End-Triassic crisis events recorded in platform and basin of the Austrian Alps.
The Triassic/Jurassic and Norian/Rhaetian GSSPs

By

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With 54 figures

Field Trip Guide

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Content

Abstract

During the latest Triassic, the Austrian Northern Calcareous Alps built 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 off-shore 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 (condensed pelagic limestone). In the early Rhaetian, the diversity of the pelagic fauna began to decline whereas the reefs reached their climax. The Northern Calcareous Alps record this 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. Two GSSPs (Global Stratigraphic Section and Point), for the Rhaetian and the Hettangian stages - the later defining the boundary between the Triassic and Jurassic system - corroborate the global geological importance of the area during that interval of time.

1. Topics and area of the field trip

The Austrian Northern Calcareous Alps give the opportunity to observe the influence of the Late Triassic crisis intervals 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 barrier 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 and Triassic-Jurassic GSSPs (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 of multiple crisis.
This whole Late Triassic story is present in the Northern Calcareous Alps (Salzkammergut region, Salzburg, and Tirol), a scenic, mountains and lakes region with breathtaking landscapes (Fig. 1).

2. Introduction

This general introduction is mainly taken from 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 metamorphic overprint, which offers the opportunity to study and reconstruct the depositional history of a major segment of 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

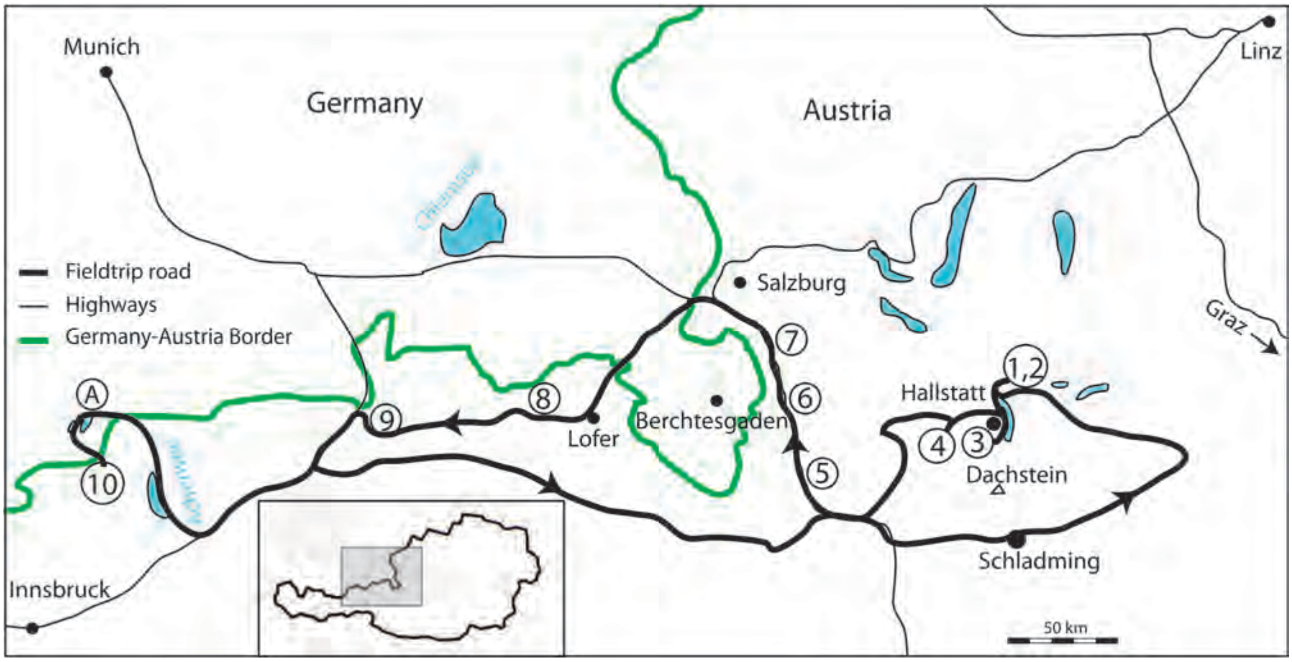


Fig. 1: Localities to be visited: 1- Leislingkogel; 2- Grosser Zlambach; 3- Steinbergkogel; 4- Gosausee; 5- Eisriesenwelt; 6- Pass Lueg; 7- Adnet; 8- Steinplatte; 9- Eiberg; 10- Kuhjoch. 4, 8 and A are overnight places.

