallow water settings, which in turn suggest that the early

Frasnian reefs of the Carnic Alps were in decline earlier than in most of the reef localities throughout the Middle–Upper Devonian world (PAS et al., 2014). This appears to be related to the extensional or transtensional tectonic episode supposed by SPALLETTA et al. (1980, 1982) and SPALLETTA & VAI (1984). The progressive sea-level rise is marked by deposition of red nodular limestone overlying the thick sequence of reef and fore-reef ''transitional'' facies of the Devonian Carnic Alps carbonate platform (PAS et al., 2014).

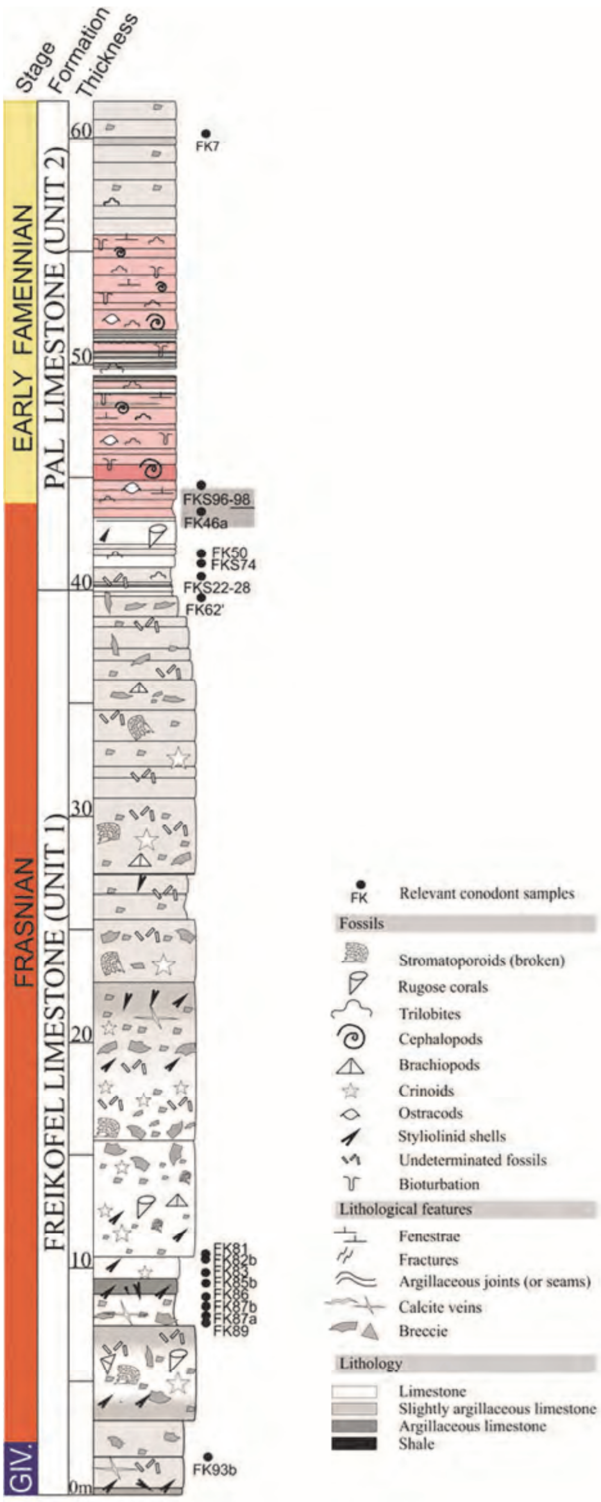

Fig. 19. Stratigraphic log of the Freikofel-Pal Grande Fms. transitions, (after PAS et al., 2014).

3.3. Lake Wolayer area (Days 3–4)

In the last two days of the field trip a hike to Lake Wolayer area is planned (Fig. 20). We will start at Untere Valentin Alm (1220 m) and walk through the Valentin Valley up to Valentintörl (2138 m). Then we will continue to Lake Wolayer (1951 m). Several sections will be shown along the trail, and geological overviews will be given, too. An overnight stay is scheduled at Rifugio Lambertenghi-Romanin.
On the next morning we will visit the Costone Lambertenghi/Seekopf Sockel section, and will walk along the Geotrail Lake Wolayer until the famous Rauchkofel Boden section. After that, we will walk back to Untere Valentin Alm, where the field trip will end.

3.3.1. Stop 8 – Geological overview along the Valentin Valley

The Valentin Valley formed in correspondence of a large strike-slip fault that represents the most recent deformational structure of this area. In the northern part of the Valley, following the Variscan and Alpine compressional and strike-slip phases, the Middle Devonian shallow water units of Mt. Mooskofel are thrusted by the Middle Devonian lagoonal units of the Mt. Gamskofel; both are referred to the Polinik Fm. A large NW-SE trending fault separates these units from the Mt. Rauckhofel where several tectonic repetitions from Upper Ordovician to Upper Devonian strata occur. The Devonian units here belong to the transitional facies.

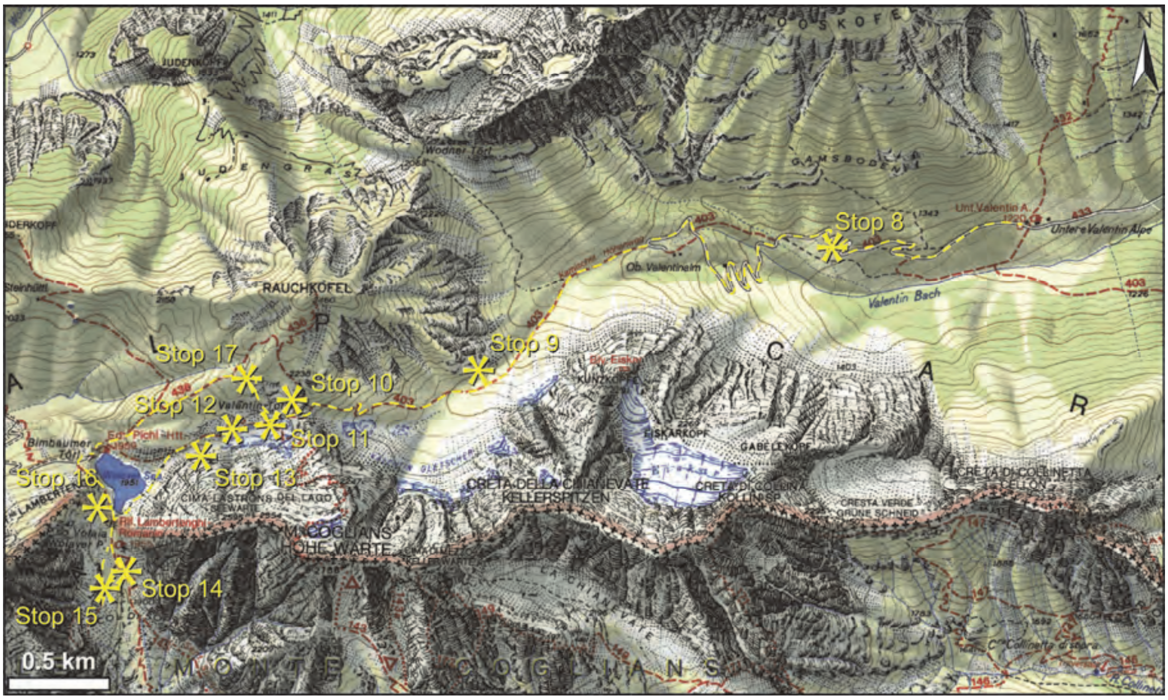

Fig. 20. Topographic map with indication of the itinerary of Days 3–4 and location of the stops.

The southern spectacular side of the valley, named the Kellerwand cliff, shows sub-horizontal layers of mostly Silurian to Upper Devonian age (Fig. 21). In particular, the Rauchkofel Fm. and the Devonian transitional units (Kellerwand-Vinz-Cellon-Freikofel Fms) are exposed.

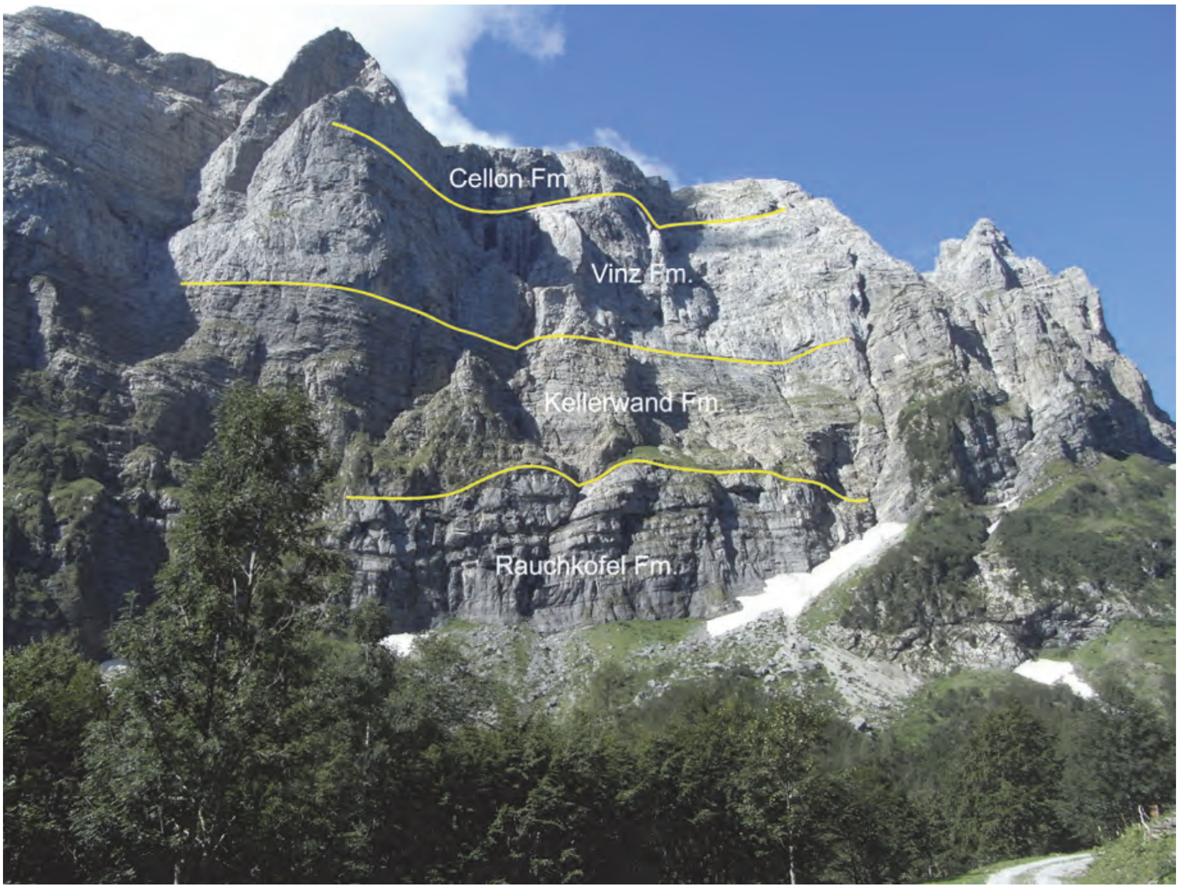

Fig. 21. Panoramic view of the northern wall of Mt. Kellerwand, with indication of the lithostratigraphic units.

Close to the Valentintörl the transition from the Devonian slope deposits characterising the Cellon section to the Devonian shallow water facies, with the Seekopf Fm. passing into the Hohe Warte and Seewarte Fms can be observed.

3.3.2. Stop 9 – Geological overview at the Rauchkofel South section

The Rauchkofel South section (Fig. 22) crops out in the northern side of the Valentin valley at an altitude of about 1990 m., at coordinates N 46°36'58.5", E 12°53'23.0". The section exposes rocks from Upper Ordovician to Lower Devonian, belonging to the following 7 formations: Valbertad Formation, Uqua Formation, Plöcken Formation, Kok Formation, Alticola Formation, Rauchkofel Formation and Kellerwand Formation.

Fig. 22. The Rauchkofel South section.

The Rauchkofel South section is the type section of the Rauchkofel Formation (CORRADINI et al., 2015c), that is here about 120 m thick.

References: SCHÖNLAUB (1970).

3.3.3. Stop 10 – Valentintörl section

The Valentintörl section (Fig. 23) has been measured in the prominent calcareous cliff, which separates the north and the south Valentin passes, at coordinates N 46°36'49.5", E 12°52'51.5", and altitude 2138 m. The area is tectonically complicated by faults and thrusts. Therefore, also in the Valentintörl section large parts of the sequence are missing or extremely condensed.

The sections starts with a few metres of the light grey encrinitic limestone of the Wolayer Fm. The Kok Fm. lies above, with an irregular basal contact. The Llandovery and Wenlock are missing, and the older Silurian bed belongs to the *K. crassa* Zone. The thickness of the Kok Fm. is here reduced to 4.3 m.

The Cardiola Fm. is not present and the section continues with the Alticola Fm., and the Lower Devonian units (Rauchkofel Fm., La Valute Fm. and Findenig Fm.), not yet studied in detail in this section.

References: SCHÖNLAUB (1971, 1980), HISTON et al. (1999b), BRETT et al. (2009).

3.3.4. Stop 11 – Base of Sewarte section

The Base of Seewarte section (Fig. 24) is exposed a few metres west of the southern pass of Valentintörl, at altitude 2100 m. Rocks from Upper Ordovician to Silurian in a transitional facies between the Plöcken and the Wolayer facies are here exposed.

The section starts with a few metres of badly exposed Valbertad Fm. grading into reddish carbonaceous sandstones and the greyish Katian Wolayer Fm.

The oldest Silurian beds belong to the *Pt. celloni* Superzone and are represented by dark grey shales, followed by grey to reddish siliceous mudstones and iron and manganese rich

Fig. 23. The Valentintörl section (view to the east).

carbonate beds. The rest of the Kok Fm., that has a total thickness of 12 m, varies from the typical brownish cephalopod-bearing Kok Fm. by its greyish color and its rich brachiopod and crinoid content. The accumulation of small brachiopods ("Pentamerids") has not been studied yet.

Above 3.3 m of Cardiola Fm. crop out, represented by dark grey to black shales with limestone intercalations.

The section continues with the Alticola Fm., constituted of massive cephalopod-bearing, grey to pinkish wackestones and packstones.

<u>References:</u> SCHÖNLAUB (1971, 1980), BRETT et al. (2009).

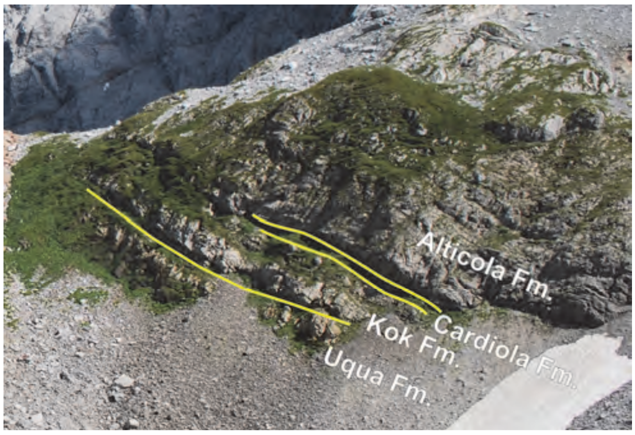

Fig. 24. The Base of Seewarte section (view to the south).

3.3.5. Stop 12 – Wolayer glacier section

The Wolayer glacier (Fig. 25) section is located in the northern side of the Wolayer valley at altitude 2080 m, about half distance between Valentintörl and Lake Wolayer, at coordinates N 46°36'48.8", E 12°52'34.9".

That section is the type section for the Valentin Fm. (SPALLETTA et al., 2015b), and also exposes limestones of the Pal Grande Fm. in the upper part. The section has been investigated

Fig. 25. The Wolayer glacier section (view to the northeast).

for conodont biostratigraphy, sedimentology, isotope geochemistry by SCHÖNLAUB (1980), GÖDDERTZ (1982), JOACHIMSKI et al. (1994) and HÜNEKE (2006).
The Valentin Fm. is represented by about 14 m of bioturbated greyish wackestone, and packstone, deposed in a pelagic environment, with very low sedimentation rate and erosion/re-deposition controlled by bottom currents.
Here, the Pal Grande Fm. is very condensed, being the interval between the Upper *hassi* and the Lower *crepida* Zone represented by about 2.5 m of limestone. A 6 cm thick black shale horizon between sample 89 and 90 is interpreted as an equivalent of the Lower Kellwasser Horizon (JOACHIMSKI et al., 1994), whereas well-oxygenated conditions with bioturbations are documented at the Frasnian/Famennian boundary. The Upper Devonian strata are overlain by siliciclastics of the Lower Carboniferous Hochwipfel Fm.

In terms of chronostratigraphy, the following boundaries have been recognised along the section:
- The Lower/Middle Devonian boundary (= Emsian/Eifelian boundary) is placed between beds 28 and 29, by the entry of the marker *Po. partitus* in bed 29 (SCHÖNLAUB, 1980).
- The Eifelian/Givetian boundary is located in the upper part of the Valentin Fm., between beds 70 and 71.
- The Middle/Upper Devonian boundary (= Givetian/Frasnian boundary) can be traced at the top of the bed marked by sample 72, where a distinct phosphorite layer separating limestones of Givetian (*varcus* Zone) and Frasnian (Lower *hassi* Zone) age occur (SCHÖNLAUB, 1985; JOACHIMSKI et al., 1994).
- The Frasnian/Famennian boundary is located about 1 m above the base of the Pal Grande Fm., between samples 91 and 92 (SCHÖNLAUB, 1980; JOACHIMSKI et al., 1994).
<u>References:</u> SCHÖNLAUB (1980, 1985, 1999), GÖDDERTZ (1982), JOACHIMSKI et al. (1994), HÜNEKE (2006).

Fig. 26. Panoramic view of Mt. Seewarte, with indication of the lithostratigraphic units. The Seewarte section has been measured at the base of the mountain, form north to south (left to right in the photo).

3.3.6. Stop 13 – Seewarte section

The Seewarte section (Fig. 26) is located along the northwestern and western base of Mt. Seewarte, starting from the western end of the Wolayer valley, and continuing south across the state border, at coordinates N 46°36'44.5", E 12°52'21.4" (base).

The section is the type section of the four formation of the shallow water sequence exposed:

- Seekopf Fm. (SUTTNER et al., 2015). Lithology: well-bedded nodular and lithoclastic limestone to dolostone in the lower part, and peloidal and crinoidal pack- grain and rudstones in the upper part. A megaclast horizon, dated at the base of the Pragian, occur in the central part of the unit. Thickness: about 120 m. Age: uppermost Silurian? to Pragian (Upper *Oul. el. detortus*-*Pel. serratus* zones).
- Hohe Warte Fm. (BANDEL et al., 2015). Lithology: thick-bedded echinoderm-rich grainstone and rudstone in the lower part and massive reefal limestone interbedded with crinoid grainstone and rudstone in the upper part. Thickness: about 250 m. Age: Pragian- ?lower Emsian.
- Seewarte Fm. (POHLER et al., 2015a). Lithology: dark grey fossiliferous limestone, slightly dolomitic in places. Thickness: about 40 m. Age: lower Emsian.
- Lambertenghi Fm. (POHLER et al., 2015b). Lithology: well-bedded grey fossiliferous limestones intercalated with laminated yellow-stained dolostone beds; meter-long red mudstone layers, birdseye structures, graded bedding, flat-pebble lithoclasts and cavities lined with fibrous calcite are common. Thickness: about 110 m. Age: Emsian.

In terms of chronostratigraphy, the following boundaries have been recognised along the section:
- The Silurian/Devonian boundary is located in the lowermost part of the section at the base of sample 01/03.
- The Lochkovian/Pragian boundary is traced in the central part of the Seekopf Fm., at the base of the megaclast horizon, where *Icriodus steinachensis* beta morph is present (SUTTNER, 2007).
- The Pragian/Emsian boundary is tentatively traced in the uppermost part of the Hohe Warte Fm., or at the transition between the Hohe Warte and the Seewarte formations.

References: BANDEL (1972), SUTTNER (2007).

3.3.7. Stop 14 – Rifugio Lambertenghi Fontana section

The Rifugio Lambertenghi Fontana (RLF) section (Fig. 27) is located about 100 m south of the mountain hut in the eastern side of the valley, along the path reaching Rifugio Lambertenghi Romanin from the south, at coordinates N 46°26'22.6" E 12°52'07.8". About 18 m of *Orthoceras* limestone belonging to the Alticola Fm. are here exposed.

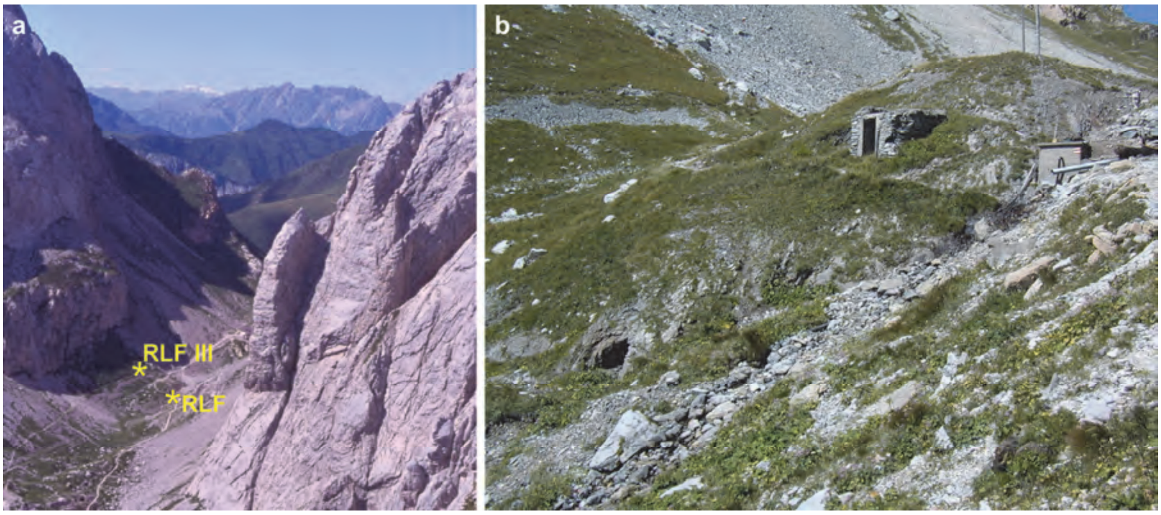

Fig. 27. a) Panoramic view of the valley south of Pass Wolayer, with location of Rifugio Lambertenghi Fontana (RFL; stop 14) and Rifugio Lambertenghi Fontana III (RLF III; stop 15) sections; b) View of the Rifugio Lambertenghi Fontana section.

The section starts with about three meters of highly fossiliferous reddish limestones, where fossil remains are mainly represented by crinoids, brachiopods, cephalopods and bivalves, often fragmented and packed together at the centimeter scale. A covered interval corresponding to a World War I trench is present in the lower part of the section. The central part of the section comprises grey micritic limestone rich in orthoceratid nautiloids; concentrations of small crinoidal debris are observable in some levels, as well as a few brachiopod casts. The fossiliferous content strongly decreases above sample RLF 6 and only a few poorly preserved cephalopods occur in the upper part of the section, where the colour of the rock frequently grades to red due to weathering. A mineralised horizon, bearing hematite and limonite, occurs just above sample RLF 9.

The age of the sections ranges from the *Ped. latialata/Oz. snajdri* interval Zone to the Lower *Oul. el. detortus* Zone. The Ludlow/Pridoli boundary is approximately traced around sample RLF 6, where the last occurrence of *Oz. crispa* is documented.

References: CORRADINI & CORRIGA (2010).

3.3.8. Stop 15 – Rifugio Lambertenghi Fontana III section

The Rifugio Lambertenghi Fontana III (RLF III) section (Fig. 28) is located about 100 m south of the mountain hut in the western side of the valley, along the path from Rifugio Lambertenghi Romanin to Mt. Capolago/Seekopf, at coordinates N 46°26'22.7", E 12°52'05.4". More than 15 meters of limestone crop out in a World War I trench, immediately west of the path. The section is subdivided into two parts, 5 and 10.5 m thick respectively, separated by a covered interval about 10 m thick.

The lower part of the section, up to sample RLF III 3A, is represented by grey micritic limestone, with a sparse crinoid remnants and scattered rare brachiopods. It represents a transitional facies between the Alticola and the Seekopf formations, still attributed to the former.

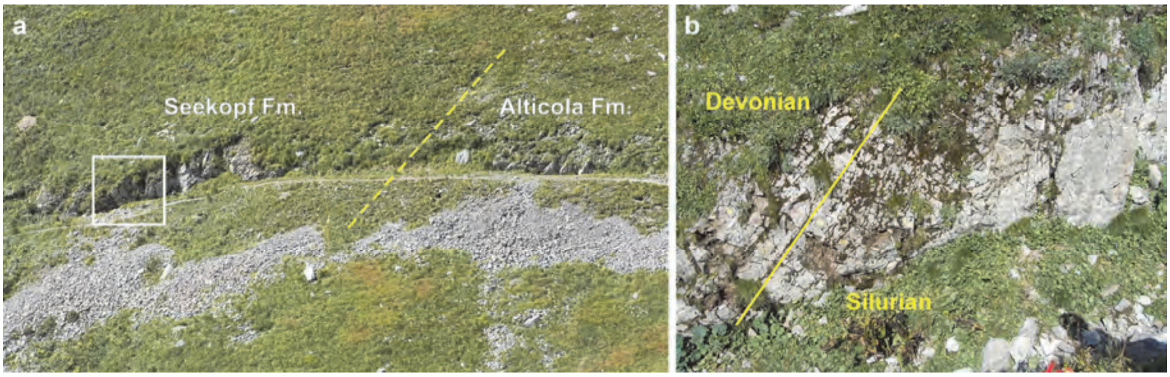

Fig. 28. The Rifugio Lambertenghi Fontana III section. a) Panoramic view of the section with indication of the lithostratigraphic units; b) Detail of the part of the section across the Silurian/Devonian boundary (box in fig. a).

The upper part of the section belongs to the Seekopf Fm. It is represented by a fossiliferous packstone and wakestone, with the fossil content increasing toward the top of the section. However, the state of preservation of the fauna is poor. Crinoids are always abundant and brachiopods often present, at places concentrated in centimeter-thick coquina-like levels. The fauna includes bivalves, nautiloid cephalopods, rare trilobites and solitary corals. In the uppermost part of the section, above sample RLF III 2, bedding planes are difficult to observe, due to heavy weathering and fracturing of the rocks.

The age of the section ranges from the Lower *Oul. el. detortus* Zone to the *Icr. hesperius* Zone.

The Silurian/Devonian boundary is located in the uppermost part of the section, at level of sample RLF III 1L, slightly above the entry of *Z. remscheidensis* and in the upper part of the prominent $\delta^{13}C$ shift typical of uppermost Pridoli.

<u>References:</u> CORRIGA et al. (2009), CORRADINI & CORRIGA (2010).

3.3.9. Stop 16 – Costone Lambertenghi/Seekopf Sockel section

The Costone Lambertenghi/Seekopf sockel section (Fig. 29) is located along the state border west of the Wolayer Pass, at coordinates N 46°36'33.6" E 12°51'58.5" (base), N 46°36'32.0" E 12°51'52.6" (top). Strata of Ordovician to Carboniferous ages are here exposed which are tectonically superimposed The lower and the upper parts belong to different sedimentary sequences, separated by a major thrust. The lower part of the section has been studied much more in detail than the upper part.

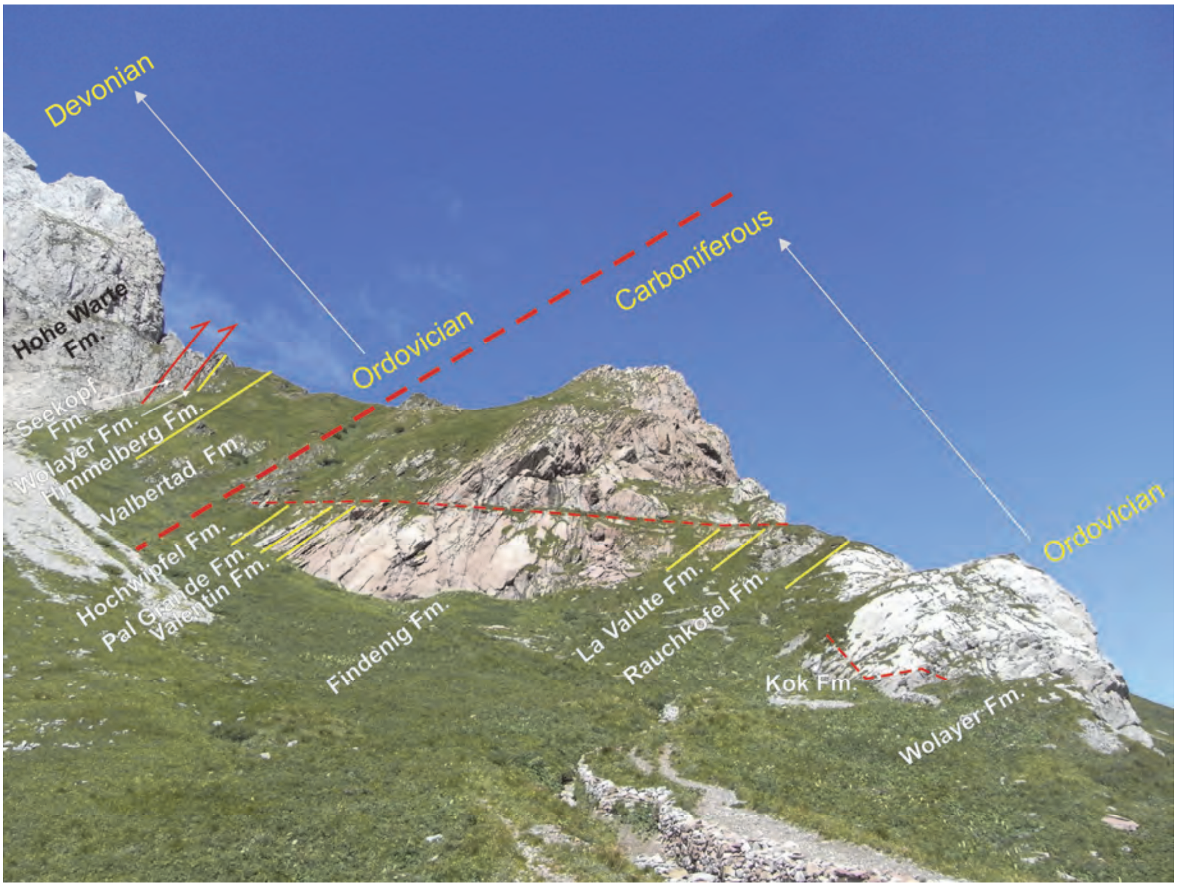

Fig. 29. Panoramic view to the northwest of the Costone Lambertenghi/Seekopf Sockel section, with indication of lithostratigraphic units and structural features.

The following lithostratigraphic units can be recognised (from base to top):
- Wolayer Fm.: coarse grained cystoid limestone. Thickness: about 15 m. Age: Katian-Hirnantian.
- Kok Fm.: red patchy laminated limestone with stromatolite-like structures and pink-colored wackestone/packstone with abundant trilobite remain resting disconformably upon the Wolayer Fm. Thickness: up to 1.1 m. Age: Wenlock-Ludlow (*Oz. s. rhenana-Pol. siluricus* zones, BRETT et al., 2009).
- Alticola Fm.: light grey limestone, also resting on the Wolayer Fm. Thickness: 80 cm. Age top Pridoli? to Lochkovian.
- Rauchkofel Fm.: dark grey platy limestone with centimetric black shale intercalation, followed by pinkish crinoidal limestone. Thickness: 13.90 m. Age: Lochkovian.
- La Valute Fm.: light grey flaser limestone. Thickness: 1.90 m. Age: Lochkovian.
- Findenig Fm.: red argillaceous tentaculite limestone. Thickness: estimated 30-40 m. Age: Pragian to Middle Devonian.
- Valentin Fm.: well bedded light grey micritic limestone. Thickness: 2 m. Age: No data available from this part of the section.
- Pal Grande Fm.: grey limestone. Thickness: 3 m. Age: Frasnian? (SCHÖNLAUB, 1980).
- Hochwipfel Fm: siltstone and shale. Age: Carboniferous.

In the upper part of the section, above the overthrust, the following formations crops out: Valbertad Fm., Himmelberg Fm., Wolayer Fm., Seekopf Fm. and Hohe Warte Fm. The latter forming the high white cliff of Mt. Seekopf/Capolago.

<u>References:</u> VAI (1967), SCHÖNLAUB (1970, 1980), BRETT et al. (2009).

3.3.10. Stop 17 – Rauchkofel Boden section

The Rauchkofel Boden section (Fig. 30) is located on the southwestern slope of Mt. Rauchkofel, at coordinates N 46°36’54", E 12°52’30", and altitude 2175 m. Rocks from Upper Ordovician to Lower Devonian in Wolayer facies are here exposed, but a significant gap in the lower Silurian is present. Various studies and monographic works have been carried out on this section (for a brief summary see FERRETTI et al., 1999). The conodont stratigraphy of the Silurian and Devonian parts has first been published by SCHÖNLAUB (1980) and is presently under revision by M.G. Corriga and C. Corradini.

The Rauchkofel Boden section is the type section of the Wolayer Fm. (SCHÖNLAUB & FERRETTI, 2015a) and of the La Valute Fm. (CORRADINI et al., 2015b).

The following lithostratigraphic units can be recognised (from base to top):

1. Wolayer Fm. Lithology: whitish cistoid massive limestone. Thickness: 8.6 m. Age: Katian-Hirnantian (*Am. ordovicicus* Zone).
2. Kok Fm. Lithology: Grey-brownish highly fossiliferous cephalopod limestone. The contact with the Wolayer Fm. is strongly irregular with basal pockets infilled with ooidal ironstone (FERRETTI, 2005); Thickness: 3.4 m. Age: Wenlock-Ludlow (*Pt. am. amorphognathoides-A. ploeckensis* zones), but several conodont biozones are not documented and probably missing.
3. Cardiola Fm. This unit is badly exposed in the war trench. Lithology: bituminous shale with dark limestone lenses. Thickness: 20-30 cm. Age: a Ludlow age can be inferred by the age of the adjacent units, because no direct data are available from the section.
4. Alticola Fm. Lithology: Grey-pink cephalopod packstone to wackestone in the lower part of the unit, grading to darker grey in the upper part; a level with abundant lobolith of scyphocrinitids occur in the uppermost part of the formation. Thickness: 16.50 m. Age: Ludfordian-Lochkovian (*Po. siluricus-Icr. hesperius* zones).

5 Rauchkofel Fm. This unit is poorly exposed in an almost covered interval at the base of the steep cliff, but was excavated for the field trip of the 2nd European Conodont Symposium (SCHÖNLAUB, 1980). Lithology: blackish platy limestone with shale intercalations. Thickness: 1.8 m. Age: Lochkovian (*Icr. hesperius-Ad. carlsi* zones).

6. La Valute Fm. Lithology: well bedded light grey cephalopod bearing limestone. Thickness: 18 m. Age: Lochkovian (*Ad. carlsi-P. gilberti*? zones).
7. Findenig Fm. Lithology: reddish flaser limestone. Thickness: about 20 m. Age: Pragian.

In terms of chronostratigraphy, the following boundaries have been recognised along the section:

- the Ordovician/Silurian boundary is drawn between the Wolayer and the Kok Fm. It should be noted that a large hiatus is present, corresponding to the whole Llandovery.
- the Sheinwoodian/Homerian boundary can be traced just above the thin ooidal infillings at the base of the Kok Fm.
- the Wenlock/Ludlow boundary (= Homerian/Gorstian boundary) can be tentatively traced just below sample 314, where *K. crassa* occurs.
- the Gorstian/Ludfordian boundary can be tentatively traced within the cephalopod rich bed referred to the *A. ploeckensis* Zone, about 1 m below the top of the Kok Fm.
- the Ludlow/Pridoli boundary can be tentatively located in the lower part of the Alticola Fm., in the uppermost part of the steep slope, where *Oz. crispa* has been collected.
- the Silurian/Devonian boundary occurs in the uppermost part of the Alticola Fm., just below sample 201, where *Icr. hesperius* first appears.

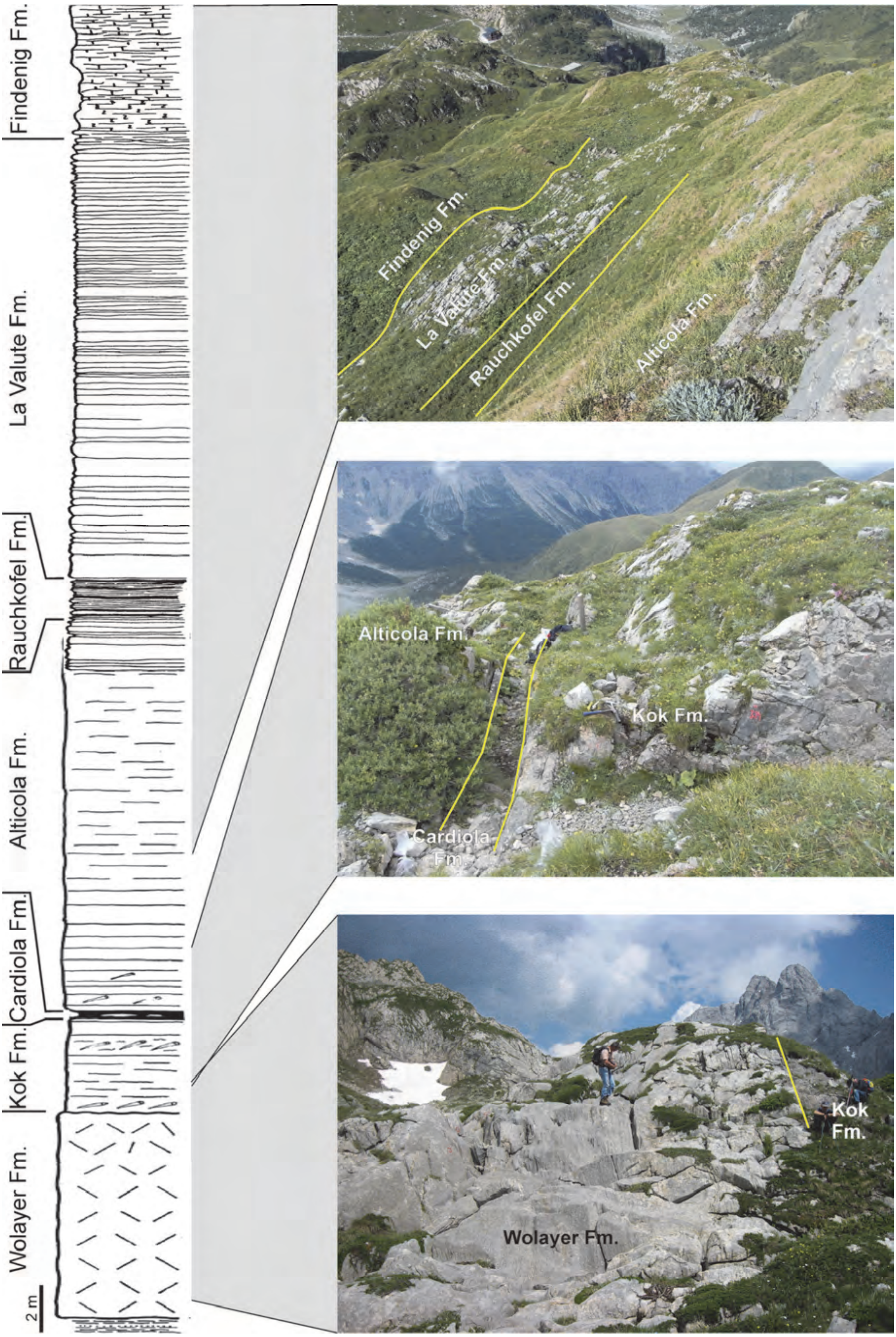

Fig. 30. The Rauchkofel Boden section. Stratigraphic log modified after SCHÖNLAUB (1980), with indication of lithostratigraphic units and selected views of the section.

- the Lochkovian/Pragian boundary can be traced just above the transition between the La Valute and Findenig formations, around sample 227, where *Nowakia acuaria* is reported (SCHÖNLAUB, 1980).

References: SCHÖNLAUB (1970, 1980), FERRETTI et al. (1999), BRETT et al. (2009).

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The vicinity of Graz: Upper Silurian to upper Carboniferous of the Graz Palaeozoic, upper Cretaceous of the Kainach Gosau and middle Miocene of Gratkorn

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Contents

Abstract
The city of Graz is dominated by mountains belonging to the Graz Palaeozoic, a thrusted series of Silurian to upper Carboniferous sediments. Some parts, like the Rannach Facies are slightly metamorphosed. The western part of the Graz Palaeozoic is partly covered by upper Cretaceous sediments of the Kainach Gosau, comprising alluvial sediments at the northern margin of the basin grading into deep marine fan depositions of the centre. In the southern and southeastern parts the Graz Palaeozoic is covered by Neogene sediments of the Styrian Basin. These sediments are dominated by fluvial and limnic deposits of middle to late Miocene age. Marine intercalations are rare, which renders correlations to more distal parts of the Styrian Basin challenging. The fossil site Gratkorn yields one of the most diverse and best studied vertebrate faunas of late middle Miocene age in Central Europe.

1. Introduction

The mountains that surround the city of Graz belong to the *Graz Palaeozoic* (GP), a thrust complex of Silurian to upper Carboniferous sediments capped by upper Cretaceous *Gosau* clastics. In the west, north and east the GP exhibits tectonic contacts to basal Austroalpine metamorphic complexes. To the south and southeast the GP is covered by Neogene sediments of the Styrian Basin.

Internally the GP consists of several facies nappes. The *Rannach Facies*, in the uppermost tectonic position, indicates a sedimentation area changing from a passive continental margin with intra-plate volcanism to shelf and platform geometries during Silurian to Devonian time. During early to middle Devonian time deposition changed from near-shore facies to open platform environments, during the late Devonian and Carboniferous the carbonate platform was drowned and pelagic limestones were deposited. Basal nappes of the GP are made up of late Silurian to early Devonian sequences that were subjected to metamorphic overprint under upper greenschist to exceptionally occurring amphibolite facies metamorphic conditions. Meggen-type lead/zinc-barite Sedex mineralizations occur in some upper Silurian–lower Devonian volcaniclastic sequences.

In its western sector the Graz Palaeozoic is sealed by upper Cretaceous (upper Santonian–Maastrichtian sediments of the *Kainach Gosau* (KG). The facies inventory of the *KG* comprises proximal alluvial sediments at the northern margin of the basin grading into deep marine fan depositions of the centre. Bituminous marls at the eastern margin represent a lacustrine environment which was temporarily affected by marine flooding.

Neogene sediments in the vicinity of Graz comprise largely fluvial and limnic deposits of middle to late Miocene age. Marine intercalations are rare, which renders correlations to more distal parts of the Styrian Basin challenging. The fossil site Gratkorn yields one of the most diverse and best studied vertebrate faunas of late middle Miocene age in Central Europe. Due to its origin from a rapidly accumulated floodplain palaeosol, time-averaging is low and the taphocoenose reflects well the original vertebrate community. As the Gratkorn site is dated independently from vertebrate biochronology, it is a very important benchmark for a vertebrate-based, continental biostratigraphy of the Central Paratethyan realm, and probably beyond.

The excursion focuses on the stratigraphy and facies architecture of the slightly metamorphosed *Rannach Facies* at the upper structural level of the GP thrust complex, marginal marine sequences of the KG and terrestrial deposits at the Gratkorn vertebrate locality.

2. Overview of the Graz Palaeozoic, the Cretaceous Kainach Gosau and the Styrian Neogene Basin

2.1. Graz Palaeozoic

In the Eastern Alps the Palaeozoics belong to the Upper Austroalpine Nappe System (SCHMID et al., 2004) in which non metamorphosed Palaeozoic sequences were primarily superposed unconformably by late Palaeozoic to Eocene stratigraphic sequences of the Calcareous Alps. The nappe structure of the Upper Austroalpine System was triggered by the closure of the Meliata Ocean during early Cretaceous and sealed by late Cretaceous to Eocene overstep sequences (Gosau Group). Later, during the indentation of the Apulian

Plate to the north and the southward subduction of the Penninic units under the Apulian Plate, the Upper Austroalpine Nappe System was thrusted into the uppermost tectonic position of the Eastern Alps. Contemporaneous with the Apulian indentation uplift of the Penninic Tauern Window and other core complexes triggered lateral ex-trusion of the eastern parts of the Eastern Alps within the Alpine-Carpathian-Pannonian unit to the east (RATSCHBACHER et al., 1991; NEUBAUER et al., 2000). Today lowgrade and non metamorphosed Palaeozoic successions are irregularly distributed in Austria (Fig. 1). Two major regions of Palaeozoic domains can be distinguished which are separated by the Periadriatic Fault, the most prominent Alpine fault system: the Eastern Alps with the Greywacke Zone, the Gurktal Nappe, the Graz Palaeozoic (GP), some isolated domains in south Styria and Burgenland and the Southern Alps with famous fossiliferous Palaeozoic sequences in the Carnic Alps and the southern Karawanken Mountains (SCHÖNLAUB & HEINISCH, 1993; HUBMANN et al., 2014).

Fig. 1. Austria and its disconnected Palaeozoic units (shaded areas). Major Palaeozoic domains in Austria belong to the Eastern Alps (Graz Palaeozoic, Greywacke Zone, Gurktal Nappe, South Burgenland) and the Southern Alps (Carnic Alps, South Karawanken Mts.).

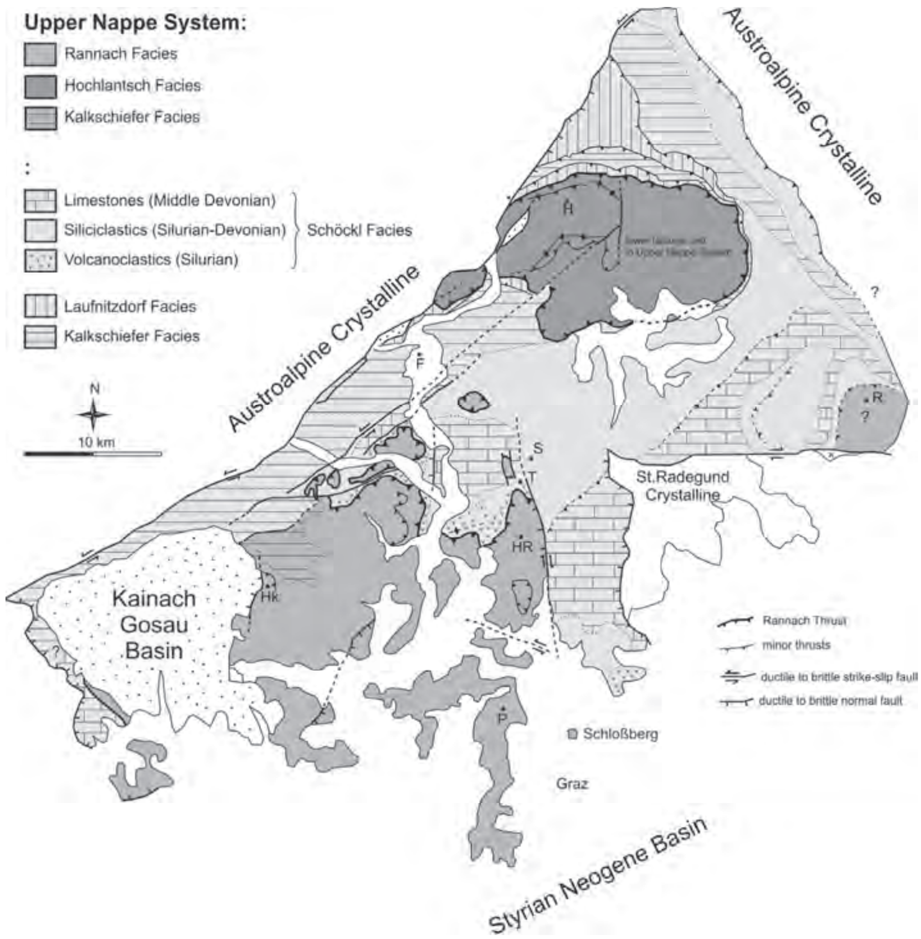

Fig. 2. The Graz Palaeozoic, its framing and internally organisation in nappe groups (modified after GASSER et al., 2009). H = Hochlantsch, Hk = Höllererkogel, HR = Hohe Rannach, P = Plabutsch, R = Raasberg, S = Semriach, T = Taschen (modified after GASSER et al., 2010).