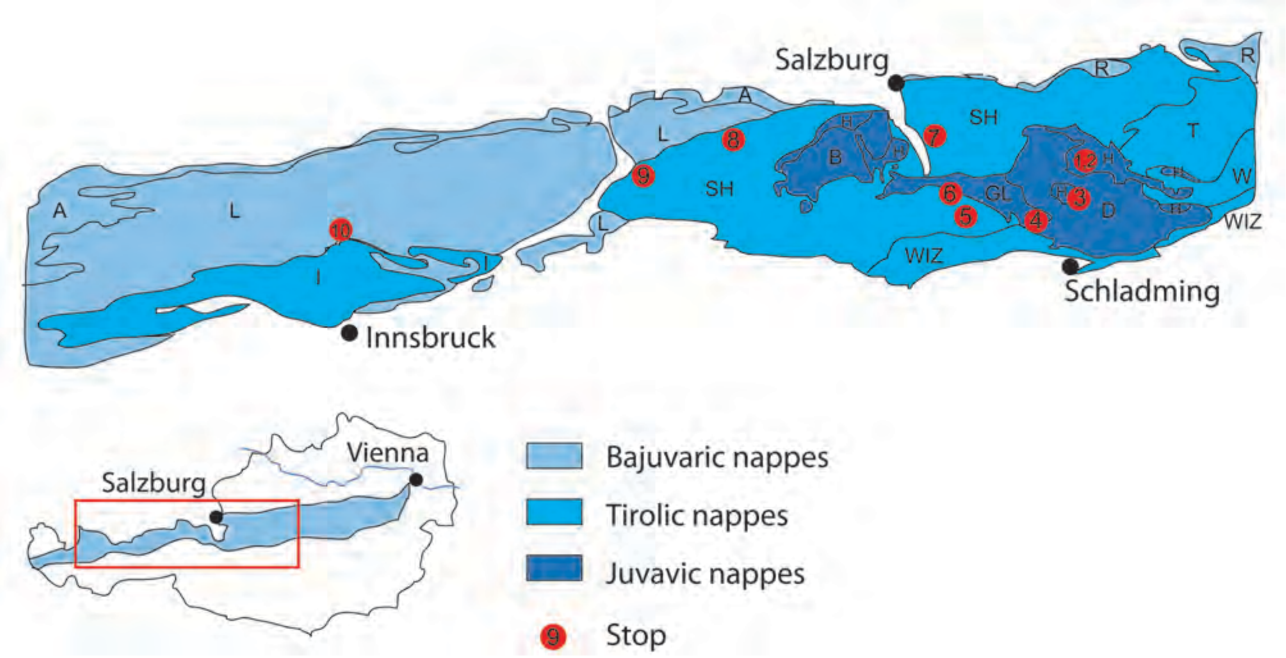


Fig. 2: The nappe complex of the Northern Calcareous Alps (modified from Mandl 2000). Explanation of abbreviations: Juvavic nappes: B = Berchtesgaden nappe, D = Dachstein nappe, GL = Göll-Lammer unit, H = Hallstatt units. Tirolic nappes: I = Inntal nappe, SH = Stauffen-Höllengebirge nappe, T = Totengebirge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

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 nappe 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 (Fig. 2). 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 Calcareous Alps, Werfen imbricated zone). Although large portions of the Northern Calcareous Alps indicate only anchimetamorphism (Kralik et al. 1987), investigations of the Conodont Colour 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

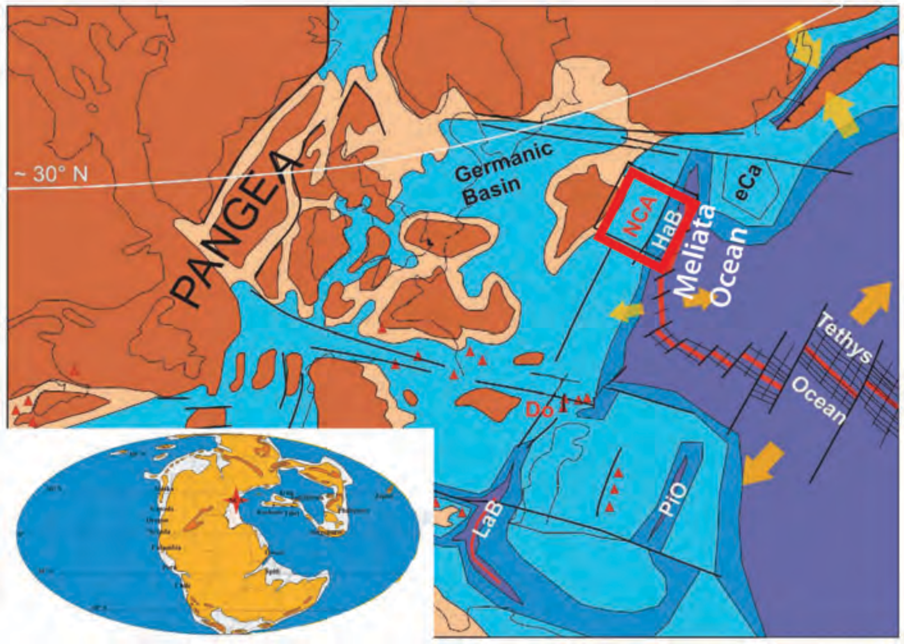


Fig. 3: Palaeogeographic reconstruction for the Western Tethyan margin during the Late Triassic (from Hornung et al. 2008). Explanation of abbreviations: NCA = Northern Calcareous Alps, eCA = East Carpathians, HaB = Hallstatt Basin, Do = Dolomite, PiO = Pinde Ocean, LaB = Lagonegro Basin.