The GP comprises an outcropping area of approximately 1,250 km^2 tectonically resting on metamorphic basement. Metamorphic units in the northwest, west, northeast and southeast belong to the Upper Austroalpine Silvretta-Seckau and Koralpe-Wölz Nappe Systems (SCHMID et al., 2004). The boundary between metamorphic units and the GP is formed by distinct thrust planes and a significant NE–SW striking sinistral wrench corridor at the northwestern border (Fig. 2). The nappes of the GP are unconformably overlain by the upper Cretaceous Kainach Group („Kainach Gosau"; EBNER & RANTITSCH, 2000) in the west and by Neogene sediments of the Styrian Basin in the south (EBNER & SACHSENHOFER, 1991, 1995; GROSS et al., 2007a). SW of Rothleiten upper Cretaceous conglomerates are also included along the sinistral wrench corridor between the GP and the Austroalpine metamorphic units.

The succession of the GP (?Silurian–upper Carboniferous) belongs to the "classical" non to only low grade metamorphic fossiliferous Austroalpine Palaeozoic units. The Eo-Alpine (Cretaceous) internal structure is composed of a Lower and an Upper Nappe System (GASSER et al., 2009, 2010). Each of them is differentiated into individual facies domains which reflect basal pre-Devonian volcanoclastics and a pronounced platfom to basinal facies geometry during the Devonian. The excursion focuses to the most famous and best investigated Rannach Facies of the Upper Nappe System. The sequence of the Rannach Facies begins with a volcanoclastic influenced environment (Reinerspitz Group; ?Ludlow–Lochkovian) followed by a Lochkovian to Frasnian carbonate shallow water environment (Rannach Group) which interfingers with basinal calcareous schists ("Kalkschiefer-Fazies"). During Frasnian the facies changed to a pelagic environment (Forstkogel Group) which continued until the Serpukhovian and is followed by limestones and slates of the Dult Group (Bashkirian). The concordant marine sequence which persists to the Bashkirian is interrupted by some erosion events.

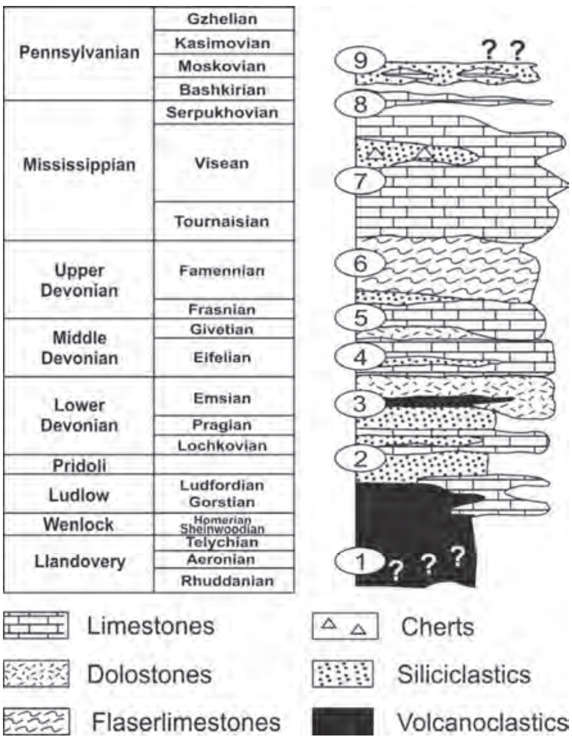

Fig. 3. Stratigraphic column of the Rannach Nappe indicating main lithologies.
Kötschberg Group: 1. Kehr Fm., Kötschberg Fm.
Rannach Group: 2. Parmasegg Fm., 3. Flösserkogel Fm., Bameder Fm; 4. Plabutsch Fm., 5. Kollerkogel Fm.
Forstkogel Group: 6. Steinberg Fm., 7. Sanzenkogel Fm.
Dult Group: 8. Höchkogel Fm., 9. Hahngraben Fm. (after EBNER & HUBMANN, 2012).

The architecture of the Rannach Facies is controlled by the specific tectonic and sedimentological history of the Noric Composite Terrane (FRISCH & NEUBAUER, 1989) and global environmental trends (sea level fluctuations, climatic changes etc.). The primary basement as well as the beginning of sedimentation in the Rannach Facies is still unknown (Fig. 3). Nevertheless, the Reinerspitz Group (FLÜGEL, 2000) forms the stratigraphic footwall in which alkaline basic volcanism (Kehr Fm.; >100 m; upper Ludlow in its upper parts; FLÜGEL, 2000) and fine clastic and pelagic carbonate sedimentation (Kötschberg Fm.; up to 30 m; FLÜGEL, 2000) reflect the evolution at passive margins of the separating terrane. Carbonate lenses/layers with fossils (conodonts, orthoceratides, brachiopods) indicate a Ludlow–Lochkovian age of the Kötschberg Fm.

Some massive basic volcanics (diabase) at top of the Kehr Fm. (Haritzgraben, Eggenfeld) with lava flows, block lavas, lapilli and ash tuffs derive from volcanic islands with volcanic activity in shallow water and subaerial domains. Trace element analysis reveals weak alkaline affinities of the basaltic volcanics formed in an intracontinental rifting basin (FRITZ & NEUBAUER, 1988). Due to the morphology of the island, the superposition is heterochronous. On the slope (e.g., Eggenfeld) a several metres thick alternation of bedded dark fossil rich dolomite and fine grained tuffite (Ludlow–Lochkovian; EBNER, 1976a; PLODOWSKI, 1976; HIDEN, 1996; HISTON et al., 2010) developed, whereas the top of the volcano (Haritzgraben) was still covered by dolomites of the basal Flösserkogel Fm. (Pragian).

During Pragian to lower Emsian times, intertidal to shallow subtidal deposits developed on a carbonate ramp which were comprised to the Parmasegg Fm. (FRITZ, 1991).

From the lower Devonian, probably in causal connection with a gradual movement of the plate to which the depositional area of the GP belonged into lower latitudes (FRITZ & NEUBAUER, 1988; FENNINGER et al., 1997), increase of carbonate production is obvious. Thick successions of coarse-grained sandstones with layers of diabase tuff were deposited in a shallow marine, near-shore environment (Flösserkogel Fm., Heuberg Mb.).

Due to different lithological characteristics, FENNINGER & HOLZER (1978) distinguished four facial types which were considered as members by FLÜGEL (2000). In general, the Flösserkogel Fm. comprises different kinds of dolostones, silt- to sandstones and subordinated dolomitic limestones which are interpreted as depositions of a supra- to shallow subtidal, barrier-surrounded lagoon, or tidal flats (FENNINGER & HOLZER, 1978). Near Graz the lower parts of the succession are interpreted as sand bars whereas the upper parts which are separated by volcanic tuffs contain meadows of the spaghetti-like stromatoporoid *Amphipora* (HUBMANN et al., 2006; HUBMANN & SUTTNER, 2007). Although conodonts are very rare they point to a (lower?) Emsian age (cf. EBNER et al., 2000).

A highly fossiliferous sequence dominated by dark marly bioclastic limestones overlies or rather interfingers the Flösserkogel Fm. This sequence, called Plabutsch Fm., exhibits in the lower parts especially at the boundary to the underlying Flösserkogel Fm. yellow to brownish shales occasionally blotched with moulds of chonetid brachiopods. In the upper parts of the formation intercalations of red marls and marly limestones are common phenomena.

Among the organisms typical “reefbuilders“ are common (HUBMANN, 1993, 2003) in all sectional sites. Nevertheless, there is no evidence in the field of a “true reef“; rather coral-stromatoporoid-carpets and lagoonal sediments are the dominant features. Environmental investigations indicate deposition on a differentiated and slightly inclined carbonate platform (HUBMANN, 1993). The following features support the assumption that sedimentary conditions were unfavourable for reef formation: the rarity of in situ organisms, the intermittent high supply of clayey sediments (marl-limestone intercalations) and high supply of lime mud, temporary influx of high amounts of continental phytoclasts, storm impacts (several tempestite sequences within the profiles) and especially their effects on the biocoenosis (HUBMANN, 1995).

This phase of the Plabutsch Fm. is terminated by a repetition of tidal flat deposits similar to the Flösserkogel Fm. and obviously caused by an eustatic sea level fall.

Transgression resulted in a sequence with sharp (bio)facial contrasts between patch-reefs and monotonous mudstones of Givetian age (Rannach Facies: Kollerkogel Fm., Hochlantsch Facies: Tyrnaueralm Fm., Zachenspitz Fm.) in the Upper Nappe System. Grey dolomites with biolaminations, light bluish limestones (mostly mudstones), locally bioclastic limestones with chert nodules which are interpreted to have developed in major parts in an open platform setting are comprised to the Kollerkogel Fm. According to FLÜGEL (2000) four members in the Kollerkogel Fm. are discernible: Gaisbergsattel Mb. (dark grey biolaminated dolostones; about 20 m), the basal part of the formation representing tidal flat deposits and sediments of a restricted lagoon, Kanzel Mb. (light grey to bluish limestones; mostly mudstones; up to 100 m), Platzlkogel Mb. (grey limestones with locally developed biohermal structures; about 75 m), Platzl Mb. (grey limestones intercalated with carbonatic argillaceous shales; about 50 m; reaches up to the upper Devonian). In contrast to the Kanzel Mb. which is very poor in conodonts the conodont fauna of the Platzlkogel Mb. is much richer. The *Polygnathus-Icriodus* ratio indicates a higher energetic open platform environment (EBNER, 1998).

During uppermost Givetian to lower Frasnian the sedimentation of shallow platform carbonates was replaced by variegated micritic cephalopod limestones (Forstkogel Group) which continued until the Serpukhovian (Fig. 4). The thickness of this pelagic group reaches in maximum 100 m. In the eastern parts of the Rannach Facies it is reduced to ~30 m by an intraformational stratigraphic gap across the Devonian–Carboniferous boundary caused by karstification (EBNER, 1978, 1980a, b). Colour (grey–yellowish brown–reddish–violet) and lithology (thin to thick bedded, flaser- to nodular marly limestones) are strongly changing. By means of conodonts the Forstkogel Group can be subdivided in the upper Devonian Steinberg Fm. and the Carboniferous Sanzenkogel Fm. Locally, the Givetian parts of the Steinberg Fm. are separated as the 20–30 m thick Höllererkogel Mb. (EBNER, 1978, 1980a, b, 1985; EBNER et al., 1979, 2000; NÖSSING, 1974, 1975; SURENIAN, 1978; BUCHROITHNER et al., 1979). Marker beds within the Upper Sanzenkogel Fm. are the Trolp Phosphorite Bed (up to 40 cm thick shale and lydite with phosphorite nodules) in the western and the Hart Lydite Bed (250 cm lydite; EBNER, 1978; BOSIC, 1998, 1999; FLÜGEL, 2000) in the eastern parts of the Rannach Facies.

All known conodont zones from the *varcus* Zone (latest Givetian) until the Serpukhovian *Gnathodus bilineatis bollandensis* Zone were proved in the Forstkogel Group (FLÜGEL & ZIEGLER, 1957; NÖSSING, 1975; EBNER, 1977a; SURENIAN, 1978; BUCHROITHNER et al., 1979; BOSIC, 1998, 1999).

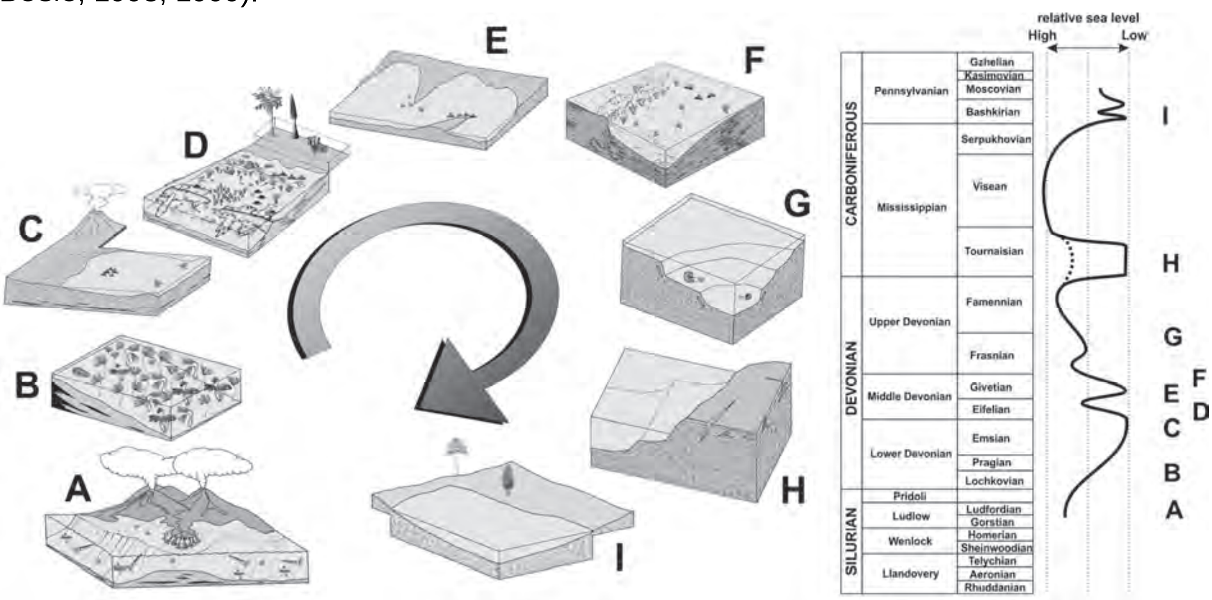

Fig. 4. Cartoon of the depositional environments of the Rannach Facies.
A. Kötschberg Fm., B. Parmasegg Fm., C. Flösserkogel Fm., D. Plabutsch Fm., E. Gaisbergsattel Mb., F. Kanzel Mb., G. Steinberg Fm., H. Sanzenkogel Fm., I. Höchkogel and Hahngraben Fms.
Note the relative sea-level curve through time estimated from sedimentological and palaeontological data (modified after EBNER et al., 2000).

Generally continuous sequences across the Devonian–Carboniferous boundary occur in the western parts of the Rannach Facies. In the east this level is dominated by erosional gaps which increase in their stratigraphic extent towards the east. In maximum the erosion phase includes the time span from early Famennian to early Visean. Therefore, the strongly condensed and only 220 cm thick Lower Sanzenkogel Fm. (Tournaisian, *Siphonodella sulcata–Scaliognathus anchoralis* Zone) occurs only in the western domains.
Since no evidence for a facial change is traceable, it is assumed that the considered area remained in an off-shore shelf position. Thus, to explain the conodont mixed faunas the depositional environment must have been affected by synsedimentary tectonics and/or sea level fluctuations causing a shallowing of the sea with local desiccation followed by rapid deepening within the latest Tournaisian to early Visean time interval. The western domain with continuous sections remained always in marine, pelagic positions. Sedimentation of shales, lydites and phosporites (Trolp Phosphorite Bed) may indicate upwelling zones at the margin of the outer shelf just at the beginning the Carboniferous transgression (EBNER et al., 2000).
Tentatively the bathymetric path of the Forstkogel Group was interpreted from Mn contents (BUCHROITHNER et al., 1979; EBNER & PROCHASKA, 1989; EBNER et al., 2000). These data, calibrated with Mn contents of 400–1750 ppm for Palaeozoic cephalopod limestones (BUGGISCH, 1972; LÜTKE, 1976), suggest a depth of 60–300 m for the formation of phosphorite and cephalopod limestones in the GP (NÖSSING, 1974). Additionally increasing Mn contents indicate an environmental deepening. During the upper Devonian the western domains represent deeper and more open shelf conditions. A deepening trend until the early Famennian *crepida* Zone was followed by shallowing until to the *styriacus* Zone. The generic composition of the conodont biofacies of the *styriacus* Zone indicates „shallow to moderate deep water on the continental shelf" (SANDBERG, 1976). The decreasing and low level Mn contents of the western domains reflect the uplift/shallowing of the eastern parts culminating in subaerial erosion and karstification. During late Tournaisian increasing Mn contents reflect the transgression of the Upper Sanzenkogel Fm. and a deepening of the environment in which lydite formation may indicate the deepest parts in both areas. Possibly the crossing of the bathymetric paths in the eastern and western domains after the phosphorite event indicates diverse synsedimentary tectonics of the two blocks. Decreasing Mn contents at top of the Sanzenkogel Fm. coincides with another erosion event between the Forstkogel and Dult Groups.
The Dult Group (EBNER, 1978; FLÜGEL, 2000) began after an erosion gap at top of the Sanzenkogel Fm. (EBNER, 1976b, 1977a, b, 1978, 1998; EBNER et al., 2000; FLÜGEL, 2000). At its basal part the Höchkogel Fm. consists of dark coloured limestones (Hartbauer Mb.) which are interfingering/superposed with/by an alternation of shales with black limestones. The latter sometimes contain birdseye-structures (Schrausbauer Mb.) indicating a shallow water deposition. At top of the Dult Group approximately 50 m thick black slates, sometimes with intercalations of silt- and sandstone with fine phytoclastic materials are comprised to the Hahngraben Fm.
The Höchkogel Fm. is dated by conodonts of the *Declinognathodus-Idiognathoiodes* group as lower Bashkirian (EBNER, 1977, 1980a; ZHI-HAO & YU-PING, 2002). The boundary between the pelagic Forstkogel Group and shallow marine Dult Group is formed by an erosion surface. Locally at the very base of the Hartbauer Mb. 20 cm thick fine-grained limestone breccias contain mixed conodont faunas with autochthonous elements of the lower Bashkirian and reworked conodonts (Visean–Serpukhovian) from the Upper Sanzenkogel Fm. At one site the entire Upper Sanzenkogel Fm. was eroded, thus affecting a direct

superposition of upper Devonian limestone (*velifer* Zone) by the Bashkirian Hartbauer Mb. (EBNER, 1978, 1980a).

2.2. Kainach Gosau

The depositional environment of Kainach Gosau (KG) originated as an extensional basin during the late Cretaceous (late Santonian to Maastrichtian). Subsidence of the basin is explained by synchronous uplift of the Gleinalm dome (see also Fig. 2) in a sinistral wrench corridor (EBNER & RANTITSCH, 2000; BODROGI et al., 1994, cum lit.). On three sides, in the west, north and east, the KG is bordered by Devonian limestones and dolomites the GP. In its southern and southeastern part the KG is overlain by middle Miocene limnic-fluvial sediments. Contact with the Gleinalm crystalline is nowhere given. The basal face is formed by a pre-upper Cretaceous karst topography on mainly lower to middle Devonian successions of the GP.
The inventory of deposits comprises proximal alluvial conglomerates, marine fan sediments, and bituminous marls of a restricted lacustrine environment. Alluvial fan sediments are exposed in the northern sector of the basin in the area of Geistthal. These sediments, mostly coarse-grained conglomerates, grade into deep marine fan deposits characterised by more fine-grained clastics (sand/siltstones, clays) located in the centre of the basin. Bituminous marls and marly limestones are known from the eastern margin the basin. In the southeast of the basin hydraulic limestones, marls, calcareous marls and bioclastic limestones occur. Four lithostratigraphic units can be distinguished:
(1) Geistthal Fm. (EBNER & RANTITSCH, 2000): The basal sequence comprises several 100 metres of intensively red coloured conglomerates mainly exposed at the northern margin of the basin (GRÄF, 1975; SCHIRNIK, 1995). The clasts (up to 100 cm in diameter) are dominated by reworked limestones and dolostones, subordinate alkaline volcanics, shales/slates and sandstones of the GP. Interestingly some “exotic” pebbles indicate a northern alpine provenance (e.g., Dachstein Limestone, Hierlatz Lst., Tressenstein/Plassen Lst., radiolarian cherts) whereas others indicate a southern alpine origin (Silurian cephalopod limestones, red sandstones of the Gröden Formation, fusulinid limestone) (cf. GRÄF, 1975; FLÜGEL, 1983; GOLLNER et al., 1987; SCHIRNIK, 1995; EBNER & RANTITSCH, 2000; BOJAR et al., 2001). Upper parts of the formation may locally contain snail shells of *Trochactaeon* which point to a late Santonian to early Campanian age (GRÄF, 1975).
(2) St. Pankrazen Fm. (EBNER & RANTITSCH, 2000): Bituminous marls reach up to 50 metres in thickness at the eastern margin of the basin (Platzlkogel–St. Pankrazen area). A subdivision in three members were proposed by EBNER & RANTITSCH (2000): (A) Conglomerate member: up to 2 m thick monomict conglomerates, transgressively overlying the Palaeozoic basement. (B) Limestone member: marly gastropod limestones with crustacean coprolites (FENNINGER & HUBMANN, 1994). (C) Bituminous marl member: Bituminous, calcareous clay to siltstones, up to 50 metres in thickness, with allochthonous (terrigenous) vitrinites and autochthonous (lacustrine) alginites and liptodetrinites as main constituents of the organic matter (SACHSENHOFER et al., 1995; RUSSEGGER et al., 1998).
(3) Afling Fm. (EBNER & RANTITSCH, 2000): This formation comprises about 1.000 to 1.200 m thick grey-brown clay-, silt- and sandstones with locally intercalated by conglomerate layers. Some sections in the northern and western basin point to proximal turbiditic conditions.
(4) St. Bartholomä Fm. (EBNER & RANTITSCH, 2000): In an “adjacent basin“ around the village St. Bartholomä the Afling Fm. is overlain by approximately 250 m thick grey to yellow marls.

Sometimes these 'hydraulic marls' ("Zementmergel") contain in some layers clasts of rudist bivalves. Microfossils point to a late Santonian to early Campanian age (BODROGI et al., 1994).

2.3. Styrian Basin

The Styrian Basin is located at the SE margin of the Alps and belongs to the Pannonian Basin System (Fig. 5). Its N, W and SW border is build up by metamorphic Austroalpine units and the Graz Palaeozoic. In the NE the Güns Mountains (Pennic unit) forms its boundary. Towards the E the South Burgenland Swell separates the Styrian Basin from the Western Pannonian Basin. The Styrian Basin is approximately 100 km long, 60 km wide and basin filling reaches a maximum thick-ness of up to 4000 m. The Middle Styrian Swell (Sausal Mountain range) divides it into a Western and an Eastern Styrian Basin. Additionally, subordinate swells and basement spurs cause a complex differentiation in several subbasins and bays.

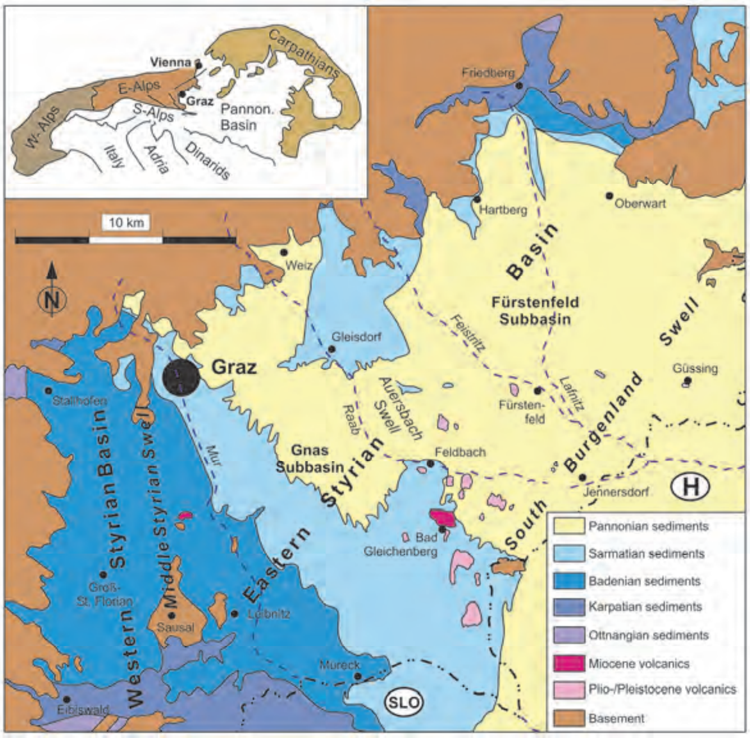

Fig. 5. Geological sketch of the Styrian Basin.

The basin filling (synrift phase) started in early Miocene times (Ottnangian) with limnic–fluvial sediments in central basin areas ("Limnic Series") as well as with alluvial fan, fluvial to deltaic deposits at the basin margins (Radl Fm., "Lower Eibiswald Beds", Köflach-Voitsberg Fm.; Fig. 6). In the Karpatian enhanced subsidence as well as a sea level rise led to the deposition of several hundred metres thick offshore mud- and siltstones ("Kreuzkrumpl Fm." resp. "Styrian Schlier"), which interfinger to the basin margins with mass flow, fluvial fan and deltaic sediments (e.g., Sinnersdorf Fm., "Conglomerate-rich Group"). Extensional tectonics were accompanied by volcanic activity ("Gleichenberg Volcanics"), which continued until the early Badenian. Around the early/middle Miocene boundary, a global sea level fall and tectonic movements caused block tilting as well as a major unconformity ("Styrian Tectonic Phase"). In the early Badenian (onset of the postrift phase), the marine environments reached its largest extend. While sedimentation of fine clastics ("Marl, Silt/Sand") prevailed in central basin position, variegated mixed-siliciclastic-carbonatic systems became established on morphologic highs (Kreuzberg Fm., Weissenegg Fm, Tauchen Fm.). Lagoonal deposits dominate the central Western Styrian Basin ("Florian Beds"), including basaltic intrusions ("Weitendorf Volcanics") at the transition to the Eastern Styrian Basin. After a marked regression at the Badenian/Sarmatian boundary, late middle Miocene sedimentation is characterised by pelitic sediments (Rollsdorf Fm.) or bryozoan-serpulid biocontructions (Grafenberg Fm.). A regressive event ("Carinthian Phase") caused basin ward progradation

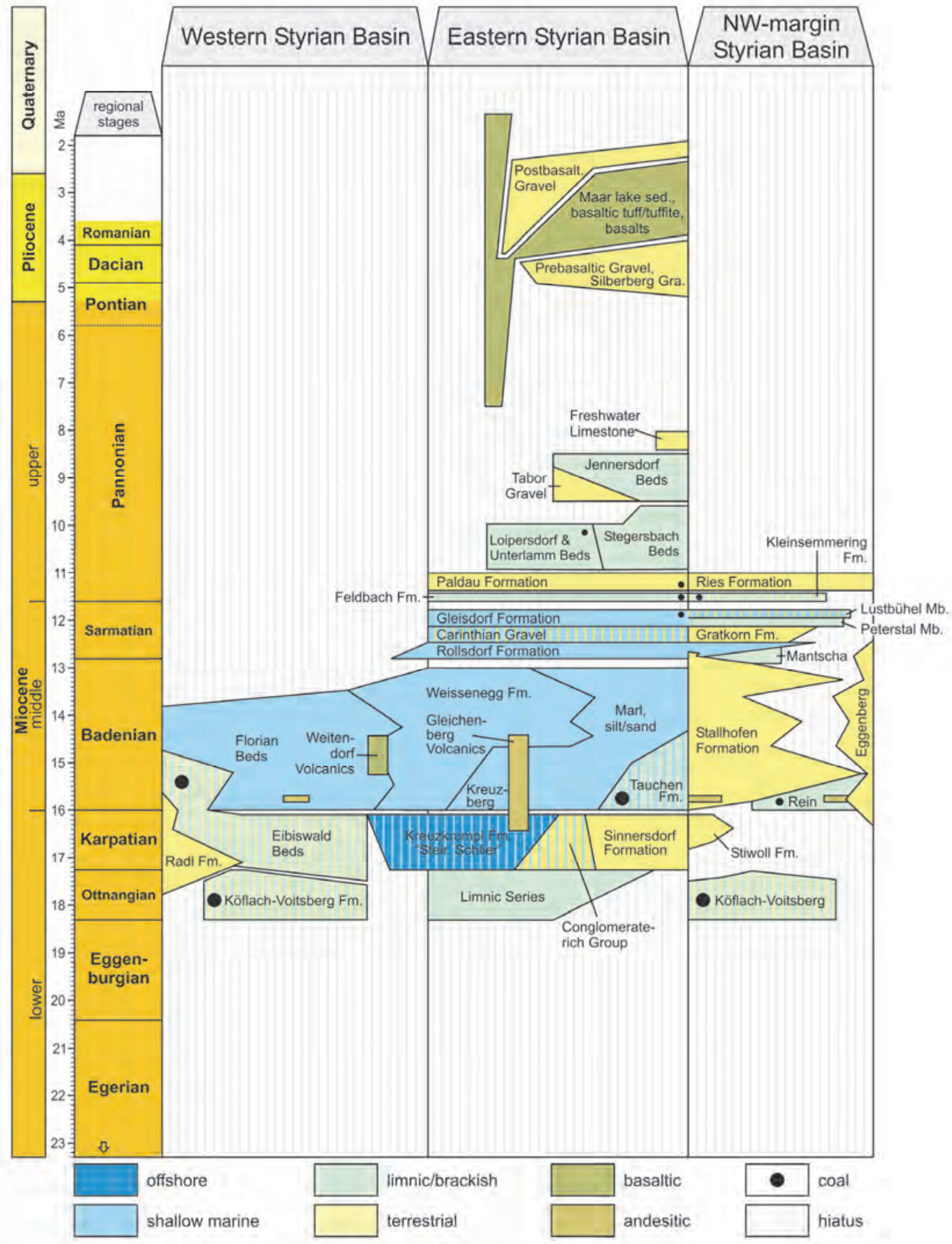

Fig. 6. Lithostratigraphic units of the Styrian Basin and correlation with Neogene Formations at the NW-margin of the Styrian Basin (after GROSS, 2015).

of fluvial environments ("Carinthian Gravel", Gratkorn Fm.), followed by cyclic successions of siliciclastics and carbonates (e.g., silt/sand/oolites; Gleisdorf Fm.). The separation of the Central Paratethys Sea around the middle/late Miocene boundary is accompanied by significant erosion and the evolution of Lake Pannon. Repeated alternations of limnic–deltaic–fluvial or even terrestrial environments determined sedimentation in Pannonian times (Feldbach Fm., Paldau Fm., "Loipersdorf and Unterlamm Beds", "Stegersbach Beds", "Tabor Gravel", "Jennersdorf Beds", "Freshwater Limestone"). Subsequent basin inversion caused considerable erosion and a hiatus ranging up to the Pliocene. Fluvial clastics are observed

below or adjacent ("Prebasaltic Gravel, Silberberg Gravel") as well as on top ("Postbasaltic Gravel") of variegated alkali basaltic volcanics of Plio-/Pleistocene age.
Except the works of WINKLER-HERMADEN (e.g., 1957), especially the paper of KOLLMANN (1965), the studies of KRÖLL et al. (1988), EBNER & SACHSENHOFER (1991, 1995) and SACHSENHOFER et al. (1997) offer detailed data about the basement and basin filling. GROSS et al. (2007a) provide a more recent compilation; SCHREILECHNER & SACHSENHOFER (2007) present a sequence stratigraphic framework.

3. The Field Trip

3.1. Stop 1 – Plabutsch–Fürstenstand

Topic: Introduction to the geology of the vicinity of Graz.
Locality: Fürstenstand, 4.5 km WNW Hauptplatz Graz, 47°05'25"N/15°23'6"E.
Description: After the incorporation of some municipalities in the year 1938 the hill Plabutsch with 754 m altitude became the highest elevation of the city Graz. The derivation of the name "Plabutsch" is not clarified. Possibly Celtic roots of „pla" indicate the meaning of iron smelt.
At the summit of the Plabutsch a little observation tower called "Fürstenstand" is located more than 400 metres higher than the centre of Graz and therefore provides a magnificent view over Graz and a panoramic view over the hilly landscape of the surrounding countryside, fair weather provided. The most important geologic units recognisable from here are illustrated in Fig. 7.

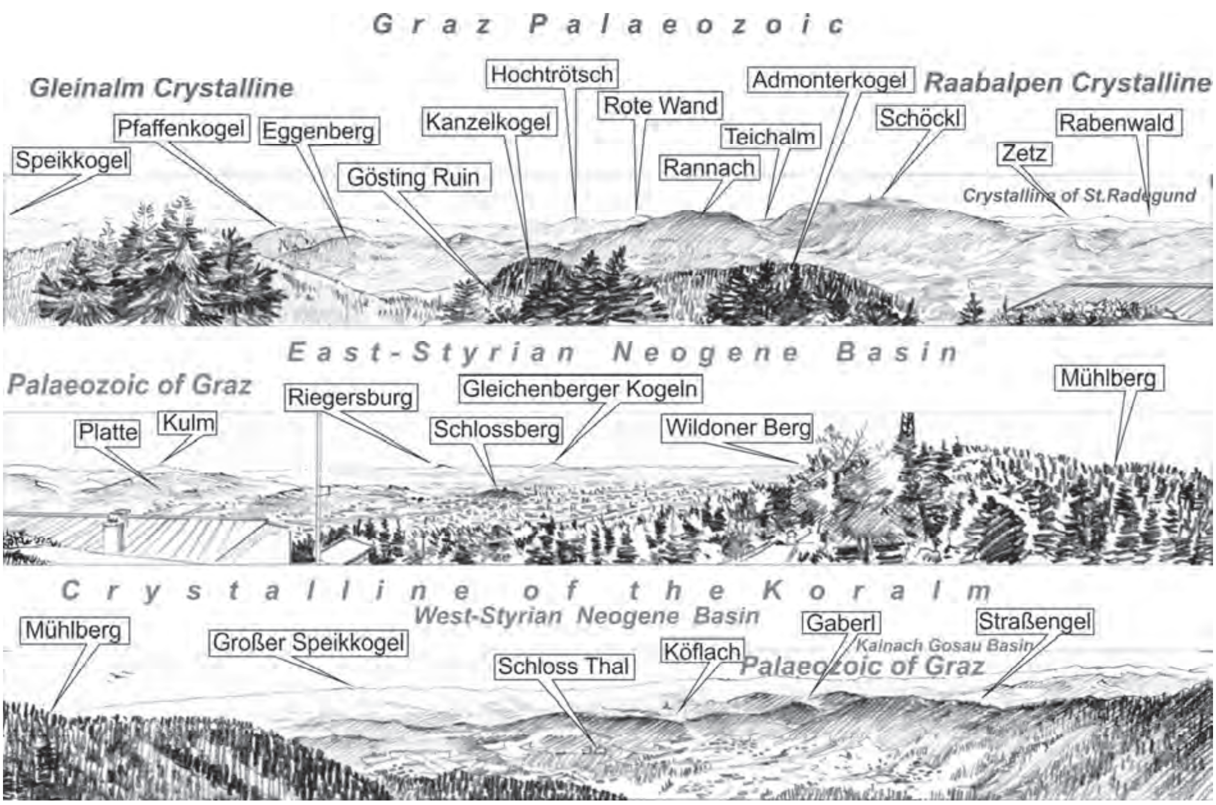

Fig. 7. Panoramic view from the "Fürstenstand". Main geologic units indicated. Drawing by Fritz Messner.

Already ROLLE (1856: 238) reported from the crest of the Plabutsch lots of fossils (i.e., rugosans, tabulates, stromatoporoids, crinoids, “bivalves”) occurring in dark grey limestones and assumed a reef structure. Since these limestones were used as building stones, the walls of the observation tower give an instructive insight into the organic composition of the environment (Fig. 8).

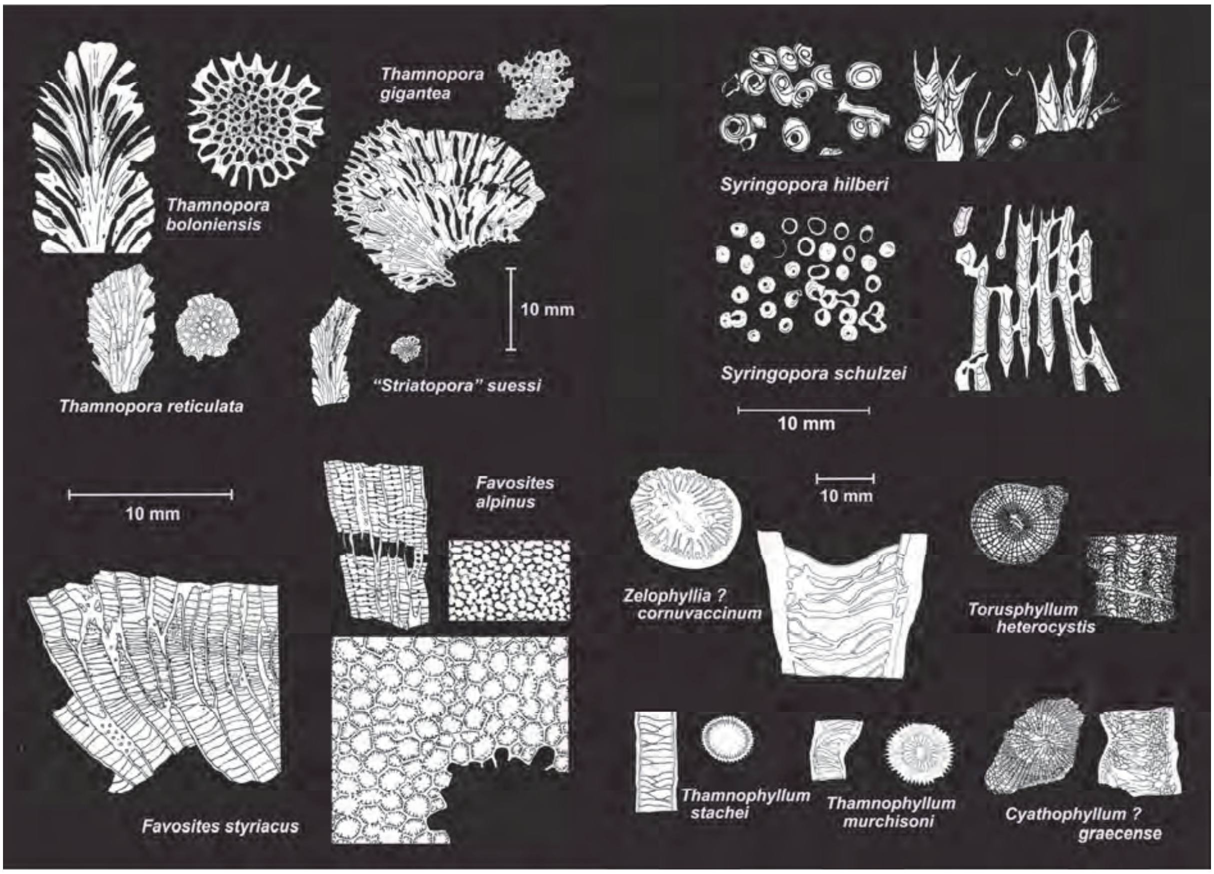

Fig. 8. Sectional images of the most important coral taxa of the Plabutsch Fm. as they can be seen in the building stones at the Fürstenwarte (after EBNER et al., 2000).

One and a half decade before Rolle, Franz Unger (1800–1870), a famous palaeobotanist at the Joanneum in Graz, published in 1843 taxonomic determinations of the following corals and stromatoporoids (UNGER, 1843): *Gorgonia infundibuliformis* GOLDF., *Stromatopora concentrica* GOLDF., *Heliopora interstincta* Bronn (*Astraea porosa* GOLDF.), *Cyathophyllum explanatum* GOLDF., *Cyathophyllum turbinatum* GOLDF., *Cyathophyllum hexagonum* GOLDF., *Cyathophyllum caespitosum* GOLDF., *Calamopora polymorpha* a. var. *tuberosa* GOLDF., *Calamopora polymorpha* b. var. *ramoso - divaricata* GOLDF., *Calamopora spongites* a. var. *tuberosa* GOLDF. and *Calamopora spongites* b. var. *ramose* GOLDF.
Today this listing of taxa is only of historical value. Nevertheless honour is due to Unger having presented the first faunal list of Devonian fossils in Austria. The crest area of the Plabutsch from where the fossils originate is therefore the first area outside Great Britain and Germany where sediments were assigned to the Devonian system. Note that the Devonian period was established by Murchison and Sedgwick only 4 years before in 1839!
References: EBNER & HUBMANN (2012), HUBMANN et al. (2003).

3.2. Stop 2 – Forest road Attems

Topic: Fossiliferous shallow marine succession; type locality of the Plabutsch Formation; type locality of the udoteacean taxon *Pseudolitanaia graecensis*.
Locality: Forest road "Attems" at the southern slope of Frauenkogel, 47°05'18"N/15°22'05"E.
Lithostratigraphy: Plabutsch Formation (type section).
Biostratigraphy: –
Chronostratigraphic age: Eifelian; locally the sequence may range from upper Emsian to lower Givetian.
Description: Along the road variegated dolostones of the Flösserkogel Formation, marly shales and marly limestones (Gaisbergsattel Member) and dark grey marly bioclastic limestones of the Plabutsch Formation are exposed.
The outcrop along the road starts with whitish sandy dolostones of the Flösserkogel Fm. (Emsian) which passes into laminated dolomitic limestones (tidal flat deposits) in the uppermost part of the formation.
Separated by a fault brownish to yellow marly shales with moulds of chonetid brachiopods and very rare trilobites (*Maladaia* sp.) on bedding planes follow. At the base of this succession the shale is intercalated by marly limestone-beds less than 10 cm in thickness. The yellow to reddish-brown limestones are densely packed brachiopod or Eridostraca shell accumulations. Some brachiopod shells were used by auloporid tabulates (*Aulostegites* sp.) as substrate for anchorage. Partly the ostracods (unidentifiable smooth valved individuals) and eridostracs (*Eridoconcha papillosa* and *Cryptophyllus* sp.) are silicified in contrast to other fossil remains. The succession described reaches up to 8 to 10 metres in thickness and is assigned to the Gaisberg Bed of the Plabutsch Fm. (HUBMANN, 2003). The uppermost part of the Gaisberg Bed is characterised by the settlement of mound shaped favositid tabulates (*Favosites styriacus*) with diameters of colonies up to 80 cm. The occurrence of corals coincides with a rapid lithological change from orange marls and marly limestones to greyish blue limestone beds.
The first few metres of these limestones are dominated by a stromatoporoid-coral faunal association which passes into a coral-brachiopod biofacies. This community includes *Favosites*, *Thamnophyllum*, *Thamnopora*, *Zelophyllia* and other corals. Approximately at the middle part of the unit this community is replaced by a biofacies which is dominated by calcareous green algae (e.g., *Pseudopalaeoporella*, *Pseudolitanaia*; HUBMANN, 1990) and thamnoporids.
In the upper part of the Plabutsch Fm. thick valved brachiopods which are assigned to *Zdimir* cf. *hercynicus* occur. Together with „*Striatopora*" and *Thamnopora* they compose the brachiopod-coral biofacies (Fig. 9).
Within the entire sequence along forest road Attems, conodonts are sparsely distributed. Mainly icriodontids were found which suggest an Emsian–Eifelian age for the lower part of the Plabutsch Fm. (SUTTNER & BERKYOVÁ, 2009). Despite a very rich fauna (Fig. 10) the age of this formation remains problematic, because distinctive age-constraining fossils are rare (HUBMANN & MESSNER, 2005). Generally the faunal association indicates an uppermost Emsian to lowermost Givetian age.
References: EBNER & HUBMANN (2012), HUBMANN (1993, 2003), HUBMANN et al. (2003), HUBMANN & MESSNER (2005).

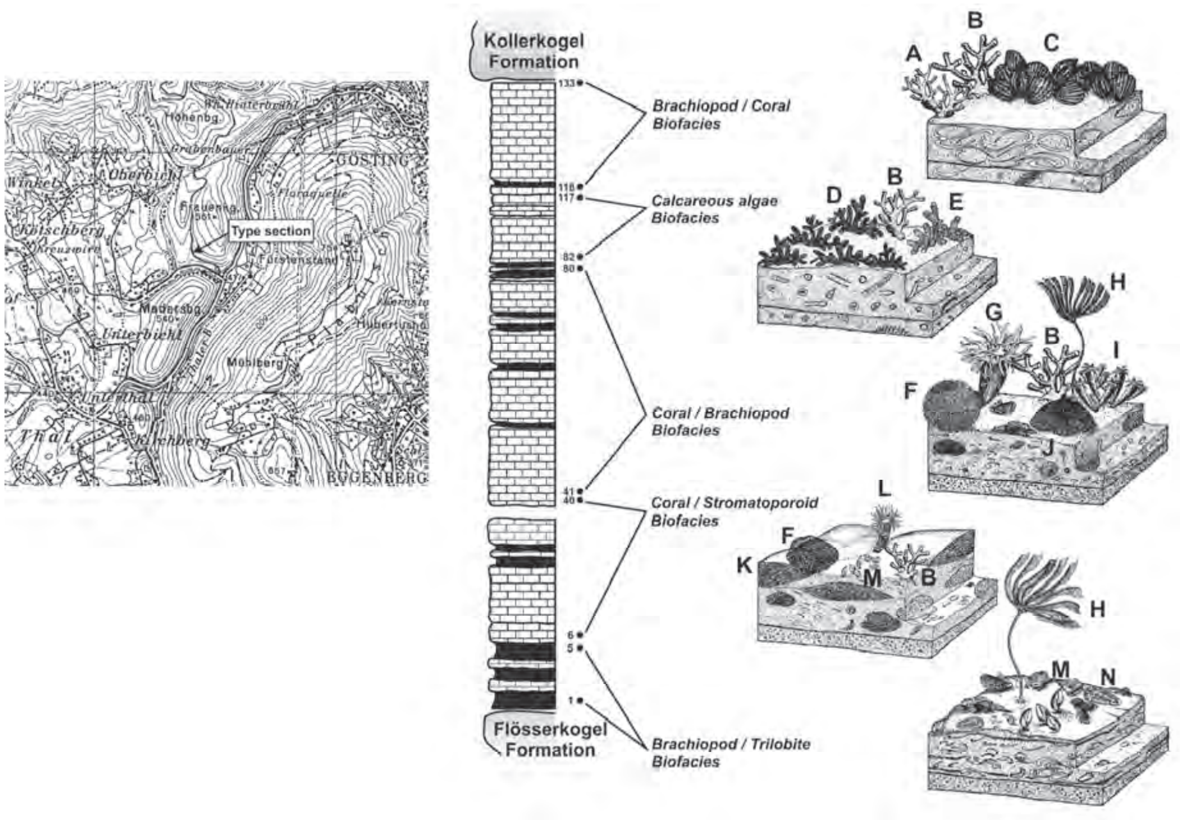

Fig. 9. Forest road Attems. Section of the Plabutsch Fm. subdivided into 5 biofacial sections: a: Siliciclastic Brachiopod-Trilobite-Biofacies ("Chonetenschiefer" = Gaisberg Bed) with: *Chonetes* sp., *Maladaia* sp., and crinoids; b: Coral-Stromatoporoid-Biofacies with: *Actinostroma* sp., *Thamnophyllum stachei*, *Thamnophyllum murchisoni*, *Favosites styriacus*, *Thamnopora* sp., *Striatopora* sp., *Pachycanalicula barrandei*, *Heliolites* cf. *peneckei*, Crinoids; c: Coral-Brachiopod-Biofacies with *Thamnophyllum stachei*, *Thamnophyllum murchisoni*, *Thamnopora reticulata* ?, *Thamnopora* sp., *Striatopora* (?) *suessi*, *Favosites* sp., *Chonetes* sp., "Spiriferids", Crinoids; d: Algae-Biofacies with *Pseudopalaeoporella lummatonensis*, *Pseudolitanaia graecensis*; e: Brachiopod-Coral-Biofacies with: *Zdimir* cf. *hercynicus*, *Thamnopora* cf. *reticulata*, *Striatopora* (?) *suessi* (modified from HUBMANN, 2003).

3.3. Stop 3 – Quarry Trolp/Forstkogel

Topic: Devonian–Carboniferous boundary; type locality of Lower Sanzenkogel Formation; type locality of the conodont taxon *Polygnathus styriacus*.
Locality: Abandoned quarry "Trolp", 47°04'7"N/15°19'18"E.
Lithostratigraphy: Steinberg Formation and Lower Sanzenkogel Formation (type section).
Biostratigraphy: *Bispathodus costatus* Zone to the *Gnathodus typicus* Zone.
Chronostratigraphic age: Famennian/Tournaisian boundary.
Description: The abandoned quarry exhibits an overturned stratigraphic sequence of the upper parts of the Steinberg Formation (Frasnian–Famennian) and the Lower Sanzenkogel Fm.; it is the type locality of the Famennian conodont taxon *Polygnathus styriacus*.
In the eastern face of the quarry an overturned section from the latest Devonian *Bispathodus costatus* Zone to the *Gnathodus typicus* Zone is exposed. This section includes the site which was discussed as a favourite for the international Devonian–Carboniferous boundary stratotype (SANDBERG et al., 1983; ZIEGLER & SANDBERG, 1984), the type section of the 220 cm Tournaisian Lower Sanzenkogel Fm. and a 20 cm thick horizon with shale, lydite and

Fig. 10. Typical fossils of the Plabutsch Formation. 1) *Thamnophyllum stachei* PENECKE, 1894, x 1,5; 2) *Thamnophyllum murchisoni* PENECKE, 1894, x 1,5; 3) Fragment of a calyx of *Tryplasma devonica* (PENECKE, 1894), x 1,5; 4) Fragment of a calyx of *Zelophyllia cornuvaccinum* (PENECKE, 1894), x 0,75; 5) *Disphyllum caespitosum* (GOLDFUSS, 1826), x 1,5; 6) *Pachycanalicula barrandei* (PENECKE, 1887), x 1,5; 7) *Thamnopora reticulata* (BLAINVILLE, 1830), x 2,2; 8) *Thamnopora vermicularis* (M'COY, 1850), x 2,2; 9) „*Striatopora*“ *suessi* PENECKE, 1894, x 2,2; 10) *Thamnopora boloniensis* (GOSSELET, 1877), x 2,2; 11) *Favosites styriacus* PENECKE, 1894, x 1,5; 12) *Atrypa reticularis* LINNE, x 1,5; 13) *Zeapora gracilis* PENECKE, 1894, x 3. All specimens are from the private collection of Fritz Messner.

phosphorite nodules (Trolp Phosphorite Bed) at the bottom of the Upper Sanzenkogel Fm. (Figs. 11, 12).

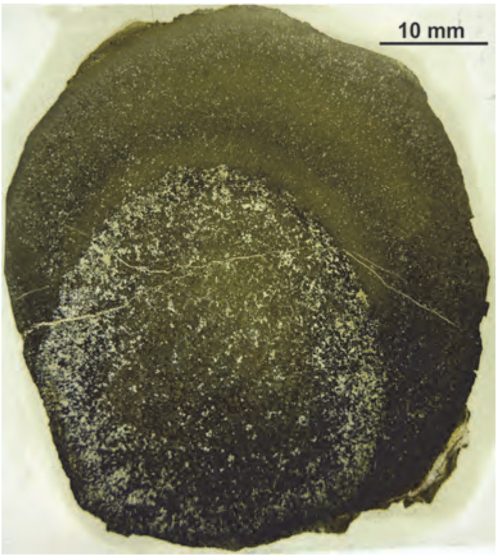

Fig. 11. Thin section of a phosphorite nodule with radiolarians from the Trolp Phosphorite Bed.

The sparsity of macrofossils and siphonodellid conodonts excluded this section as international boundary stratotype. In the section (Fig. 13) the beginning of the Carboniferous is indicated by the first occurrence of *Protognathodus kuehni. Siphonodella sulcata* as the international index conodont for the base of the Carboniferous was not yet found in the lowermost 20 cm of the Lower Sanzenkogel Fm. (EBNER, 1980; SANDBERG et al., 1983; ZIEGLER & SANDBERG, 1984; KAISER, 2005).

The boundary section is part of a 220 cm intensively investigated (conodonts, microfacies, stable isotope geochemistry) section (KAISER, 2005). The light-grey to ochre, sometimes nodular and flaser-bedded marly cephalopod limestones are rich in conodonts (CAI ~4.5) and represent a complete succession from the latest Famennian *Siphonodella praesulcata* to the Tournaisian *Siphonodella sulcata* Zone. At top of bed 9 there is a lithological change in form of a 1 cm thick argillaceous layer followed by thin bedded (~1–2 cm) marly limestones (mud- and wackestones) above which the base of the Carboniferous was recognised by the occurrence of *Protognathodus kuehni*. Due to the poor conodont fauna the marly bed is correlated with the main extinction phase of the Hangenberg event at top of the middle *Siphonodella praesulcata* Zone. This level is characterised by a positive $\delta^{13}C$ isotope excursion which coincides also with a main extinction phase during the deposition of the Hangenberg black shale in Germany and indicates a global perturbation of the carbon cycle during a period of warm seawater (KAISER, 2005).

Fig. 12. Type section of the Tournaisian Lower Sanzenkogel Fm. and the 20 cm thick horizon with shale, lydite and phosphrite nodules (Trolp Posphorite Bed) at the bottom of the Upper Sanzenkogel Fm.

The Tournaisian Trolp-Phosphorite Bed at the base of the Upper Sanzenkogel Fm. includes lydite with fragments of radiolarians (EBNER & HUBMANN, 2012). It indicates the deepening of the environment resulting in the formation of phosphorite nodules along upwelling zones of the Carboniferous shelf margin (EBNER et al., 2000).

<u>References:</u> NÖSSING (1974), EBNER (1980), EBNER et al. (2000), EBNER & HUBMANN (2012), KAISER (2005).

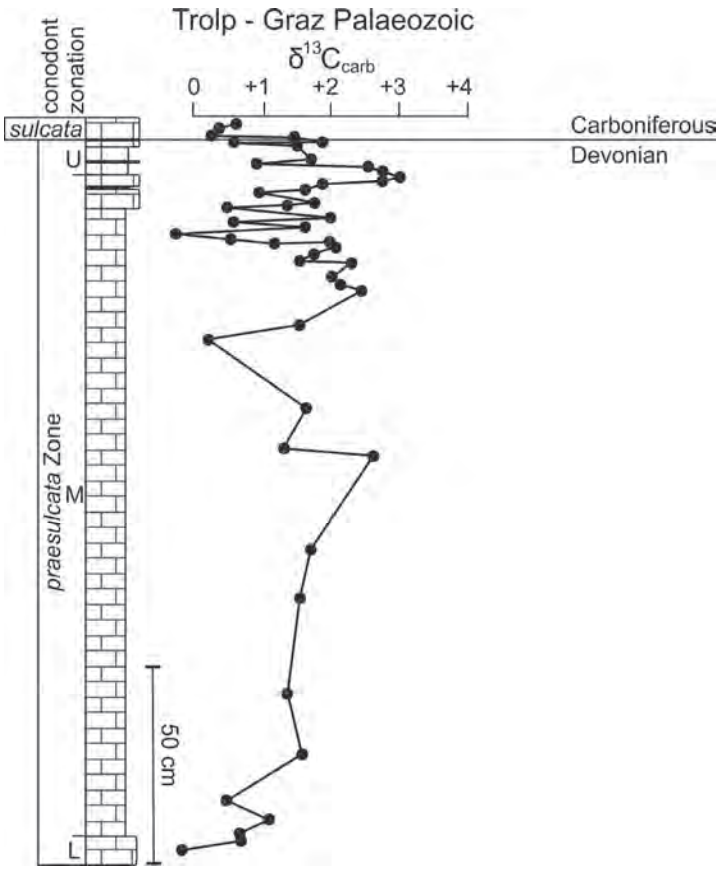

Fig. 13. Detail section across the Devonian–Carboniferous boundary (Steinberg Fm.–Lower Sanzenkogel Fm.) in the Trolp Quarry with the range of the conodonts and $\delta^{13}C_{carb}$ values (KAISER, 2005). Note the isotopic excursion in bed 10 and 11 and that in nature the section is inverted.

3.4. Stop 4 – Eastern slope of Höllererkogel (as an alternative to Stop 2 – Forest road Attems)

Topic: Shallow marine succession, very rich in tabulate and rugose corals and stromatoporoids.
Locality: Forest road at the eastern slope of Höllererkogel, 47°09'20"N/15°12'28"E.
Lithostratigraphy: Plabutsch Formation.
Biostratigraphy: –
Chronostratigraphic age: Eifelian; locally the sequence may range from upper Emsian to lower Givetian.
Description: The recently exposed section through the Plabutsch Formation along a forest path at Höllererkogel (near St. Pankrazen; W-Styria) provides an outstanding insight into a sequence of bioclastic limestones very rich in fossils.
In the course of forestry work a new profile through the upper portions of the Plabutsch Fm. was exposed which is built of mostly thick beds of dark grey-blue limestones. These beds (up to 60 to 80 cm) often result in layers strongly enriched fossil detritus. Corals or branches of coral respectively are often enriched suggesting that they did not have wide transport (Fig. 14). Presumably they derive from a thamnoporid coral carpet, which was destroyed by storm events.
References: EBNER & HUBMANN (2012), HUBMANN (1993, 2003), HUBMANN et al. (2003), HUBMANN & MESSNER (2005).

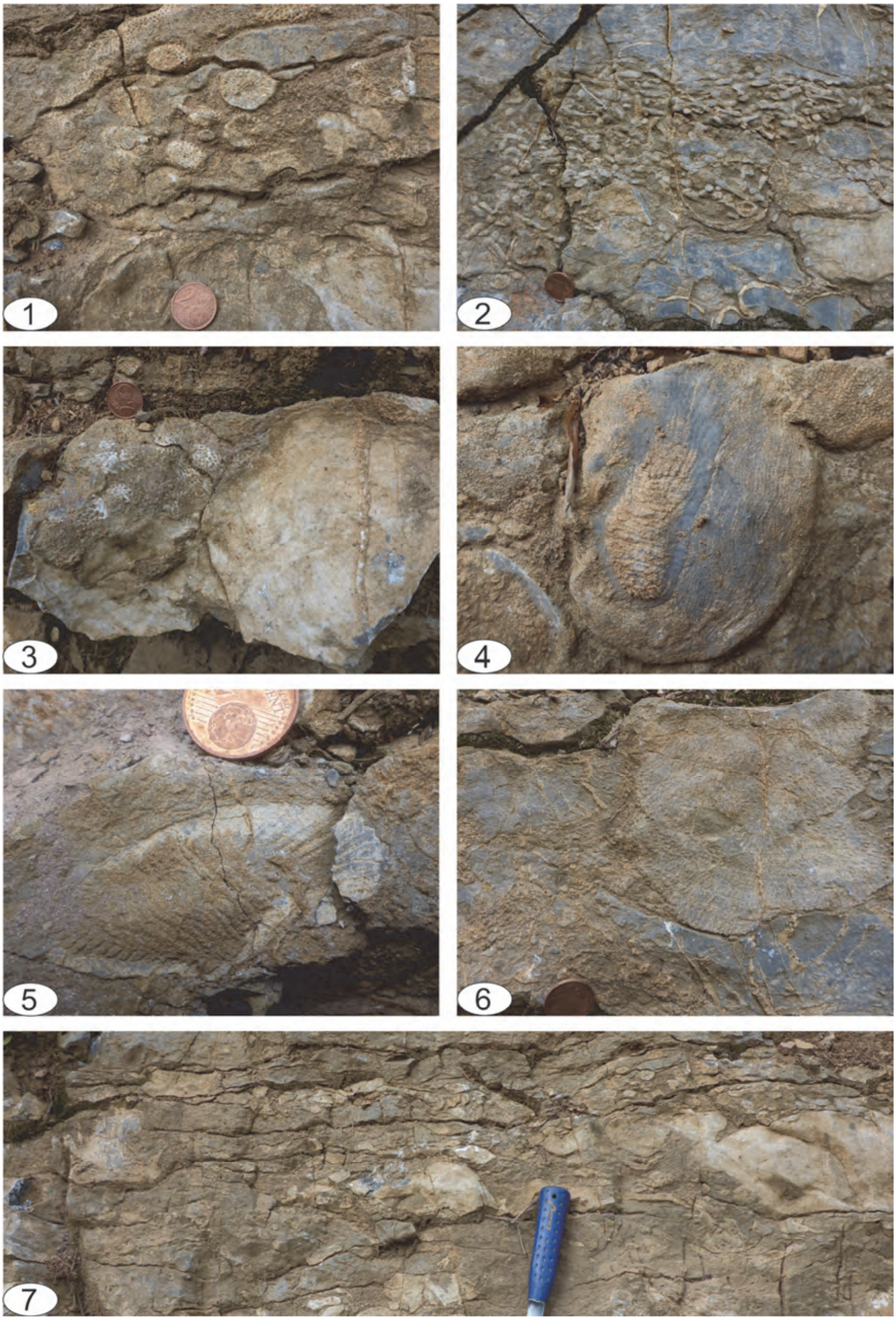

Fig. 14. Plabutsch Fm. at Höllererkogel. Details of weathered surfaces normal to bedding. Two cent coin for scale. 1) Cross sections of several branches of *Thamnopora boloniensis*; 2) Storm generated layer with densely packed of *Thamnopora reticulate*; 3) *Thamnopora boloniensis* and massive stromatoporoid (probably *Actinostroma*); 4) *Thamnophyllum* sp. in oblique longitudinal section incrusted by a stromatoporoid; 5) Oblique cross section of *Zelophyllia cornuvaccinum*; 6) Overturned heliolitid coral (? *Pachycanalicula barrandei*); 7) Vertical view on a bed (hammer shaft for scale).

3.5. Stop 5 – Farmstead Linshalmer (Geistthal)

Topic: Upper Cretaceous bituminous marls ("oil source rock") and uplifted block of lower Devonian dolomites ("oil reservoir rock").
Locality: "Linshalm road", a small side road of state road L315 to Geistthal, 47°10'30"N/15°10'29"E.
Lithostratigraphy: St. Pankrazen Formation.
Biostratigraphy: –
Chronostratigraphic age: Upper Santonian to lower Campanian and Emsian.
Description: Dark brown bituminous marlstones with rare occurrences of very small gastropods and fish scales crop out along a road to the farmstead Linshalmer. According to RUSSEGGER et al. (1998) these marlstones were deposited in a temporary highly productive bituminous marl lake which was situated in near distance to the marine Gosau basin thus occasionally suffering alternatively from terrigenous influence and marine disturbances.
Approximately 100 metres to the north lower Devonian dolomites (Flösserkogel Fm. of the GP) are exposed at the road L315 to Geistthal. Bitumen on open joint planes of the dolomites indicate that these dolomites served as "oil reservoir rock" for bitumen emigrating from the bituminous marls (Fig. 15).
References: BOJAR et al. (2001), EBNER & RANTITSCH (2000), RUSSEGGER et al. (1998).

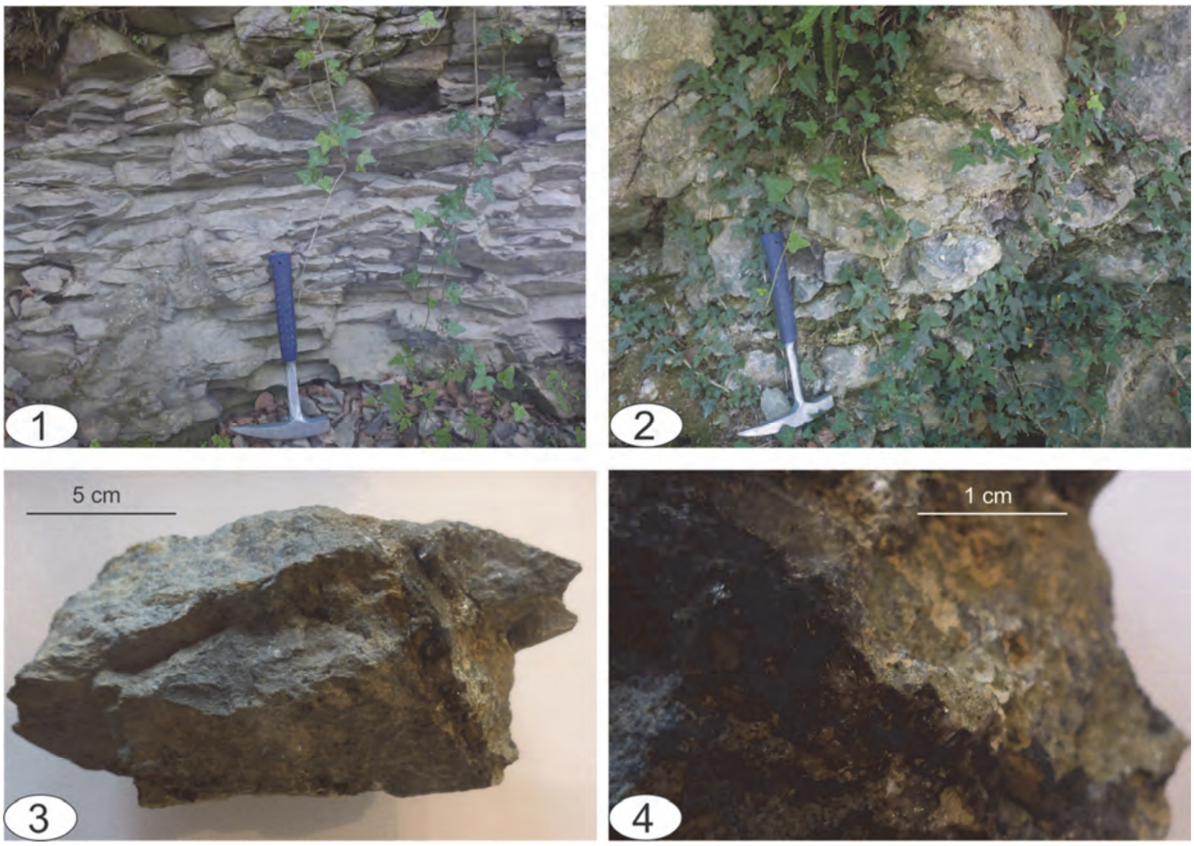

Fig. 15. 1) Dark brown bituminous marlstones of the St. Pankrazen Fm. at Linshalm road. Hammer for scale; 2) Lower Devonian dolomites (Flösserkogel Fm.) at road L315 to Geistthal; 3) Hand rock sample of the Devonian dolomite with bitumen on open joint plane; 4) Detail of 3).

3.6. Stop 6a – Geistthal

Topic: Basal sequence of the Kainach Gosau (lower part).
Locality: Road junction Almgrabenweg/Muralterweg northwest of Geistthal, 47°10'41"N/15°09'38"E.
Lithostratigraphy: Geistthal Formation.
Biostratigraphy: –
Chronostratigraphic age: Upper Santonian to lower Campanian.
Description: Polymict conglomerates in red (haematitic) matrix alternating with red siltstones (alluvial fan) (Fig. 16, 1–2).
References: SCHIRNIK (1995).

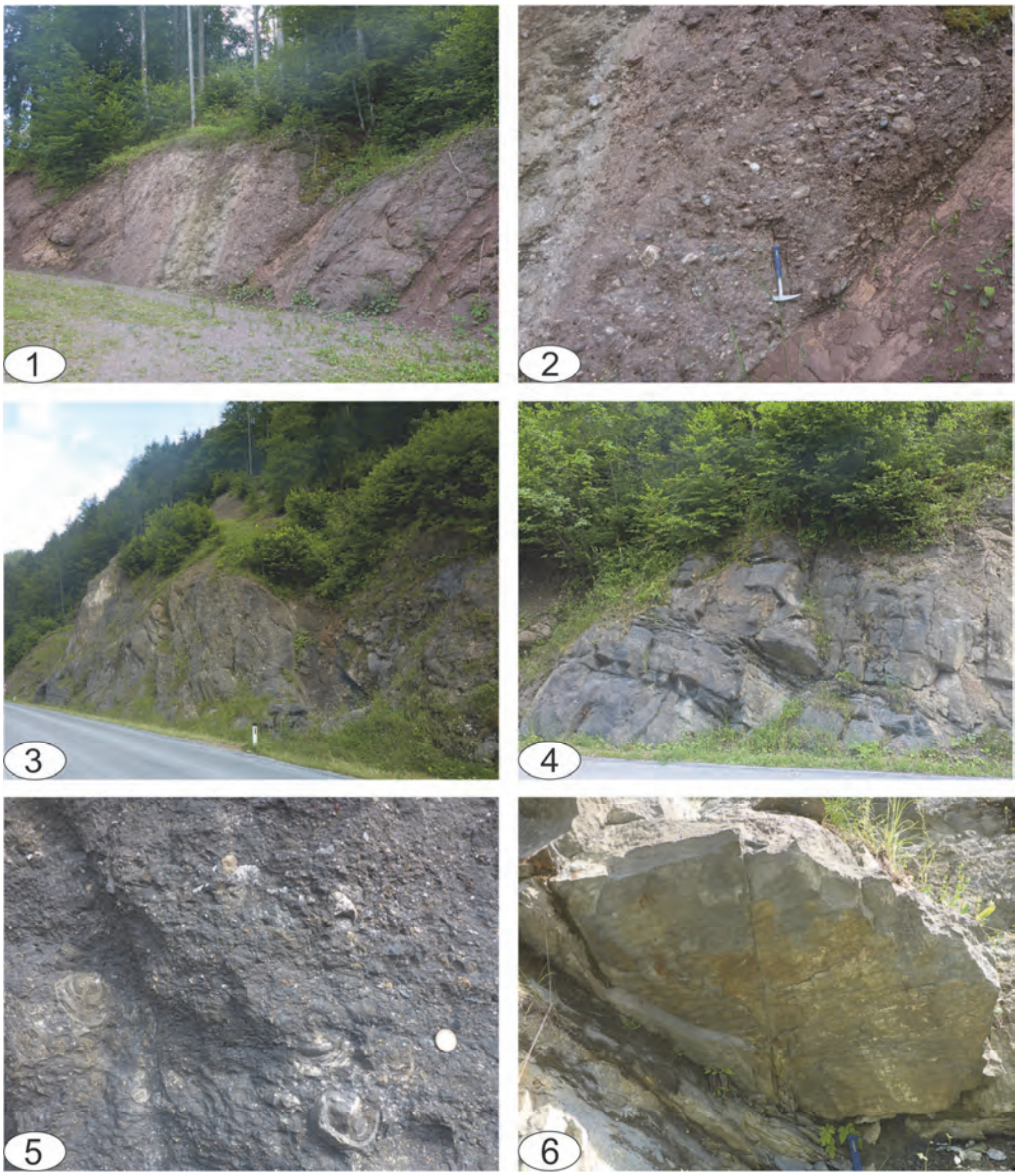

Fig. 16. Lower Geistthal Fm. at Geistthal (1–2) and upper Geistthal Fm. at Gallmannsegg.
1) Basal succession of the Geistthal Formation at Almgrabenweg/Muralterweg northwest of Geistthal; 2) Polymict conglomerate with red (haematitic) matrix. Hammer for scale (Detail of 1); 3) Section through conglomerate-sandstone alternation of the upper Geistthal Fm. along Gallmannsegg road; 4) Upper part of the section containing snail shells of 5) Some *Trochactaeon* shells in life position. One Euro coin for scale; 6) Symmetrical ripple marks on the lower surface of a sandstone bed.

3.7. Stop 6b – Gallmannsegg

Topic: Basal sequence of the Kainach Gosau (upper part).
Locality: Road junction Gallmannsegg Hauptstraße/Gschmurgraben, Gallmannsegg, 47°09'28"N/15°05'47"E.
Lithostratigraphy: Geistthal Formation.
Biostratigraphy: –
Chronostratigraphic age: Upper Santonian to lower Campanian.
Description: Polymict conglomerates with various limestone pebbles and black lydites alternating with dark grey sandstones. In the upper part of the outcrop thick-walled snail shells of *Trochactaeon* (Ø up to 10 cm) occur indicating an aquatic (brackish) depositional environment. Sandstones show symmetrical ripple marks (Fig. 16, 3–6).
References: SCHIRNIK (1995).

3.8. Stop 7 – Gratkorn Clay Pit

Topic: Late middle Miocene vertebrate site; palaeosol; limnic sedimentation.
Locality: Gratkorn Clay Pit, ~0.7 km E Gratkorn (~10 km NNW Graz), 47°08’14”N/15°20’56”E.
Lithostratigraphy: Gratkorn Formation and Gleisdorf Formation (Peterstal Member).
Biostratigraphy: Mammal Neogene zones MN 7+8; indirectly *Elphidium hauerinum–Porosononion granosum* foraminifera Zone.
Chronostratigraphic age: Upper Serravallian (upper Sarmatian *sensu* regional Central Paratethyan stages).
Description: The Gratkorn pit is situated in the eastern part of the Gratkorn Basin, which belongs to a series of embayments along the northern margin of the Styrian Basin (Fig. 17). Sedimentation in the Styrian Basin as well as in its satellite basins was – beside tectonics – strongly affected by short-term sea level changes of the Central Paratethys. This enabled the development of a detailed sequence stratigraphic concept in addition to a comprehensive aquatic biota-based biostratigraphy (e.g., KOLLMANN, 1965; HARZHAUSER & PILLER, 2004; SCHREILECHNER & SACHSENHOFER, 2007). However, in marginal basin areas, where alluvial to lacustrine deposition predominates, stratigraphic tie points are scarce. Especially, at the northern and north-eastern fringe of the Styrian Basin (including the Gratkorn Basin) these hardly exposed sediments are (index)fossil-poor and radiometrically datable volcanoclastic intercalations are unknown. Nevertheless, a correlation with the high-resolution stratigraphic framework of the open Styrian Basin could be established during the last years (GROSS et al., 2007b; HARZHAUSER et al., 2008; GROSS, 2015; Figs. 6, 18).

3.8.1. Litho-, bio- and chronostratigraphy

In the eastern Gratkorn Basin, more than 20–30 m thick, polymict coarse gravels/conglomerates with sandy or pelitic matrix form the lowermost part of the exposed basin fill. Occasionally, horizontally or cross-bedded fine–medium grained gravels and sands are intercalated; locally, palaeosol formation is observed (e.g., Gratkorn pit). These strata are termed Gratkorn Formation and are interpreted as deposits of a braided river system, partly influenced by distal alluvial fans.

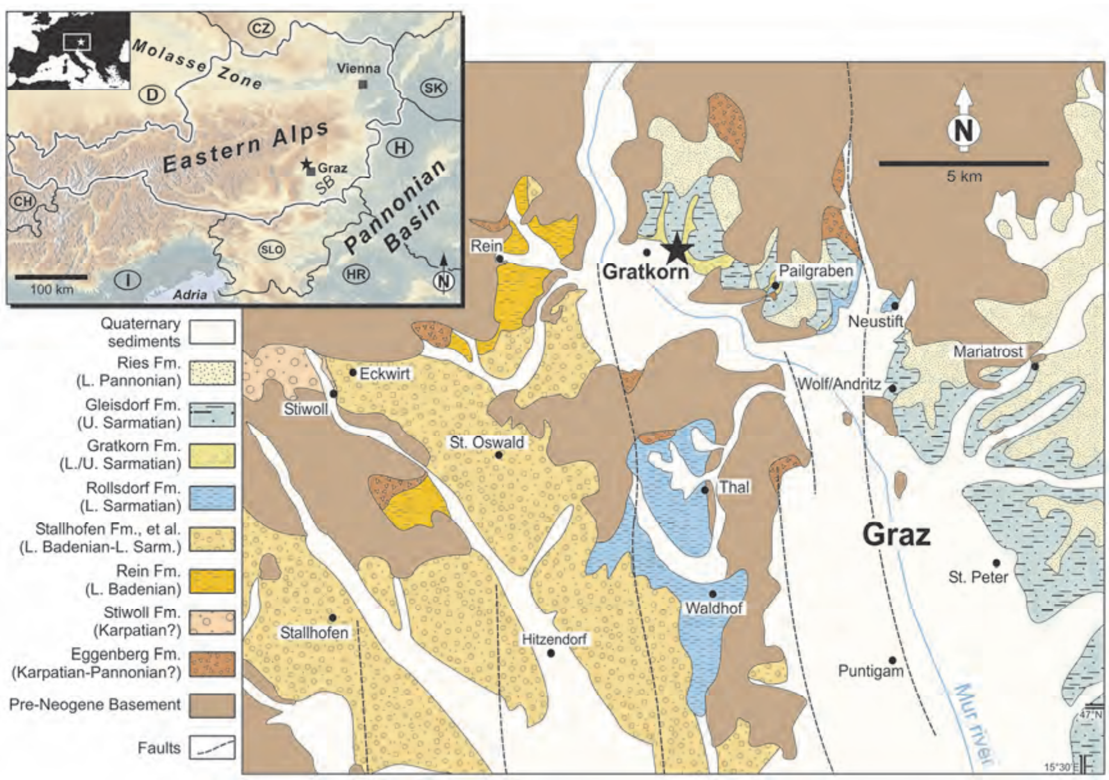

Fig. 17. Location of the Gratkorn clay pit (L. = lower; U. = upper; after GROSS et al., 2014).

The Gratkorn Fm. is overlain by up to 25 m thick, massive or laminated, frequently plant-bearing, largely limnic pelites (Peterstal Member/Gleisdorf Formation; e.g., clay deposit at the Gratkorn site). Alternations of gravel–sand–pelite follow above (Lustbühel Member/Gleisdorf Fm.), which are topped by fluvial gravels/conglomerates with rare sandy and pelitic intercalations (Ries Formation; lower upper Miocene/Pannonian; for a recent compilation of the lithostratigraphic framework see GROSS, 2015).

The Gratkorn Fm. can be traced out into the Styrian Basin, where it is underlain by marginal marine, lower Sarmatian sediments (Rollsdorf Formation; *Elphidium reginum–Elphidium hauerinum* Zone; GROSS et al., 2007b). Index fossils are missing in the overlying Peterstal Mb., however, in the area of Graz, the Lustbühel Mb. contains rare marginal marine faunas as well as thin oolitic layers, indicative for a late Sarmatian age (*Porosononion* Zone; GROSS et al., 2007b).

The position of the Gratkorn Fm. between biostratigraphically dated underlying lower Sarmatian strata (Rollsdorf Fm.) and upper Sarmatian hanging wall sediments (Gleisdorf Fm.) relates its deposition to the so-called “Carinthian Phase” at the end of the early Sarmatian (e.g., GROSS et al., 2007b, 2011; Fig. 18). During that phase a wide-ranging sea level fall is recorded in the Vienna Basin as well as in the adjacent Pannonian Basin and Austrian Molasse Zone (e.g., HARZHAUSER & PILLER, 2004; STRAUSS et al., 2006; SCHREILECHNER & SACHSENHOFER, 2007; KOVÁČ et al., 2008). This enables a correlation of the Gratkorn Fm. with the sequence stratigraphic concept of the Styrian Basin. LIRER et al. (2009) proposed an age of about 12.2. Ma for the early/late Sarmatian boundary. As for the limnic pelites of the Peterstal Mb./Gleisdorf Fm. normal magnetic polarity is recorded at the Gratkorn pit, a correlation to Chron C5An.1n (12.174–12.049 Ma after HILGEN et al., 2012) is possible. Hence, the vertebrate-bearing palaeosol of the Gratkorn pit is assumed to have formed around the early/late Sarmatian boundary, about 12.2–12.0 Ma (GROSS et al., 2011).

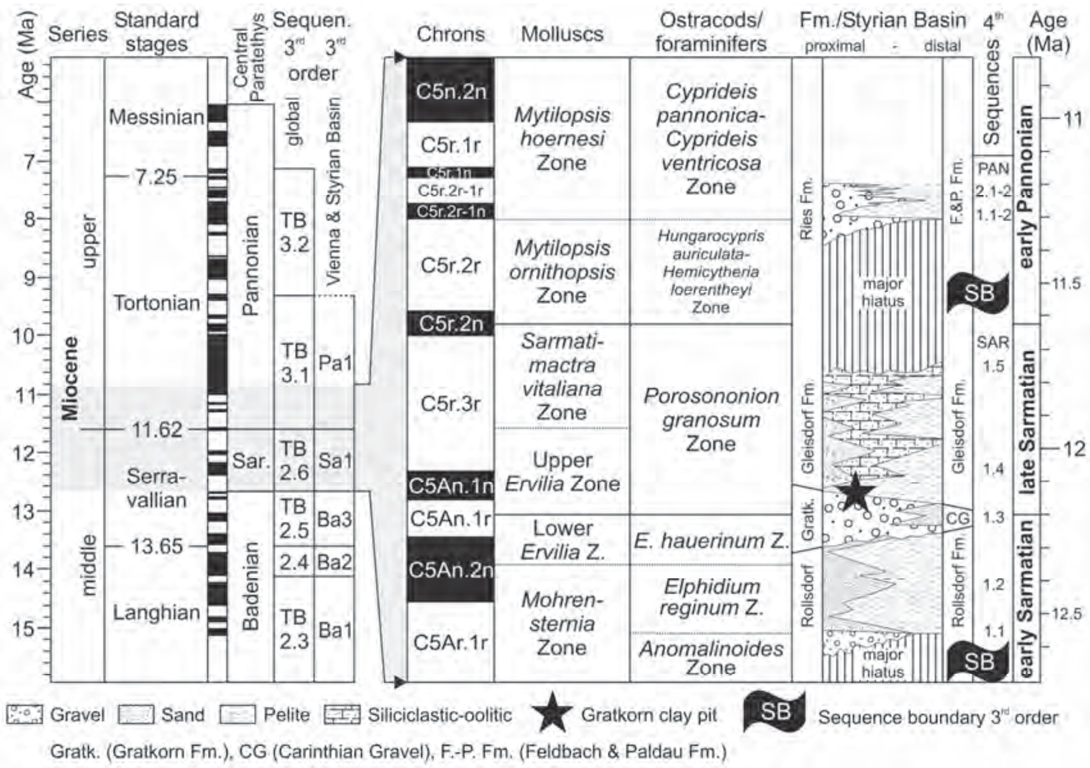

Fig. 18. Stratigraphic position of the Gratkorn site (after Gross et al., 2011, 2014).

3.8.2. Section and facies interpretation of Gratkorn

At the Gratkorn pit calcareous pelites are exploited for cement production (Fig. 19). The vertebrate-bearing palaeosol represents the mining floor. The sediments below working level could be studied in prospecting holes only (Figs. 20, 21a).

The basal gravels (1) are interpreted as gravel bar deposits of a braided river system, topped by sandy and silty fine sand layers (2, 3) of flash floods (crevasse splays) in an overbank environment (Fig. 20). Subsequent soft sediment deformation (dewatering) and indistinct pedogenic processes overprinted these layers to a certain degree. Similarly, layers 4–5 are assumed to represent post-sedimentary altered (including tectonic activity) deposits of a succeeding flooding event (crevasse splay).

Above, a sand layer (6) forms the base of a calcic horizon (7). The calcrete horizon contains ferruginous nodules (some might be rhizoconcretions) as well as cemented meniscate burrows (up to dm long, some cm wide). Carbonate nodules are discrete or amalgamated to each other. Upon a diffuse, irregular boundary, a pelitic layer (8) follows, which includes many ferruginous nodules and some meniscate burrows. Layers 6–8 are interpreted as deposits of another flooding event (crevasse splay) within an overbank environment. The moderately developed calcrete (7) directs to an extended period (10^3–10^4 yrs?) of pedogenesis as well as to an overall arid/semi-arid climate with seasonally variable precipitation (for further palaeoclimate estimations see Gross et al., 2011; Böhme & Vasilyan, 2014).

The sandy layer (9) indistinctly fines upwards and merges into silty fine sand (10) with abundant ferruginous nodules as well as burrows of variable shape and size (Fig. 21b, c). Large meniscate burrows of both layers equal possible freshwater crayfish burrows from the Bavarian Upper Freshwater Molasse (Schmid, 2002). We interpret both strata as crevasse splay deposits, which subsequently experienced weak pedogenesis and intensive bioturbation.

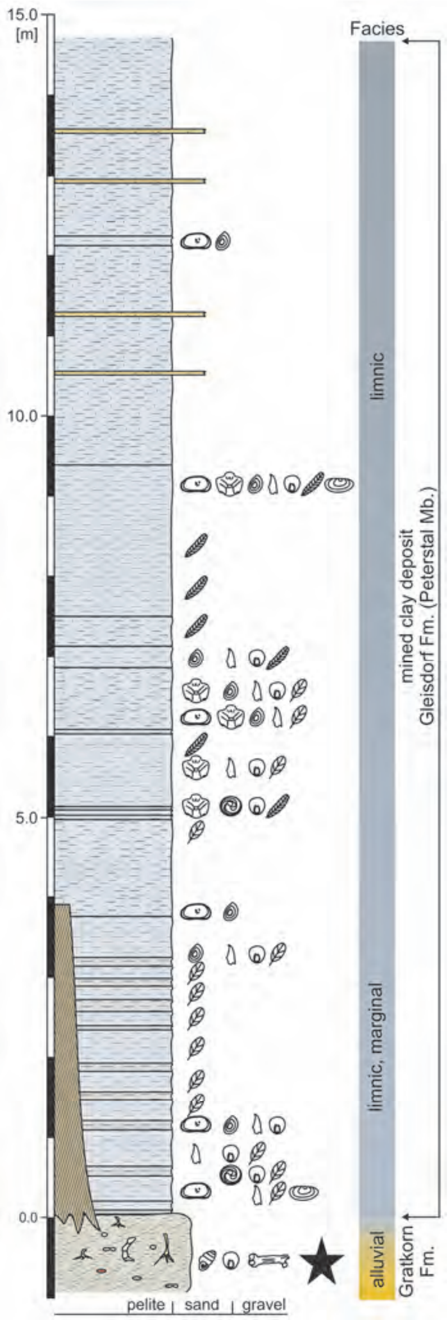

Fig. 19. Section of the Gratkorn clay deposit (after GROSS et al., 2014; for legend see Fig. 20).

Layer 10 grades upwards into a ~0.4 m thick, angular blocky structured, silty fine sand to fine sandy silt horizon (layer 11a; Fig. 21d). Frequently ferruginous nodules, numerous oxidised root traces, some septaria-like glaebules, clustered pits of hackberry (*Celtis*), few terrestrial snails as well as extremely rare phosphatic coprolites occur. Layer 11a pass gradually into a slightly laminated, intensively mottled fine sandy silt (11b; Fig. 21e), which enclose a lot of oxidised root traces, *Celtis* endocarps, snails and locally accumulated owl pellets as well as sand filled burrows of variable dimensions. The vertebrate fauna of Gratkorn (except rare fish remains from the hanging wall pelites) originate from layers 11a and b. Vertebrate remains are largely rubiginously stained, adhere ferruginous rhizoconcretions and coatings as well as fibrous, drab-haloed root traces. However, several remains (in particular from layer 11b) are almost whitish, while others are nearly black coloured.

These strata are interpreted as pedogenically altered overbank deposits, influenced only occasionally from the braiding river system during flooding. The rather uniform appearance of this floodplain palaeosol (no distinct soil horizons), semi-articulated vertebrate remains (without signs of fluvial relocation), preserved pellets of nocturnal raptors and rare coprolite findings argue for a fairly short period of soil formation (probably in the order of a few decades only; GROSS et al., 2011; HAVLIK et al., 2014; PRIETO et al., 2014).

The co-occurrence of calcic- (some are septaria) and ferric nodules, of aragonitic *Celtis* endocarps and snail shells as well as vertebrate bones and teeth indicate transient water logging during soil development and thus to alternating wet and dry periods (RETALLACK, 2001). This match to a semi-arid to sub-humid climate with less than 500 mm mean annual precipitation during soil formation (GROSS et al., 2011; BÖHME & VASILYAN, 2014). Relict bedding, intense mottling and drab colouring hints to a more pronounced hydromorphic setting for the upper part of the vertebrate bearing layer (11b) and a shorter inference of pedogenic processes in comparison to the lower part (11a). Especially, the preserved owl pellets signify a very fast (<1 yr?) burial of layer 11b (PRIETO et al., 2010, 2014; GROSS et al., 2011).

Ferric staining and incrustation of vertebrate remains as well as ferruginous rhizoconcretions refer to varying redox-conditions within the soil. Selective bleaching of bones due to thin, drab-haloed root traces points to seasonal variations in water logging of the rhizosphere (RETALLACK, 2001). Anyway, the variable colouring of vertebrate remains (especially in layer 11b) hints to changing moisture of the palaeosol. Possibly, even within one season, water logging varied significantly laterally due to the local topography of the overbank area.

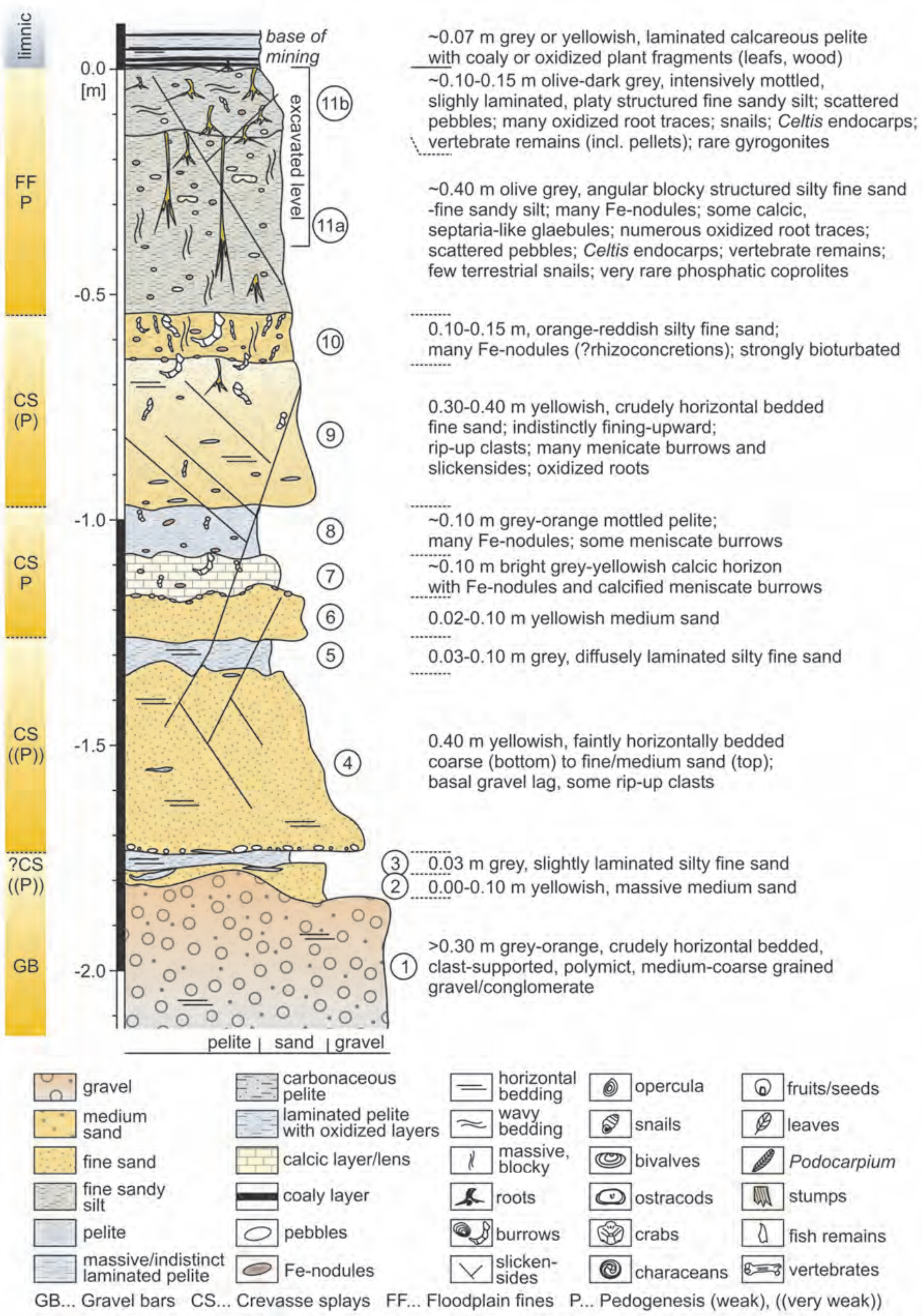

Fig. 20. Section below the mining floor of the Gratkorn clay pit (after GROSS et al., 2011, 2014).

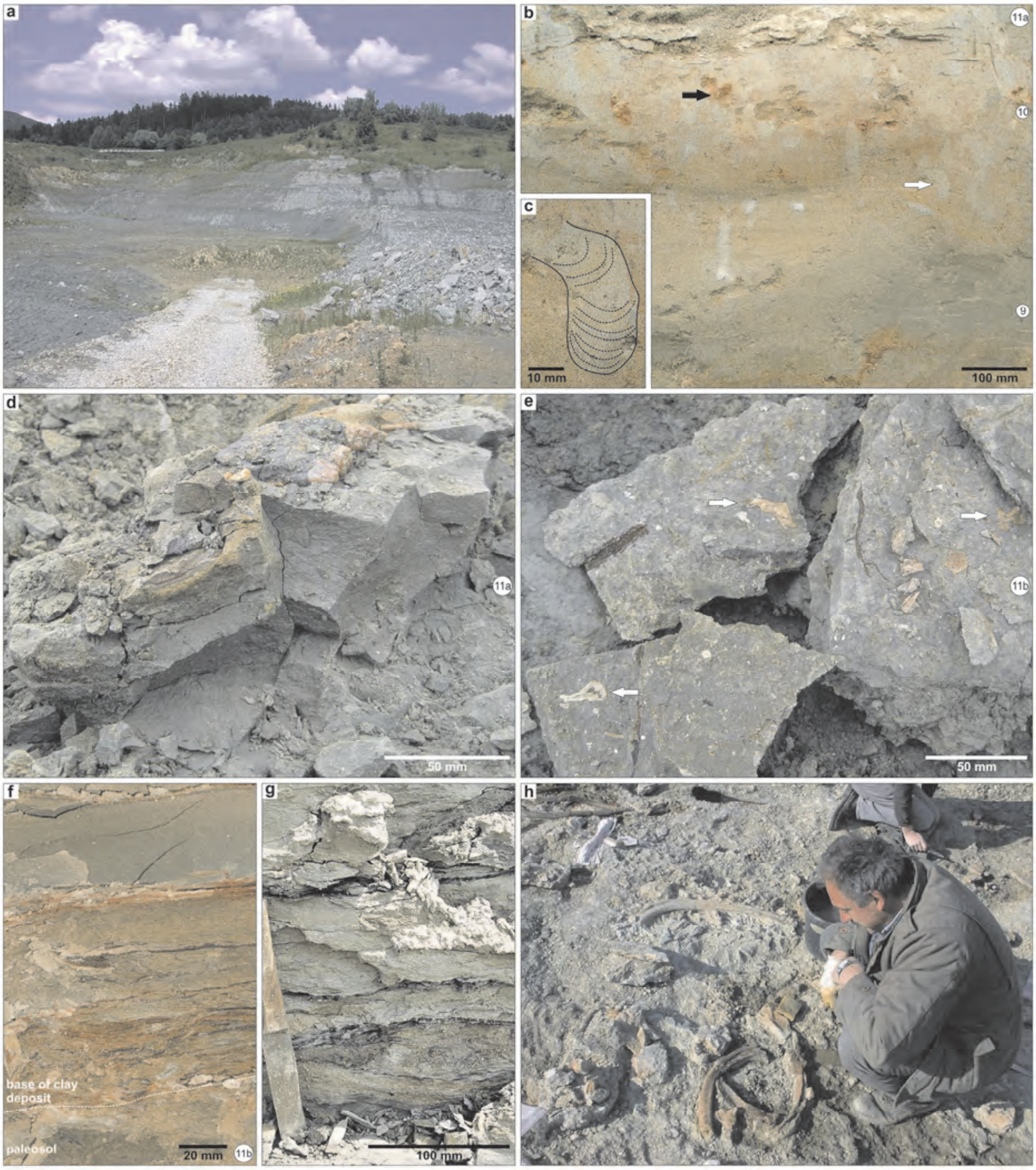

Fig. 21. a) Gratkorn clay pit: below the grey clay deposit, the brownish palaeosols is partly exposed (May 2005); b) Intensively bioturbated sand (especially layer 10; white arrow = burrow redrawn in c; black arrow = ferruginous nodules, possibly rhizoconcretions); c) Example of a large (dm deep), meniscate burrow; d) Angular blocky structured, silty to fine sandy lower part (layer 11a) of the Gratkorn palaeosol enclosing a suid jaw; e) Platy structured, silty upper part of the Gratkorn palaeosol (layer 11b) enclosing a cricetid skeleton (white arrows), numerous, oxidised rhizoconcretions as well as whitish coloured gastropod and *Celtis* remains; f) Transition from the uppermost part of the palaeosol (layer 11b) to plant rich, laminated pelites (in this case, both are in an oxidised stage); g) Laminated, non-oxidised, grey pelite with cm-thick lignitic interlayers (lower part of clay deposit); h) Excavation of a disarticulated *Deinotherium*-skeleton (April 2006).