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. 4C). 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 salt mine. The Early Triassic is characterized 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 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 have indications of the existence of such an oceanic realm only in the form of olistolites of Ladinian red radiolarite in the Meliata slides in eastern sectors of the Northern Calcareous

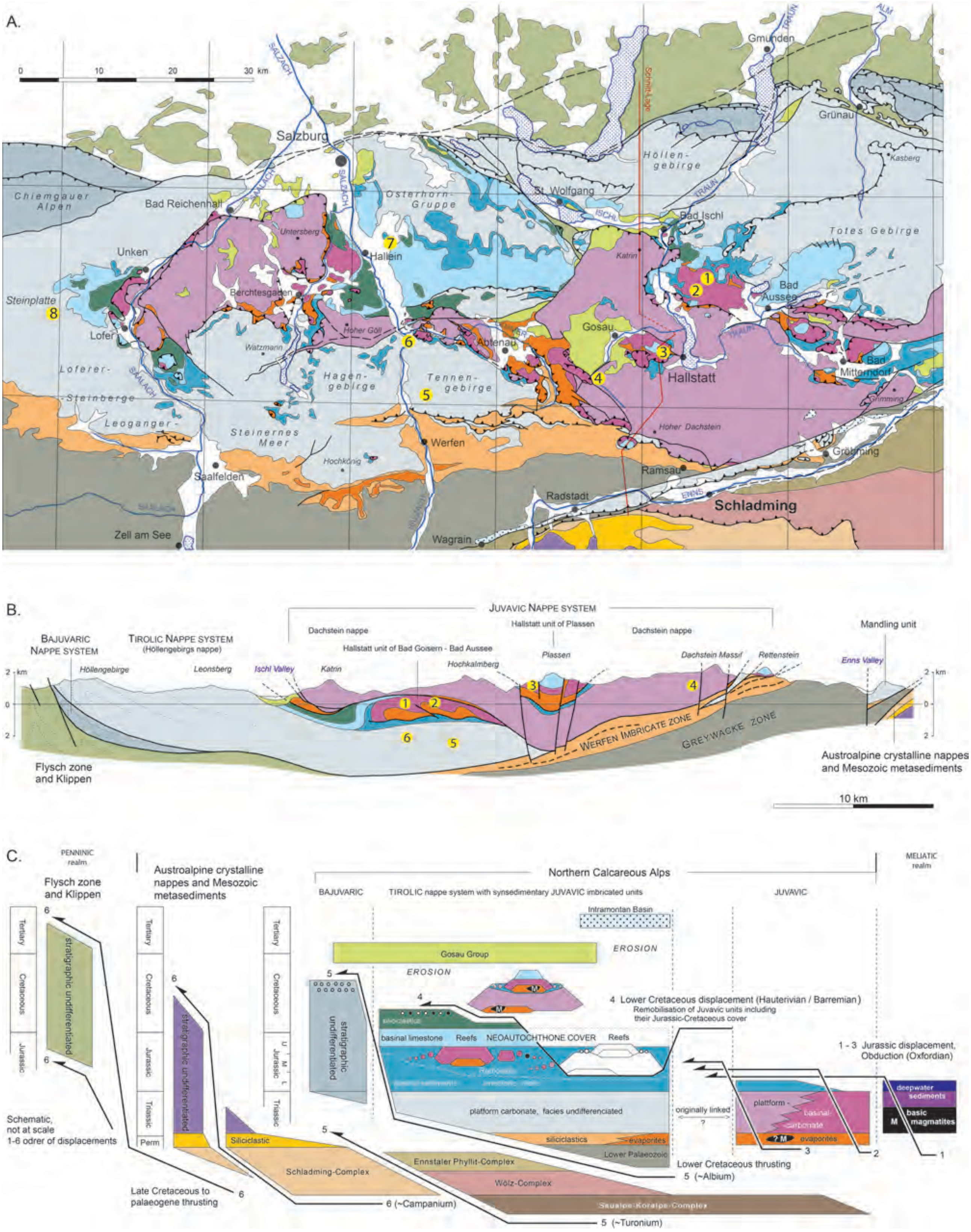


Fig. 4: The Dachstein region geology and evolution (from MANDL 2000): A) Geological map of the Salzkammergut region with visited localities. B) Cross section of the nappe complex in the Salzkammergut region with visited localities. C) Interaction of sedimentation and tectonical displacements in the middle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

Alps (Mandl & Ondrejickova 1991, 1993). The Wetterstein platforms in general show a platform progradation over the adjacent basinal sediments until the early Carnian. 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 intraplatform 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 event is called the Carnian Pluvial Event (e.g., Hornung et al. 2007). As the sea-level began to rise in the late Carnian, carbonate production increased, 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.

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 characterizes the eastern sector of the Northern Calcareous Alps. 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 (Locality 4) are connected by the allodapic Gosausee Limestone to the Pötschen Limestone of the Hallstatt facies realm. The Hallstatt Group shows a great variability of variegated pelagic limestones (Locality 1 and 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 6) close to the reefs (Locality 5) 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 9 and 10), which was bordered by Rhaetian reefs (Steinplatte (Locality 8) and Adnet quarries (Locality 7)). 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. 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 northeastern most nappes of the

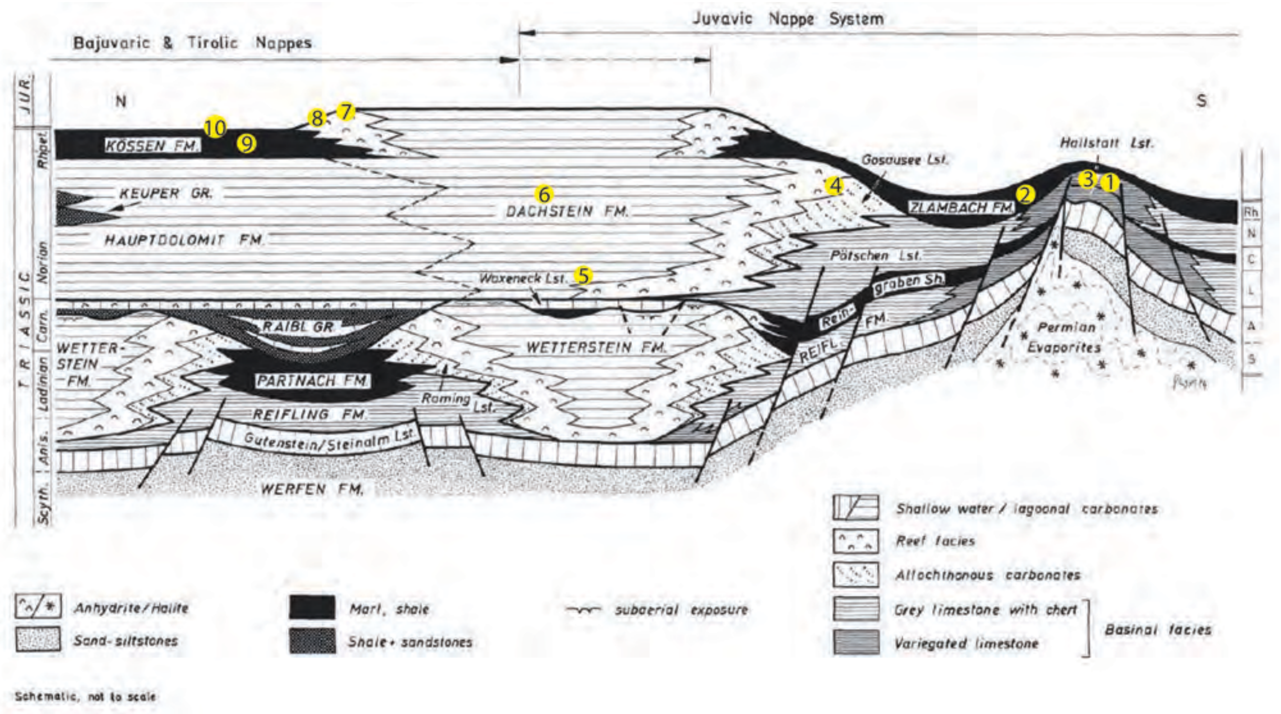


Fig. 5: Triassic stratigraphy of the Northern Calcareous Alps, middle sector (from Mandl 2000). Numbers correspond to visited locality.

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 synsedimentary 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:

- The Dachstein Platform with an initial reefal and prograding backreef development (Locality 5 Tennengebirge), a lagoonal development (Locality 6), its late progradational phase (Locality 4 Gosausee), and northern terminal fringing reefs (Locality 7 and 8) .
- The Zlambach facies between the Dachstein platform and the Hallstatt facies realm (Locality 2).
- The Hallstatt facies realm (Locality 1 Leislingkogel and Locality 3 Steinbergkogel).
- The intraplatform Eiberg basin north of the Dachstein platform (Locality 9 and 10).

2.3.2. The Dachstein facies

During Late Triassic times, the passive continental margin of the northwestern 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). The type locality of the Dachstein limestone is the Dachstein Massif in the southern Salzkammergut region (Figs. 4, 5) that consists of cyclical bedded lagoonal limestone with a south- and southwestward 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). 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 (Locality 5) 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", which grades toward the north by an increase of intertidal dolomites into the Hauptdolomit facies (Locality 6). In the central and eastern sectors of the Northern Calcareous Alps, the cyclic, metre-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 3.2.4. 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 summarized 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. This Gosausee reef likely represents part of the same barrier reef system that sourced the Gosaukamm reef debris (see further discussion in section 2.2.2) 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 characterized by carbonate-clastic sediments, which were derived from the platform, as well as from the slope. These sediments are summarized 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 southwestern slopes of the Gosaukamm. Details of sedimentology 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