Similarly, gastropod, small and large mammal assemblages as well as isotope analyses refer to a well-structured, riparian landscape (HARZHAUSER et al., 2008; AIGLSTORFER et al., 2014a; PRIETO et al., 2014).
Ubiquitous root traces testify that the soils surface was planted in some way. However, only the primarily mineralised and thus favourably preservable *Celtis* endocarps provide concrete palaeobotanical evidence that medium-sized hackberry trees have been growing on the fossiliferous substrate (layer 11a–b) at its time of formation (HAVLIK et al., 2014). Vital infaunal life on the floodplain soil is indicated by the abundant occurrence of subterranean snails (HARZHAUSER et al., 2008) and tentative insect ichnofossils (HAVLIK et al., 2014).
The vertebrate bearing layer (11) is covered by laminated, calcareous pelites with a large amount of carbonaceous or diagenetically oxidised leaf litter (largely monocotyledons, *Salix*, *Potamogeton*; Fig. 21f, g). Except rare root traces in the lowermost centimetres of the clay deposit, pedogenic features are absent. Sporadically, slightly silicified, autochthonous lignitic tree trunks (*Taxodioxylon*; HAVLIK et al., 2014), possibly several metres in height, were excavated during mining.
In particular, the lower four metres of the >15 m thick clay deposit yield frequently cm-thick lignitic intercalations. Up-section, the pelites include only subordinately plant-rich and fine sandy layers. Diversity of the fossil leaf flora is quite low but dozen of seed and fruit taxa, beside several freshwater ostracod species are documented from the clay deposit (MELLER & GROSS, 2006; GROSS, 2008). Some layers enclose claws and exuvia of freshwater crabs (KLAUS & GROSS, 2010), freshwater gastropods (e.g., *Bithynia* opercula), characean gyrogonites and fish fragments (bones and cyprinid pharyngeal teeth; BÖHME & VASILYAN, 2014). Sphaeriid bivalves were occasionally found in the lowermost parts of the section, while unionids are rarely present in the upper part. Sporadically, insect (beetle, bug) and isopod (wood lice) remains as well as avian eggshells were discovered in the lowermost part (GROSS et al., 2011; HAVLIK et al., 2014).
Based on the ostracod record as well as on potamid crab and fish findings, a shallow, partly richly vegetated freshwater lake environment within a warm, perhaps subtropical climate is assumed as depositional setting for the clay deposit (GROSS, 2008; KLAUS & GROSS, 2010; BÖHME & VASILYAN, 2014).

3.8.3. Taphonomy of larger vertebrates

At the beginning of the excavations, postcranial elements (ribs, limb bones, vertebras) and isolated teeth of a *Deinotherium*-skeleton were found scattered within an area of ~140 m^2 (Fig. 21h). The bones are weakly permineralised and experienced some post-depositional damage due to compaction. Some bones are clearly affected by slickensides, others were heavily decomposed, indicating a longer surface exposure and weathering of the carcass. However, several specimens might have suffered damage because of trampling (GROSS et al., 2011; AIGLSTORFER et al., 2014b; HAVLIK et al., 2014).
Although all skeletons of larger vertebrates were found disarticulated, many skeletal parts belonging to the same individual are embedded in short distances from each other. The material displays no obvious signs of abrasion (e.g., rolling) or re-working due to, e.g., fluvial transportation and lacks any preferred orientation.
The bones of medium sized animals (e.g., turtles, tragulids) show a high degree of primary fragmentation and are often heavily splintered. These cracked bones infer the activity of predators and/or scavengers, which might be partially responsible for local accumulation and/or dislocation, and, maybe, for some taphonomical biases. The record of carnivores is

still poor; however, very rare coprolites, a few teeth and one mustelid skull indicate their presence. Due to the findings of *Varanus* sp., this large-sized monitor lizard might have been represented a significant predator/scavenger within this terrestrial food web additionally.
Frequently, the bone splinters itself bear minute biting traces. Equally, many tortoise plates and mammalian bones exhibit similar, several mm-long and ~mm-wide, more or less parallel series of grooves, affecting regularly the complete margins of these bones. These marks resemble well the ichnogenus *Machinus*. They are assumed to be traces of gnawing produced by rodents and/or insectivores (e.g., squirrels, hamsters or shrews) to obtain nutrients (collagen and vitamins) from the bones. Alternatively, such animals simply could have used it to sharpen their teeth. Additionally, randomly arranged, several mm-long and -wide scratches sometimes occur on compact bones. These marks are very similar to structures related to traces of osteophagous termite activity (GROSS et al., 2011; HAVLIK et al., 2014; PRIETO et al., 2014).

3.8.4. Taphonomy of small vertebrates

In the first excavation campaign, small vertebrates were only scarcely found. Afterwards in an area of about two square metres a few dozen of gymnures, hamsters and ectothermic vertebrate skeletons and associated elements (skulls, jaws, extremities) were discovered in the upper part of the palaeosol (layer 11b; Fig. 21e). Bones and teeth are generally very well preserved, most often only insignificantly corroded and mainly beige coloured (PRIETO et al., 2010). PRIETO et al. (2010, 2014) explain such extreme local concentration of small vertebrate remains as the result of pellet accumulations at feeding/resting places of birds of prey, in more detail of owls. In contrast to, e.g., diurnal raptors or mammalian carnivores, owls cause only minor effects of digestion. Thus, the low grade of corrosion, the extreme concentration and the roughly equal co-occurrence of cranial and postcranial elements point to accumulated owl pellets. Those pellets reflect more or less the local small vertebrate fauna around the locality. Taxonomical biases may have occurred due to alimentary preferences of the owl as well as the abundance of prey (PRIETO et al., 2010, 2014).
Moreover, the presence of pellets excludes a considerable postdepositional dislocation or a long surface exposure and therefore underlines a rapid deposition (<1 yr?) of the upper part of this palaeosol (layer 11b). Perhaps, some single microvertebrate skeleton associations might be persevered *in situ*, maybe in their burrows (e.g., spadefoot toads, glass lizard, hamsters or talpids). Unfortunately, such burrows are not recorded up to now, making this suggestion tentatively.

Altogether, the vertebrate taphocoenose of Gratkorn experienced a variety of predepositional modification, and after burial, compaction (in early phases probably also trampling) and subterranean life as well as abiotic soil forming processes acted on it. However, the weak stage of soil development and the observed taphonomic features point to a rather low extent of time-averaging of the fossil community (maybe only or even less than tens or hundreds of years). The presence of pellet remains even indicate a much more rapid burial for the upper part of the palaeosol (layer 11b). In a strict sense, this is definitely not an example for an “event horizon” – like a sudden mass mortality event – and the structure of the taphocoenose is certainly obscured to some degree. Nonetheless, we are facing to an *in situ* evolved *Fossillagerstätte*, which developed quite rapidly.

3.8.5. Biochronological significance of the Gratkorn vertebrate fauna

Fossil vertebrates from Gratkorn are exceptional by their preservation as well as their diversity. Do date, 65 vertebrate species (except carnivore mammals) are described, belonging to fishes (2 taxa), amphibians (8 species), reptiles (17 species), birds (4 species), and mammals (34 species), thus comprising all major vertebrate groups. To our knowledge, this is the highest recorded vertebrate diversity for stratified deposits in the late middle Miocene of Europe.

This high diversity, which is also documented by 17 terrestrial gastropod species (HARZHAUSER et al., 2008), may be explained by ecosystem diversity, rapid sediment accumulation and long-term systematic excavations, minimizing taphonomic biases. Furthermore, integrated stratigraphic investigations firmly correlate the Gratkorn Fm. chronostratigraphically with the beginning of the late Sarmatian *s.str.*

Thus, exceptional preservation, high biodiversity, extremely low time-averaging, and a substantiated chronostratigraphy are outstanding features, which render Gratkorn to a key locality for the Central Paratethys and beyond. Especially mammalian biochronology suffers from problems related to low diversity, missing documentation of excavations, high time-averaging, unresolved geologic and chronostratigraphic background, preventing so far mammalian biostratigraphic schemes on continental scale for the Miocene.

Biochronologic investigations concordantly place Gratkorn to MN 7+8 at the end of the middle Miocene (DAXNER-HÖCK, 2010; PRIETO et al., 2010, 2014; GROSS et al., 2011). However, a more detailed stratigraphic correlation is complicated by still insufficiently resolved evolutionary lineages, stratigraphically mixed comparative faunas, and, maybe most importantly, by lack or uncertainty of chronostratigraphic ages for many of the Central European mammalian faunas (e.g., AIGLSTORFER et al., 2014b, c; PRIETO et al., 2014). To overcome these problems future work is needed in which Gratkorn is a benchmark towards a mammalian biostratigraphic subdivision of the Central Paratethyan area.

References: AIGLSTORFER et al. (2014a–c), BÖHME & VASILYAN (2014), GROSS (2008, 2015), GROSS et al. (2007b, 2011, 2014), HARZHAUSER et al. (2008), PRIETO et al. (2014).

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The Upper Triassic events recorded in platform and basin of the Austrian Alps. The Triassic/Jurassic GSSP and Norian/Rhaetian GSSP candidate

Sylvain Richoz & Leopold Krystyn

47 figures

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Contents

Abstract

The Austrian Northern Calcareous Alps give the opportunity to observe the evolution of the Upper Triassic on the sedimentary record of various settings (lagoon, reefs, intra-platform basin, slope, pelagic plateau). The Norian inshore platform sedimentation with typical peritidal Lofer cycles, the barriere reef facies and the off-shore Hallstatt type facies (red condensed pelagic limestone) will all be visited in their type areas. The Reefs are still flourishing during the Lower Rhaetian despite the pelagic fauna has already started decreasing. The final bloom of the reefs and their stepwise drowning/extinction history is to be seen as well as the ultimate breakdown of the carbonate factory on the platform and its response in the basin during the end-Triassic crisis.

This field trip will allow i) to see both the Norian/Rhaetian GSSP candidate and theTriassic/Jurassic GSSP (Global Stratotype Section and Point), ii) to see how Upper Triassic biotic crisis events are recorded in basinal and platform settings of this classical carbonate sedimentology study area and iii) to understand the sedimentary interactions between platform and basin during this time.

1. Topics and area of the Field Trip

During the Late Triassic, the Austrian Northern Calcareous Alps was a region of huge carbonate platforms with large lagoons and intra-platform basins in the north and prominent fringing reefs in the south facing a southward transition to the open-ocean where pelagic offshore facies developed. Within the Norian inshore platform sediments, one can find the type sections of the lagoonal Dachstein facies with classic peritidal Lofer cycles, and towards off-shore those of the Dachstein reef and the Hallstatt facies (red condensed pelagic limestone). In the early Rhaetian, the diversity of the pelagic fauna began to decline whereas the reefs reached their climax. The late Rhaetian sediments record the final bloom, the following stepwise decline and drowning/extinction history with, finally, the ultimate breakdown of the carbonate factory on the platform during the end-Triassic crisis, and the expression of this breakdown in the basin. The Northern Calcareous Alps give thus the opportunity to observe the influence of the Late Triassic crisis intervals on the sedimentary record of very different settings from lagoon to reefs, intra-platform basin, slope, pelagic plateau.

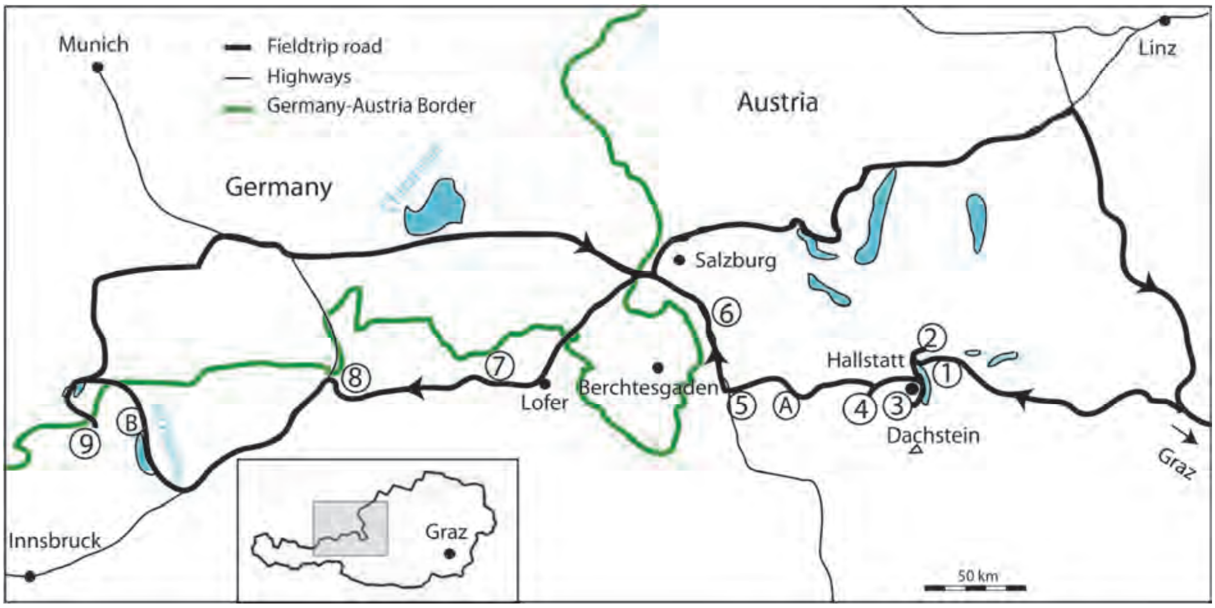


Fig. 1. Locality to be visited: 1 - Pötschenhöhe Quarry; 2 - Großer Zlambach; 3 - Steinbergkogel; 4 - Gosausee; 5 - Pass Lueg; 6 - Adnet; 7 - Steinplatte; 8 - Eiberg; 9 - Kuhjoch. A and B are overnight places.

This field trip will allow
i) to see both the proposed GSSP (Global Stratigraphic Section and Point), for the Rhaetian and the accepted GSSP for the Hettangian stages - the later defining the boundary between the Triassic and Jurassic system. This corroborates the global geological importance of the area during that interval of time.
ii) to see how Upper Triassic biotic crisis events are recorded in basinal and platform settings of this classical carbonate sedimentology study area and
iii) to understand the sedimentary interactions between platform and basin during this time of multiple crisis.

This whole Late Triassic story is present in the Northern Calcareous Alps (Salzkammergut region, Salzburg, and Tyrol), a scenic, mountains and lakes region with breathtaking landscapes (Fig. 1).

2. Introduction

This field guidebook is a renewed version of the one published by RICHOZ et al. (2012). The introduction follows generally MANDL (2000).

2.1. The Northern Calcareous Alps

One of the most prominent units of the Eastern Alps is the nappe complex of the Northern Calcareous Alps, which forms a 500 kilometres long and 20 to 50 kilometre wide thrust belt of sedimentary rocks (Fig. 2). The sedimentary features in the Northern Calcareous Alps are mostly well preserved, due to only local and very low-grade metamorphic overprint, which offers the opportunity to study and reconstruct the depositional history of a major segment of

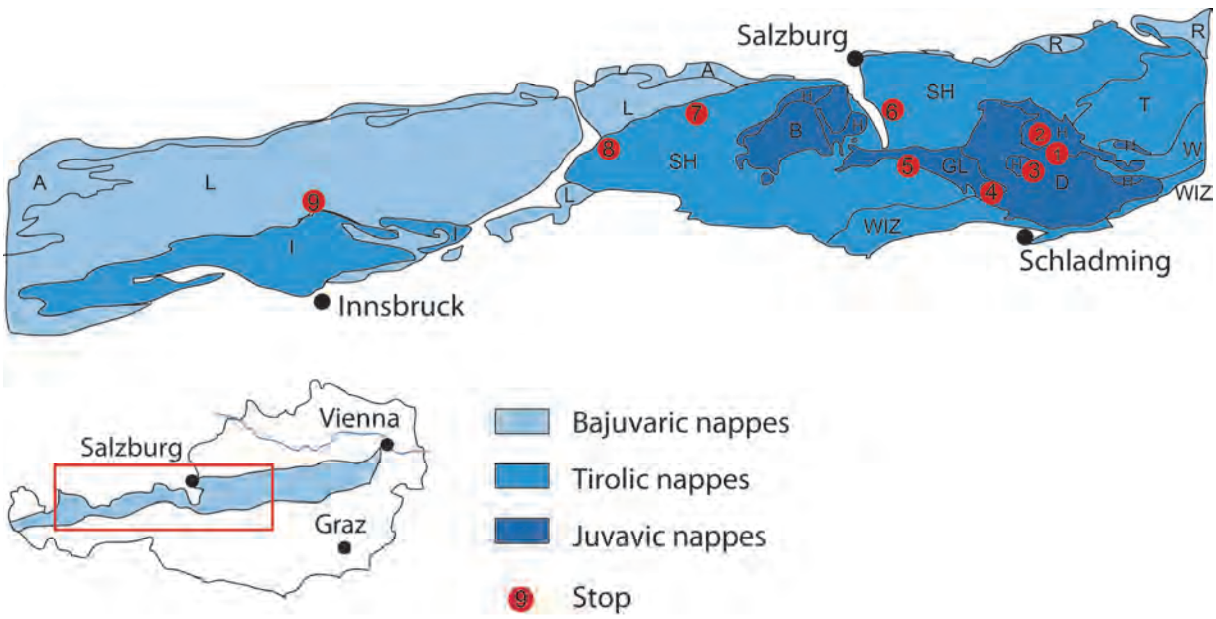


Fig. 2. The nappe complex of the Northern Calcareous Alps (modified from MANDL, 2000). Explanation of abbreviations: Juvavic nappes: B = Berchtesgaden nappe, D = Dachstein nappe, GL = Göll-Lammer unit, H = Hallstatt units. Tirolic nappes: I = Inntal nappe, SH = Staufen-Höllengebirge nappe, T = Totes Gebirge nappe, W = Warscheneck unit, WIZ = Werfen imbricated zone. Bajuvaric nappes: A = Allgäu nappe, L = Lechtal nappe, R = Reichraming nappe.

the Western Tethyan shelf. The Northern Calcareous Alps consist of mountain ranges with impressive plateau mountains, which are a remnant of a Late Paleogene peneplain, faulted and uplifted since the Miocene (FRISCH et al., 1998). In the western and middle part, the highest peaks reach altitudes of up to 3,000 meters and are locally glaciated (Dachstein area). In the eastern part, elevations are up to 2,000 meters. At their eastern end, the Northern Calcareous Alps are bounded by the Neogene Vienna basin. Below the Neogene sediments of the Vienna basin, however, the Northern Calcareous Alps nappe complex continues into the Western Carpathians (KRÖLL et al., 1993). The uppermost tectonic unit of the Northern Calcareous Alps - the Juvavic Nappe complex - ends in the Slovakian part of the Vienna basin. Equivalent units occur again in the eastern part of the Western Carpathians. In the Northern Calcareous Alps, Mesozoic carbonates predominate, but clastic sediments are also frequent at several stratigraphic levels. The succession starts with the Permian and extends locally into the Eocene (Gosau Group), but the Triassic rocks are the most prevailing units.

2.2. Principles of the structural evolution

The Permo-Mesozoic sediments of the Northern Calcareous Alps have largely lost their crustal basement in the course of the Alpine orogeny. During Late Jurassic to Tertiary times, several stages of deformation (folding and thrusting) created a nappes complex which rests with overthrust contact on the Rhenodanubian Flysch Zone in the north and on Variscan basement (Greywacke Zone) in the south. The Northern Calcareous Alps include the following succession of nappes from north to south, and from bottom to top (Figs. 2 and 4). The northern, frontal part of the Northern Calcareous Alps is built by the Bajuvaric nappes, with narrow synclines and anticlines. Toward the south they dip down below the overthrusted Tirolic nappe complex. Due to their dominant dolomitic lithology, the Tirolic nappes exhibit internal thrusting and faulting and only minor folding. The Juvavic nappes represent the uppermost tectonic element, overlying the Tirolic nappes. The Greywacke Zone is thought to represent the Palaeozoic basement of the Mesozoic rocks of the Tirolic nappes, remaining often several kilometres behind in the south during the nappe movements. Permian and Early Triassic siliciclastics clearly transgress onto Early Palaeozoic rocks, but their sedimentary continuation into the Middle Triassic carbonates of the Tirolic nappe complex is either covered by Juvavic nappes (eastern Northern Calcareous Alps) or disturbed by thrusts (middle Northern

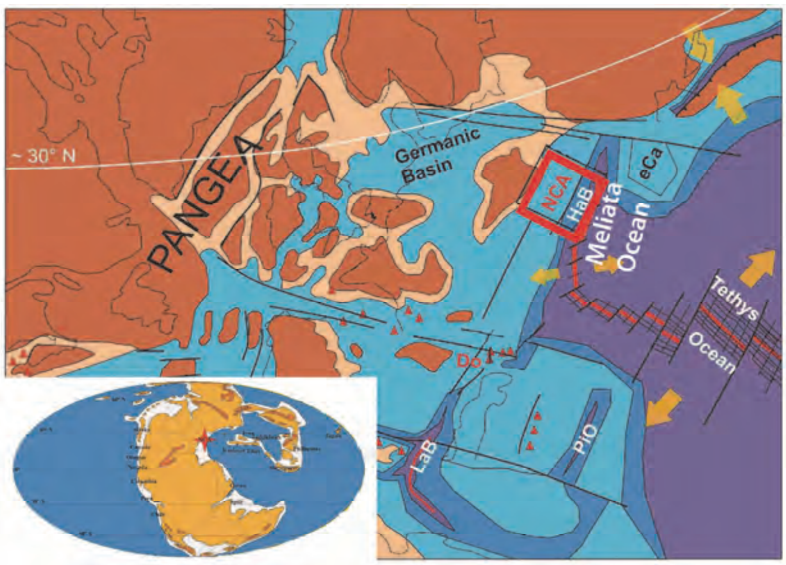


Fig. 3. Palaeogeographic reconstruction for the Western Tethyan margin during the Late Triassic (from HORNUNG, 2007). Explanation of abbreviations: NCA = Northern Calcareous Alps, eCA = East Carpathians, HaB = Hallstatt Basin, Do = Dolomite, PiO = Pinde Ocean, LaB = Lagonegro Basin.

Calcareous Alps, Werfen imbricated zone). Although large portions of the Northern Calcareous Alps indicate only anchimetamorphism (KRALIK et al., 1987), investigations of the Conodont Color Alteration Index have revealed a considerable thermal overprint in parts of the Juvavic nappes, predating the oldest (Late Jurassic) overthrusts (GAWLICK et al., 1994; KOZUR & MOSTLER, 1992; MANDL, 1996). There is a common assumption that the depositional realm of the Northern Calcareous Alps during the Permo-Triassic was a passive continental margin, which was formed on a Variscan basement (part of Pangaea) by rifting and spreading of the Tethys Ocean (Fig. 3). The sector of this ocean bordering the Northern Calcareous Alps and the Western Carpathians is named "Hallstatt-Meliata-Ocean" (KOZUR, 1991 and STAMPFLI & BOREL, 2002) and it is thought to have been closed during Jurassic to Early Cretaceous. During the Jurassic, the Austroalpine realm (including the Northern Calcareous Alps) became separated from its European hinterland by the birth of a transtensional basin known as the Penninic opening, an eastward propagation of the central Atlantic and Ligurian Oceans. Contemporaneous compressional tectonics has affected the Tethyan Ocean and the adjacent shelf of the Austroalpine realm, causing the first destruction of the margin and its displacement and transformation to the Juvavic nappe complex (Fig. 4). Subduction processes at the southern margin of the Penninic Ocean have started in the Cretaceous, accompanied by crustal shortening within the Austroalpine crystalline basement and by nappe movements and deposition of synorogenic elastics in its sedimentary cover (DECKER et al., 1987; FAUPL & TOLLMANN, 1979; VON EYNATTEN & GAUPP, 1999). Late Cretaceous clastic sediments of the Gosau Group transgressed after a period of erosion onto the Northern Calcareous Alps nappe stack (e.g. WAGREICH & FAUPL, 1994). Ongoing subduction of the Penninic realm toward the south below the Austroalpine units led to the closure of the Penninic Ocean. Beginning in the Late Eocene the sediments of the Rhenodanubian Flysch Zone became deformed and partly overthrusted by the nappes of the Northern Calcareous Alps. The large-scale thrusts of the Northern Calcareous Alps over the Flysch Zone, the Molasse Zone and the European foreland are proven by several drillings, which penetrated all units and reached the basement (e.g. SAUER et al., 1992). The uplift of the central part of the Eastern Alps in the Miocene was accompanied by large strike-slip movements, e.g. the sinistral Salzach-Ennstal fault system, which also affected the Northern Calcareous Alps nappe complex (e.g. LINZER et al., 1995; DECKER et al., 1994; FRISCH et al., 1998).

2.3. Triassic depositional realms

2.3.1. General features

The sedimentary succession of the Northern Calcareous Alps starts with Permian continental red beds, conglomerates, sandstones, and shales of the Prebichl Formation, transgressively overlying Early Palaeozoic rocks of the Greywacke Zone. A marginal marine Permian facies is the so-called Haselgebirge, a sandstone- clay-evaporite association containing gypsum and salt. This facies is frequent in the Juvavic units, exposed for example in the Hallstatt’s salt mine. The Early Triassic is characterised by widespread deposition of shallow shelf siliciclastics of the Werfen Formation, containing limestone beds in its uppermost part with a depauparate fauna including Scythian ammonoids and conodonts. From Middle Triassic times onward carbonate sedimentation prevailed (Fig. 5). The dark Gutenstein Limestone/Dolomite is present in most of the Northern Calcareous Alps nappes. It can be

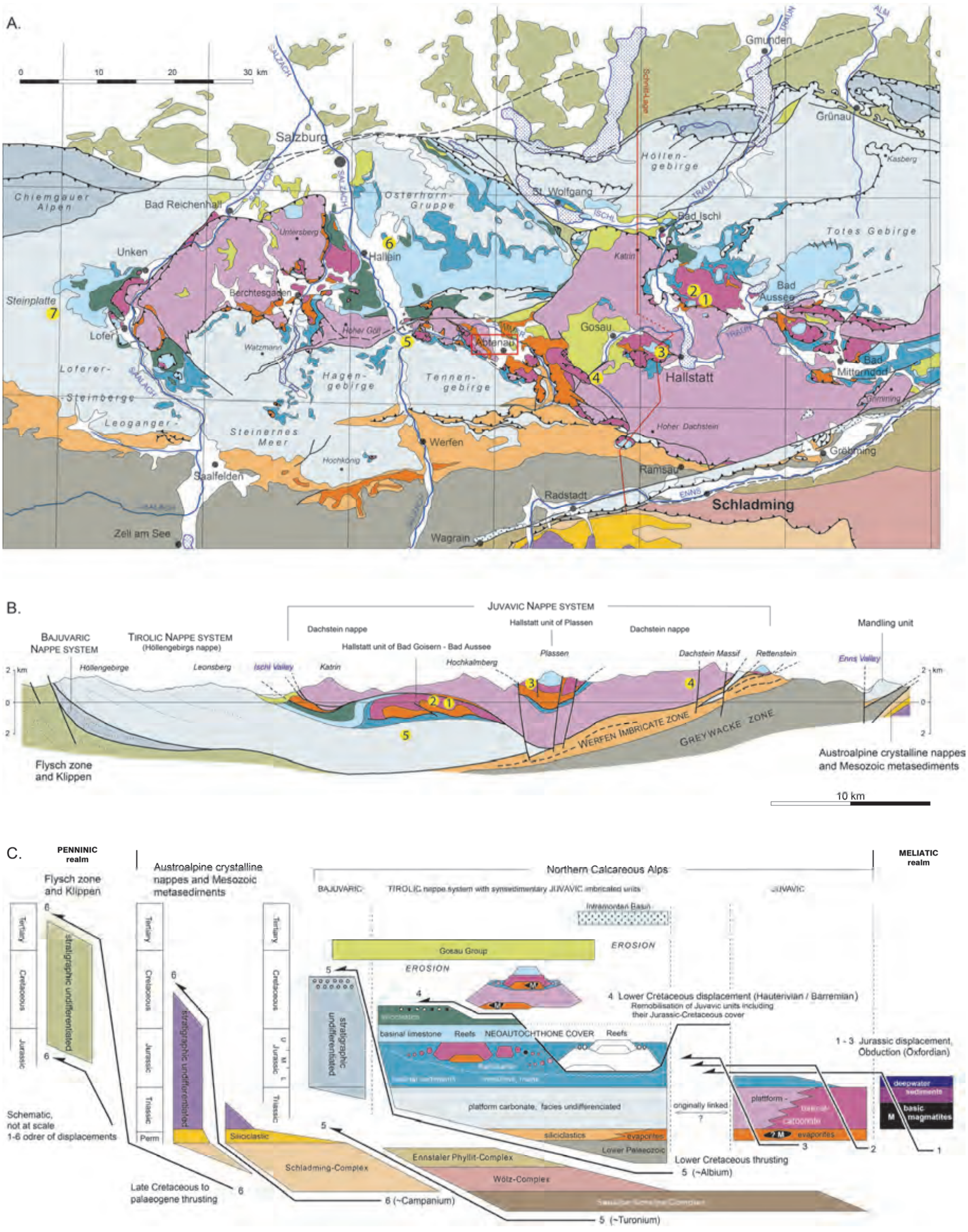


Fig. 4. The Dachstein region geology and evolution (from MANDL, 2000). A) Geological map of the Salzkammergut region with visited locality; B) Cross section of the nappe complex in the Salzkammergut region with visited locality; C) Interaction of sedimentation and tectonical displacements in the middle sector of the Northern Calcareous Alps.

laterally replaced in its upper part by light dasycladacean bearing carbonates, the Steinalm Limestone/Dolomite. During the middle Anisian, a rapid deepening and contemporaneous block faulting of the so-called Reifling event caused sea floor relief, responsible for the subsequent differentiation into shallow carbonate platforms (Wetterstein Formation and lateral slope sediments of the Raming Limestone) and basinal areas. The basins can be subdivided into the intrashelf Reifling/Partnach basins and the Hallstatt deeper shelf, the latter bordering the open Tethys Ocean. Due to strong Alpine nappe tectonics, the original configuration of the southern (Juvavic) platforms and basins is still a matter of discussion. The transition from the Hallstatt depositional realm into oceanic conditions with radiolarites is not preserved in the Northern Calcareous Alps. We see indications of the existence of such an oceanic realm only in the form of olistolites of Late Anisian to Ladinian red radiolarite in the Meliata slides in central and eastern sectors of the Northern Calcareous Alps (MANDL & ONDREJICKOVA, 1991, 1993; GAWLICK & MISSONI, 2015). The Wetterstein platforms in general show a platform progradation over the adjacent basinal sediments until the early Carnian (Fig. 5). Then the carbonate production rapidly decreased, the platforms emerged, and the remaining basins received siliciclastics from the European hinterland. Through the Carnian, the Reifling basin was completely filled by clastic sediments of the Raibl Group, including marine black shales, carbonates, and marine to brackish sandstones (Lunz Formation) containing coal seams. Local intra-platform basins and the Hallstatt realm toward the south also received fine-grained siliciclastics (Reingraben Shale) interbedded with dark cherty limestones and local reef debris ("Leckkogel facies"), derived from small surviving reef mounds at the basin margins. This interval is widely known as Carnian Pluvial Event (e.g. HORNUNG et al., 2007) for which, however, the term Carnian Pluvial Phase (see MUELLER et al., 2015) is more adequate. As the sea-level began to rise in the late Carnian, carbonate production resumed, locally filling a relief in the flooded platforms with lagoonal limestones (Waxeneck Limestone). The relief (several tens of meters) may be caused by erosion during the lowstand time and/or by tectonic movements.

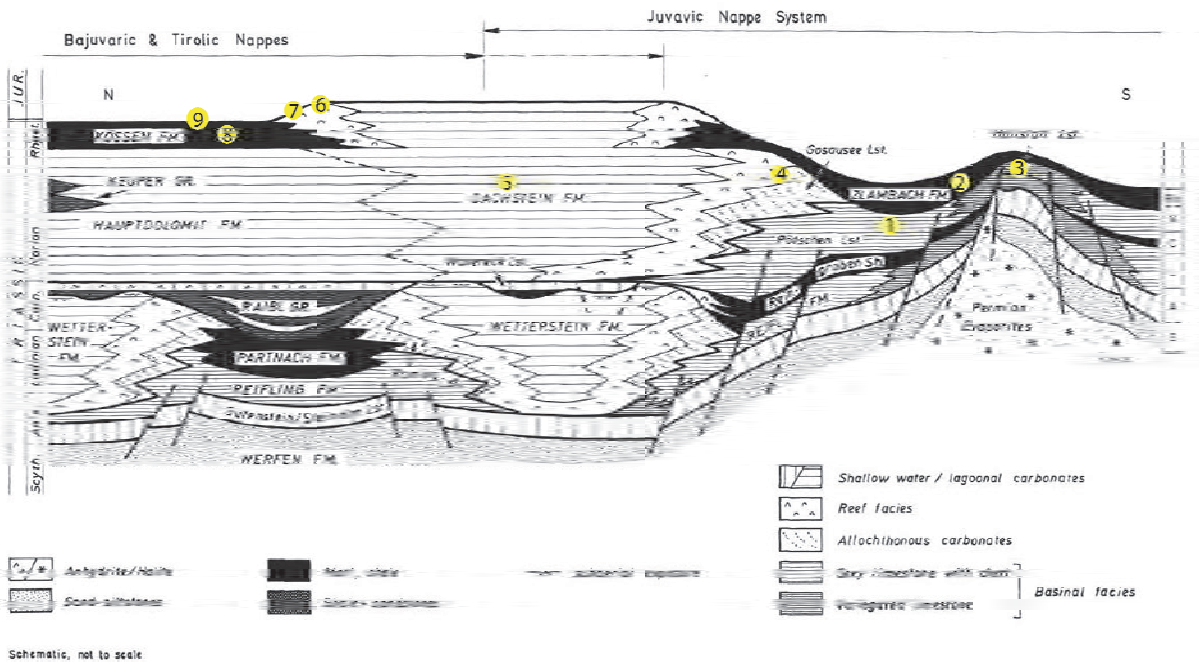


Fig. 5. Triassic stratigraphy of the Northern Calcareous Alps, middle sector (from MANDL, 2000). Numbers correspond to visited locality.

A transgressive pulse just below the Carnian/Norian boundary caused an onlap of pelagic limestones onto parts of the platform and initial reef growth on remaining shallow areas. Due to local differences in platform growth conditions, we can distinguish two different evolutions. In the central part of the Northern Calcareous Alps (e.g. Hochkönig, Tennengebirge, Dachstein area), the pelagic onlap represents only a short time interval and became covered by the prograding carbonate platform of the Dachstein Limestone. In these areas, the Late Triassic reefs are situated approximately above the Middle Triassic ones. A different evolution characterises the eastern sector of the Northern Calcareous Alps (Fig. 5). The latest Carnian pelagic transgression ("pelagic plateau") continues until the late Norian (LEIN, 1987). Dachstein Limestone is only known from the late Norian and the reefs are situated above the former platform interior, several kilometres behind the former Wetterstein reef front. Such a configuration seems to be typical also in the eastern Hochschwab/Aflenz area, in the Sauwand- and Tonion Mountains and for the Western Carpathians (Slovakian karst and the Aggtelek Mountains). In contrast, the "Southern marginal reefs" of the central Northern Calcareous Alps are connected by the allodapic Gosausee Limestone **(Locality 4)** to the Pötschen Limestone **(Locality 1)** of the Hallstatt facies realm. The Hallstatt Group shows a great variability of variegated pelagic limestones **(Locality 3)**, often with rapidly changing sedimentary features due to its mobile basement (diapirism) of Permian evaporites. Behind the Dachstein reefs, a large lagoonal environment extended all over the Northern Calcareous Alps with bedded Dachstein Limestones **(Locality 5)** close to the reefs and the intertidal Hauptdolomit in distant sectors. In the Rhaetian once again increasing terrigenous influx reduced the areal extent of carbonate platforms. The Hauptdolomit area and parts of the Dachstein lagoon became covered by the marly Kössen Formation **(Locality 8 and 9)**, which was bordered by Rhaetian reefs (Steinplatte **(Locality 7)** and Adnet quarries **(Locality 6)**). In the Hallstatt realm, as well as in the intraplatform basin of Aflenz Limestone, the marly Zlambach Formation **(Locality 2)** was deposited onlapping and interfingering with the Dachstein platform slope (Fig. 5). Towards the north, the carbonate shelf of the Northern Calcareous Alps passed into a siliciclastic shelf (Triassic "Keuper facies"), today mainly exposed in some Central Austroalpine nappes and Penninic units. Indications of this facies occur in the north-eastern most nappes of the Northern Calcareous Alps as intercalations of sandy shales within the Hauptdolomit. At the beginning of the Jurassic, the Austroalpine shelf drowned completely. Basinal conditions prevailed until the Early Cretaceous the only exception being the local Plassen carbonate platforms (latest Jurassic - Early Berriasian) in the southern Northern Calcareous Alps. Drowning and syn-sedimentary faulting caused complex seafloor topography with sedimentation of reddish/grey crinoidal limestones (Hierlatz Limestone) and red ammonoid limestones (Adnet and Klaus Limestone), mainly above former carbonate platforms as well grey marly/cherty limestones (e.g. Allgäu Formation) in the troughs in between. The early Hettangian is often missing at the base of Hierlatz Limestone, e.g. at the type locality. Neptunian sills and dykes filled with red or grey Liassic limestones are frequent, cutting down into the Rhaetian shallow water carbonates for more than 100 meters. According to BÖHM (1992) and BÖHM & BRACHERT (1993), Adnet- and Klaus Limestones are bioclastic wackestones, mainly made up of nannoplankton *(Schizosphaerella,* coccoliths) and very fine-grained biodetritic material. The macrofauna mainly consists of crinoids and in some places very abundant brachiopods and ammonites. Strong condensation, Fe/Mn stained hardgrounds and deep-water stromatolites, are frequent. According to KRYSTYN (1971), the Klaus Limestone at the type locality unconformably covers the upper Norian Dachstein Limestone and is represented only in neptunian dykes; it contains an ammonite fauna indicating Late Bajocian.

We will visit four depositional realms:

a) The Dachstein Platform with a lagoonal development (**Locality 5**), its late progradational phase (**Locality 4** Gosausee), and northern terminal fringing reefs (**Locality 6 and 7**)
b) The Zlambach basin between the Dachstein platform and the Hallstatt facies realm (**Locality 2**)
c) The Hallstatt facies realm with its two main development: The Pötschen Facies (**Locality 1**) and the Salzberg Facies (**Locality 3** Steinbergkogel)
d) The intraplatform Eiberg basin north of the Dachstein platform (**Locality 8** and **9**)

2.3.2. The Dachstein Mountains

During Late Triassic times, the passive continental margin of the north-western Neotethys was a (up to) 1000 km wide shelf situated about 30° north of the equator (MARCOUX et al., 1993). Tropical conditions and arid hinterland favoured the establishment of giant, (up to) 1200 m thick, carbonate platforms. These shelf carbonates are known as Dachstein limestone and form large mountain plateaus in the Northern Calcareous Alps of central and eastern Austria (MANDL, 2000; Fig. 4.). The type locality of the Dachstein limestone is the Dachstein Massif in the southern Salzkammergut region that consists of cyclical bedded lagoonal limestone with a south- and south-westward transition to a broad reefal rim and adjacent slope, bordering the open marine deeper Hallstatt shelf of the Tethys Ocean. Due to an exceptionally diverse Norian-Rhaetian reef biota the Dachstein limestone of the Northern Calcareous Alps has become a classical palaeontological study site (FLÜGEL, 1962; ZANKL, 1969, 1971; WURM, 1982; RONIEWICZ, 1989, 1995). Its facial and sedimentological characters (FISCHER, 1964; ZANKL, 1971; WURM, 1982; SATTERLEY, 1994; ENOS & SAMANKASSOU, 1998; SCHWARZACHER, 2005; HAAS et al., 2007, 2009, 2010) are equally important for comparisons with similar Late Triassic shallow-water carbonate platforms. Dachstein-like reefs and lagoonal carbonates are widespread along the Tethys margins and known from Sicily, the Carpathians, the Dinarids, Greece, Turkey, Oman, and even the Indonesian Islands (FLÜGEL et al., 1996; FLÜGEL & SENOWBARI-DARYAN, 1996; FLÜGEL & BERNECKER, 1996). The first developments of this platform are the deposition of lagoonal limestone (Waxeneck Limestone) mainly in local depressions of the eroded underlying Wetterstein platform due to a sea-level rise in the late Carnian (Tuvalian substage, Fig. 5). Contemporaneous dolomites with relictic reef structures are thought to represent Waxeneck marginal reefs. In the late Tuvalian, a distinct transgressive pulse led to widespread pelagic conditions, covering the drowning platform. The prevailing relief caused a complex pattern of local reef patches separated by depressions, where massive micritic crinoidal limestones were deposited. They exhibit a mixture of components from the platform interior, reef debris, crinoids, and pelagic biota (ammonoids, conodonts, radiolarian, bivalves). This initial stage of Dachstein platform growth (MARTINDALE et al., 2014) was rapidly overlaid within the early Norian by lagoonal limestones, while the reefs became concentrated at the platform margin. The open platform changed into a rimmed platform configuration, characteristic of the main Dachstein facies: The lagoonal platform interior exhibits cyclic bedded, inter- to subtidal "Lofer facies" **(Locality 5)**, which grades toward the north by an increase of intertidal dolomites into the Hauptdolomit facies. In the central and eastern sectors of the Northern Calcareous Alps, the cyclic, meter-sized bedding of the Dachstein Limestone is a characteristic morphological feature, clearly visible along the steep slopes as well as on the top of the large plateau mountain ranges. FISCHER (1964) has given a description of this phenomenon, which remains a classic even now, named by him "Lofer cycle". It is based on sequences from the plateaus of the Dachstein and the Loferer Steinberge. The cyclicity is caused by an interbedding of lagoonal limestones, thin layers of variegated argillaceous material and intertidal/supratidal dolomites and dolomitic limestones. We will discuss the Lofer Cycles in greater detail in chapter 3.2.2. The Dachstein reefs are connected to the lagoonal area by a narrow back-reef belt (BÖHM, 1986), showing massive to thick bedded limestones with ooids, oncoids and other coated grains, "black pebbles", grapestones, algae and reef debris. Palaeontological and microfacies research on the Dachstein reefs is summarised in FLÜGEL (1981). Reports on the macrofauna are given by ZAPFE (1962, 1967), on the corals by RONIEWICZ (1995). Sedimentological and biofacies details from the Gosaukamm have been reported by WURM (1982). The massive Dachstein reef limestone of the Gosaukamm is dominantly composed of coarse-grained rud-/floatstones and reef debris with only small, widely distributed reef patches (built mainly by calcisponges; less frequent are corals, solenoporaceans and encrusting organisms). Fauna and flora of the patch reefs and the detrital limestones is very rich. More than 50 species contribute to the construction of the reef framework, while more than 60 species must be regarded as benthonic reef-dwellers. Although the main Gosaukamm reef is not preserved (just the reef debris), a barrier reef of similar age, construction, and biotic composition can be found on the Gosausee margin of the Dachstein Mountain (MARTINDALE et al., 2013; **Locality 4**). This Gosausee reef likely represents part of the same barrier reef system that sourced the Gosaukamm reef debris (see further discussion in section 3.1.5). Pelagic elements from the open sea are known like *Heterastridium,* ammonites and conodonts. The investigations by WURM (1982) at the Gosaukamm have shown that the associations of foraminifera and of calcareous algae are significant for distinct environments within the reef zone. Large-scale bedding (some tens of meters) can be seen. The original dip of the reef slope was more or less 30° as visible today (KENTER & SCHLAGER, 2009), inferable from displaced geopetal fabrics. Slope and nearby basin-facies are characterised by carbonate-clastic sediments, which were derived from the platform, as well as from the slope. These sediments are summarised under the term "Gosausee Limestone", which is often referred to in literature as "Pedata Schichten" according to the locally abundant brachiopod *Halorella pedata.* Exposures can be mainly found around the Gosau lakes **(Locality 4)** and on the south-western slopes of the Gosaukamm. Details of sedimentology (MARTINDALE et al., 2013) and cyclicity of this bedded calciturbiditic limestone are given by REIJMER (1991) and an exact dating giving a time framework is presented by KRYSTYN et al. (2009). According to REIJMER (1991) the variations in turbidite composition can be attributed to fluctuations in sea-level and resulting flooding and exposure of the platform. The resulting variation of platform sediment production could be matched with Milankovitch quasi-periodicities.

In the Northern half of the Dachstein carbonate-platform, an intrashelf basin called the Eiberg basin (see below) take place. At the transition between this intrashelf basin and the platform, carbonate buildups like the Steinplatte complex (PILLER, 1981; STANTON & FLÜGEL, 1989; KAUFMANN, 2009; **Locality 7**) and the Adnet reef (SCHÄFER, 1979; BERNECKER et al., 1999; REINHOLD & KAUFMANN, 2010; **Locality 6**) developed. These Rhaetian reefs (‘Oberrhätriffe’) are the first ‘‘modern’’ reefs in earth history in terms of being dominated by scleractinian corals. Reefal and shallow carbonate platform sedimentation was terminated at the end of the Rhaetian when the whole Austroalpine carbonate shelf was affected by subaerial exposure (MAZZULLO et al., 1990; SATTERLEY, 1994; BERNECKER et al., 1999). Subsequent drowning occurred in the Early Jurassic when pelagic deeper marine ammonite bearing limestones (e.g. Adnet Formation) were deposited (BÖHM, 1992).