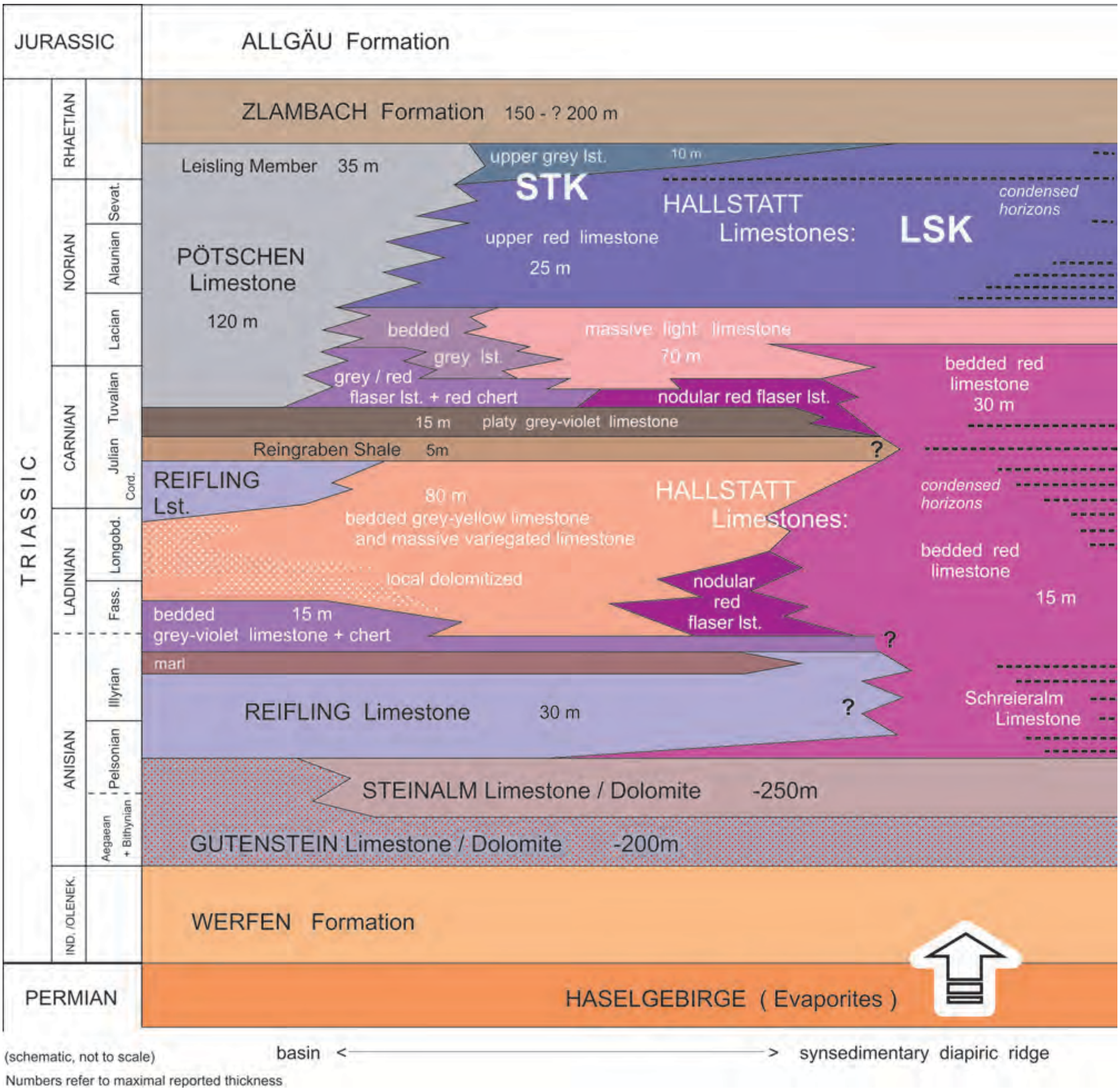


Fig. 6: Lithostratigraphy of the Hallstatt Triassic (from Mandl 2000). STK = Steinbergkogel, LSK = Leislingkogel.

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 8) and the Adnet reef (Schäfer 1979, Bernecker et al. 1999, Reinhold & Kaufmann 2010, Locality 7) developed. These Rhaetian reefs (‘Oberrhät-riffe’) 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 et al. 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 Rhaetian terrigenous event of the Zlambach Formation ended the former pelagic carbonate deposition throughout the Hallstatt facies (Fig. 5) 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. Ammonoids (*Choristoceras haueri* Mojsisovics, *Ch. marshi* (Hauer)) occur within the autochthonous beds. The microfacies of Zlambach limestones is characterized 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 (Boltz 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) where patch reefs may have originally growned, producing 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 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 (Fig. 6). 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) and the Salzberg Facies (variegated Hallstatt limestones, Locality 1 and 3) have lateral transitions which can be demonstrated at nearly each stratigraphic level (Fig. 5).

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, 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 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 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 (Figs. 1, 2). It was bordered to the southeast by the Dachstein Lagoon and locally with fringing reefs (e.g., Steinplatte and Adnet, 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 9). 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 10). 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). 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). 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. The Hallstatt and Zlambach facies

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 facies is of particular importance for questions of primary producers (nannoorganisms) 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 in a deep marine setting. The Leislingkogel section (~50 m) documents an overall Norian accumulation rate of 2-3 m per million years. The proposed GSSP section at Steinbergkogel exposes 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 magnetostratigraphy, allow for a multistratigraphic event correlation of the Norian-Rhaetian boundary. The Zlambach facies, 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 Schladming along state road 320 and 166, we will go first to Leislingkogel (Fig. 7). We will take a

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

small mountain road to the east in St. Agatha just before Bad Goisern. From the small forest road going to Halleralm and Sandling, we will have a short walk (400 m distance, 100 m elevation). Coming down from outcrop 1 we will stop along the road to look at the Zlambach Formation (Locality 2). We will drive through Hallstatt and go west along another mountain road to an old mine for the Norian/Rhaetian boundary. If the timing allows, we will stop at the scenic Hallstatt village before going to Gosau where we will spend the night.

3.1.2. Locality 1: Leislingkogel

This is one of the classical Hallstatt facies outcrops of the Salzkammergut and is mainly Norian with a Rhaetian top. This site is located at a small un-named summit to the south of Raschberg at coordinates N 47°38’46,2’’ E 13°41’59,4’’ altitude 1125 m (Fig. 8). It was recently studied by Leopold Krystyn, Philipp Heilig and Christian Fleis (unpublished data) and exposes three of the typical Hallstatt lithofacies of Schlager (1969):

- Massiger Hellkalk (= massive light limestone): Irregularly thick bedded to massive micritic limestone up to 70m thick. Colour predominantly white, light grey, or pink. Early Norian in age.
- Hangendrotkalk (= upper red limestone): Platy to nodular bedded biomicritic limestone with mostly strong bioturbation pattern. Locally flaser-structure can be found. Subsolution patterns occur frequently with