2.3.3. The Zlambach facies – the deep shelf environment

The Rhaetian terrigenous event of the Zlambach Formation ended the former pelagic carbonate deposition throughout the Hallstatt facie and was deposited in a toe-of-slope to basin environment. Slumping structures point to a pre-existing submarine relief of the depositional environment (MATZNER, 1986). The background sedimentation of alternating marls and subordinate micritic limestone is episodically overlain by allodapic carbonate sedimentation. Some of the marls contain a rich coral fauna-well known since FRECH (1890). Additional elements are non-segmented calcareous sponges, spongiomorph, hydrozoans, solenoporaceans, bryozoans, brachiopods, echinoderms, serpulids, foraminifera and ostracods. The highly diverse fauna of foraminifera was described by KRISTAN-TOLLMANN (1964). Ammonoids (*Choristoceras haueri* MOJSISOVICS, *Ch. marshi* (HAUER)) occur within the autochthonous beds. The microfacies of Zlambach limestones is characterised by abundant reworked corals with encrusting organisms (e.g. *Nubecularia, Tubiphytes)* and some calcisponges and bryozoans. A graded grainstone to packstone fabric is common and grain contacts often show stylolites (MATZNER, 1986). Miliolid and textulariid foraminifera are found in the micritic matrix (TOLLMANN & KRISTAN-TOLLMANN, 1970). Based on an autochthonous interpretation of the fauna, earlier authors (BOLZ, 1974; MATZNER, 1986) have favoured a comparably shallow depositional depth. FLÜGEL (1962) interpreted the environment as off-reef shoals within a muddy basin, somewhat deeper than and near to the fore reef of the Gosaukamm reef. KENTER & SCHLAGER (2009) point to a much greater depth of at least 300 meters, but probably 500m, based on geopetal fabrics measurements along the platform slopes. These data suggest a deep-basin model but with a depth varying significantly in space and time. This interpretation is in better agreement with the presence of deep-marine trace fossils (*Palaeodyction*) and the recognition of almost all of the benthos rich layers as mud turbidites (KRYSTYN, 1991). In the western part of the Gosaukamm area, the Zlambach Formation is rich in allodapic limestones and shows onlapping with the uppermost Dachstein Limestone **(Locality 4**) from where patch reefs may have produced the reefal material now redeposited in the basin, similar to the Cipit boulders of the South Alpine Cassian Formation of Carnian age. The deeper and distal part of the Zlambach basin facies **(Locality 2)** is preserved several kilometres to the northeast of the Gosaukamm, at the type locality within the Hallstatt unit of Ischl-Aussee (for details see BOLZ, 1974; PILLER, 1981; MATZNER, 1986).

2.3.4. The Hallstatt facies – the condensed deep shelf environment

Attention has been drawn to the variegated limestones of Hallstatt since the beginning of the geological research in the Northern Calcareous Alps in the 19th century, due to its local richness in cephalopods; about 500 species have been described from these strata, (e.g. MOJSISOVICS, 1873-1902; DIENER, 1926). Mojsisovics's ammonoid chronology (MOJSISOVICS, 1873, 1875, 1902), based on this fauna, has been widely used after several revisions as a standard for Triassic time. SCHLAGER (1969) established the first lithostratigraphic subdivision of the Hallstatt successions based on distinct lithological features. Additional work, like reinvestigation of classical ammonite sites (KRYSTYN et al., 1971), correlation of lithostratigraphy and conodont zonation (e.g. KRYSTYN, 1980) and studies on the lithological variability of the Hallstatt successions (e.g. MANDL, 1984) led to a more precise picture (Fig. 6). The two subfacies types, the Pötschen Facies (grey cherty limestones, marls, shales, **Locality 1**) and the Salzberg Facies (variegated Hallstatt limestones, **Locality 3**) have lateral

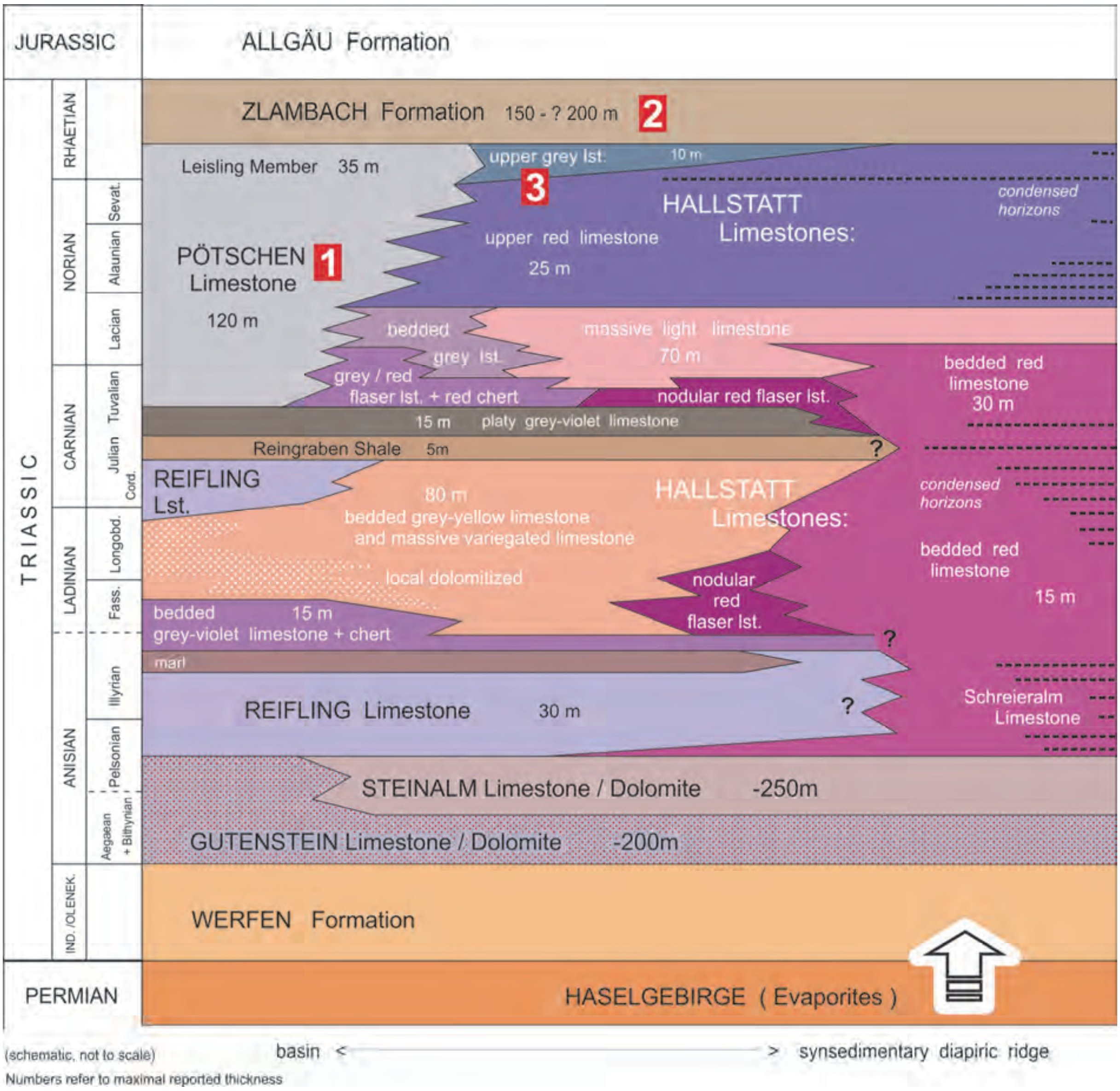


Fig. 6. Lithostratigraphy of the Hallstatt Triassic with position of Pötschenhöhe Quarry (1), Zlambach (2) and Steinbergkogel (3) (from MANDL, 2000).

transitions which can be demonstrated at nearly each stratigraphic level. Syndepositional block faulting and local uplift due to salt diapirism of the Permian evaporites are thought to be the reasons for the differentiation into basinal areas and intrabasinal ridges with reduced sedimentation. Syndepositional faulting is well documented (SCHLAGER, 1969) by numerous sediment-filled fissures at several stratigraphic levels at a scale of millimetres to some meters in width and up to 80 meters in depth, cutting down at a maximum from upper Norian red limestone into Anisian dolomites. Faulting is sometimes accompanied by block tilting and rotation, causing sedimentary gaps, discontinuities with breccias, and remarkable differences in sediment thicknesses of nearby successions. The pelagic sedimentation of the Hallstatt facies has started with the drowning of the Steinalm shallow platform (dasycladacean limestone) during the middle Anisian (Pelsonian). Beginning with the Ladinian (Fig 6.), a characteristic lithological succession developed, which is repeated in a similar manner after the terrigenous Reingraben event also in the Late Triassic: Within the basin, the deposition of grey cherty limestones continued (Reifling and Pötschen Limestone); towards the ridges, they pass laterally either via variegated cherty limestones into bedded red limestones or via bedded grey transitional types into light-coloured massive limestones. The red Hallstatt limestones, covering the top of the diapiric ridges, frequently show subsolution horizons and condensation (ferromanganese crusts). For example, the thickness of the "Hangendrotkalk" can be reduced within a lateral distance of 200 meters from about 25 meters to zero (KRYSTYN et al., 1971). Most of the classical ammonoid sites are situated in red limestones within layers with reduced sedimentation and subsolution. Beside the cephalopods, certain pelagic bivalve coquina layers ("*Styriaca* beds", "*Monotis* beds") can be used as lithostratigraphic as well as chronostratigraphic marker beds in the Norian. The Hallstatt limestone succession is terminated by increasing terrigenous input in the early Rhaetian (Zlambach Marl). Early to Middle Jurassic sediments (spotted marls of the Allgäu Formation) are preserved only in a few localities. Late Jurassic radiolarites and shelfal limestones, resting disconformably on Hallstatt sequences, do not belong to the sequence in a strict sense, because they represent a matrix and a sealing "neoautochthonous" cover during and after displacement and gravitational transport of Hallstatt units during the Oxfordian tectonic event.

2.3.5. The Eiberg Basin

The Eiberg Basin is a Rhaetian intraplatform depression, which can be traced over 200 km from the Salzkammergut (Kendlbachgraben, Upper Austria) in the east to the Lahnenwiesgraben valley (northwest of Garmisch-Partenkirchen, Bavaria) in the west. It was bordered to the southeast by the Dachstein Lagoon and locally with fringing reefs (e.g. Steinplatte (**Locality 7)** and Adnet (**Locality 6)**, Fig. 5). North of the Eiberg Basin there existed another partly terrigenous-influenced carbonate ramp (Oberrhaet limestone lagoon) of the Allgäu nappe. Within this unit also are found intraplatform depressions with sedimentary successions across the Triassic-Jurassic boundary (e.g. Restental, Upper Austria; NE Aschau, Chiemsee, Bavaria; Tannheim, Allgäu). The Allgäu Unit was bordered landward by the Keuper area of Southern Germany (or was separated from the latter by the Vindelician high). The Rhaetian Kössen Formation spreads over the Hauptdolomit lagoon with subtidal mixed lime and clay bearing bioclastic rocks. The sedimentary facies of the Rhaetian Kössen Formation changed around the early to late Rhaetian boundary (base of *marshi* Zone) by the onset of a basinal facies (Eiberg Member) above the underlying shallow water sequence (Hochalm Member) (GOLEBIOWSKI, 1989; **Locality 8**). The continuously subsiding Eiberg basin reached up to 150 m water depth in late Rhaetian time and was, therefore, less affected by the end-Triassic sea level drop which led to widespread and longer-lasting emersion of the surrounding shallow water areas **(Locality 9)**. Instead, marine conditions prevailed in the basin across the system boundary, though a distinct and abrupt lithological change from basinal carbonates of the Eiberg Member to marls and clayey sediments of the lower Kendlbach Formation (Tiefengraben Member, corresponding to the British Pre-*planorbis* Beds) is interpreted as a result of this sea level fall and is said to be connected with the start of the volcanism of the Central Atlantic Magmatic Province (CAMP) (MARZOLI et al., 2011; PÁLFY & ZAJZON, 2012). This drastic change in lithology was interpreted during the last decades as the Triassic-Jurassic boundary (GOLEBIOWSKI, 1990; HALLAM & GOODFELLOW, 1990) because it coincides with the disappearance of typical Triassic fossils such as ammonoids and conodonts. New studies demonstrate, however, that the lower metres of the Tiefengraben Member still yield a Triassic micro- and nannoflora (KUERSCHNER et al., 2007; HILLEBRANDT et al., 2013). The regression was fast; it started at the end of the Kössen Beds with a bituminous layer, culminated with the Schattwald Beds near the end of the Rhaetian and was followed by a slow long-term sea level rise that started in the latest Rhaetian, continued through the Hettangian and exceeded the Rhaetian highstand relatively late in the late Sinemurian (KRYSTYN et al., 2005). Due to enhanced transgression the Kendlbach Formation is replaced up-section by Lower Jurassic carbonates of both increasing water depth and pelagic influence (Adnet Formation). Within the Eiberg basin, between Lake St. Wolfgang (Kendlbach) and Garmisch-Partenkirchen all sections show the same sedimentary record across the Triassic-Jurassic boundary with varying carbonate vs. clay content depending on their more marginal or more distal position within the basin.

3. The Field Trip

3.1. Shelf margin (Day 1)

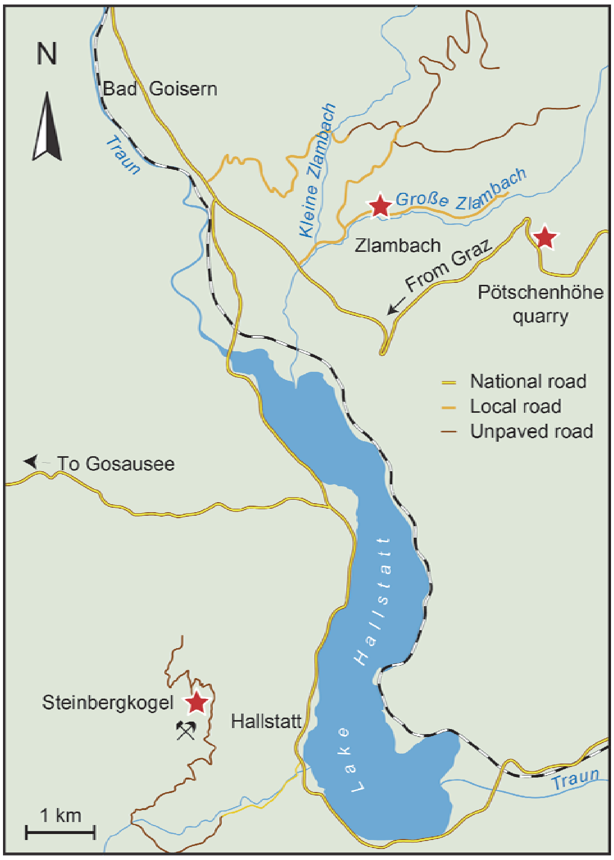


Fig. 7. Map of Salzkammergut with the visited localities.

The specific stratigraphic importance of the cephalopod-rich Hallstatt facies of the Salzkammergut is expressed in the fact that all Late Triassic substages, except for the Early Carnian, are defined herein. The Hallstatt limestones are of particular importance for questions of primary producers (nanno-organisms) of this extremely fine-grained pelagic mud as well as of very specific sedimentation features such as early cementation, condensation, synsedimentary tectonics with fissure building and local off- and onlaps – all within a deep marine setting. Still deeper basin sediments between the slope of Dachstein reef and the Hallstatt highs are recorded in den Pötschen Formation of the Pötschenhöhe quarry. The proposed GSSP section for the base of the Rhaetian exposes at Steinbergkogel a pelagic basin facies of red and grey Norian to lower Rhaetian Hallstatt Limestone with a rich ammonoid, bivalve, and microfauna that, together with chemo- and magneto-stratigraphy, allow for a multistratigraphic event correlation of the Norian-Rhaetian boundary. The Zlambach Formation, muddy limestone and allodapic limestone alternation represents a basinal transition between the Dachstein platform and the Hallstatt basin. These sediments allow a comparison of age-equivalent off-shore homogeneous carbonatic and terrigenous facies vs. the cyclically staked mixed carbonatic-terrigenous intraplatform Kössen facies.

3.1.1. Route

Coming from Graz along motorway A9 and Road B145, we will reach our first stop at the pass between Bad Aussee and Bad Goisern (Pötschen pass, **Locality 1**: Pötschenhöhe Quarry) (Figs. 1 and 7). Then in St. Agatha, 3 km ahead of Bad Goisern, we will follow a small mountain road to the east. We will stop along the road leading to Leislingalm to look at the Zlambach Formation (**Locality 2**). We will then drive through Hallstatt and depart to the west along another mountain road to an old salt mine for the Norian/Rhaetian boundary outcrop (**Locality 3)**. From Hallstatt we will drive to the Gosausee (Gosau Lake) where one can get a good look at both the Gosaukamm Mountain and the Gosausee margin of the Dachstein Mountains (**Locality 4)**. From here, we will drive up a forest road taking us from the lake up the northern plateau. We will stop at the base of the Gosausee reef (Fig. 17), a relatively intact barrier reef (when compared to other Dachstein reefs), with an almost continuous fore reef to lagoon transect preserved. From Gosau, we will drive westerly through the Pass Gschütt to the small village of Abtenau where we will stay overnight.

3.1.2. Locality 1 – Pötschenhöhe Quarry

The Pötschenhöhe-quarry (Fig. 7), located along the road between Bad Goisern and Bad Aussee, exposes sediments that are probably the bathymetrically deepest Norian sediments of the Salzkammergut (Fig. 8). It is the type locality of the Pötschen Formation. It is a sequence of about 120 m in thickness, comprising a uniform series of grey, well bedded micritic 'deeper water' limestones alternating with argillaceous-marly layers. The average thickness of the limestone beds is around 15 cm; the clayey interlayers are a few centimetres thick. The limestone beds often show nodular upper bedding surfaces caused by pressure solution. Chert occasionally occurs, whilst biogenic burrowing is commonly observed; the microfacies show radiolarian, sponge spicules and subordinate filament-bearing wackestones.

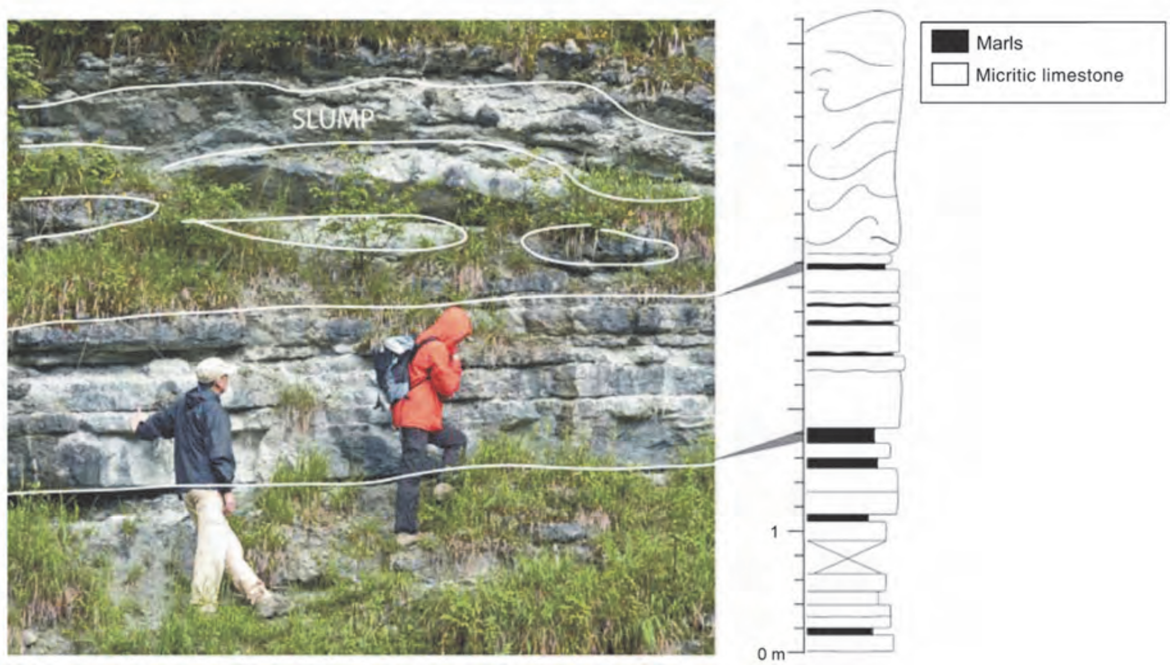


Fig. 8. Pötschenhöhe outcrop with schematic lithology (modified from GARDIN et al., 2012).

The Pötschen Formation is of Late Carnian (Tuvalian) to Early Rhaetian age, as demonstrated by the presence of conodonts (MOSTLER, 1978). The Pötschenhöhe 'quarry' exposes beds of Early Middle Norian age (= Alaunian 2, *Himavatites hogarti* Zone) dated by ammonoids (TATZREITER, 1985), redeposited as big gliding block in a late Norian matrix with *Monotis salinaria* (LK, unpublished).

3.1.3. Locality 2 – Großer Zlambach

The Großer and Kleiner Zlambach are distributaries of the Traun River and name-giving for the Rhaetian Zlambach Formation. Though the formation displays an at least 150 m thick deep-marine succession, continuous sections are rare, due to common weathering of the soft sediments and a strong tectonic overprint with faults of unclear displacements making difficult a bed-by-bed correlation. The Kleiner Zlambach located north of the visited outcrop is the best exposed and less tectonised section but is unfortunately difficult to access (Fig. 9). Three closely neighbouring outcrops of the Großer Zlambach (Fig. 7; 47°37'47,5"N / 13°40'02,7"E) represent a partly folded and – though against each other fault bounded – lithologically complete Rhaetian sequence in far-reef basinal facies. The autochthonous background sedimentation of alternating marls and marly micritic limestone (Figs. 9 and 10) dominates here clearly the allochthonous carbonate sedimentation. An upward increasing thickness of the marls is characteristic for younger Rhaetian parts (Fig. 9). The allochthonous carbonate sedimentation consists of distal fine-grained turbidite, even if most of the beds do not show any characteristic turbiditic features. Except for the top black marls they contain only rarely a diverse biota derived from platform or reef environments (corals, dasycladacea, solenoporacea, sponges, bryozoans, hydrozoans, bivalves, brachiopods, ammonoids, gastropods, ostracods, foraminifers, echinoderms, radiolarian and Problematica). The autochtonous limestones show a rare fauna (some foraminifers, ostracods, conodonts, ammonoids, radiolarians). The first outcrop 2.1 displays the lower, limestone dominated part of the formation with the early to middle Rhaetian transition, whereas the boundary between the middle and late Rhaetian is visible at outcrop 2.2 where marls become more prominent. Black laminated marls with very rare allodapic coral-bearing layers of late Rhaetian age will be visible at outcrop 2.3 (Fig. 10).

3.1.4. Locality 3 – Steinbergkogel: Proposed Norian/Rhaetian GSSP section

The Steinbergkogel is a small, unnamed summit (1245 m above sea level, Fig. 7) situated in the south-western corner of sheet 96 (Bad Ischl), official topographical map of Austria 1:50,000. It is located just south of the western-most salt mine gallery symbol (crossed hammers in Fig. 12), corresponding to the entrance of the Ferdinandstollen (Stollen = gallery in English) at an altitude of 1140 m. Access to Steinbergkogel is possible by a forest road that starts in the Echerntal and after 7 km reaches the Salzberg and the Ferdinandstollen from where the quarry Steinbergkogel with the Norian-Rhaetian GSSP candidate section can be seen, approximately 25 m away (Figs. 11 and 12). Alternatively one can reach the Steinbergkogel directly from Hallstatt (Fig. 7) by taking the cable car to Rudolfsturm (855 m), following a marked footpath along the prehistoric burial ground of the Hallstatt (Celtic) period, past some Salt mine buildings in the north-westerly direction towards the Plassen peak, and finally arriving at Ferdinandstollen (about a one hour walk). The proposed Norian-Rhaetian GSSP candidate (coordinates 47°33'50''N / 13°37'34"E) is exposed in a long abandoned quarry where blocks have been extracted to mantle the galleries of the salt mine (Fig. 11). Most of the classical Steinbergkogel ammonoid fauna (MOJSISOVICS, 1873–1902) may have

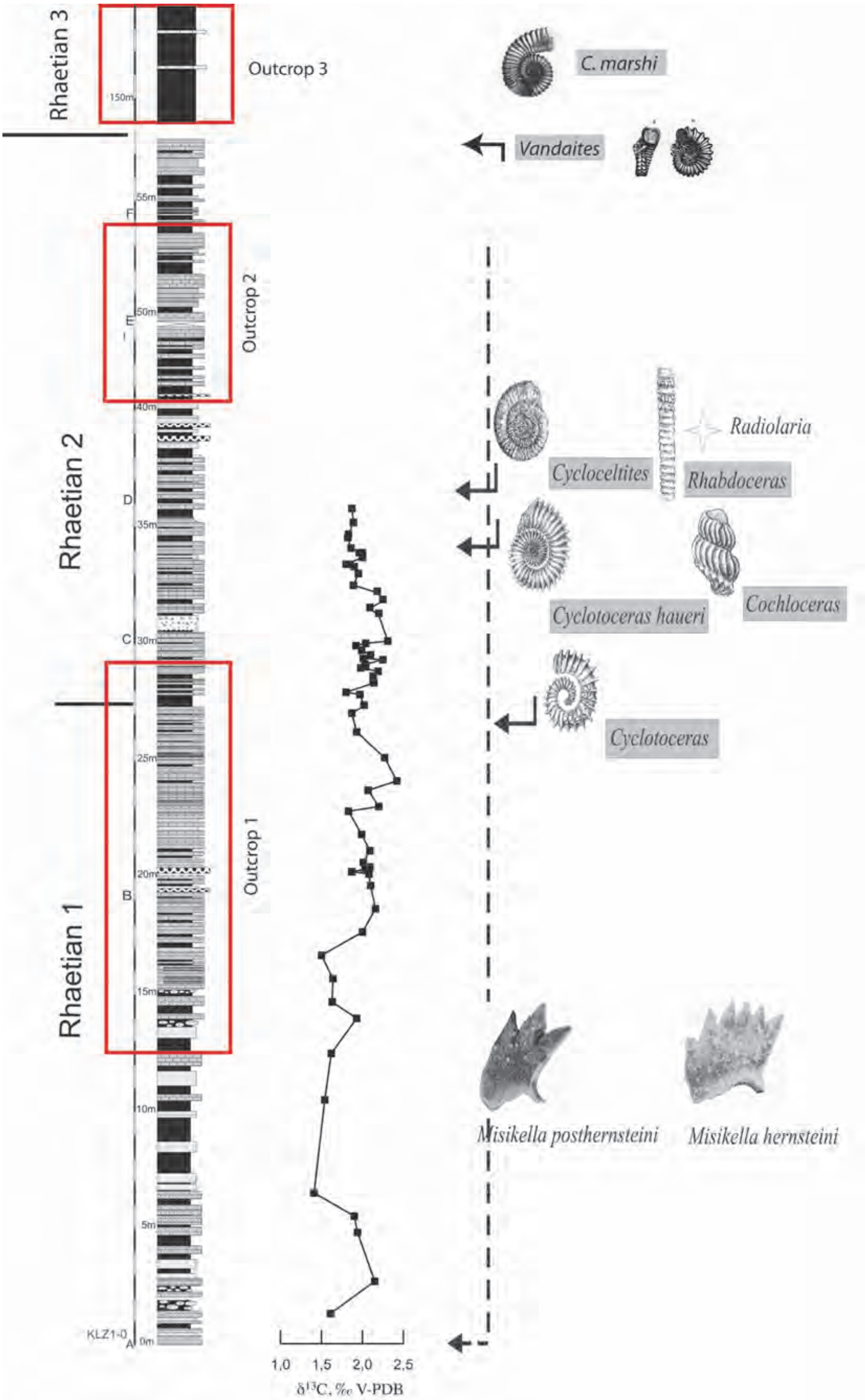
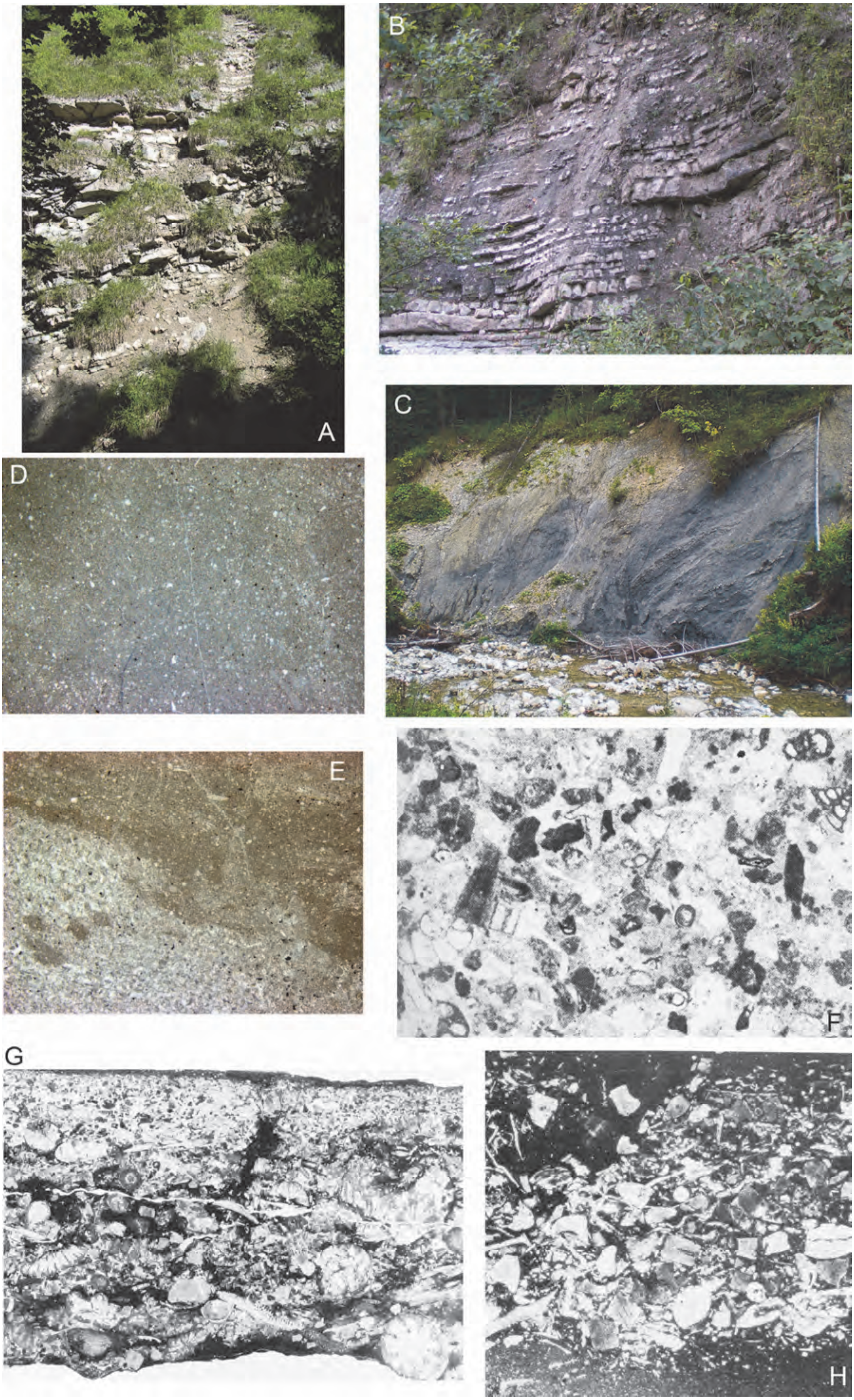


Fig. 9. Profil of the Zlambach Formation (Kleiner Zlambach) with the visited outcrop, carbon isotope curve and important biostratigraphic markers (from RICHOZ et al., 2012).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been collected by miners from that place, but DIENER (1926) mentions another fossil locality about 100 m on strike to the west (ST 2 in Fig. 12B). As the latter is of slightly younger age than the quarry rocks, the old faunal record may be of stratigraphically mixed origin in the sense of “rucksack-condensation”. There is a wealth of literature referring to invertebrate faunas of the Steinbergkogel. Ammonoids have been described by MOJSISOVICS (1873-1902), pelagic bivalves by KITTL (1912), gastropods by KOKEN (1897), brachiopods by BITTNER (1890) and conodonts by MOSHER (1968) and KRYSTYN et al. (2007a, b). A comprehensive faunal list is found in SPENGLER (1919) with reference to specific locations.

The Steinbergkogel is composed of a uniformly (70°N) dipping sequence starting with a thick whitish, massive and macroscopic unfossiliferous lower Norian Hallstatt facies type (*Massiger Hellkalk* Member) overlain by about 30-40 metres of bedded predominantly red (*Hangendrotkalk* Member) and in the top grey, fine-grained pelagic limestones (bioclastic wackestones) of latest Norian to earliest Rhaetian age; the upper half of the grey limestone (*Hangendgraukalk* Member)) shows a microfacies change to sponge spicules dominated wacke- and mudstones; it develops thin clay interbeds that have eased the quarrying of stones and indicate a gradual transition to grey marls of the Zlambach Formation. The proposed Norian-Rhaetian boundary interval corresponds to the basal part of the *Hangendgraukalk*. Stratigraphically below the quarry section, more than 20 m of red upper Norian limestones (ST 4 in Fig. 12B) contain several layers with *Monotis salinaria, Heterastridium*, ammonoids, and conodonts that allow a cross-correlation with the quarry sections (Fig. 13).

The Steinbergkogel quarry consists of 4 meters of medium to thin bedded micritic limestones with the proposed candidate section STK-A located at the eastern end (Figs. 11, 12). About 20 beds have been studied in detail, numbered from bottom to top as 103 to 122 (Fig. 14). Beds 108 to 112A (one meter thick) are of relevance to the Norian-Rhaetian boundary and differ from over- and underlying rocks by a high bioclastic fossil content made up of ammonoids and subordinate echinoderms. Above bed 113 the microfacies shifts to a shelly-poor, mud-dominated facies type. Rock colours change around bed 107 from red to grey and return locally to grey-reddish mixed above bed 115. The Norian-Rhaetian GSSP is proposed at Bed 111A with the FAD of *Misikella posthernsteini,* 2.2 m above the base of the section. A low CAI of 1 excludes any thermal overprint and favours the preservation of the original palaeomagnetic signal and of a primary δ^{13}C-record (Fig. 14). Another measured sequence 10 m to the west (STK-C) with faunistically comparable results strengthens the biochronologic significance of section STK-A and enlarges the palaeomagnetic database into

← Fig. 10. A) Großer Zlambach, section GZ1 – Zlambach Formation, Lower Member. Alternation of limestone and marls with distinct slumping interval (Early Rhaetian); B) Großer Zlambach, Section GZ2- Zlambach Formation, Lower Member. Alternation of limestone and bituminous marls (Early Rhaetian); C) Großer Zlambach, Section GZ3- Zlambach Formation, Upper Member. Black laminated marls with thin allodapic limestone (Late Rhaetian); D) Bioturbated sponges spicules bearing mudstone with graded allodapic grainstone layers containing echinoderms, foraminifers and dasycladaceans bioclast (Zlambach Formation Lower Member, sample LL4-2 GZ1); E) Radiolarian and sponge spicule rich autochtonous wackestone higly bioturbated (Zlambach Formation Lower Member, sample L5 GZ1); F) Foraminiferal bioclastic packstone. Characteristi allochtonous sediment of distal turbidite (from MATZNER, 1986), magnification x 20; G) Echinoderm-packstone laying on a marly limestone with shell fragments, sponge spicules, ostracods and foraminifera, magnification x 3,5 (from MATZNER, 1986); H) Graded detrital reef limestone with densely packed corals, gastropods, solenoporaceans, dasycladaceans, microproblematica, foraminifera, ostracods, echinoderms and shell fragments and geopetal fabrics. Magnification x 2,7 (from MATZNER, 1986).

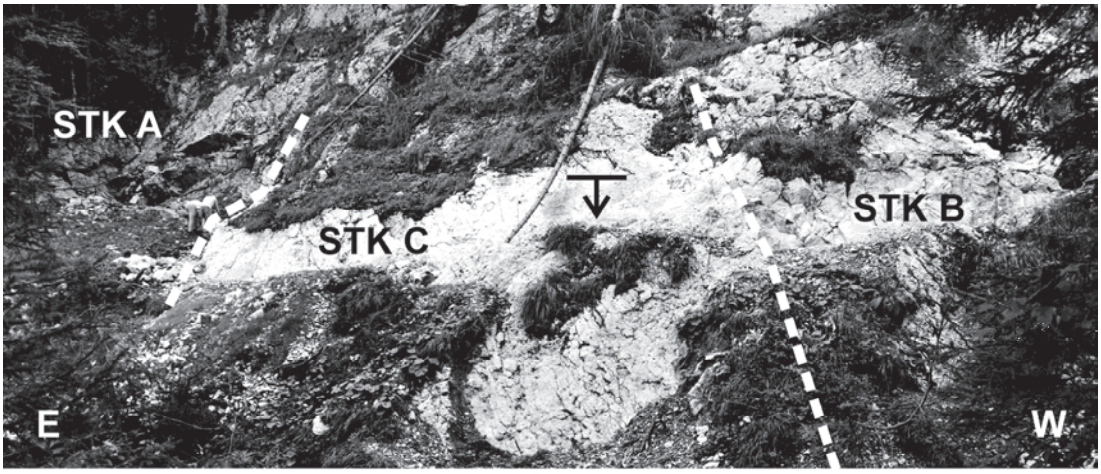

Fig. 11. Steinbergkogel quarry with sections A, C and B.

the lower Rhaetian considerably (KRYSTYN et al., 2007a) (Figs. 11, 12C, 15). The microfacies of Steinbergkogel's sections are quite homogenous, characterised by sparse fine-grained skeletal detritus of echinoderms (crinoids and echinoids), ammonites, bivalves, rare gastropods, ostracods, sponge spicules, as well as poorly-preserved radiolarians and benthic foraminifers in different proportions (Fig. 16). Small burrows are quite abundant in this section. The microfacies analyses did not reveal any marked facies change through the Boundary beds 108 to 112 and indicate a persistent low-energy, outer shelf, upper slope setting. The constant presence of stenohaline sessile organisms such as echinoderms indicates persistent, normal marine salinity conditions. The relatively diversified benthic fauna, together with high density of burrows, are generally interpreted to be due to oxic sea floor conditions.

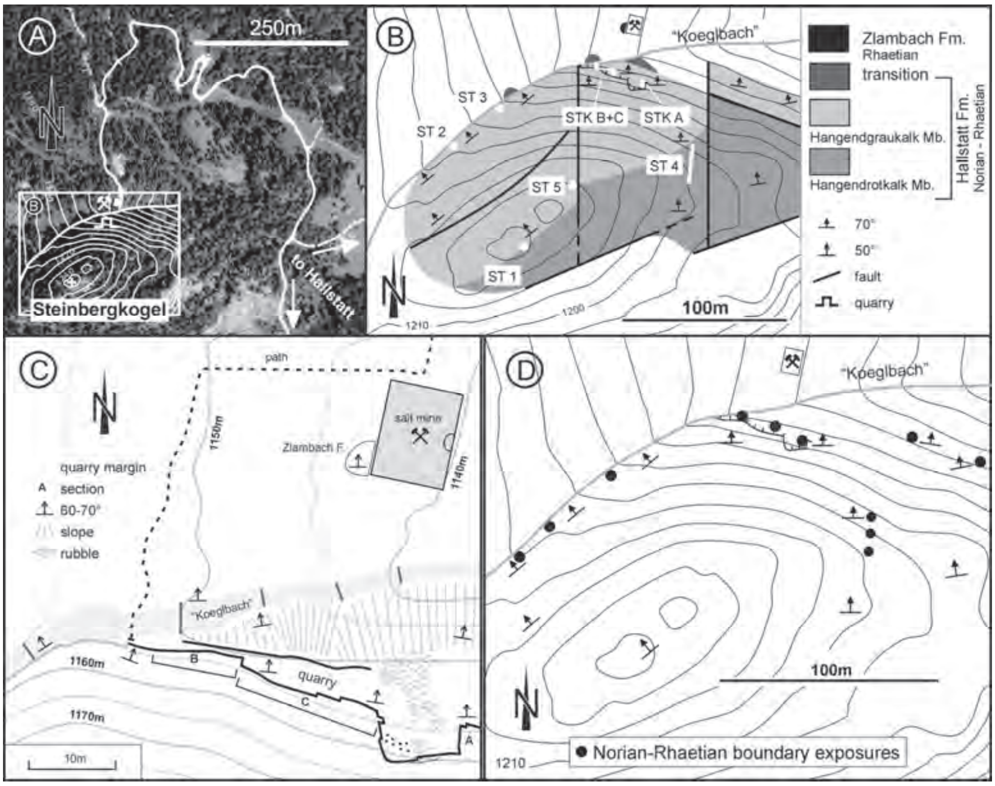

Fig. 12. Detailed Steinbergkogel maps. A) Aerial view; B) Geology with sections and fossil localities; C) Steinbergkogel quarry; D) Location of Norian-Rhaetian boundary exposures.

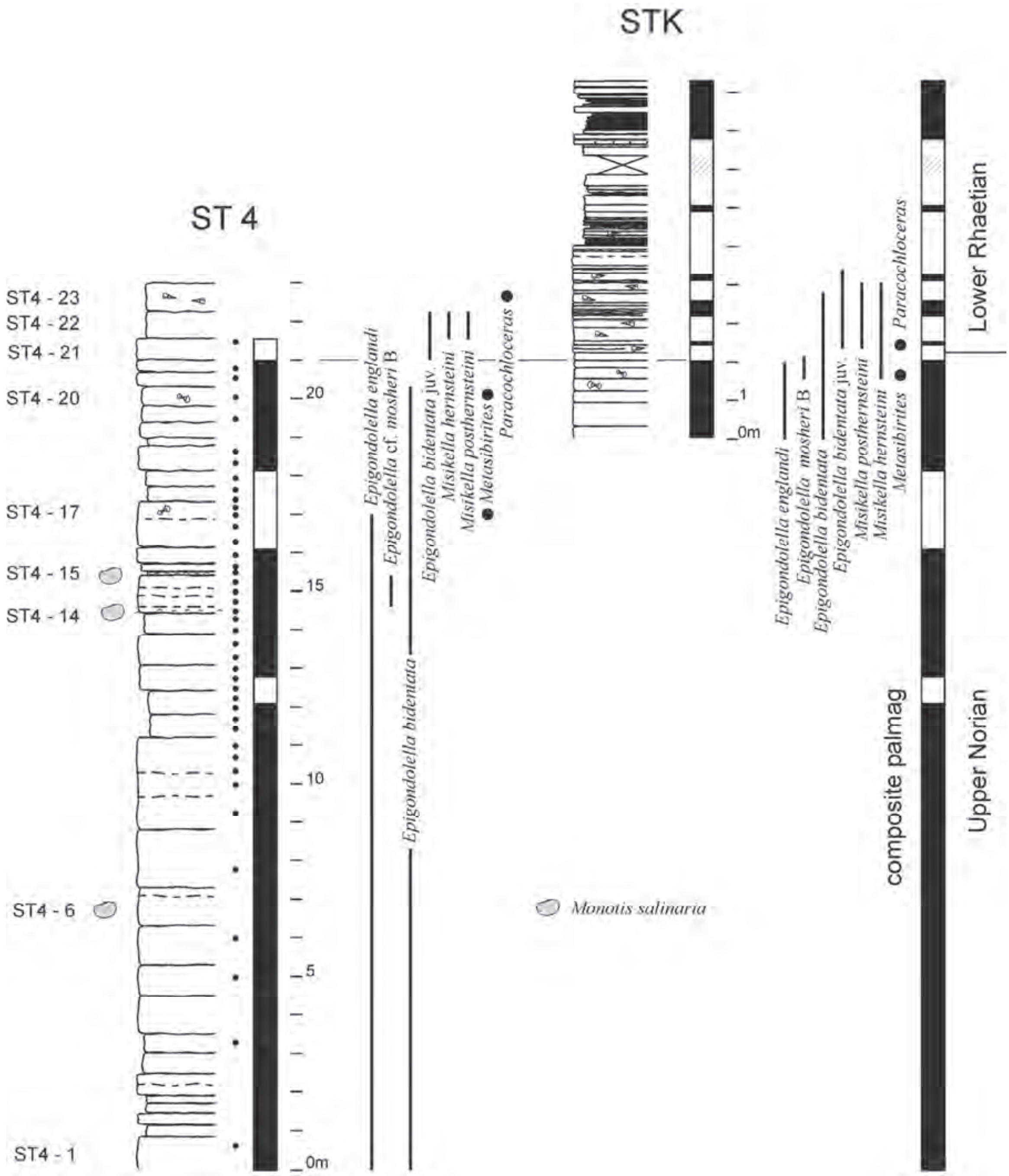

Fig. 13. Composite Upper Norian to lower Rhaetian magnetostratigraphy of the Steinbergkogel, with sections ST4, STK A and B/C (from RICHOZ et al., 2012).