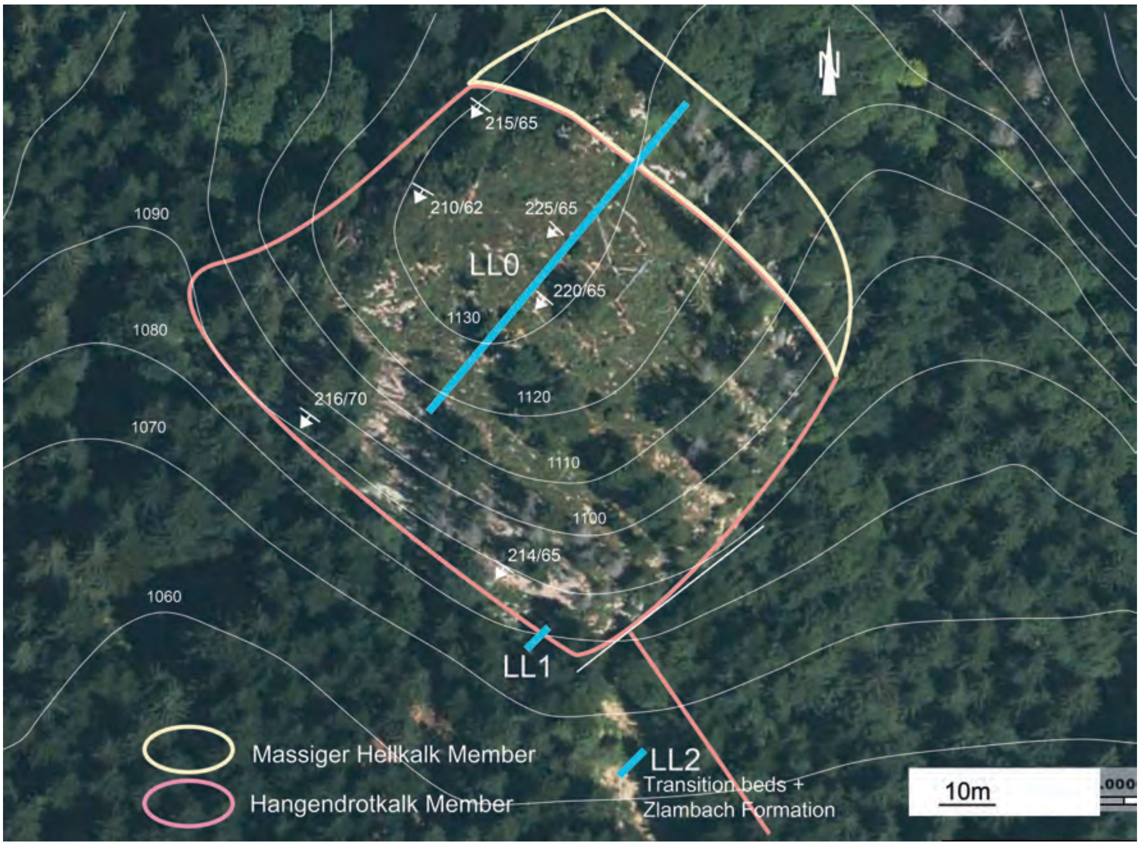


Fig. 8: Aerial situation of the Leislingkogel locality with the three sub-sections LL0, LL1 and LL2 and the main lithologies.

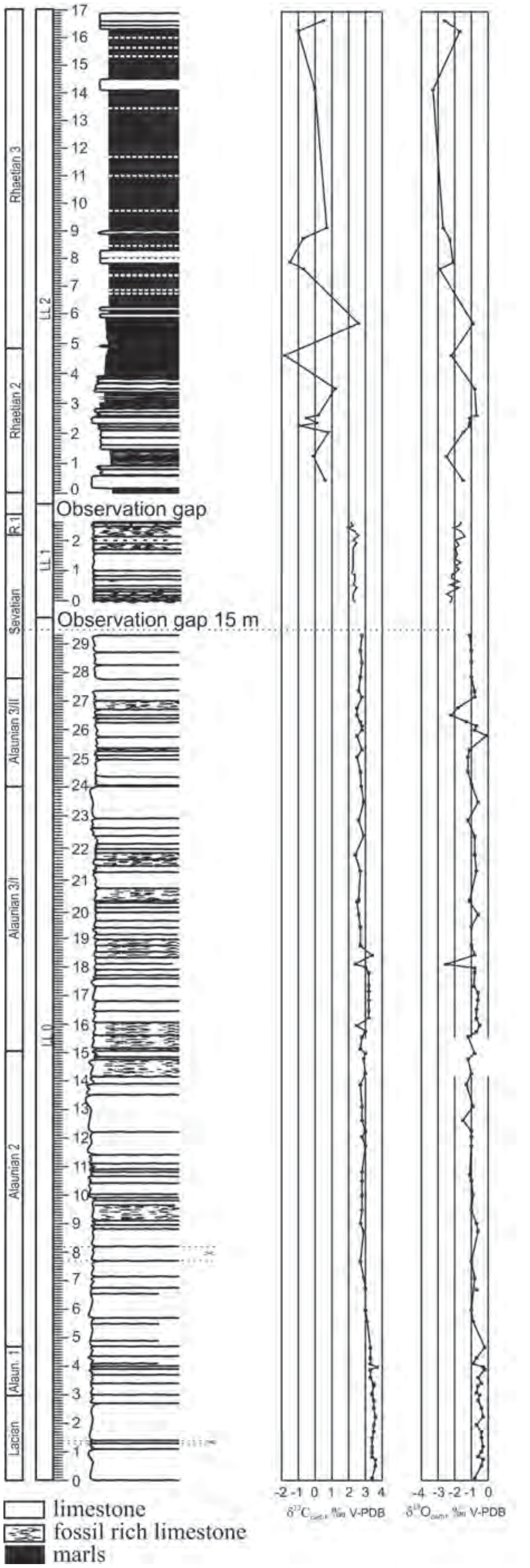


Fig. 9: Leislingkogel section with carbon and oxygen isotope (Heilig, unpublished data).

thinning of individual beds in the direction of a submarine ridge. Late early Norian to early Rhaetian in age.

- Hangendgraukalk (= upper grey limestone) is regarded as a lateral equivalent of the Hangendrotkalk; apart from the colour, this type is slightly argillaceous and usually thinner bedded. It replaces the Rhaetian portion of the Hangendrotkalk.

According to Schlager (1969) additional types of transitional characters may occur between the basic Hallstatt lithotypes caused by variations in colour, bedding, flaser structures, and content of clay minerals, as well as content and colour of chert-nodules/layers. The mean sedimentation rate has been estimated at 3 m per million years over a period of 40 Ma, from Middle to Late Triassic. At Leislingkogel (Fig. 9) only the uppermost 17 m of the Hellkalk member are exposed containing a thin *Halobia* bearing lumachelle at the base. The Hangendrotkalk member (Fig. 10) rests disconformably on the Hellkalk developing a thickness of 35 m. Of those the lower 5 m represent two ammonoid zones (*J. magnus* and *C. bicrenatus* Zone) and are highly condensed, forming first a massive and then several decimetric beds rich in subsolution relicts and in part ammonoids. The microfacies (Fig. 11) shows strongly amalgamated wackestone fabric rich in often iron-oxide coated bio- and corroded intraclasts (subsolution relicts). The remaining middle (*H. hogarti* and *H. macer* Zone) and late Norian (*S. quinquepunctatus* Zone) part is approximately 30 m thick and consists of thick-bedded, macroscopically mostly fossil-poor bioclastic wackestone with varying content of echinoderms, juvenile ammonoids and filaments (juvenile halobiid bivalves). Certain late Norian beds are enriched in densely packed shells of the pelagic bivalve *Monotis* and the enigmatic hydrozoan *Heterastridium*. early Rhaetian rocks are represented by 1 m of bioclastic wackestone (Hangendgraukalk member) rich in cephalopods (*P. suessi* Zone) followed by 4 m of gray nodular limestones of middle Rhaetian age with a mudstone texture transitional to the overlying Zlambach Formation. The latter represents a late Rhaetian age by presence of the ammonoid *Choristoceras*; it is exposed for 20 m and built by dark clayey marls including rare gray limestone intercalations with a radiolarian bearing mudstone microfacies.

Fig. 10: Steeply SW-deeping middle Norian thick bedded Hallstatt Limestone (Hangendrotkalk Member). Middle part of subsection LLO.

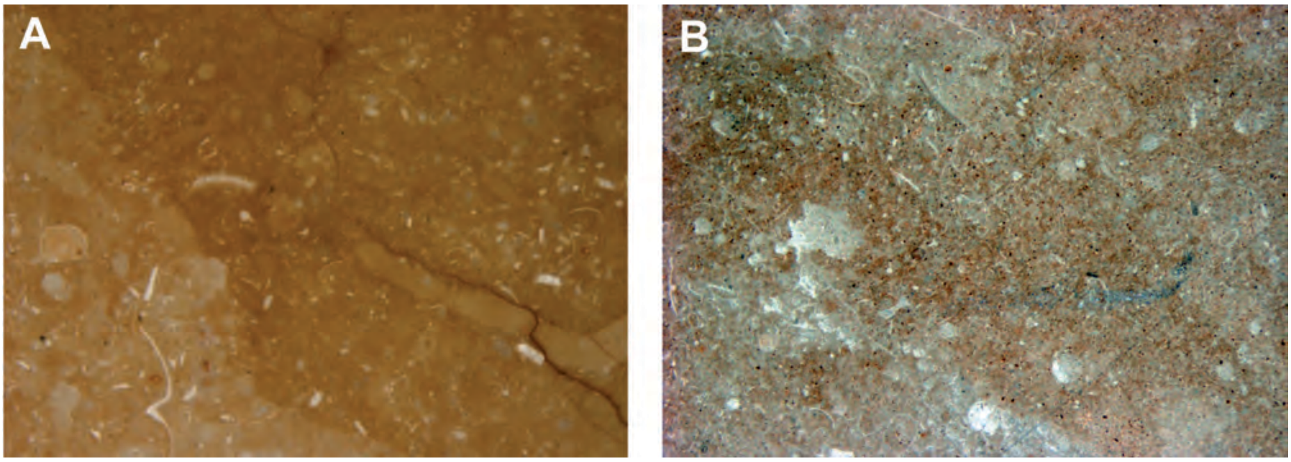


Fig. 11: Microfacies of the Hangendrotkalk Member: A) Bioclastic wackestone rich in filaments (bivalve) and calcisphere (sample LL03, Section LLO). B) Highly bioturbated bioclastic wackestone with microgastropods, filaments, corroded shell fragments, and echinoderms (sample 12, section LL1). Magnification 6x.