To achieve stratigraphically reliable conodont ranges at least 10 kg of limestone have been dissolved from each bed between 108 and 112. This intense search has led to p-element recoveries of 50-100 specimens per sample, with *Epigondolella bidentata* dominating up to bed 110 and replaced by a *Misikella* dominance above (Fig. 14). *Norigondolella steinbergensis*, usually the most frequent faunal element in this time interval is fortunately rare as well as ramiform elements. A first conodont event is seen in bed 108 where *Oncodella paucidentata* and *Misikella hernsteini* appear – without known forerunners identified only as FO dates. *Misikella hernsteini* is rare between bed 108 and 110 (max. 10%) but becomes frequent from 111A onwards (Fig. 14). Bed 111A marks the FAD of *M. posthernsteini*, as phylogenetic successor of the fore-mentioned species, responsible for the

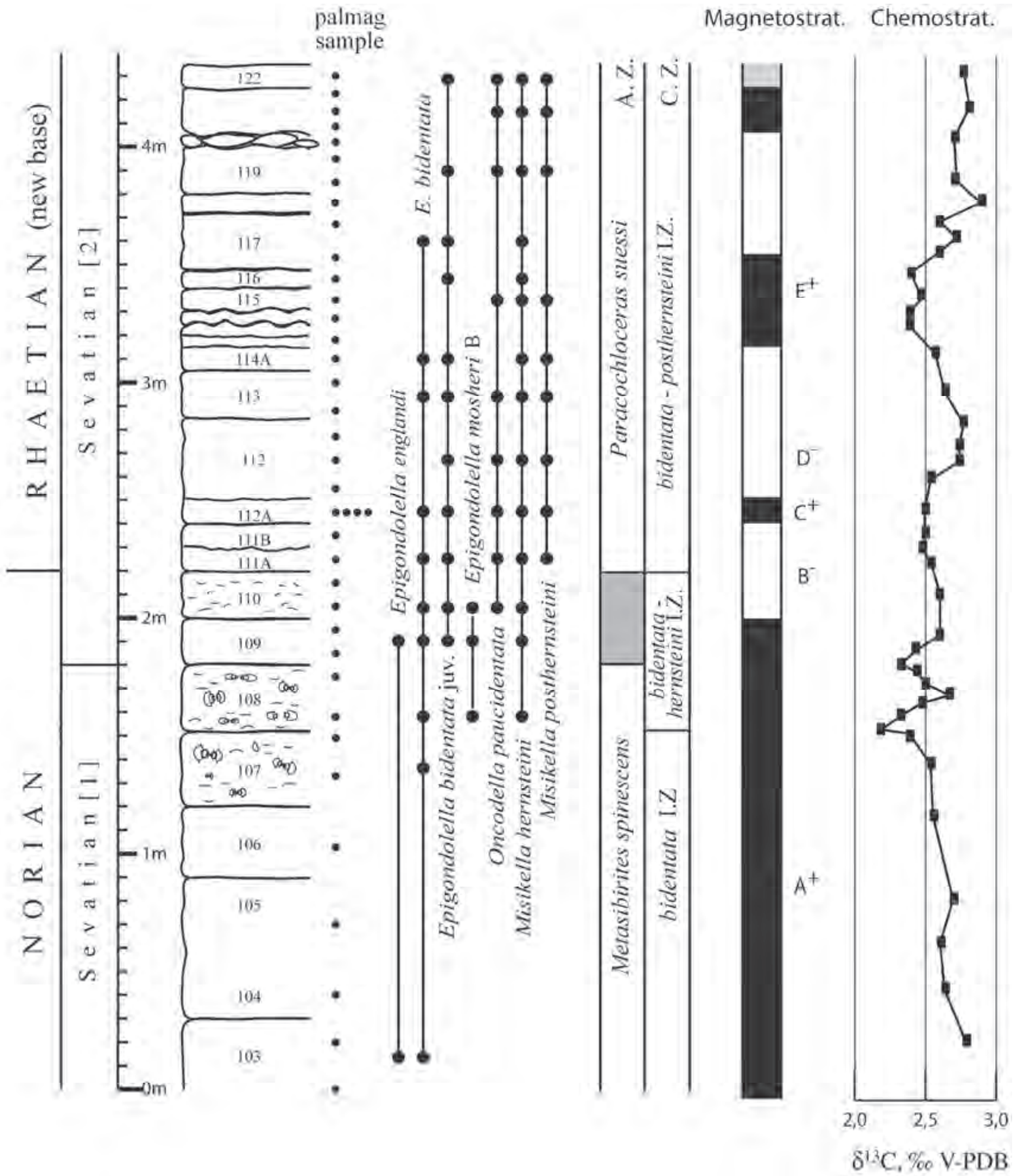

Fig. 14. Integrated bio-, magneto- and chemostratigraphy of GSSP candidate for the Norian-Rhaetian boundary section Steinbergkogel A. Note: Sevatian 1 and 2 refer to previous Upper Norian classification (from KRYSTYN et al., 2007b).

most diagnostic conodont datum in the section and probably the worldwide best-documented FAD of *M. posthernsteini* in co-occurrence with *Paracochloceras*. With just two specimens in 111A and four in 111B, *M. posthernsteini* is very rare at the beginning of the section, becomes frequent in bed 112, and rare again higher up in the section (Fig. 14). The initial infrequence highlights the problem of how to recognise the FAD of *M. posthernsteini* in biofacies less favourable and use of this event without additional control may cause uncertainties in regional or intercontinental correlations. Two conodont zones can be distinguished in the boundary interval of the proposed candidate section based on the successive appearances of species of the genus *Misikella*: 1) *Epigondolella bidentata* – *Misikella hernsteini* Interval Zone, characterised by the co-occurrence of common *E. bidentata* and rare *M. hernsteini* in beds 108 to 110 of STK-A and beds 11 to 12B of STK-C

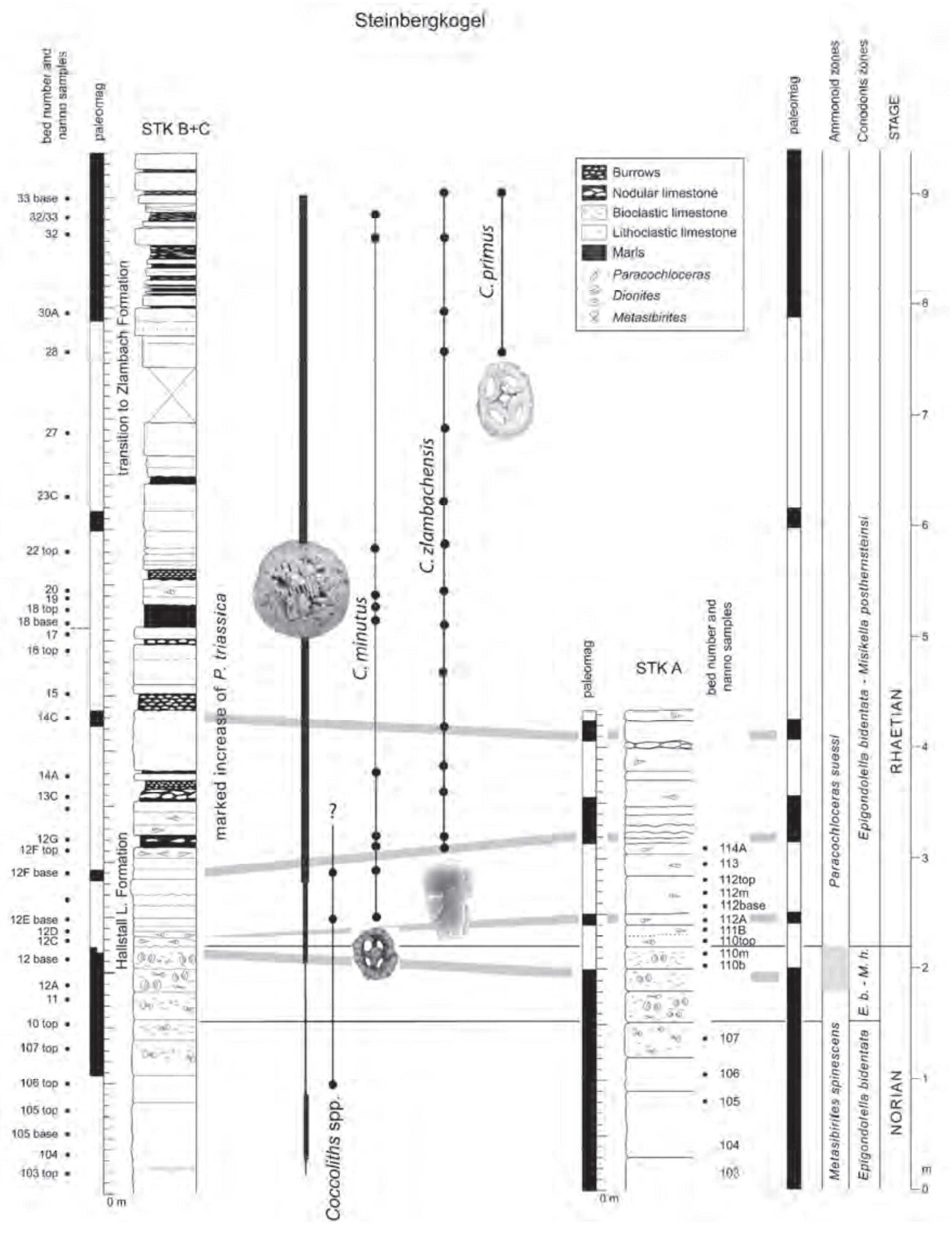

Fig. 15. Steinbergkogel A and B + C section, GSSP candidate for the Norian-Rhaetian boundary. Schematic lithology, sample location, magnetostratigraphy (black is normal polarity, white is reversed polarity) and most important calcareous nannofossil bio-events (from GARDIN et al., 2012).

respectively, and 2) *Epigondolella bidentata – Misikella posthernsteini* Interval Zone, from bed 111A resp. bed 12C onwards containing *M. posthernsteini* in low quantities compared to the very frequent *M. hernsteini* (Fig. 14). Normal sized *Epigondolella bidentata* becomes rare in Zone 2 and is usually replaced by juveniles resembling the genus *Parvigondolella* (Fig. 14). Considerable provincialism limits this zonation to the Tethyan realm where it has successfully been applied to sections in Austria (MCROBERTS et al., 2008), Turkey (GALLET et al., 2007), Oman and Timor (KRYSTYN, unpublished data).

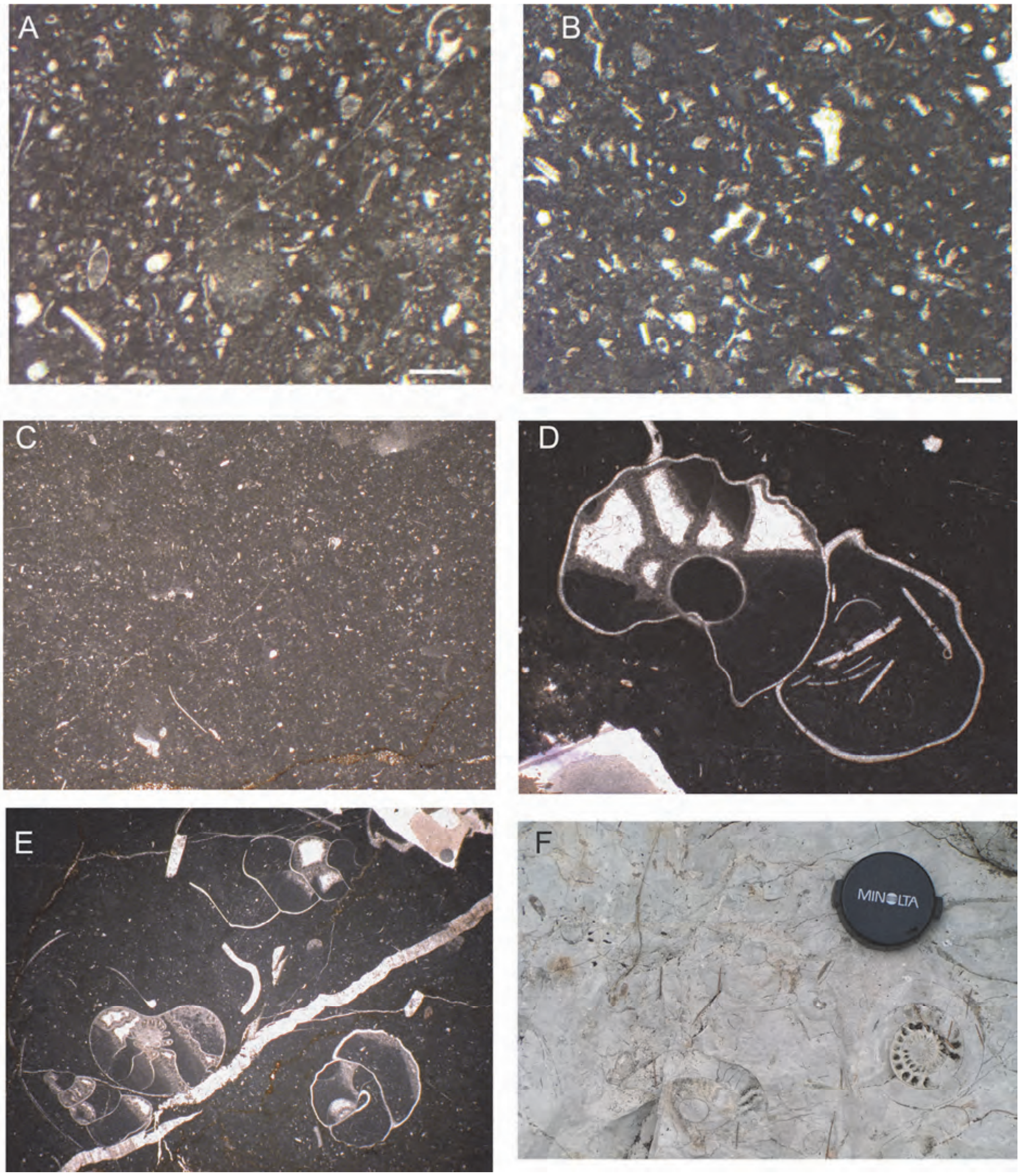

Fig. 16. A) and B) Bioclastic Wackestone with predominantly echinoderms and shell fragments (Norian, sample STK A/105, scale bar: 100 µm; GARDIN et al., 2012); C) Profil Bioclastic wackestone with predominantly sponge spicules and radiolarians (Rhaetian, sample STK B/12E, magnification x 5); D) Bioclastic wackestone with cross section through geopetaly filled Ammonoid (Metasiberites, approximately one centimetre) with geopetal filling (Latest Norian, sample STKC/11); E) Wackestone withsilicious sponge spicule and cephalopods (trochospiral Paracolocheras approximately one centimeter - Megaphyllites rich in geopetal structures (Earliest Rhaetian, sample STKC/12); F) Bioclastic rich rock surface with multiple cephalopods cross-sections (Bed STKB/10, scale 5 cm).

Concerning the ammonoids, *Metasibirites spinescens* is very common in beds 107 and 108 of STK-A and in 9 to 11 of STK-C, *Paracochloceras* (Fig. 16E) starts in bed 111 resp. 12C and is frequently found up to bed 113 with rare occurrences till the top (bed 122) in STK-A, and further up in STK-B/C till bed 22. Other *trachyostracean* ammonoids are currently rare except for rare juvenile nodose sagenitids (110 and STK-B 11), *Dionites* (beds 109 and 110) and a tiny specimen of *Gabboceras* from bed STK-B10 corresponding to bed 109. The genus *Dionites* may have a range across the Norian-Rhaetian boundary and as such may not be boundary-diagnostic. More important is the correlative presence in bed 111 of *Sagenites reticulatus* and *Dionites caesar*. Combining all above cited faunal records permits the discrimination of two ammonoid zones (Fig. 14), a lower with *Metasibirites* (bed 107 to 108; Fig. 16D) and an upper with *Paracochloceras* (from bed 111A upwards). An alternative and closely matching zonal scheme with *Sagenites quinquepunctatus* below and *Sagenites reticulatus* above seems also justified from these data. A remarkable evolutionary and biostratigraphically useful change is recorded in the family *Arcestidae* with several species newly appearing closely below the Norian – Rhaetian boundary (Fig. 14). Stratigraphically indifferent taxa including *Rhabdoceras suessi, Pinacoceras metternichi, Placites, Arcestes, Cladiscites, Paracladiscites, Rhacophyllites* and *Megaphyllites* are represented in all beds.

Monotids of the *Monotis salinaria* group are common in Steinbergkogel (KITTL, 1912; SPENGLER, 1919: 359) and almost restricted to the *Hangendrotkalk* Member where they appear in several layers within an interval of 10-15 m (Fig. 13). Of special interest is a single unhorizoned large specimen of *M. salinaria* preserved as grey micritic limestone. According to the Steinbergkogel lithologies, this piece must have been derived from the short interval corresponding to beds 108 and 109. This supposed position would confirm the top-Sevatian occurrence of *Monotis salinaria* in the Hallstatt Limestone and, in agreement with the *Monotis* data from Hernstein, Lower Austria (MCROBERTS et al., 2008), its pre-Rhaetian disappearance.

Calcareous nannofossil assemblages at Steinbergkogel are the most abundant and diversified of the Austrian Alps up to now (GARDIN et al., 2012). The nannolith *Prinsiosphaera triassica* is frequent. The section is marked by the FO of *Crucirhabdus minutus* in bed 112 A and 12E of section STK-B/C. Small coccoliths spp. are observed just below the boundary. These are the oldest dated coccolith ever found until now. This important event is directly calibrated with the entry of ammonoid *Paracochloceras suessi* and conodont *Misikella posthernsteini*, (Fig. 15), just after the last occurrence (LO) of the ammonoids *Metasibirites* and of the bivalve *Monotis salinaria*. Further the section is marked by the FO of *Conusphaera zlambachensis* in sample 12G and the FO of *Crucirhabdus primulus* in sample 28 in sections STK-B/C. A slight increase in the abundance of *Prinsiosphaera triassica* is recorded across the Norian-Rhaetian boundary and continues higher up the section. Between the FA of *M. hernsteini* and the FAD of *M. posthernsteini* lies a prominent magnetic polarity change from a long Normal to a distinct Reversal which can be recognised in other Tethyan magnetostratigraphies. The $\delta^{13}C_{carb}$ record is well preserved but unfortunately no significant variations occur around the boundary (Fig. 14).

3.1.5. Locality 4 – Gosausee: The Dachstein margin at Gosaukamm

This text is mainly taken from MARTINDALE et al. (2013) and MARTINDALE in RICHOZ et al. (2012).

In the Late Triassic scleractinian corals and hypercalcified sponges built large, diverse reef ecosystems, the most famous of which are the Dachstein reefs of the Northern Calcareous Alps. Some of the most well-known and well-studied reef material comes from the Gosaukamm; the reef material is early Norian through early Rhaetian debris shed from a nearby reef margin that is not preserved (WURM, 1982; KRYSTYN et al., 2009). Across the Gosausee from the Gosaukamm is the Gosausee margin of the Dachsteingebirge (Dachstein Mountain; Figs. 4, 5), which is largely intact, such that one can walk from the deep-water facies in the southwest, up through a shelf edge reef (the Gosausee reef), into well-bedded lagoon facies to the northeast (Fig. 17). Reefal units (Dachsteinriffkalk) are specifically well exposed along the forest road and are well constrained biostratigraphically; at the base of the

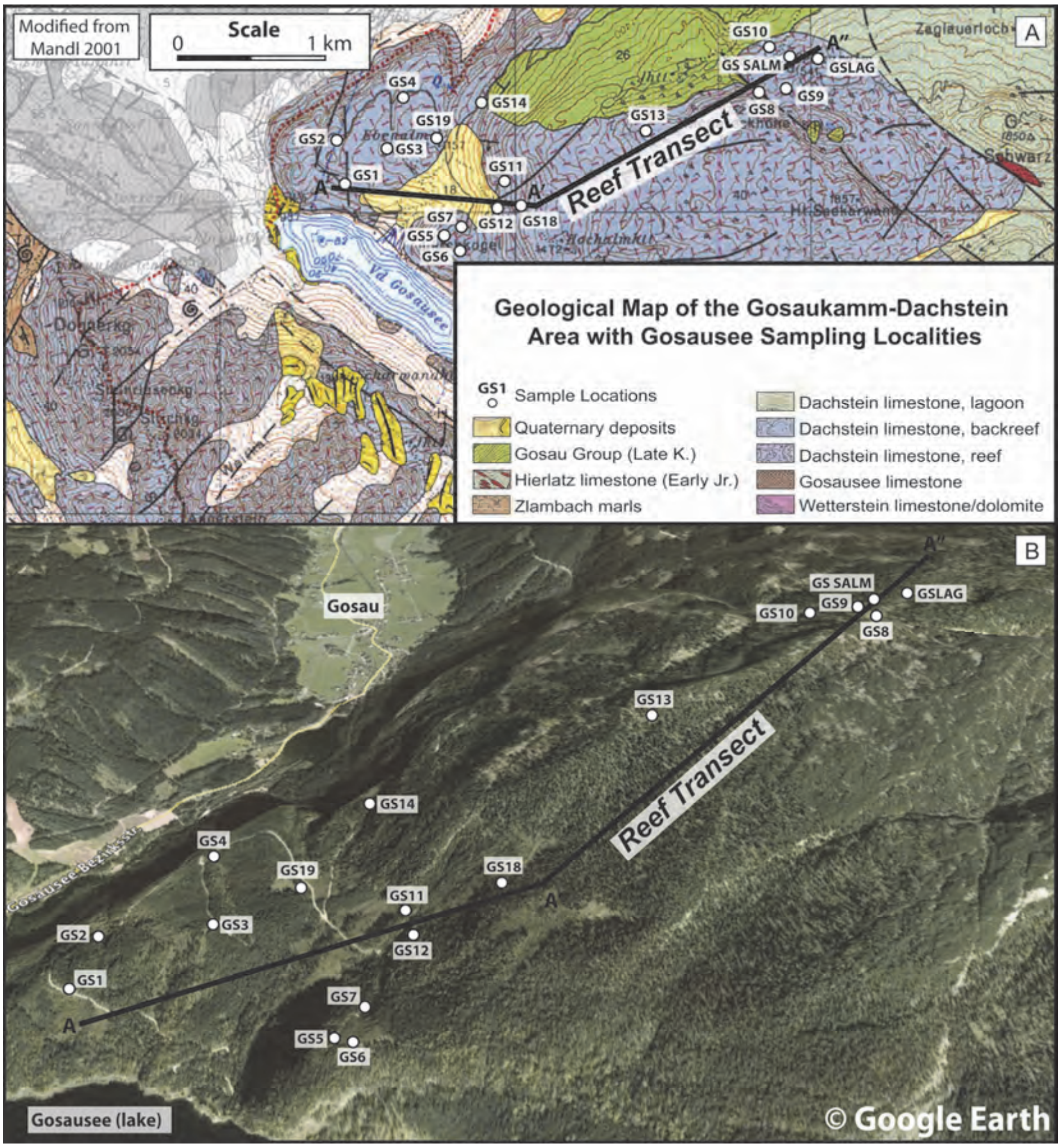

Fig. 17. The Gosausee margin of the Dachsteingebirge and sample localities from MARTINDALE et al., 2013 (transect A-A'-A" refers to reef cross section); A) Geological map of the Gosausee region, (modified from MANDL, 2001), with sample localities; B) Google Earth image of the Gosausee margin of the Dachsteingebirge, forest road visible. We will stop at GS1 and GS19.

Dachsteinriffkalk (approximately site GS1, Fig. 17), early Rhaetian conodonts, *Misikella hernsteini* and *Epigondolella bidentata* (=*Parvigondolella andrusovi sensu* KOZUR) have been identified, with additional early Rhaetian index fossils (*Norigondolelella steinbergensis, Misikella hernsteini, M. posthernsteini, Epigondolella mosheri, E. bidentata,* and *Oncodelella paucidentata*) from higher in the succession (Gosausee reef = *PI 4* unit of the Gosaukamm (KRYSTYN et al., 2009)). Reef growth continued through the early Rhaetian until the platform margin drowned in the middle Rhaetian (well before the Triassic-Jurassic boundary) and was covered by the pelagic Donnerkogel limestone (Donnerkogelkalk).

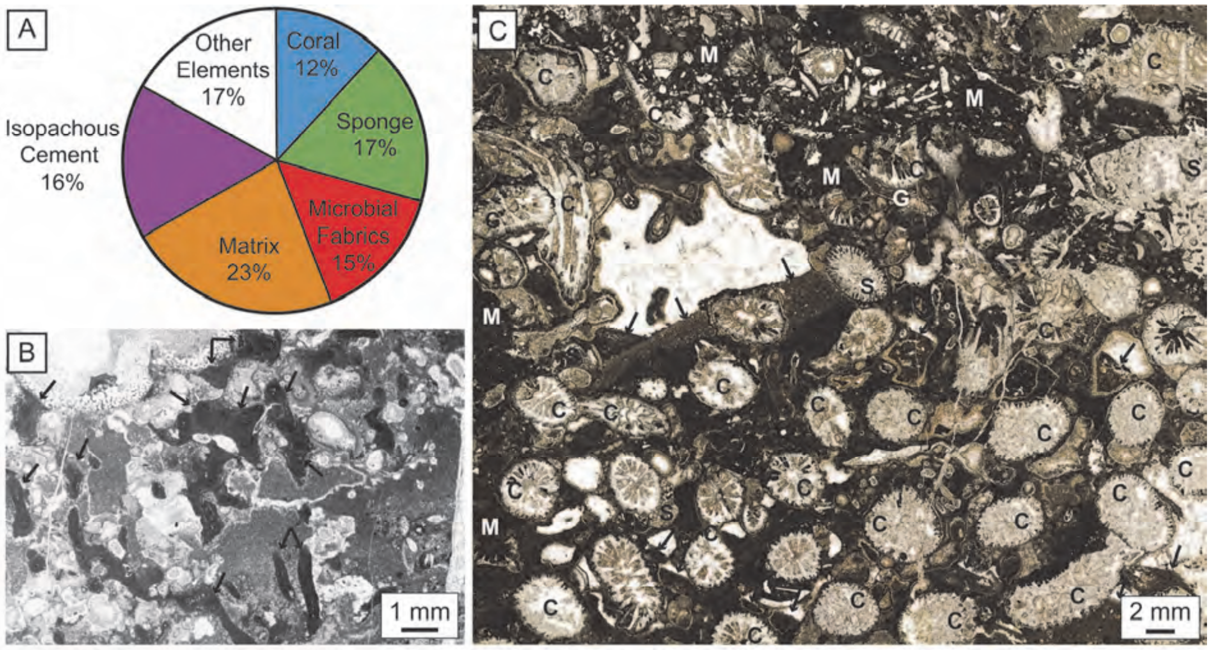

Fig. 18. The Gosausee fore reef facies from MARTINDALE et al. (2013). A) Fore reef facies composition based on mean values from point counting data (GS1, GS2, GS3, and GS4); B) "*Tubiphytes*" epibionts (best examples indicated by arrows), sample from site GS1, thin section photomicrograph (plane polarised light); C) Coral pillarstone and skeletal rudstone; note the abundance of the muddy skeletal wackestone matrix (marked with an M) and the multiple generations of geopetal sediment (arrows) and absence of thick microbialite fabrics (although there is a fine microbial crust in the largest cavity). Main phaceloid coral is *Retiophyllia gracilis* (some of the less well preserved corals are marked with a C), also present are spongiomorphids and chaetetid sponges (S), dasycladacean green algae (G) of the genus *Gryphoporella*, foraminifera (*Diplotremina* and *Endotriadella wirzi*), echinoderm fragments, and thin marine cements, sample from site GS1, thin section photomicrograph (plane polarised light).

The Gosausee reef is an intact microbial-sponge-coral barrier reef with an almost continuous fore reef to lagoon transect preserved, and thus provides a window into depth zonation of Dachstein-type reef facies and biotic succession. The Gosausee reef facies exhibit strong depth control and five classic reef facies or zones can be identified (MARTINDALE et al., 2013): the fore reef (Fig. 18), reef front, reef crest, back reef, and lagoon facies. Thin, rare microbial fabrics and a high abundance of fine-grained, mud-rich skeletal wackestones (transported reef debris) characterise the deepest fore reef (Fig. 19), particularly site GS1 (47°32.121' N / 13° 30.044' E, 1006 m above sea level) where we will stop (Fig. 17). As the reef shallows, muddy sediments decrease in abundance and are replaced by microbial fabrics, corals, and cements (Fig. 20). GS19 (47°32.206′ N / 13° 30.629′ E, 1157 m elevation, Fig. 17) is characterised by microbially bound coral pillarstones, brecciated and cemented skeletal rudstones, and coral sponge grainstones. Microbialite fabrics and corals (phaceloid,

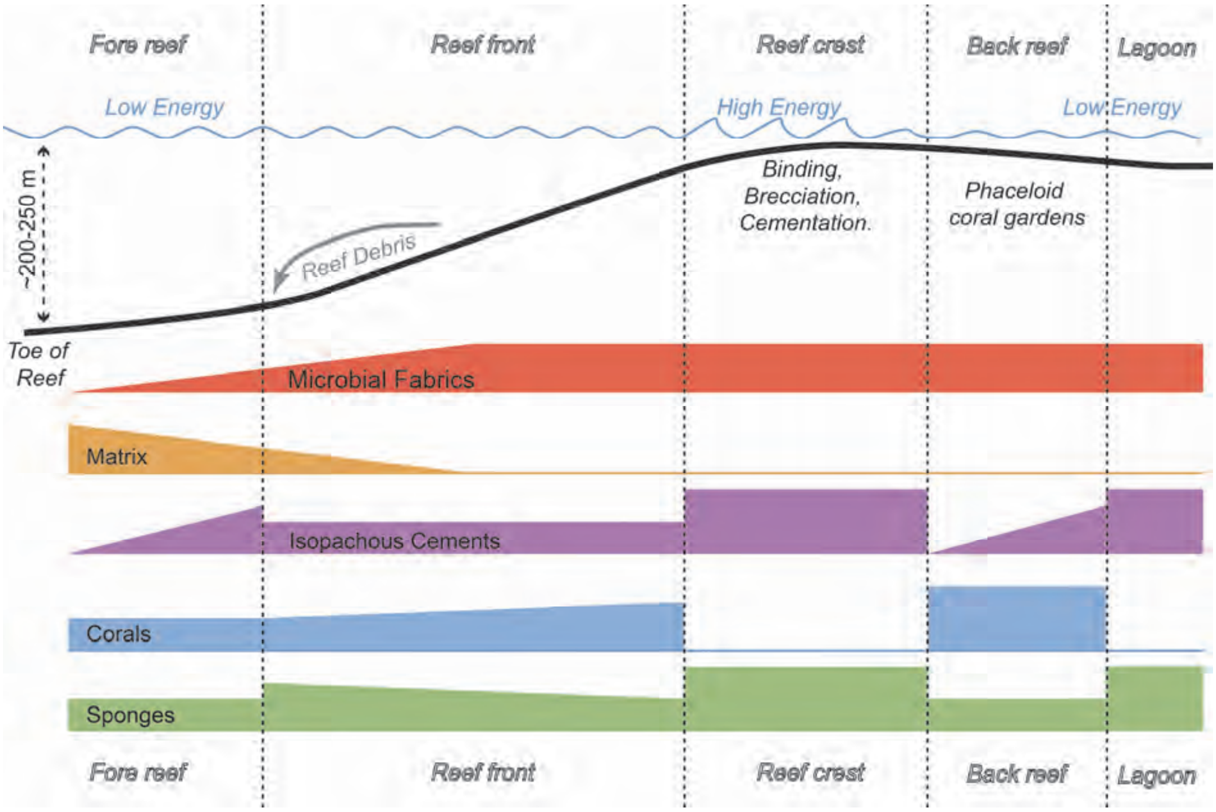

Fig. 19. Idealised transect of the Gosausee reef showing the trends in microfacies composition in different reef facies; fore reef = GS1–4; reef front = GS5–7, GS11–12, GS14, & GS18–19; reef crest = GS8 & GS13; back reef = GS9–10 & GS SALM; lagoon = GSLAG. From Martindale et al. (2013).

thamnasterioid, and meandroid) are the two most volumetrically important components with contributions from sponges (encrusting and columnar) and rare gastropods, brachiopod and bivalve shells, echinoderm fragments, foraminifera, green algae, red algae, serpulid worm tubes, encrusting brachiopods, Microtubus, “Tubiphytes”, ostracods, bored sponges, intraclasts, and skeletal debris. The samples from this site seem compositionally and texturally more similar to samples from sites higher in the reef (e.g. GS12) than their nearest neighbors; it is probable that the carbonates from this site originated higher in the reef and were transported (either by synsedimentary transport of reef blocks, or by later tectonic movement). Abundant sponges, microbial crusts, and thick, marine cements typify the reef crest (near the Modereckhöhe and the fault scarp below it, GS8 and GS13 in Fig. 17), whereas microbialite-coated phaceloid corals are dominant in the back reef facies (between the fault scarp and the Seekaralm, GS9 and GS10 in Fig. 17), which grades into heavily cemented oncoids or microbial-sponge bindstones of the lagoon (to the northeast of the Seekaralm (Figs. 17, 19). Based on their compositional, biotic, and diagenetic similarities, the Gosausee reef was likely part of the same barrier reef systems as the source reef for the Gosaukamm reef breccia (Martindale et al., 2013). The highly resolved reef zones of the Gosausee margin can be used to interpret the depth or reef zone of less well preserved reef fragments and suggest the need to revisit previous assumptions about reef depth or zone based purely on abundance of corals, sponges, or microbialite fabrics (Martindale et al., 2013). For example, the mere presence of sponge-dominated versus coral-dominated facies cannot be used to determine depth in these reefs, instead, the abundance of microbialites and cements versus muddy sediments is a much better indicator of relative depth within the reef.

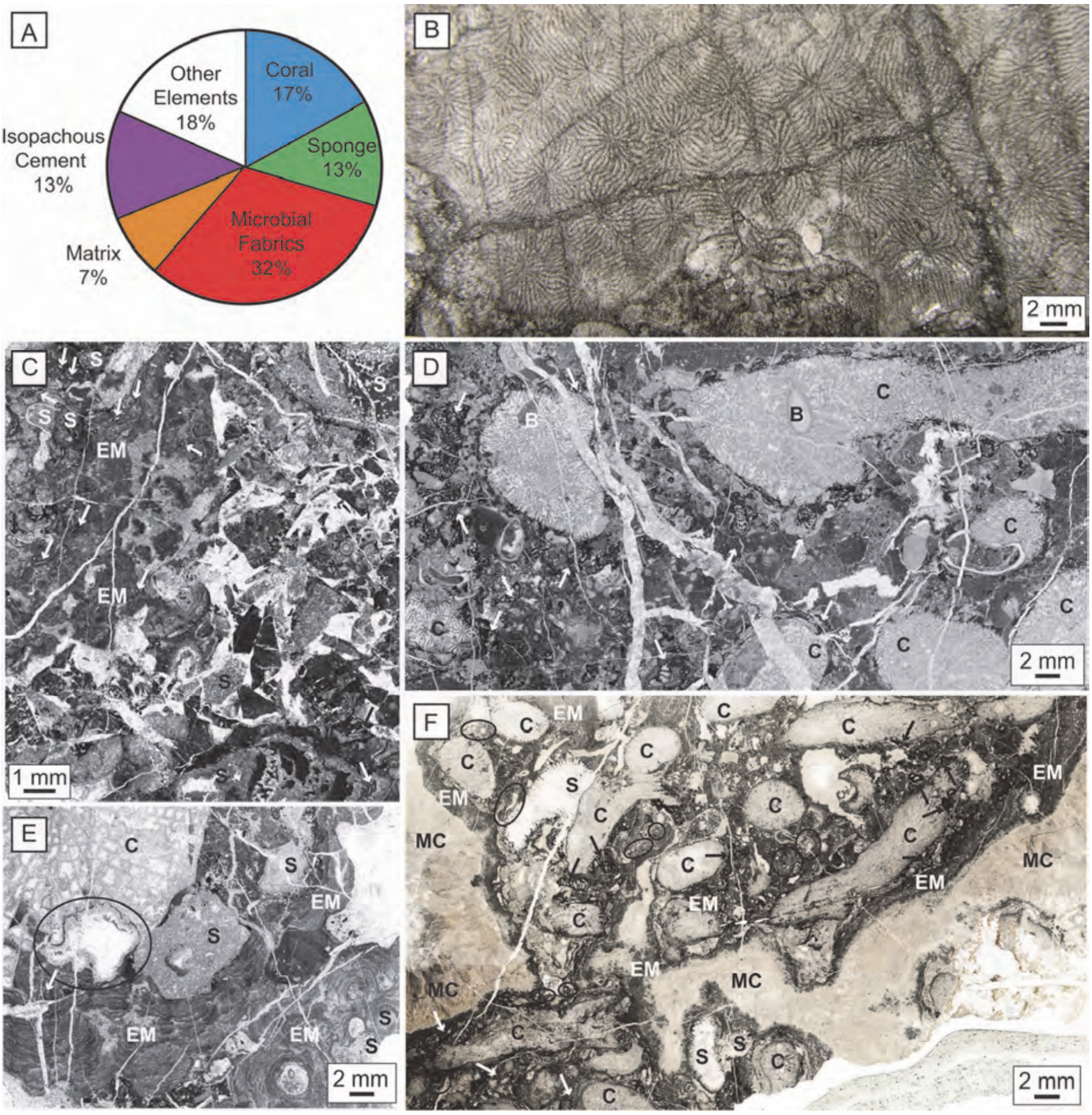

Fig. 20. The Gosausee reef front facies. A) Reef front facies composition based on mean values from point counting data (GS5, GS6, GS7, GS11, GS12, GS14, GS18, and GS19); B) Unnamed thamnasterioid coral (Genus 1) from site GS19; C) Brecciated microbial-sponge bindstone; many different sponges (S) occur in this sample, note the well-developed succession of epibionts in the top left corner, including sponges, encrusting sponges (*Uvanella* or *Celyphia*, black arrows), encrusting microbialite fabrics or algal crusts (EM), and *Microtubus* (white arrows). Sample from GS5, top of image is stratigraphic up, thin section photomicrograph (plane polarised light); D) Rudstone of a coral pillarstone, *Astraeomorpha* cf. *A. confusa* corals (C) are encrusted by *Alpinophragmium perforatum* foraminifera (white arrows, also rare *Radiomura* sponges and microbial fabrics), bored by lithophaginid bivalves (B), and then deposited in a muddy wackestone matrix; sample from GS7, thin section photomicrograph (plane polarised light); E) Microbial bindstone; large solitary coral (C), and sponges (S) encrusted by thick microbialite crusts (EM) and *Microtubus* (white arrows), there are also cavities with thin isopachous cements (acicular), crystal silt, and drusy calcite (circled). Sample from GS7, thin section photomicrograph (plane polarised light); F) Microbial bindstone; sponges and *Retiophyllia* cf. *R. oppeli* corals (C) are encrusted by microbialite fabrics (EM), *Alpinophragmium perforatum* and agglutinated foraminifera (black arrows), *Radiomura* sponges (circled), and *Microtubus* (white arrows). Sample is then coated with tan-colored marine cements (MC), sample from GS11, thin section photomicrograph (plane polarised light). From MARTINDALE et al. (2013).

3.2. Lagoon, fringing reef and Eiberg Basin (Day 2)

The huge Dachstein carbonate platforms represent a fossil counterpart to the modern Bahamian carbonate system. The bedded Dachstein Limestone together with the Hauptdolomit make up the majority of the extensive carbonate plateaus of the Northern Calcareous Alps, reaching more than 1000 m in thickness. These units reflect a variety of shallow water facies (ooids ridges, oolithic facies, grapestone facies, foraminifera and algal facies, mud facies, pellet mud facies changing laterally into muddy tidal flats with the typical "loferites" and supratidal areas with lateritic palaeosols. The frequently regular vertical arrangement of these deposits led to the formation of the well- known "Lofer cyclothem" (FISCHER, 1964).
The Dachstein carbonate platform also contains shelf-edge reefs and reef material, which are some of the oldest reefs to be built by scleractinian corals. The drowning history of Rhaetian coral builds-up is superimposed by the end-Triassic mass extinction and makes the story in the Austrian Alps thrilling.
The mixed carbonate-terrigenous intrashelf Eiberg basin allows for a comparison with the age-equivalent off-shore homogeneous carbonatic and terrigenous facies of the Hallstatt and Zlambach Facies

3.2.1. Route

From Abtenau we take the road to Golling an der Salzach along state road 162, from there 4 km to the south and stop at Pass Lueg on state road 159. Then we go back to the north along motorway A 10 in direction of Salzburg, take then exit Hallein to and through the village of Adnet and up to the quarries. We drive then further through Berchtesgaden (Germany) to the Steinplatte. As we have no time to visit Steinplatte itself we will stop along state road 178 to have a nice panoramic view on the reef margin. We move then further west on state road 173 to the Eiberg Quarry near Kufstein and through motorway A 12 and state road 181 to Achenkirch for overnight.

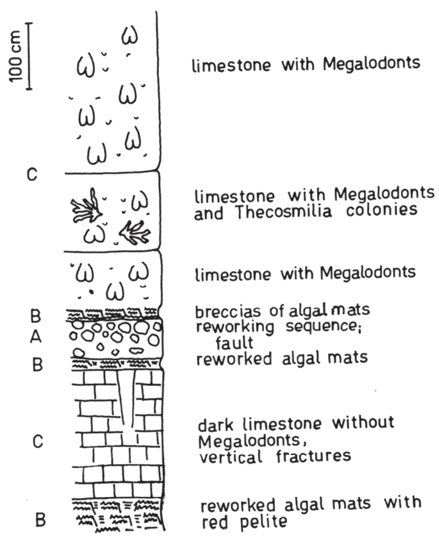

Fig. 21. Lofer Cyclothem at Pass Lueg (from FLÜGEL et al., 1975).

3.2.2. Locality 5 – Pass Lueg: The classical Lofer cycle

In the central and eastern Northern Calcareous Alps, the cyclic, meter-sized bedding of the Dachstein Limestone is a characteristic morphological feature, well visible along the steep slopes as well as on the top of the large plateau mountain ranges. Meter-scale cycles were recognised as early as 1936 by SANDER. FISCHER (1964) gave a description of this phenomenon, which remains a classic even now. Based on sequences from the plateaus of the Dachstein and the Loferer Steinberge, Fischer termed these units "Lofer cycles". The cycles are interbedding of lagoonal limestones, thin layers of variegated argillaceous material, thin layers of intertidal to supratidal laminated or fenestral dolomites and dolomitic limestones (Fig. 21). The main sediment is a light-coloured limestone (layer C, thickness up to some meters), containing oncoids, dasycladacean and codiacean algae, foraminifera, bryozoan, gastropoda, large megalodontids and other bivalves. The weathered and solution-riddled surface of this limestone is overlain and/or penetrated by reddish or greenish argillaceous limestone (layer A), which may include limestone clasts and which are interpreted as former terrestrial soils. Layer A is commonly not developed as a distinct bed, because of its erosional origin; however, remnants of A are abundant infillings in veins, cavities, and biomoldic pores (gastropod and megalodontid shells). Layer B consists of intertidal carbonates of a variety of rock types like "loferites" or birds-eye limestone of laminated or massive type, non-loferitic mudstone and intraclasts. The flat or crinkled lamination is interpreted as filamentous algal mats, also characteristic of modern tidal flats. Fenestral pores and mud cracks seem to be the result of shrinkage of unconsolidated sediment due to desiccation. All types of layer B are more or less dolomitic, some of them formed as contemporaneous brittle surface crusts, as shown by intraclasts, demonstrating the intertidal/supratidal setting. FISCHER (1964) explains the formation of the cyclothems by periodic fluctuations of the sea-level which is superimposed on the general subsidence. An amplitude of up to 15 m and 20,000 to 100,000 years is assumed for one cycle. Because this model does not explain the gradual lateral transition into the Hauptdolomit Formation and the lateral wedging of intertidal and supratidal sediments within short distance, ZANKL (1971) proposed an alternative model: Current activity and sediment producing and binding algae created mud mounds and tidal mud flats. Subsidence and eustatic sea-level fluctuations of centimetre amplitudes and periods of several hundred years may have modified growth pattern and shape of the tidal flats by erosion and transgression. FISCHER (1964) interpreted the ideal Lofer cycle: disconformity, A, B, C as an upward-deepening facies trend. HAAS (1994) proposed a symmetrical ideal cycle, whereas GOLDHAMMER et al. (1990) and SATTERLEY (1994) proposed a shallowing upward interpretation. ENOS & SAMANKASSOU (1998) pointed to the lack of evidence for subaerial exposure and interpreted it as rhythmic cycle with allocyclicity as the predominant control. HAAS et al. (2007, 2009) and HAAS (2008) however provided several evidences for subaerial exposure and related karstification. HAAS et al. (2010) pointed a differential development of the Lofer Cycle on the Dachstein Range between internal area and sections situated near the margin of the platform. The cycles shown by HAAS et al. (2010) can be summarised:

The disconformity displays erosion features and karstification in both internal and marginal areas.

- Facies A is reddish or greenish, argillaceous, 1mm to 10cm thick. It is a mix of storm redeposited carbonate mud, air transported carbonate and argillite, blackened intraclast and consolidated sediment. It is thicker with pedogenese trace in marginal sea than in internal area.
- Facies B (stromatolites, loferites) is usually present in the internal part of the range, but absent in the marginal area.
- Facies C is a peloidal bioclastic wackestone in the platform area, whereas in the reef-near zone it is an oncoidal packstone or grainstone.

The differences can be explained by the setting. The marginal zone, near the offshore edge developed oncoid shoals, whereas stromatolites develop preferentially on the slightly deeper platform interior, protected by the shoals. The sea-level drop affected both areas, but the longer shoals allowed for the development of palaeosols in the marginal part. This model reinforces the shallowing-upward trend of FISCHER (1964).

At Pass Lueg itself, a “Lofer Cyclothem” with partly reworked stromatolite, brecciated layers and bioclastic limestones rich in megalodontids, corals and echinoderm (FLÜGEL et al., 1975) is exposed (Fig. 21). Several species of *Megalus, Parmegalus, Conchodus* have been described from levels usually rich in individuals but poor in species (FLÜGEL et al., 1975).

3.2.3. Locality 6 – Adnet

The quarries of Adnet, located in the north-western Osterhorn Block, south-east of the city of Salzburg (Figs. 1, 22) expose upper Rhaetian to Lower Jurassic limestones, deposited at the southern rim of the Eiberg Basin (Fig. 5). They clearly display the succession from the Late Triassic reef-dominated carbonate factory (Stops 6.1 and 6.2) to the aphotic deep-water hemipelagic sedimentation of the Jurassic (Stops 6.2 and 6.3). If both Adnet and Steinplatte have been described as typical warm-water photic-zone reefs (e.g. STANTON & FLÜGEL, 1989, 1995; BERNECKER, 2005), STANTON (2006) proposed rather nutrient rich water favourable to heterotrophic corals. Intermediate reef drowning stages of the Hettangian are nicely exposed in the lower slope sections (Stop 6.3). The Adnet quarries have been the topic of palaeontological, sedimentological, stratigraphic, geochemical, mineralogical, palaeomagnetic, and geotechnical studies for more than 150 years (see KIESLINGER, 1964; BERNECKER et al., 1999; BÖHM et al., 1999; BÖHM, 2003; BERNECKER, 2005; REINHOLD & KAUFMANN, 2010). Nevertheless there are still considerable unknowns in the Rhaetian-Liassic sedimentary history of the area. The continuing quarrying activities create 3-dimensional views and expose new sedimentary structures every few years, but also threaten to destroy older outcrops.

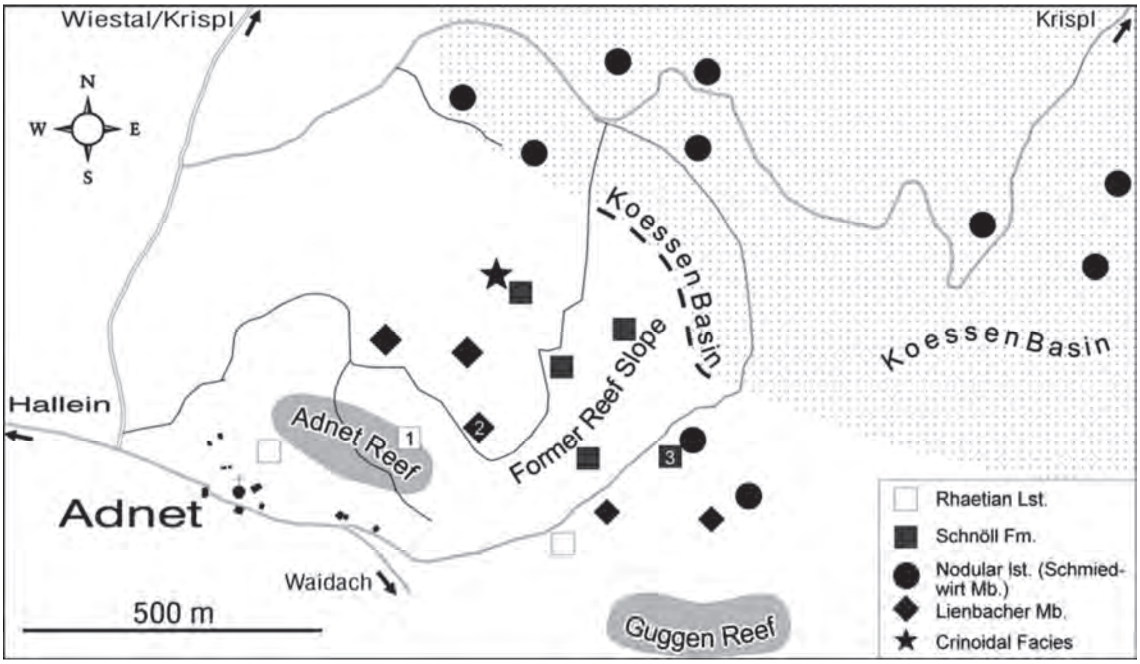

Fig. 22. Detail map of the Adnet quarries with facies distribution (from KRYSTYN et al., 2005 after BÖHM, 1992).

Outcrop 6.1 – Tropf Quarry

The Tropf quarry 47°41.7819' N / 13°08.2109' E, Fig. 22) is the most famous of the Adnet quarries, as it exposes a 3 dimensional view of a Rhaetian coral reef with metre-sized coral colonies, analogue to the late Rhaetian Steinplatte Limestone. Its facies and palaeontology were studied in detail by SCHÄFER (1979) and BERNECKER et al. (1999). Unfortunately, during the past years the most spectacular walls became unsightly or were removed by quarrying. The big branching coral colonies dominating most walls (Figs. 23, 24, 25) belong to the

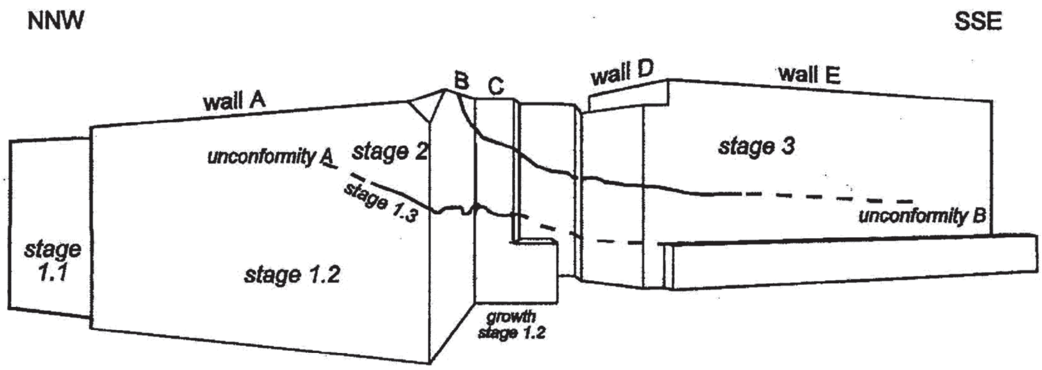

Fig. 23. Sketch of the Tropf Quarry walls as seen during the early 1990s, indicating the reef growth stages and erosional unconformities (from BERNECKER et al., 1999).

genus *Retiophyllia* (formerly called "*Thecosmilia*"). Two varieties can be distinguished by their size (A: big, B: small). Other reef builders are less common: massive and platy corals (*Pamiroseris, Astraeomorpha, Gablonzeria*), sclerosponges (mainly sphinctozoans), and "hydrozoans". Dasycladacean algae (*Diplopora adnetensis*) occur as sand-sized bioclasts and provide evidence for a shallow-water depositional setting. In the upper part of the walls a sediment layer without corals can be seen (Stage 3 in Figs. 23, 24). Megalodont bivalves are common in this layer. At the very top of the outcrop coral colonies occur again, although less frequently (Fig. 24). Possibly correlative sediments of Stage 3, exposed in the Lienbacher Quarry (Stop 6.2), continue up to the Triassic-Jurassic boundary.

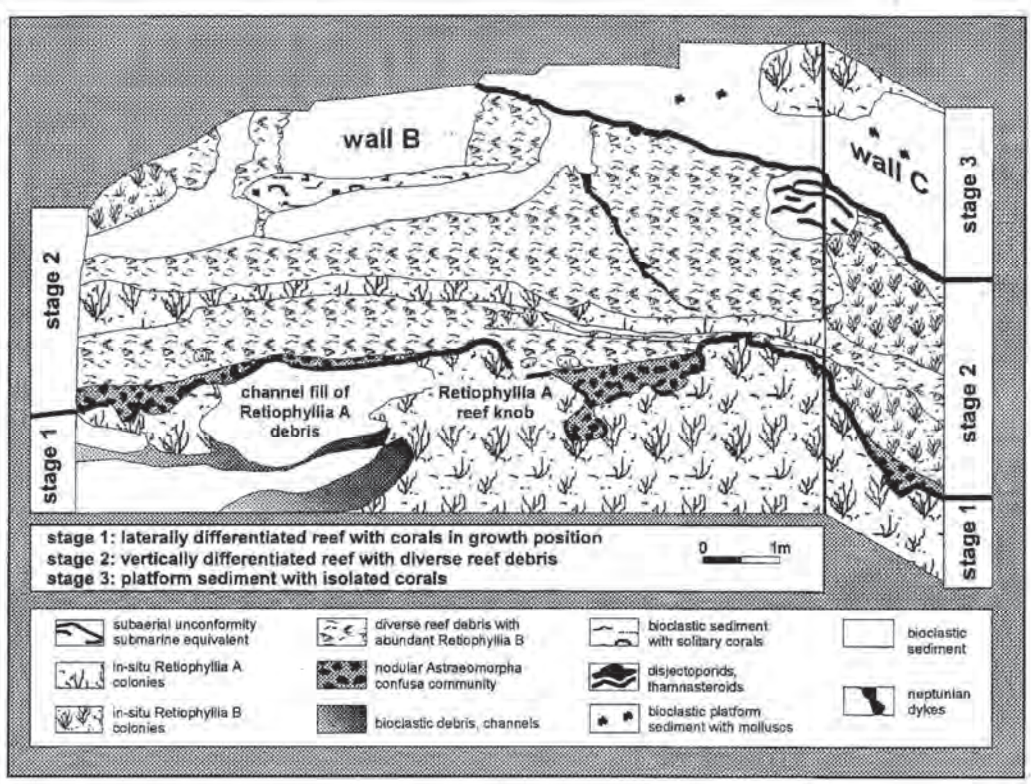

Fig. 24. Detailed facies distribution on walls B and C (Fig. 23) and positions of unconformities A and B. Note pronounced relief unconformity A (up to 4 m), Unconformity B is less pronounced (from BERNECKER et al., 1999). Notice that the capping beds of Steinplatte, locality 7, correspond to the stage 1 to 3 here and the coral garden to stage 2.

Fig. 25. Transect from growth stage 1 to stage 2 at the Tropf quarry. Small arrow point to the distinct disconformity surface between the "Large *Retiophyllia* A community" and the thiner *Retiophyllia* B colonies. Wall B, width 1.70 m, height 2.50 m (from BERNECKER et al., 1999).

BERNECKER et al. (1999) found two unconformities with distinct relief cutting through the reef and showing signs of erosion and karstification (Figs. 24, 26). A third unconformity marks the Triassic-Jurassic boundary, which is exposed in the Lienbacher Quarry (Stop 6.2). The coral reef of the Tropf Quarry probably formed at the lower slope, similar to the Capping Beds of the Steinplatte. These lowstand reefs formed after an initial sea-level drop earlier in the late Rhaetian, when the higher parts of the platform south of the Eiberg Basin became exposed and reef building had to move slope-downwards.

Outcrop 6.2 – Lienbacher Quarry

The Lienbacher Quarry (47°41.8202'N / 13°8.2572'E, Fig. 22), about 100 m northeast of the Tropf Quarry, exposes "Stage 3 Rhaetian reef" limestones (NW part of the quarry), which are overlain by a thin blanket of upper Hettangian yellow-red Enzesfeld limestone and the Sinemurian Adnet Formation (Lienbacher Member). The Rhaetian and Triassic-Jurassic boundary were described by BERNECKER et al. (1999), the Liassic by BÖHM et al. (1999) and DELECAT (2005). During the Triassic and Liassic this site was positioned downslope of the Tropf Quarry. The depositional slope was dipping by about 10°–15° to the northeast during the Sinemurian (and likely also during the Rhaetian) as indicated by geopetal infills. The

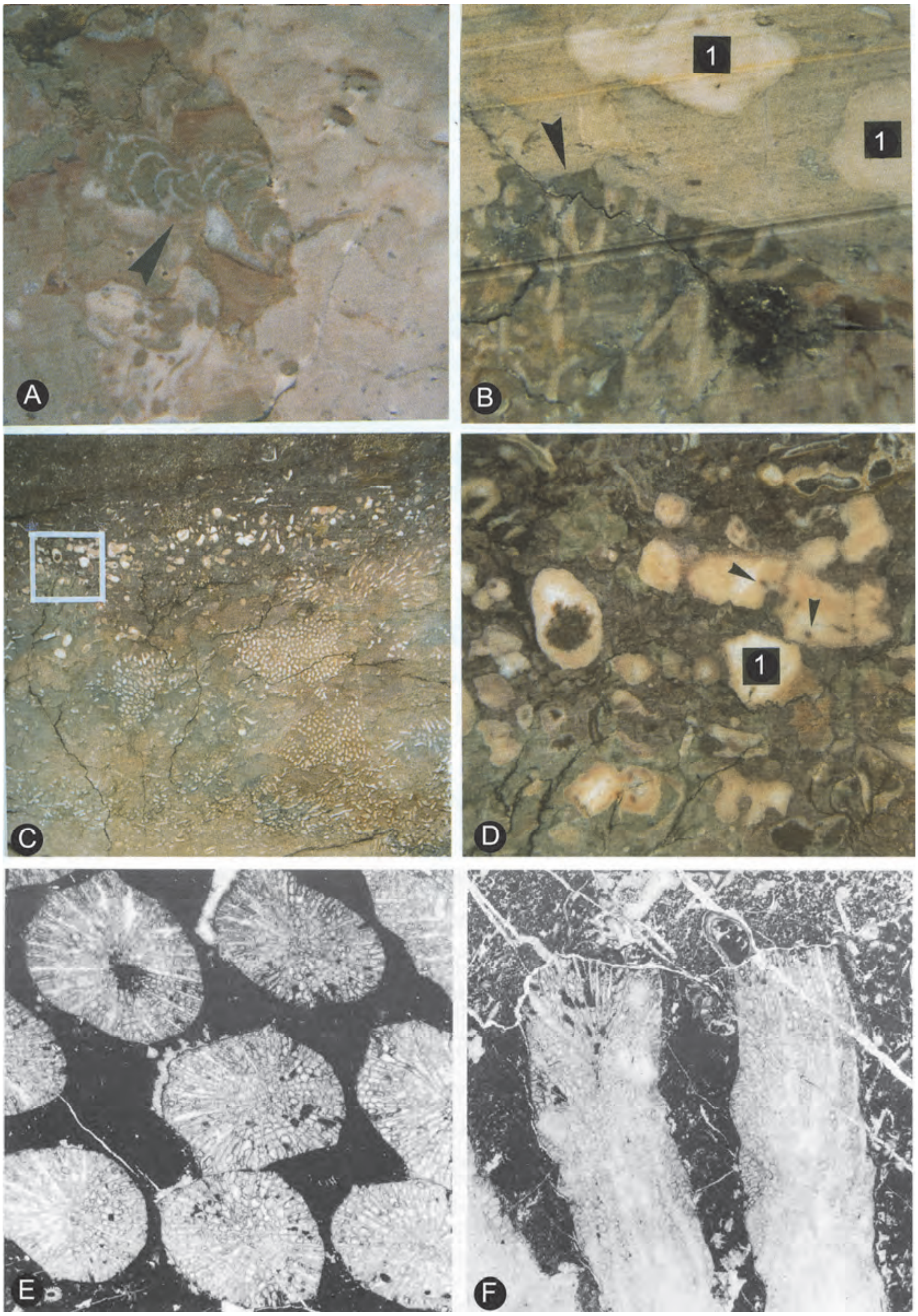

Fig. 26. A) Surface of the unconformity: Hardground encrusted by the sphinctozoid sponge *Cinnabaria? adnetensis* (arrow). x 0.9; B) Unconformity B separating growth stage 2 (bottom) and 3 (top). The arrow points the irregular surface. Note the large nodular *Astraeomorpha* colonies (1). Wall E, x 0.9; C) Unconformity A separating growth stage 1 (bottom) and 2 with the nodular *Astraeomorpha* colonies, x 0,1; D) Close-up of C), with *Astraeomorpha confusa* (1) showing evidence of bioerosion (arrow) x 0,6; E) *Retiophillya clathrata*. Cross section of a high-growing branching colony x 2.5; F) *Retiophillya clathrata*. Longitudinal section x 2.5. (All photos from Bernecker et al., 1999).

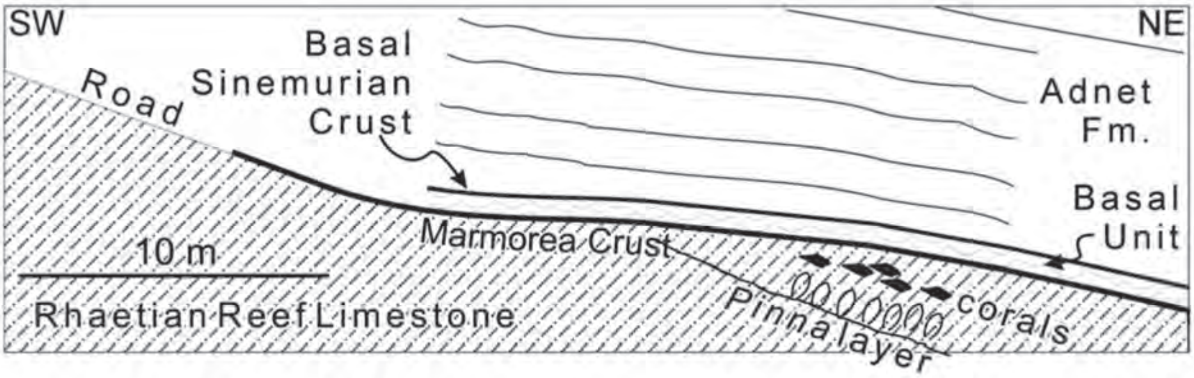

Fig. 27. Slightly exaggerated sketch of the depositional small-scale relief as exposed in the NW part of Lienbacher Quarry. The upper Hettangian Marmorea Crust covering the underlying massive Rhaetian reefal limestone is shown as a thick line. It forms the pavement of the road at left. It is overlain by the Adnet Formation (Lienbacher Mb.) with only 20 cm of stromatolites of the Basal Unit and the Basal Sinemurian Crust, followed by medium-bedded limestones. The original relief was restored by tilting the section 10° to the right, according to the mean inclination of geopetal infills. Fossils fragments in the Rhaetian limestone indicate depositional surfaces dipping steeply to the NE (from KRYSTYN et al., 2005 after BÖHM, 1992).

depositional slope is confirmed by the asymmetric growth of deep-water stromatolite domes visible on SW-NE trending walls (SE part of the quarry). On NW-SE trending walls the domes show symmetric growth forms (BÖHM & BRACHERT, 1993; BÖHM et al., 1999). The 100m distance from Tropf Quarry and the 15° slope combine to a vertical relief of about 25 m between the quarries. On the outcrop scale, the Rhaetian top surface (Triassic-Jurassic boundary) shows a slightly wavy relief with a mound-like structure forming a small terrace in the NW quarry corner (Fig. 27). The fine-scale rugged relief of the surface has been interpreted as small-scale karstification (BERNECKER et al., 1999) and REINHOLD & KAUFMANN (2010) indicating subaerial exposure at the Triassic-Jurassic boundary. Platy and massive corals (mostly *Pamiroseris*) are present in the Rhaetian limestones, but have too low coverage to form reef build-ups. Besides few in situ colonies bioclastic accumulations can be interpreted as storm layers (BERNECKER et al., 1999). The Rhaetian karst surface is overlain by 0-10 cm of yellow-red Fe-oxide rich crinoidal limestones (Enzesfeld Limestone with crinoids, brachiopods, ammonites, foraminifers, ostracods and Schizosphaerella; late Hettangian) forming the ferromanganese Marmorea Crust (with late Hettangian ammonite fauna). The upper Hettangian limestone also fills up neptunian dykes that penetrate into the Triassic. Red limestones of the Adnet Formation following disconformably above the Marmorea Crust belong to the late Sinemurian *obtusum* Zone.

Outcrop 6.3 – Rotgrau-Schnöll Quarry

The RGS Quarry (47°41.8029'N / 13°8.5872'E, Fig. 22) is positioned near the toe of the slope, just up slope from the transition of the Rhaetian limestone facies to the basinal Kössen facies. This quarry was studied by BLAU & GRÜN (1996), BÖHM et al. (1999) and DELECAT (2005). It is the type locality of the peculiar Hettangian Schnöll Formation, which represents the recovery of sedimentation on the lower slope after the hiatus of the Triassic-Jurassic boundary. The Schnöll Formation forms a wedge onlapping the slope of the Adnet reef, thinning from a maximum thickness of about 15 m in lower slope settings to a few decimetres on the higher slope (e.g. north and west of the Lienbacher Quarry; Fig. 28). Even on a smaller scale the thickness is very variable as can be seen in the RGS Quarry, where the Schnöll wedges out from a thickness of more than 5 m in the north-eastern part of the quarry to only about 1 m in the south-western part. Accordingly, the sedimentary successions differ between the two parts of the quarry. In the NE part the succession starts in the lower member of the Schnöll Formation (Langmoos Member). The base of the Langmoos is not exposed here. The exposed thickness is less than 1m of 10m in total. Sponges are very common and the occurrence of stromatactis points to early microbial diagenesis. The lowest exposed layer is rich in radiolarian (DELECAT, 2005). In the overlying Guggen Member the frequency of sponges decreases, while crinoidal debris becomes more important. Several local ferromanganese crusts occur within the Guggen Member, which is eventually capped on top by the Marmorea Crust with a rich late Hettangian ammonite fauna (e.g. DOMMERGUES et al., 1995). The succession in the SW quarry part starts with cross-bedded grey limestones (microlithoclastic packstones and grainstones) with echinoderms, bivalves, brachiopods and rare foraminifera (mostly miliolids). These submarine dunes may represent Triassic relict sediments. They form a NE dipping wedge that is onlaped by the Schnöll Formation. After correcting for tectonic tilt the inclination of the foresets is about 20° and that of the top surface about 5°, dipping to the NE. The top surface of the grey packstones is an erosional unconformity. Stable isotopes, however, give no indication that the erosion was subaerial (BÖHM et al., 1999). The packstones are strongly fractured. They are overlain by a layer exceptionally rich in siliceous sponges, with an ammonite fauna of middle Hettangian age. The layer is capped by a ferromanganese crust, partly pyritized and rich in crinoidal debris and foraminifera. "Micro-oncoids" occur (BÖHM et al., 1999). The sponge layer formed as an allochthonous accumulation (DELECAT, 2005). The sequence above the sponge layer is similar in both parts of the quarry, with thick bedded, crinoid-rich limestones of the Guggen Member, which are, however, only about 1 m thick in the SW, but more than 3 m in the NE part. They terminate in the Marmorea Crust, followed by the Basal Unit of the Adnet Formation, which has a thickness of only 0.5 m in this quarry, and is capped on top by the basal Sinemurian crust and the well-known layer of deep-water stromatolites. Above the stromatolites, the succession continues with thin-bedded nodular limestones of late Sinemurian age.

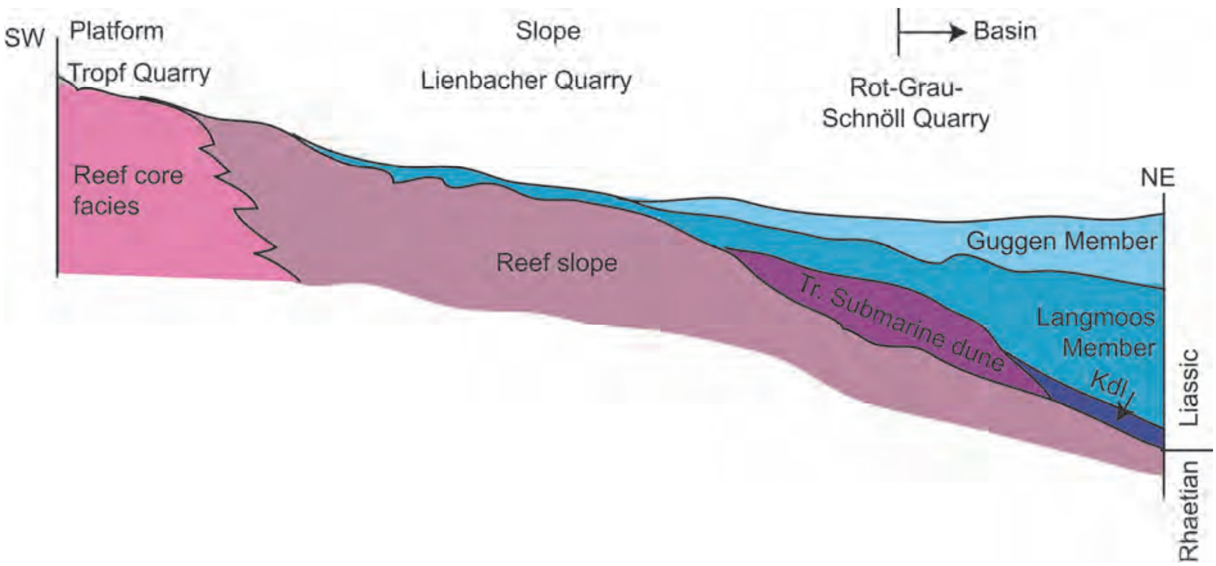

Fig. 28. Schematic distribution of the Kendelbach (Kdl.) Formation and the two members (Guggen and Langmoos) of the Schnöll Formation on the slope of the Adnet reef (modified from DELECAT, 2005).

3.2.4. Locality 7 – Steinplatte

The Steinplatte Mountain (Fig. 1), north of Waidring (Tirolic Alps) near the German-Austrian border, is located south of the Unken syncline. It forms the southern margin of the Eiberg intraplatform basin. The Steinplatte buildup consists of flat-lying platform carbonates of the Oberrhaet Limestone with a northwards inclined distally steepened ramp to finally slope margin (Fig. 5). An intact platform to basin transition allows the reconstruction of the Triassic margin architecture and a study of the onlap geometries of basal Jurassic formations (Figs. 29, 30). Oberrhaet Limestone that forms the main part of the buildup and the crest (Sonnenwände) interfingers to the NW with limestones (Kössen Formation, Eiberg Member) of the adjacent Eiberg Basin (near Kammerköhr Inn, Figs. 30, 31). Small separated mounds exposed at the base of the crest are interpreted as initial growth stages.

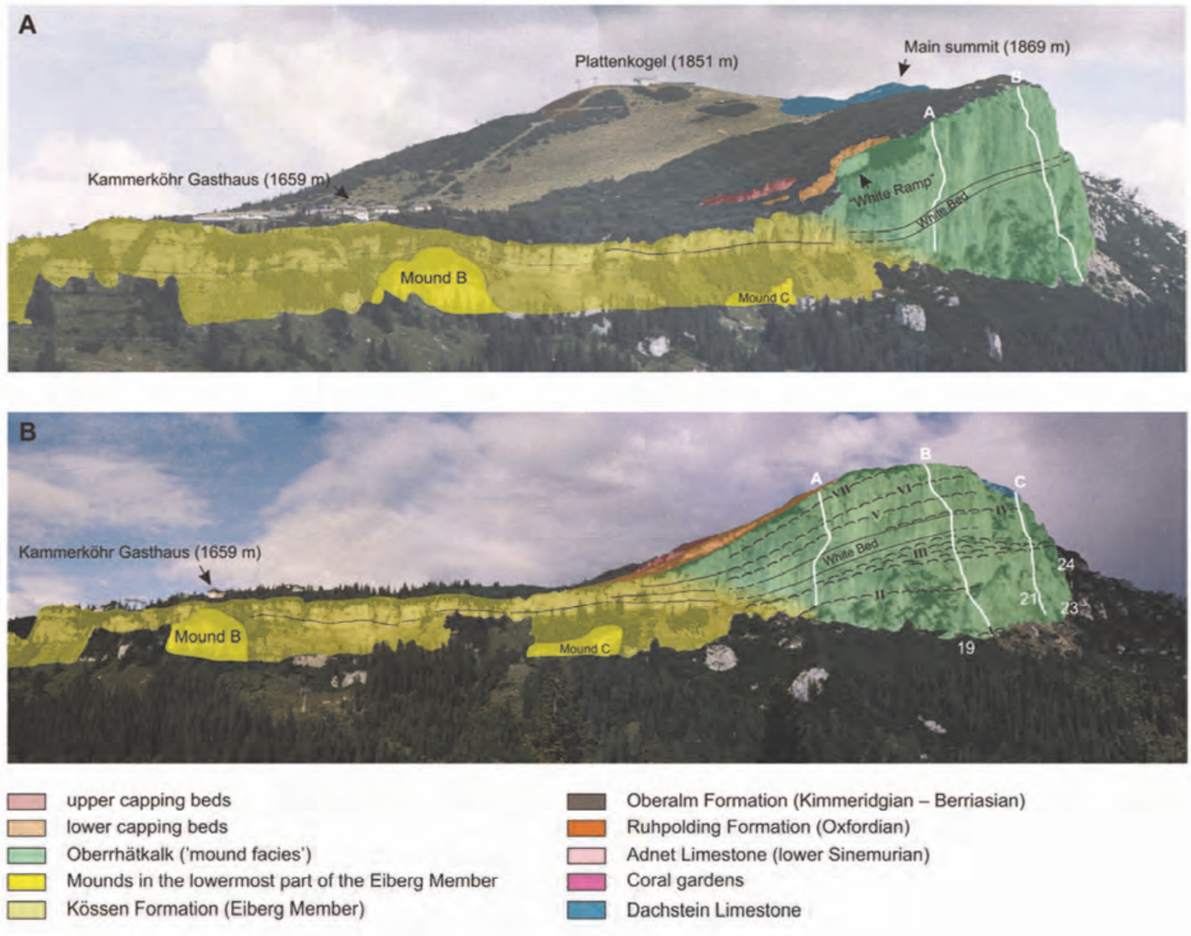

Fig. 29. The Steinplatte complex from two different perspectives. A) Looking ESE from near Brennhütte. B) Looking ENE from Grünwaldkopf. Flat-lying Kössen Beds (yellow) grade laterally into up to 36° ("White Ramp") inclined Oberrhätkalk (green). Width of outcrop is ca. 1000 m. Note overlying Dachstein Limestone (blue) in the summit area. Cliff sections (A–C), marker horizon (White Bed), shell beds (I–VII) and localities (19, 21, 23, 24) inserted from STANTON & FLÜGEL (1989), (from KAUFMANN, 2009).

East of Kammerköhr inn (Fig. 30) toe-of-slope calcarenites (bioclastic pack and grainstones rich in crinoid and bivalve debris with Rhaetian microfauna and rare brachiopods (TURNSEK et al., 1999) are exposed followed to the south by different platform carbonates respectively reef facies types (Fig. 31). The major part of the buildup is not formed by a real framework (STANTON & FLÜGEL, 1989, 1995) but mainly by fine bioclastic limestones and coral fragments. Its top is partly overgrown by large Rhaetian bushlike corals that are not intergrown (Capping Beds). The “Fischer’s Coral Garden” (Fig. 30) is an area of abundant corals which consist of a dense growth of large “*Thecosmilia”* (PILLER, 1981; STANTON & FLÜGEL, 1989). Part of the corals are still in living position, whereas two third are tilted or upside down. None has been found growing upon another, so evidence for any rigid skeletal framework is missing (STANTON & FLÜGEL, 1989). The coral heads have frequent microbial crusts, *Microtubus* and inozoan calcisponges with ostracods, miliolid foraminifera and rare nodosariids (STANTON & FLÜGEL, 1989). As in Adnet coral growth of the capping facies stopped during end-Triassic time and was covered by a still Rhaetian oncoid bearing layer with reworked Megalodont shells following the ongoing latest Rhaetian sea level drop.

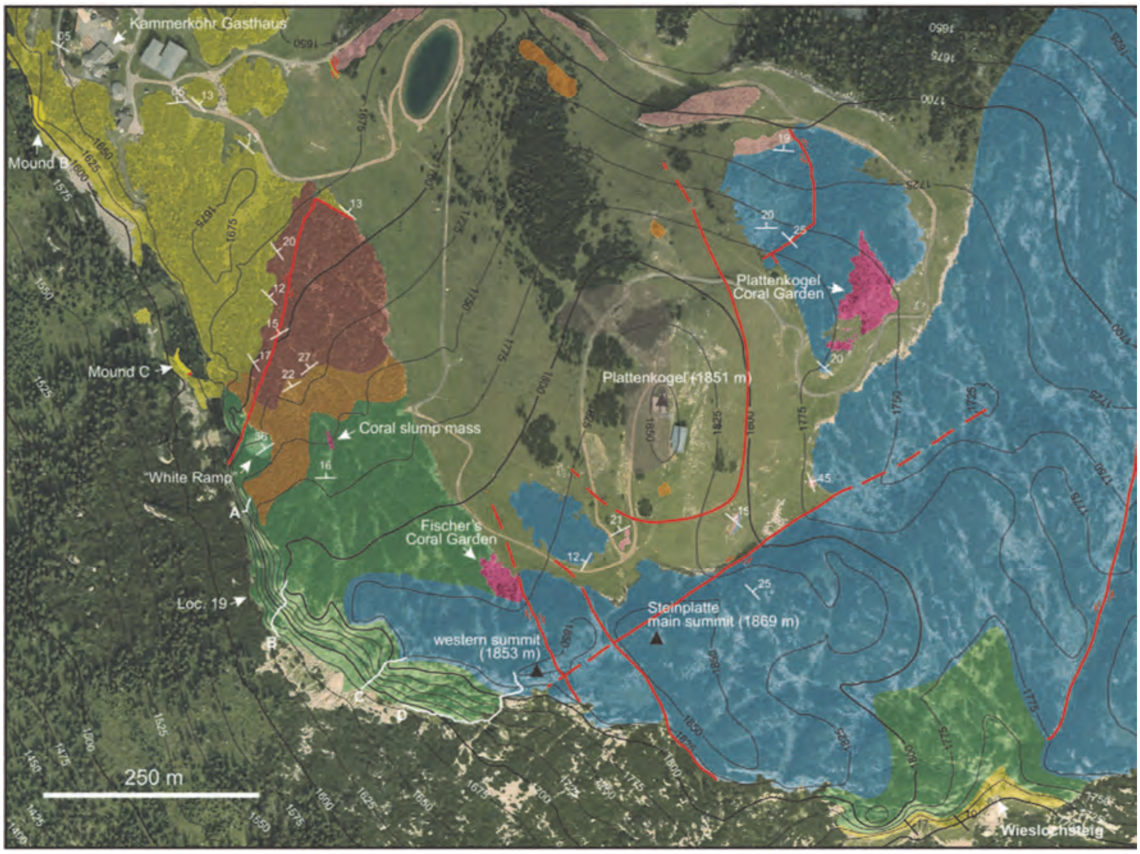

Fig. 30. Locality and geological map of the Steinplatte area. A–D = Cliff sections of STANTON & FLÜGEL (1989). Red lines = major faults. For legend see Fig. 29, (from KAUFMANN, 2009).

The palaeorelief of the carbonate platform still existed until the Middle Liassic (Fig. 32). A sedimentary break conceals both the Triassic-Jurassic boundary interval and the disappearance of the coral fauna at the Triassic-Jurassic boundary. Thus, studies of Triassic-Jurassic sections at top and slope position are restricted to local occurrences, where the onset of Liassic sedimentation is preserved in small crevices or interstices of the rough Triassic relief. Due to the strikingly similarity of their facies and age (Middle Hettangian) with beds from the Adnet reef slope, these local sediments are attributed to the Schnöll-Formation (BÖHM et al., 1999). Non-rigid siliceous sponges (mainly *Lyssacinosida*) formed spicular mats during starved Liassic sedimentation (Fig. 32). They settled on detrital soft or firm grounds that were successively dominated by spicules of their own death predecessors and infiltrated sediments. Skeletal remains and adjacent micrites were partly fixed by microbially induced carbonate precipitation due to the decay of sponge organic matter (KRYSTYN et al., 2005). The irregular compaction of the sediment as well as volume reduction during microbialite

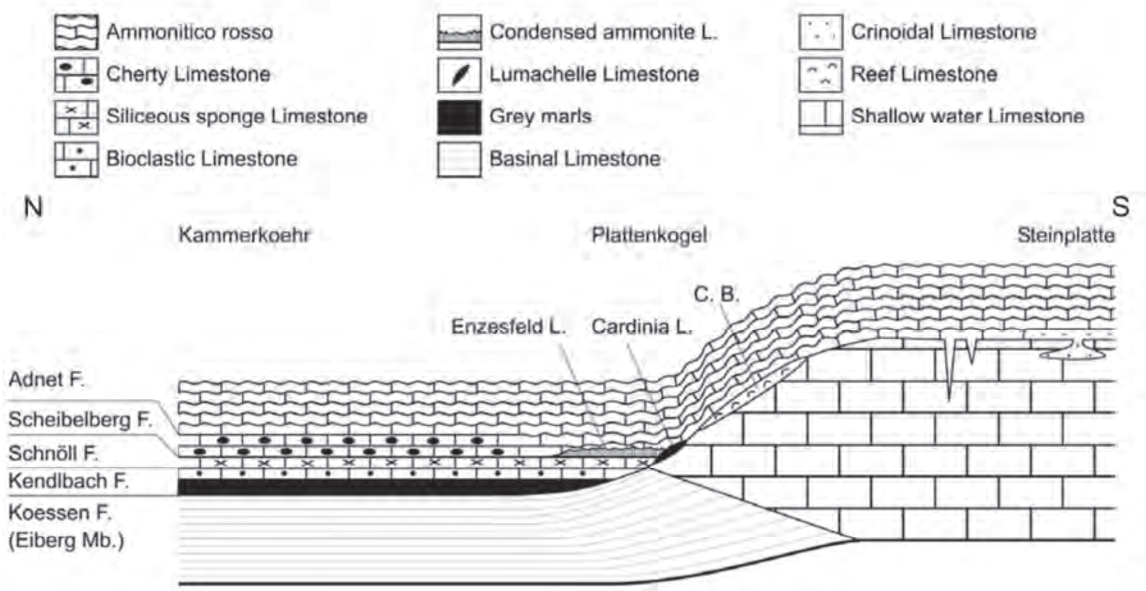

Fig. 31. Schematic Steinplatte cross-section from the platform to the basin; note the lowstand position of the Capping Beds and the onlap geometries of the Hettangian rocks (Kendlbach F., Schnöll F., Enzesfeld L.) as well as the delayed platform flooding by the Adnet Formation (from KRYSTYN et al., 2005).

formation resulted in syndiagenetic stromatactis cavities. Subjacent to the spiculite a sequence of allochthonous sediments that starts with a *Cardinia*-dominated shell layer (also ostreoids, pterioids, pectinoids) fills sinkholes and crevices of the Triassic relief. At the base of the sequence, the *Cardinia* beds contain reworked and corroded clasts of the underlying top-Triassic *Pecten*-lumachelle layer, which is also found at the edge of the depression. The clasts are often covered by black to brown goethite crusts that consist of thin and curly lamina, growing in cauliflower-like to digitate structures of up to 5 mm thickness. The succession above the spiculite continues with some red crinoidal limestones, where a few isolated sponges appear but spicular mats are absent. They are followed by the Marmorea Crust, an ammonite-rich and condensed marker horizon of late Hettangian age and the Sinemurian Adnet Formation. The Liassic sequence ends in red nodular breccias.

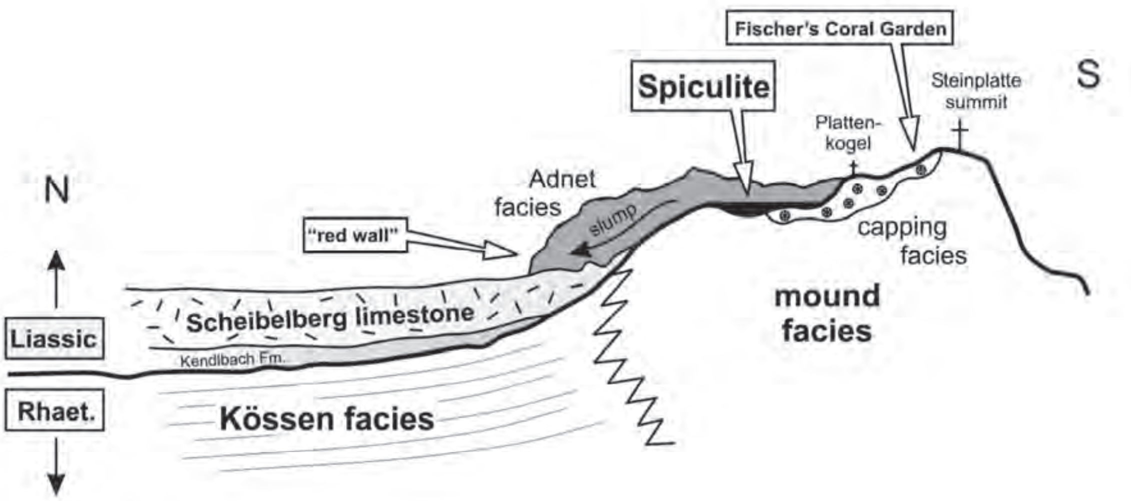

Fig. 32. Lower Jurassic events on the northern slope section of Steinplatte (from KRYSTYN et al., 2005).

In contrast, north of the Steinplatte, sedimentation of the Kössen Formation continuously passes into grey cherty limestones of the adjacent basin (Hettangian Kendlbach Formation and Sinemurian Scheibelberg Formation). The latter is characterised by varying, often high amounts of siliceous sponges and/or siliceous bulbs (MOSTLER, 1990; KRAINER & MOSTLER, 1997).

3.2.5. Locality 8 – Eiberg

The Eiberg section is located in an active cement quarry (SPZ Zementwerk Eiberg GmbH) about 3 km south of Kufstein (North Tyrol) (Fig. 1). The upper part of the Hochalm Member (upper unit 2 to unit 4, sensu GOLEBIOWSKI, 1989) and the Eiberg Member are exposed (Figs. 33, 34). The top of the Eiberg Member contains the Event Bed and the first post-extinction marls but is then separated from the Early Jurassic strata (Allgäu Formation) by a prominent fault. The Kendlbach Formation, which contains the Triassic-Jurassic boundary, is mostly missing. The Eiberg section was palaeogeographically situated in the central part of the Eiberg Basin (Fig. 5). KRYSTYN et al. (2005) supposed a connection with the open Tethys to allow the immigration of the pelagic ammonoids and conodonts. The Kössen Formation, Rhaetian in age, records a long-term deepening of the basin, with repeated shallowing upward cycles well documented by the litho and biofacies (Fig. 34). Particularly the associations of bivalves and brachiopods studied in details by GOLEBIOWSKI (1989, 1991) give indication of depth changes (Fig. 35).

Fig. 33. Eiberg Quarry behind main cement factory exposing Kössen Formation with top Hochalm Member (Units 3 + 4) and lower Eiberg Member (Units 1 + 2).

The Hochalm Member

Only the top of the Hochalm Member, Unit 2 is visible on the southern part of the quarry. If shallow water carbonate dominated bioclastic limestone in the Unit 1, these shallow water carbonate (Fig. 36B) are rarer in the Unit 2 and disappear in Unit 3. The proximal tempestite of Unit 1 become more distal in Unit 2 and the marls are increasing in thickness. The shallowing upward cycles in unit 2 are marked by alternation of distal tempestite, laminated

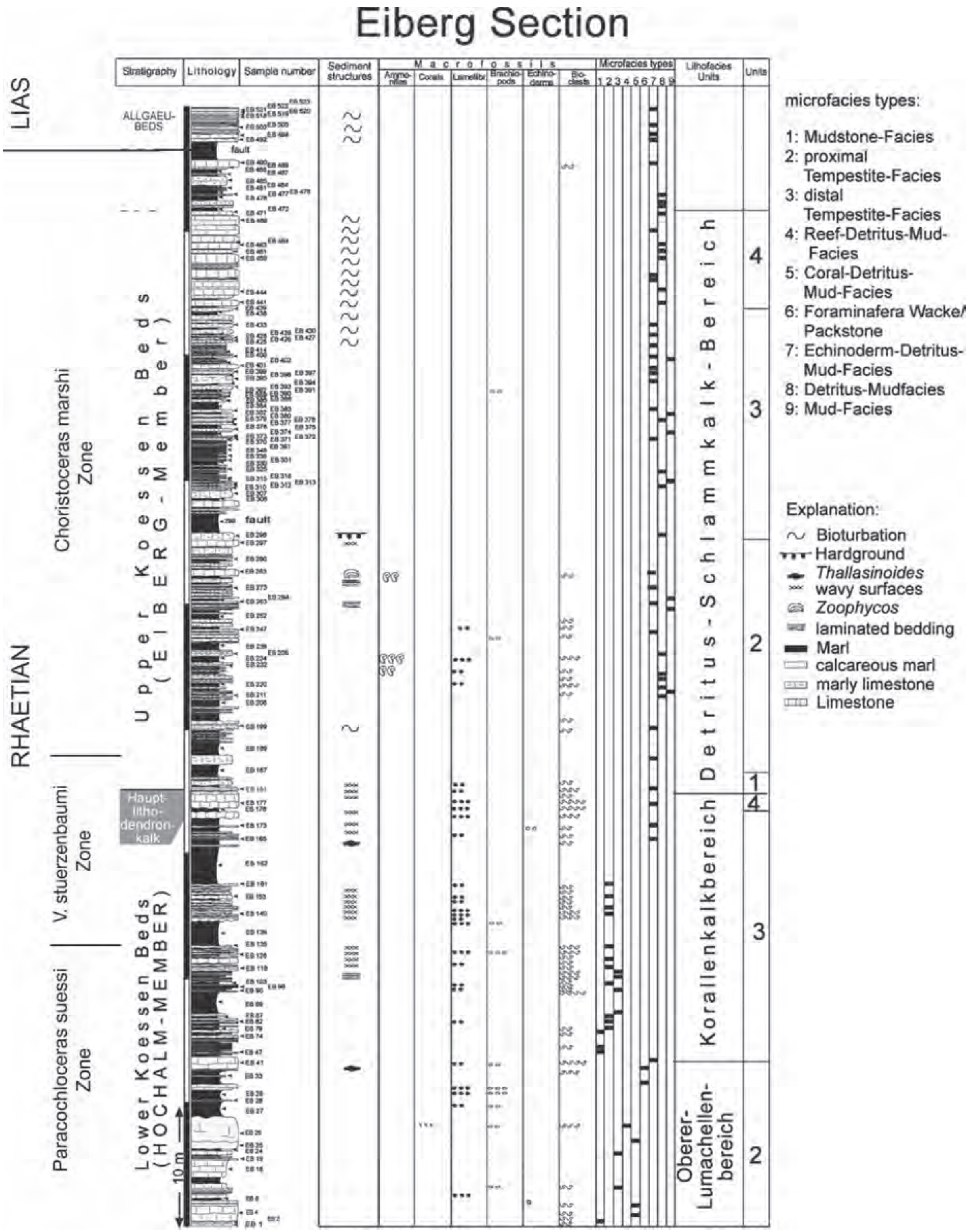

Fig. 34. Profil of the Eiberg section (modified from GOLEBIOWSKI, 1991).

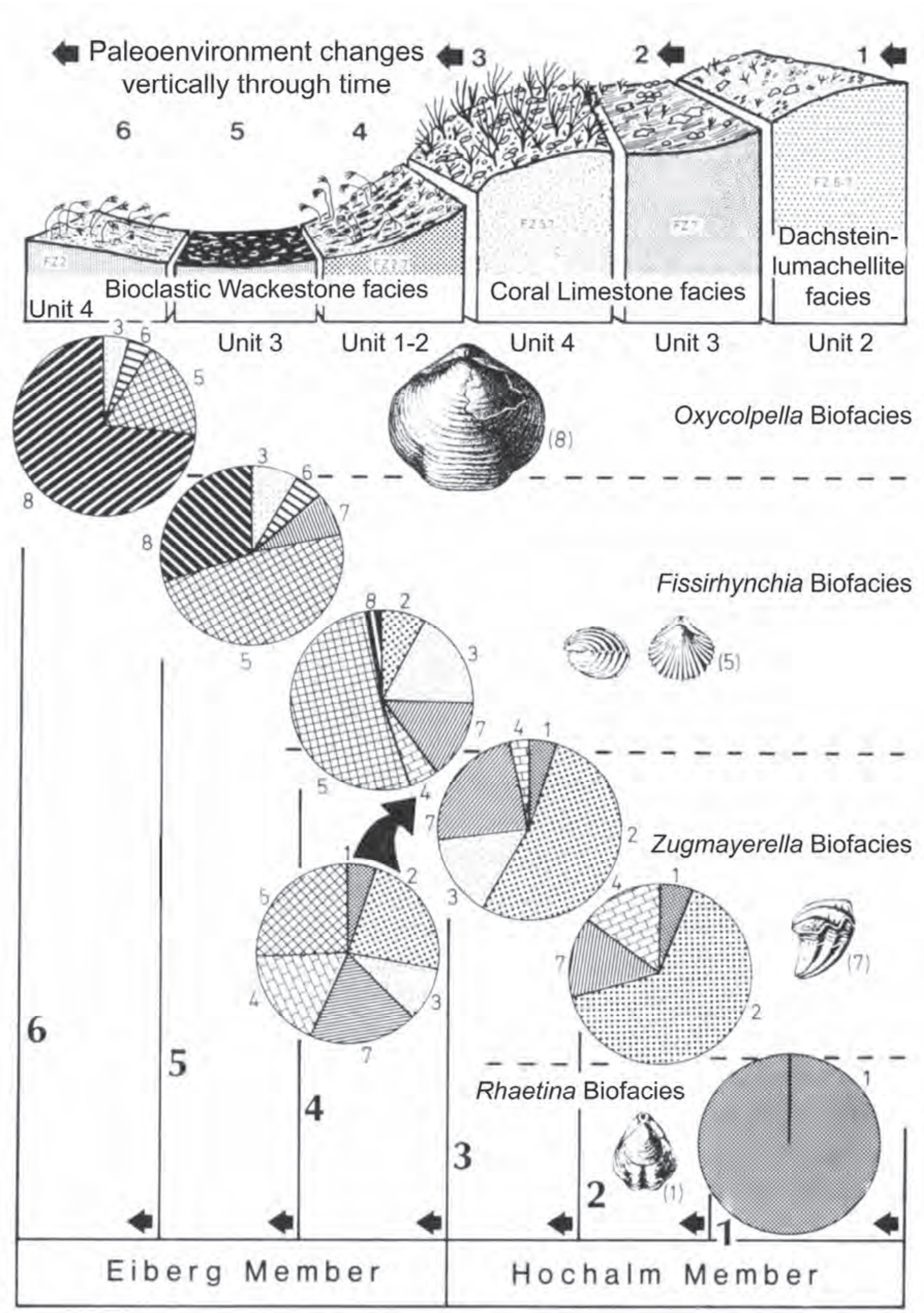

Fig. 35. Ecological stratigraphy of the brachiopods of the Kössen Formation. There are continuous changes in assemblages concomitant with the deepening of the basin. 1 - *Rhaetina gregaria*, 2 - *Rhaetina pyriformis*, 3 - *Zeilleria norica*, 4 - *Austrirhynchia cornigera*, 5 - *Fissirhynchia fissicostata*, 6 - *Sinucosta emmrichi*, 7 - *Zugmayerella koessenensis* und *uncinata*, 8 - *Oxycolpella oxycolpos*. From GOLEBIOWSKI (1991).

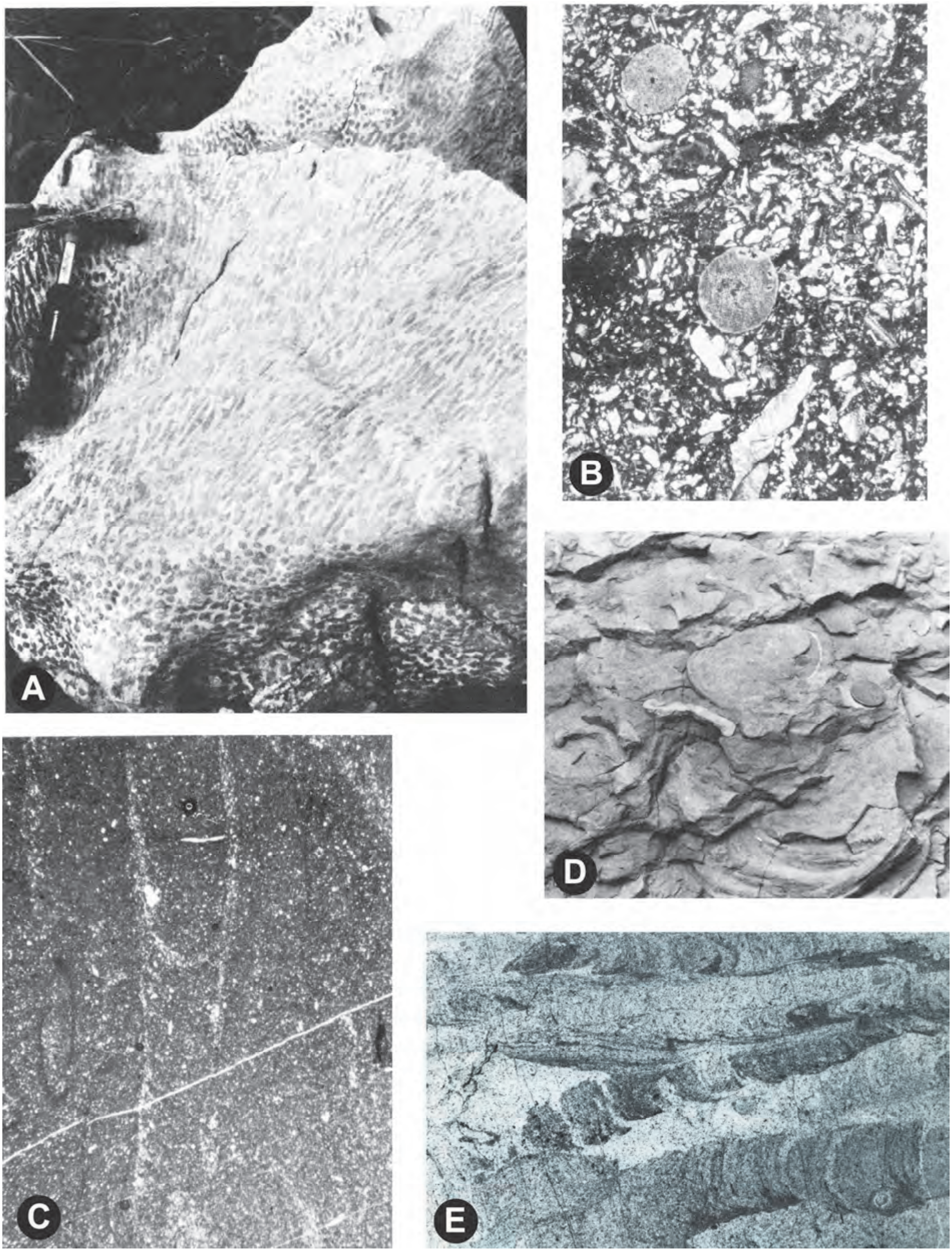

Fig. 36. A) Lithodendron Limestone (hammer for scale); B) Echinoderm bioclastic grainstone with brachiodpod fragments and crinoids, x 7; C) Bioclastic wackestone with sponges spicules and bioturbation, x 4,5; D) Zoophycos traces within the marly sediment, x 0,3; E) Vertical section of Zoophycos traces, together with later burrows, x 1. (All photos from KUSS, 1983).

mudstone and marls. Bonebeds, epifaunal bivalves, the brachiopods (*Rhaetina gregaria*) and the strong bioturbated bioclastic limestone document a high energy, low sedimentation rate, shallow deposition milieu (less than 20m water depth) (GOLEBIOWSKI, 1989, 1991). The shallow water carbonate and bivalves-rich tempestite are no more present in Unit 3 and 4. In this Coral-Limestone Interval, the bioclastic limestones are richer in terrigenous elements and low diversity solitary corals with micritic matrix are the main component. The corals are dominated by *Retiophyllia paraclathrata* RONIEWICZ (GOLEBIOWSKI, 1989, 1991). The Unit 4, the "Lithodendron Limestone" is the most important lithofacies marker of the Kössen Formation (Fig. 36A). The Units 3 and 4 mark a deepening below the wave base (30-50m) and a transition phase between a deep, open marine lagoon (Unit 1 and 2) and the intraplatrform basin deposition milieu of the Eiberg Member. According to GOLEBIOWSKI (1991), the conodonts and in part ammonoids provide a lower Rhaetian age for the Unit 1+2 and the base of the Unit 3 (*Paracochloceras suessi* Zone until 23 m in Fig. 34). The top of the Unit 3, the Unit 4 of the Hochalm Member and the Unit 1 of Eiberg Member belong to the middle Rhaetian *Vandaites stuerzenbaumi* ammonoid Zone.

The Eiberg Member

The Eiberg Member is more monotonous than the Hochalm Member. The sedimentation is marked by grey intraplatform basin limestones and marls with common *Zoophycus* and *Chondrites* burrows (Fig. 36C-E). The conditions of sedimentation do not show much variation. The bivalve biofacies sees the diminution of individuals and species, probably due to a decrease in nutrients, and is dominated by the bassinal form *Oxytoma inaequvalve* (GOLEBIOWSKI, 1989, 1991, Fig. 35). The ostracods record a change from warm to colder water (URLICHS, 1972). These changes indicate a further deepening of the basin to about 50-100 m water depths in the units 1 to 3. The maximum water depth is probably to correlate with the black shales and thin-bedded mudstone of the lower part of unit 3. The Unit 4 is developed as packstones with a shallowing upward trend, thicker bedding, and increasing bioclastic content: fragmented basinal bivalves (*Pinna*), downslope-transported, thick-shelled shallow water bivalves (*Palaeocardita*), and brachiopods (*Oxycolpella*, *Fissirhynchia*) (KRYSTYN et al., 2005), indicating a regressive phase (GOLEBIOWSKI, 1989, 1991). Two thin chert nodule layers – otherwise missing from the Kössen Formation – are useful as marker beds and result from local enrichment of siliceous sponge spicules in this interval. The top 2 cm show a distinct iron- and bivalve-enriched brown hard surface interpreted as a possibly condensed hardground layer. The Units 2, 3 and 4 of the Eiberg Member belong to the late Rhaetian *Choristoceras marshi* ammonoid Zone (Fig. 34).

3.3. The Triassic/Jurassic GSSP (Day 3)

The Triassic-Jurassic GSSP at Kuhjoch is the most expanded marine section in the world and contains the richest marine fauna with an abundant microflora allowing a cross-correlation with the continental realm. It developed in the Eiberg Basin, which continuously subsided in late Rhaetian time reaching 150-200 m water depth. It was, therefore, less affected by the end-Triassic sea level drop which led to widespread and longer-lasting emersion of the surrounding shallow water areas. Instead, marine conditions prevailed in the basin across the system boundary, where a distinct and abrupt lithological change from basinal carbonates to marls and clayey sediments – now interpreted as the result of the Central Atlantic Magmatic Province (CAMP) flood basalt province eruption - record the mass-extinction event and, above, the first appearance of Jurassic fauna. For a review of the effects of the volcanism and the potential ocean acidification event during the Triassic-Jurassic transition, see GREENE et al. (2012).

3.3.1. Route

The GSSP Kuhjoch is located about 25 km north-north-east of Innsbruck and 5 km east-north-east of the village of Hinterriss on the 1:50.000 scale topographic map of Austria (sheet 118 – Innsbruck); the coordinates are 47°29'02"N/11°31'50"E (Figs. 37, 38). It is accessible through the Baumgartenbach valley on a 16 km long forest road (driving permit from the OEBF = Österreichische Bundesforste, oberinntal@bundesforste.at) starting south of the village of Fall in Bavaria (Germany), with a 1.5-2 hour hike from the Hochstallalm Niederleger (Fig. 39). Ochsentaljoch is located 750 m to the west (47°29'0"/11°31'50").

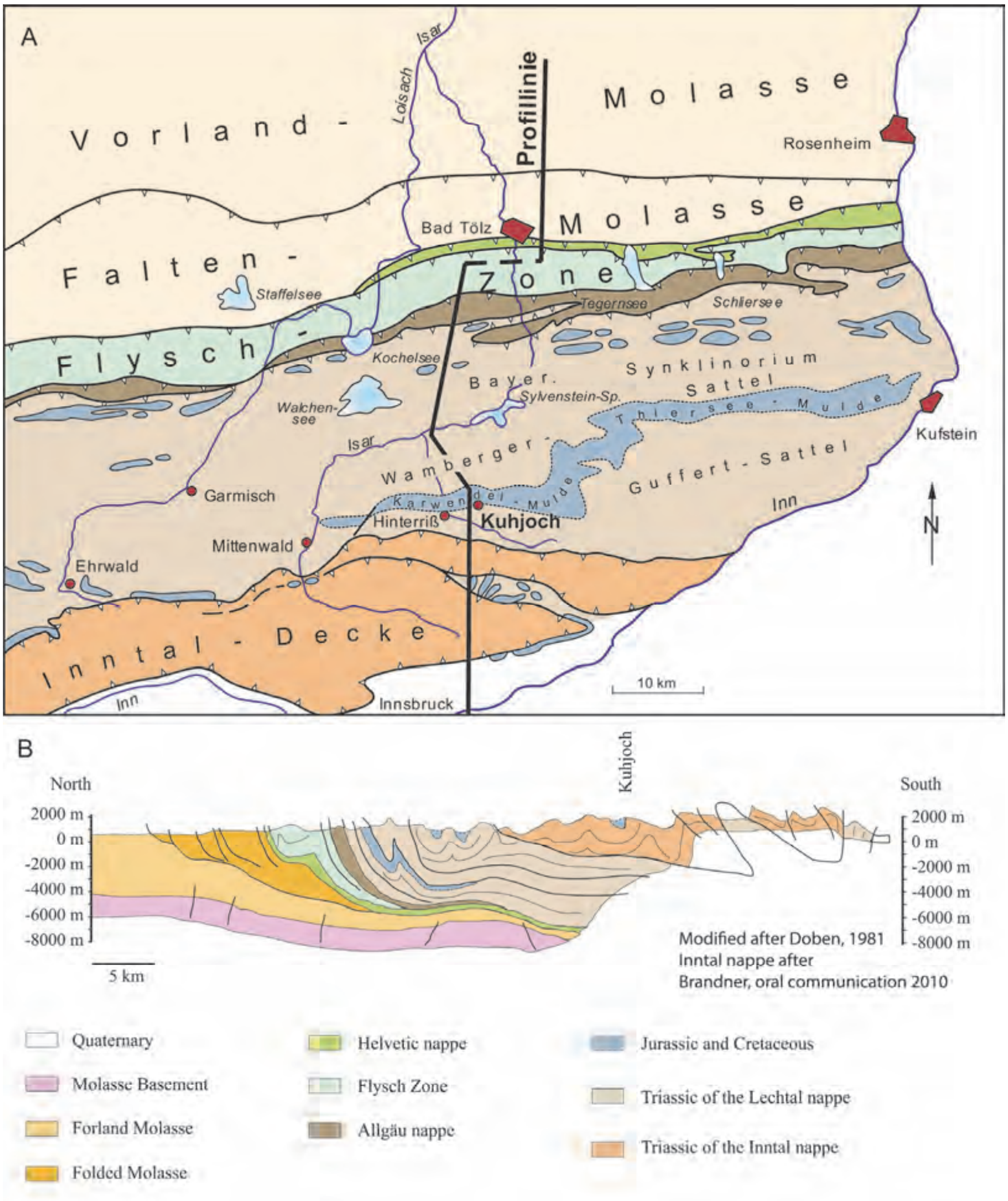

Fig. 37. Geological map and cross-section of the Karwendel Mountains (modified after HILLEBRANDT & KMENT, 2009).

3.3.2. Locality 9 – Kuhjoch

This text is mainly taken from HILLEBRANDT et al. (2013) and RICHOZ et al. (2012).

Fig. 38. Triassic – Jurassic boundary sections of the western Karwendel Syncline (modified after HILLEBRANDT & KMENT, 2009).

Within the western part of the Eiberg basin, the Karwendel Syncline is a local, East-West trending synclinal structure, approximately 30 km long, within the Inntal nappe of the western Northern Calcareous Alps, extended E-W. The syncline is wide and relatively flat near the Achensee in the east (Fig. 37) and narrows towards the west with increasingly steep to overturned flanks at its western end close to Mittenwald (Fig. 38). Triassic-Jurassic boundary sections south of the Karwendel Syncline are classical localities and have been studied by various authors (Fig. 38; references in KUERSCHNER et al., 2007). The boundary sections of the Karwendel Syncline have been much less studied and detailed biostratigraphic information about the Tiefengraben Member is only known for some years past. Most of the recently-studied outcrops belong to the southern flank of the Karwendel Syncline, and at least five of them (Hochalplgraben, Rissbach, Schlossgraben, Ochsentaljoch and Kuhjoch) have become important as a result of the findings of a new psiloceratid (*Psiloceras spelae tirolicum*) distinctly older than the well-known earliest Psiloceras from England (*P. erugatum*, *P. planorbis*) and the Alps (*P. calliphyllum*).

The continuously subsiding Eiberg basin reached 150-200 m water depth in late Rhaetian time and was, therefore, less affected by the end-Triassic sea level drop which led to a widespread and longer-lasting emersion of the surrounding shallow water areas. Instead, marine conditions prevailed in the basin across the system boundary, though a distinct and abrupt lithological change from basinal carbonates of the Eiberg Member to marls and clayey sediments of the lower Kendlbach Formation (Tiefengraben Member, corresponding to the British Preplanorbis Beds) occured. Within the Eiberg basin, between Lake St. Wolfgang (Kendlbach) and Garmisch-Partenkirchen all sections show the same sedimentary record across the Triassic-Jurassic boundary with varying carbonate vs. clay content depending on their more marginal or more distal position within the basin. A general increase in thickness of the Tiefengraben Member can be observed from east to west, nearly double in the Karwendel syncline compared with the eastern Kendlbach and Tiefengraben sections. With a thickness of more than 20 m, the Karwendel Syncline exposes one of the most expanded Triassic-Jurassic boundary successions of all known sections worldwide.

Among the diverse Triassic-Jurassic boundary sections of the Western Eiberg basin (Fig. 38), the pass of the Kuhjoch (Fig. 40) was selected as GSSP for the base of the Jurassic because it presents the best continuously available and most complete Triassic-Jurassic boundary sections of the area. Only the topmost part of the boundary sequence, with the transition to the *P. calliphyllum* horizon, 10 to 18 m above the GSSP level, has been studied

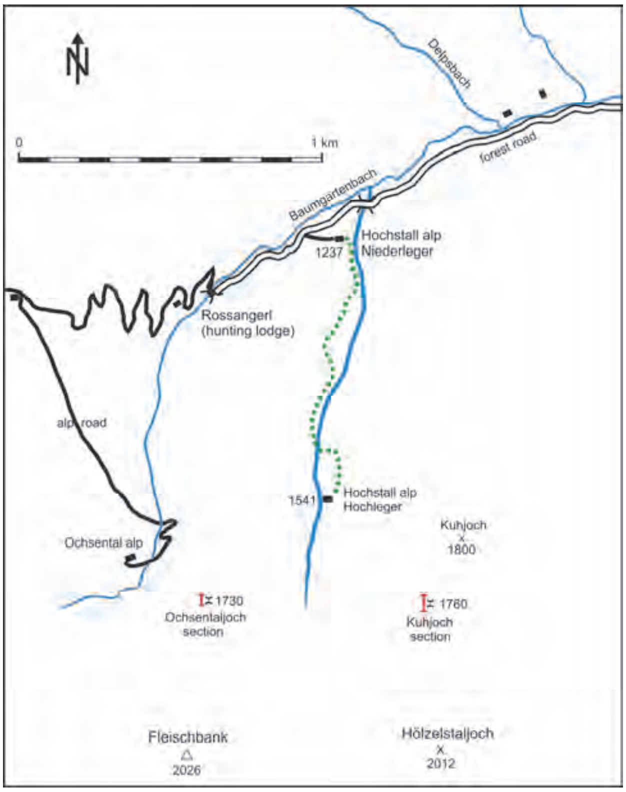

Fig. 39. Way to Kuhjoch and Ochsentaljoch sections (from HILLEBRANDT & KMENT, 2009).

Among the diverse Triassic-Jurassic boundary sections of the Western Eiberg basin (Fig. 38), the pass of the Kuhjoch (Fig. 40) was selected as GSSP for the base of the Jurassic because it presents the best continuously available and most complete Triassic-Jurassic boundary sections of the area. Only the topmost part of the boundary sequence, with the transition to the P. calliphyllum horizon, 10 to 18 m above the GSSP level, has been studied in more detail at a neighbouring locality (Ochsentaljoch) about 750 m to the west of Kuhjoch (Fig. 39), where this interval is better exposed.in more detail at a neighbouring locality (Ochsentaljoch) about 750 m to the west of Kuhjoch (Fig. 39), where this interval is better exposed.

The Kuhjoch section starts 3.8 m below the top of the Kössen Formation/Eiberg Member with a band of well-bedded and variably thick (up to 50 cm) grey bioturbated limestones (bioclastic wackestones) overlying 5 m black marls with pyrite nodules and rare thin (5-10 cm) limy mudstone intercalations (Figs. 41, 42). The 20 cm thick topmost bed (= T in Fig. 41, 43) of the Eiberg Member differs by darker colour and platy weathering; due to an increased clay content and is softer than the pure limestone below, and thinly laminated in its upper half. The top of this bed (~ 1 cm thick and also thin-bedded) is black and bituminous, rich in bivalves and fish remains (scales). Above, the Kendlbach Formation is divided in the lower 22 m thick terrigenous Tiefengraben Member and the following 3 m thick calcareous Breitenberg Member.

Grey to brownish marls (up to 13 cm thick) with concretions of pyrite and worm-shaped traces constitute the base of the Tiefengraben member and are overlain by yellowish weathering, partly laminated marls (ca. 30 cm thick) passing into reddish, partly laminated, argillaceous marls approximately 2.8 m thick (Fig. 42) and comparable with also reddish, argillaceous marls which are known as Schattwald Beds from the Allgäu basin. Grey intercalations characterise the transition to the overlying main part of the Tiefengraben Member, 19 m thick. Ammonite level (2) with *P. spelae tirolicum* (Fig. 44) is located 3.2 m above the Schattwald beds, ammonite level (3a) with *P.* ex gr. *P. tilmanni* 2 m higher and ammonite level (4) with *P.* cf. *pacificum* 4 m higher up in the section (HILLEBRANDT & KRYSTYN, 2009) (Fig. 42).

Approximately 8 m above the Schattwald Beds, the marls become more silty and from 10 m upwards also finely arenitic. A first arenitic bed (15 to 20 cm thick) occurs at around 11 m above the Schattwald Beds. The remaining part of the Tiefengraben Member, with the transition to the Breitenberg Member (“Liasbasiskalk” of ULRICH, 1960), is not well exposed. A naturally well exposed outcrop of this part of the section is found at Ochsentaljoch (750 m west of Kuhjoch).

Fig. 40. View to the West on Kuhjoch section with the main lithological Formations.

The exposed part of the Breitenberg Member consists at Kuhjoch (Fig. 42) of grey thin-bedded (glauconite-rich bioclastic packstone) limestones with thin black hard marl layers and a top bed (10 to 15 cm) that contains, in the middle and upper part, a condensed fauna of the *Calliphyllum* Zone, including a hardground layer enriched in ammonites partly preserved as limonitic moulds. At Kuhjoch and several other sections of the southern and northern flank of the Karwendel Syncline the next two or three limestone beds contain condensed ammonites of middle and late Hettangian age (KMENT, 2000; HILLEBRANDT & KMENT, 2009, 2011). At Kuhjoch follows above the *Calliphyllum* horizon a grey, sparry limestone (8 cm thick), a brownish, micritic limestone bed (10 cm thick), an ochre coloured, micritic limestone with grey clasts and *Alsatites* cf. *liasicus* of middle Hettangian age (= Enzesfeld limestone) (8 cm thick) and a brownish, sparry limestone (15 cm thick) with a limonitic crusts at the top and *Alpinoceras haueri* (marmoreum horizon) of late Hettangian age. On the western slope of Kuhjoch, a limonitic crust with concretions yielding reworked middle Hettangian ammonites (*Megastomoceras megastoma* and *Alsatites proaries*) was found. On the eastern slope, a loose rock of the Enzesfeld

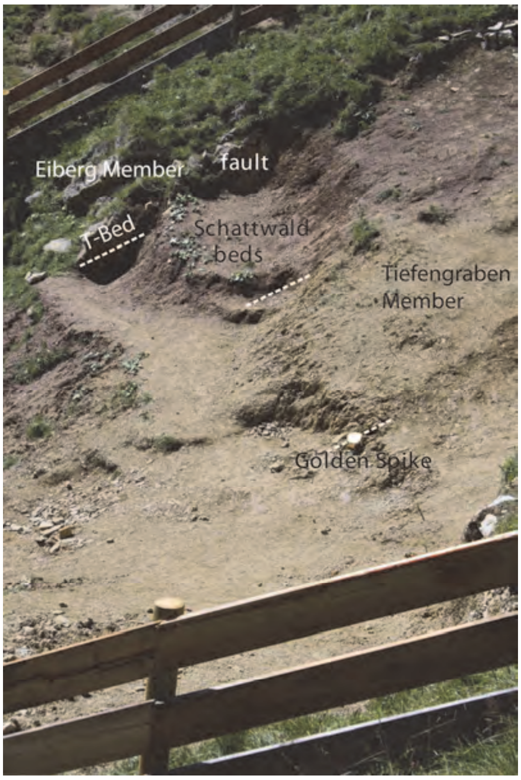

Fig. 41. Section Kuhjoch East with "Golden Spike" at Triassic-Jurassic boundary.

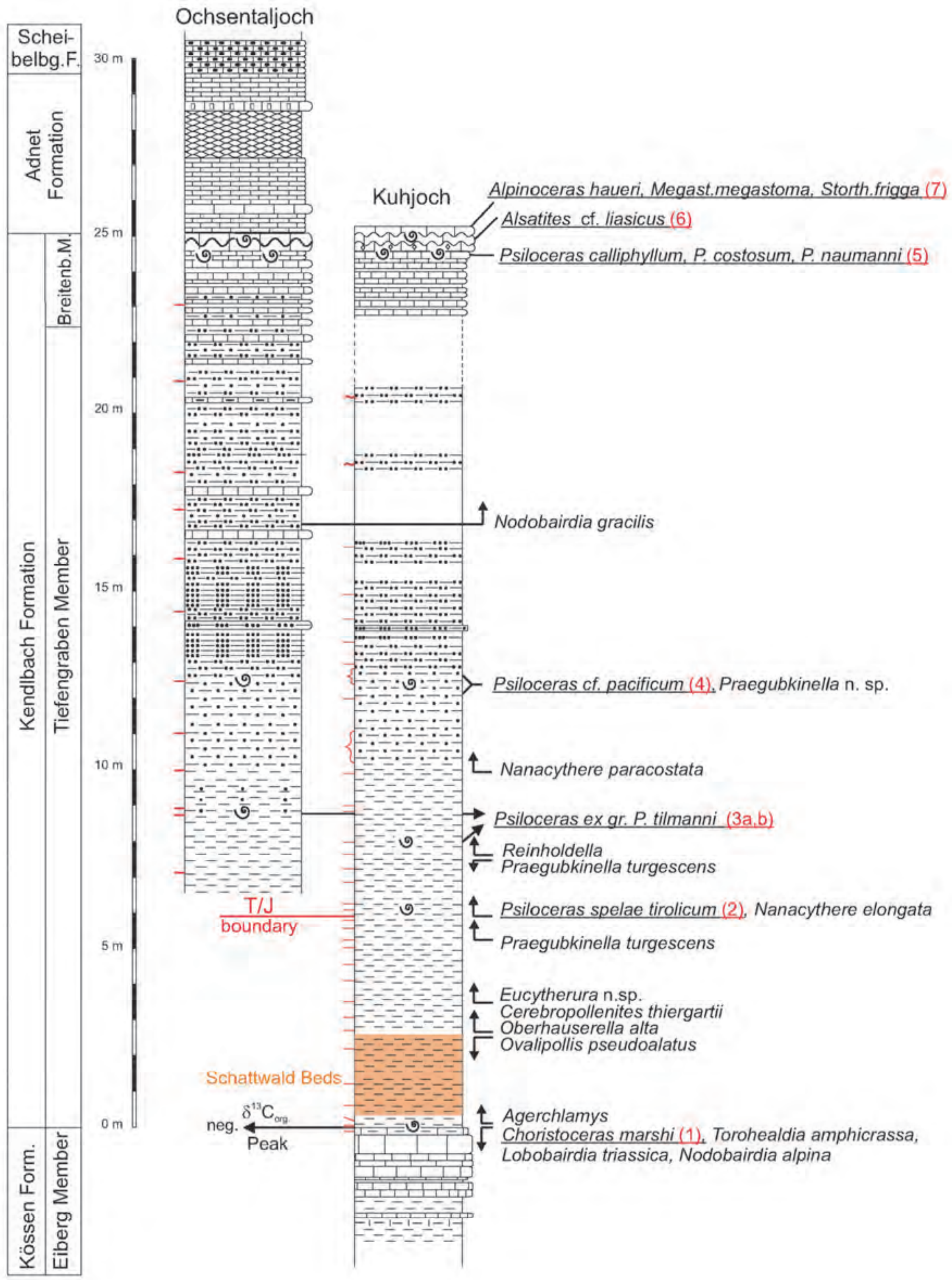

Fig. 42. First and last occurrences of biostratigraphic important fossils at GSSP Kuhjoch West (from Hillebrandt et al., 2013).

limestone (10 cm thick) contained middle Hettangian ammonites (e.g. *Megastomoceras megastoma* and *Storthoceras frigga*). The superimposed beds are nodular limestones of the Adnet formation with a Sinemurian age.

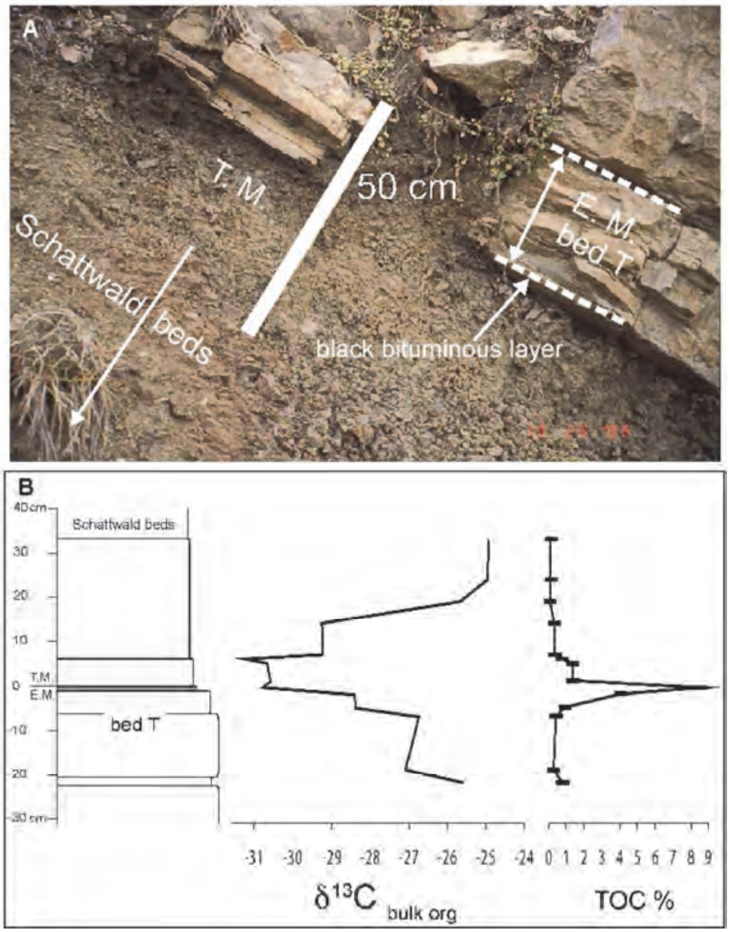

Fig. 43. A) Boundary between Eiberg (E.M.) and Tiefengraben members (T.M.) (Kuhjoch West section). Beds overturned; B) $\delta^{13}C_{org}$ and TOC curves of the Eiberg – Tiefengraben members (Kuhjoch West section) (RUHL et al., 2010) (from HILLEBRANDT et al., 2013).

A broad spectrum of marine invertebrate groups is recorded, although brachiopods are rare. Macrofossils (Figs. 44, 45, 46) are represented by biostratigraphically (ammonites) as well as palaeoecologically important groups (bivalves, echinoderms). Microfossils (Figs. 44, 45, 46) constitute a major portion of the calcareous biomass except for the Schattwald Beds where only a depauperate foraminifer record is present. Ostracods are usually less frequent than foraminifera. Nannofossils are present in many samples, though coccoliths unfortunately are very rare and extremely small. Most samples were rich in well preserved palynomorphs which have a palynomorph colour of 1-2 on the thermal alteration scale (TAS) of BATTEN (2002). The microfloral record across the Triassic–Jurassic boundary is characterised by significant quantitative changes in the terrestrial and marine components of the assemblages with a few notable palynostratigraphic events, which are very similar to those described from the Tiefengraben section in the eastern part of the Eiberg basin (KUERSCHNER et al., 2007).

At the Kuhjoch section no overprint is observable. Ammonites, bivalves and some calcareous foraminifers (in part hollow) are preserved with an aragonitic shell. There are absolutely no signs for regional or local metamorphosis of the rocks (Kuhjoch, Hochalplgraben, Schlossgraben and also Tiefengraben and Kendlbach to the East). From the preservation of palynomorphs, notably the colour, it is evident that this material was never heated above about 50°C (see also KUERSCHNER et al., 2007); conodonts again show a low Conodont Alteration Index (CAI) 1 value. Carbon-isotopes of bulk sedimentary organic matter (Figs. 43, 47) have been studied (RUHL et al., 2009). In addition, compound-specific C-isotope measurements (n-alkanes) have been carried out (RUHL et al., 2011), as detailed mineralogical studies (PÁLFY & ZAJZON, 2012; ZAJZON et al., 2012).

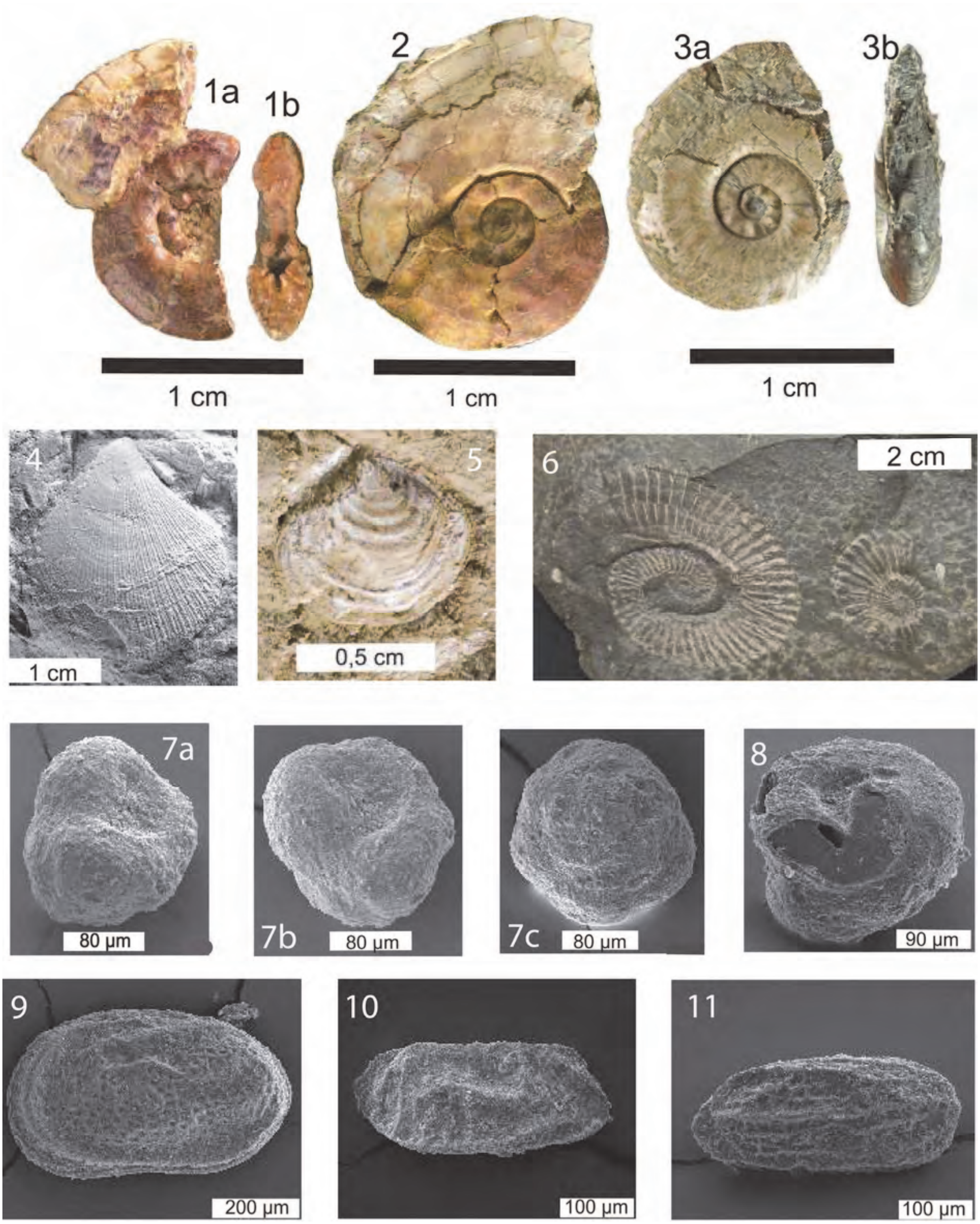

Fig. 44. Important guide fossils at the Triassic – Jurassic boundary of GSSP Kuhjoch. 1-3) *Psiloceras spelae tirolicum* HILLEBRANDT & KRYSTYN, 1a,b, 2) Kuhjoch, 3) Hochalplgraben; 4) *Agerchlamys* sp., Hochalplgraben; 5) *Astarte* sp., Kuhjoch, *spelae* horizon; 6) *Choristoceras marshi* HAUER, Kuhjoch, top T bed; 7a-c) *Praegubkinella turgescens* FUCHS, Kuhjoch, *spelae* horizon; 8) ?*Reinholdella* sp., Kuhjoch, cf. *pacificum* horizon; 9) *Cytherelloidea buisensis* DONZE, lv, Kuhjoch, *spelae* horizon; 10) *Eucytherura sagitta* SWIFT, rv, Hochalplgraben, cf. *pacificum* horizon; 11) *Eucytherura* n.sp., lv, Kuhjoch, latest Rhaetian. rv = right valve, lv = left valve (from HILLEBRANDT et al., 2013).

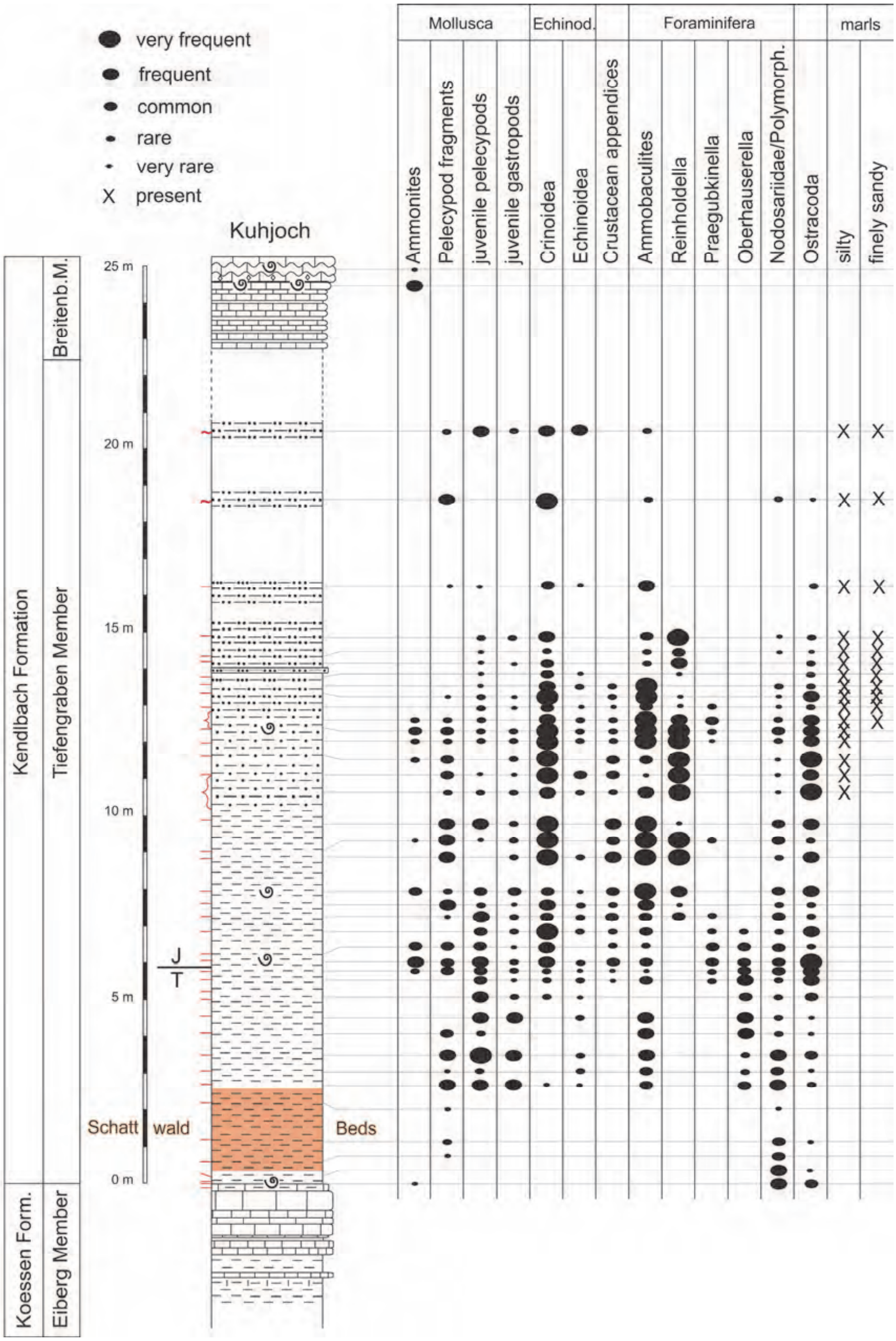

Fig. 45. Fossil at Kuhjoch section (from HILLEBRANDT & KMENT, 2009).

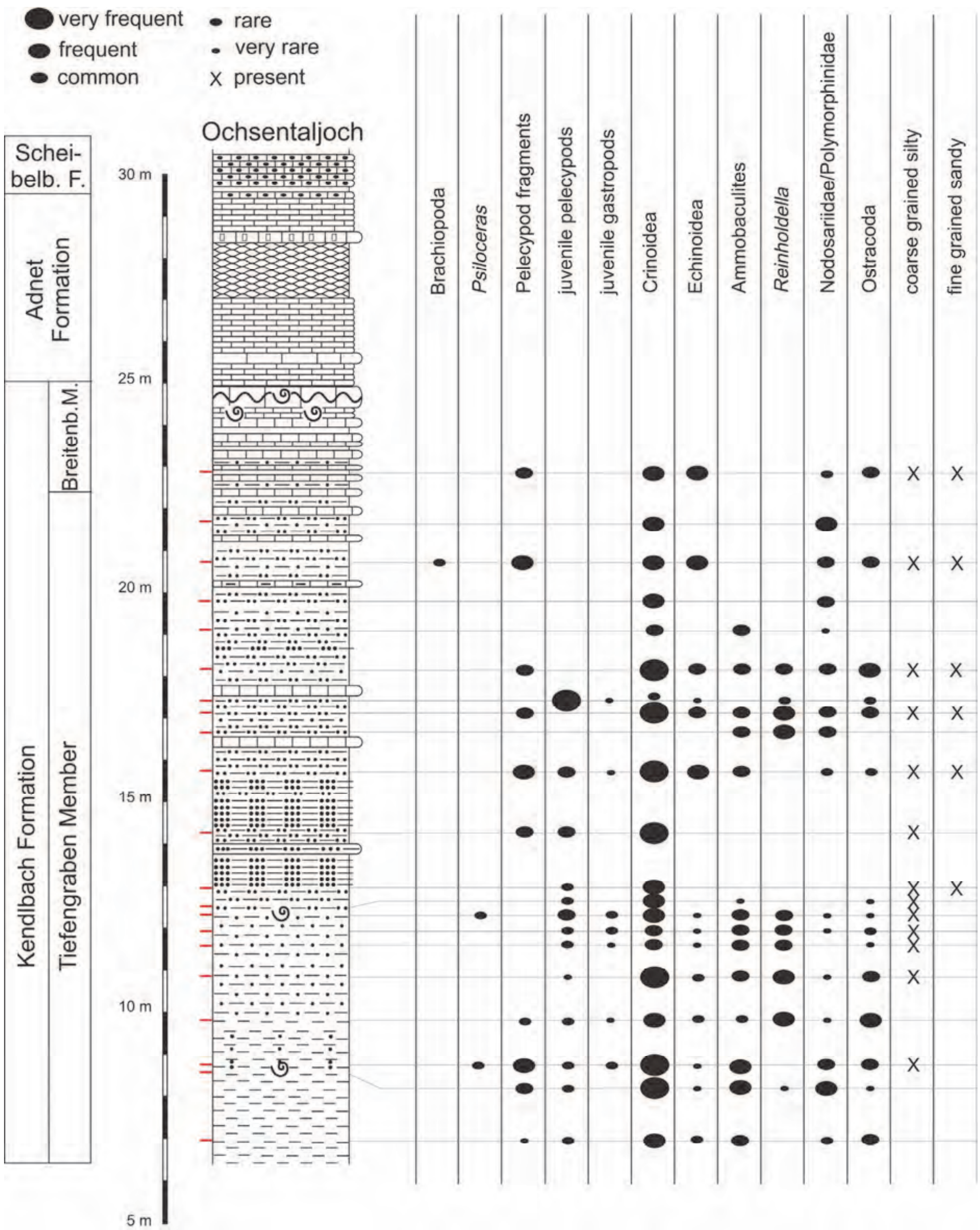

Fig. 46. Fossil at Ochsentaljoch section (from HILLEBRANDT & KMENT, 2009).

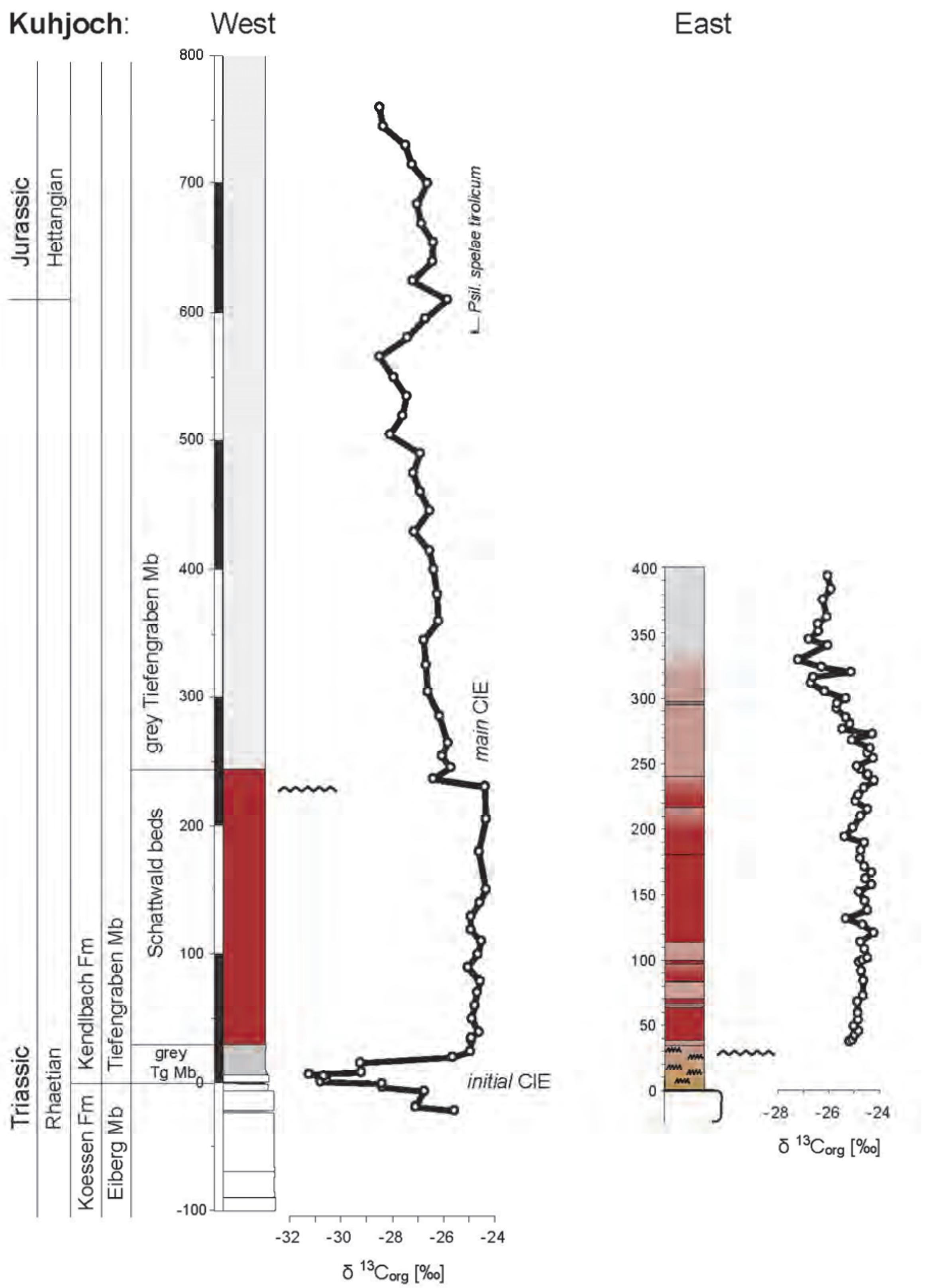

Fig. 47. Detailed C-isotope curves from the Kuhjoch West and the Kuhjoch East sections, data for Kuhjoch West are from RUHL et al. (2009), data for Kuhjoch East are from HILLEBRANDT et al. (2013).

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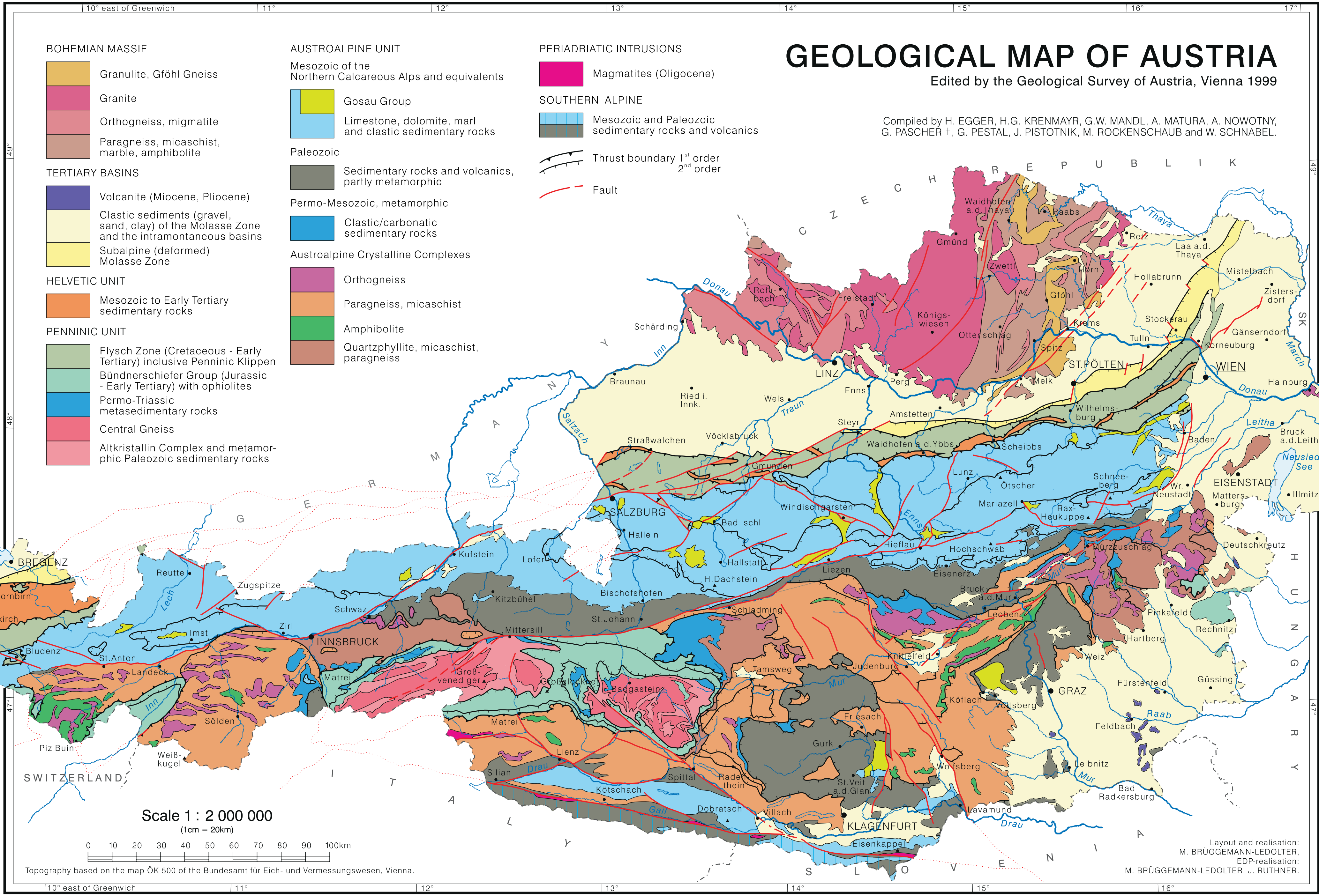

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