The macrofauna contains ammonoids (*Arcestes, Cladiscites, Placites, Didymites, Distichites, Parathisbites, Paracochloceras*, etc.), nautiloids, bivalves (*Halobia, Monotis*), crinoids and hydrozoans (*Heterastridium*). The carbon isotope record displays a very stable curve all along the section with some variations only in the Zlambach Formation (Fig. 9).

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 tectonized section but is unfortunately difficult to access. Three closely neighbouring outcrops (Fig. 7) of the Grosser Zlambach (47°37’47,5"N/13°40’02,7"E, Figs. 12 and 13) 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 (Fig. 13A, B) dominates here clearly the allochthonous carbonate sedimentation. An upward increase thickness of the marls is characteristic. 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 shallow or reef environments (corals, dasycladacea, solenoporacea, sponges, bryozoans, hydrozoans, bivalves, brachiopods, ammonoids, gastropods, ostracods, foraminifers, echinoderms, radiolarian and problematica, Fig. 13F-H). The autochthonous limestones show a rare fauna (some foraminifers, ostracods, conodonts, ammonoids, radiolarians, Fig. 13D, E). 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 upper 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.

3.1.4. Locality 3: Steinbergkogel or the Norian/Rhaetian GSSP proposed section

The Steinbergkogel is a small, unnamed summit (1245 m above sea level) 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 salt mine gallery Ferdinandstollen at an altitude of 1140 m (Fig. 7). 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 (Fig. 14). Alternatively one can reach the Steinbergkogel directly from Hallstatt 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 an 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. Most of the classical Steinbergkogel ammonoid fauna (Mojsisovics 1873-1902) may have 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. 15). 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-

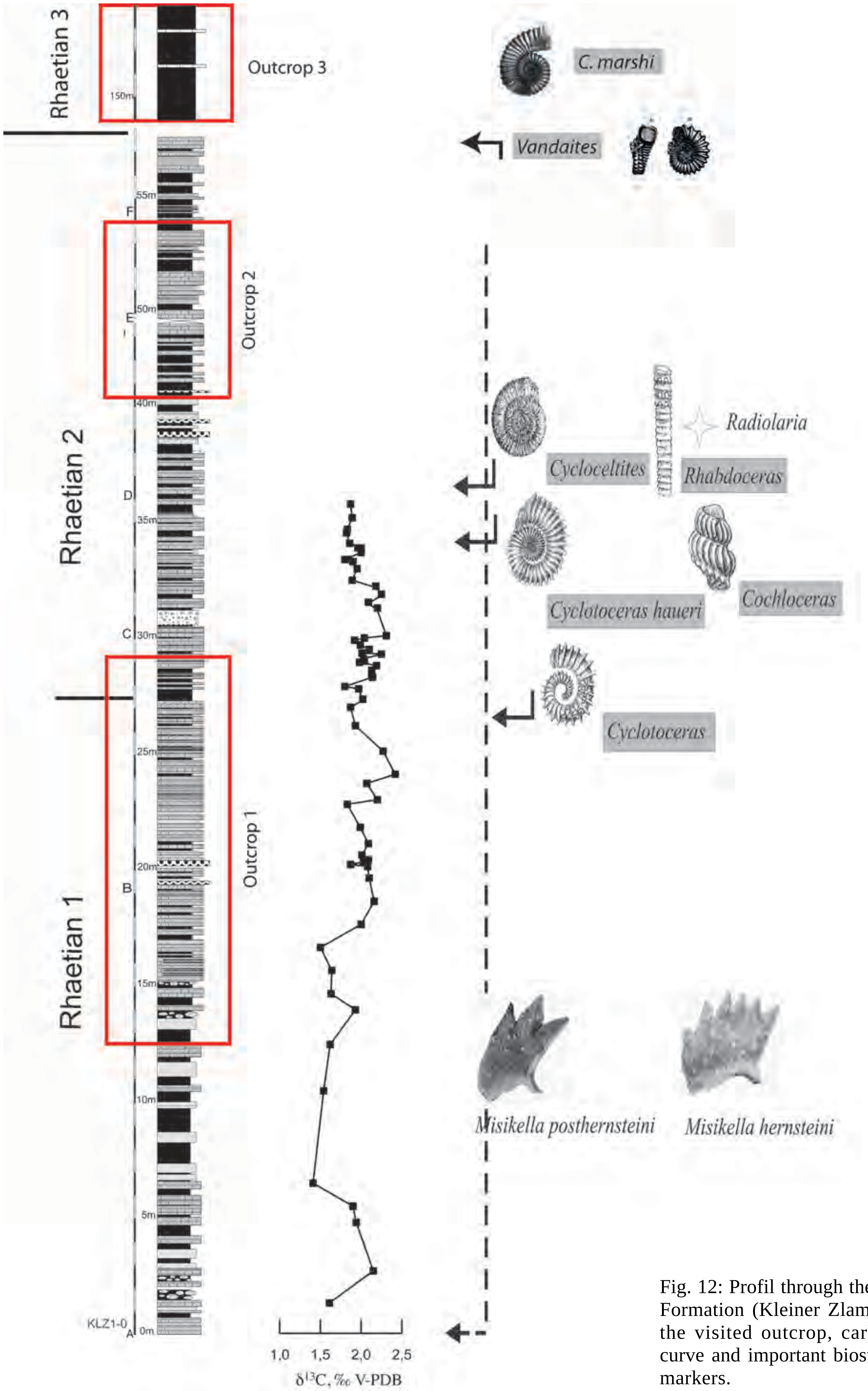
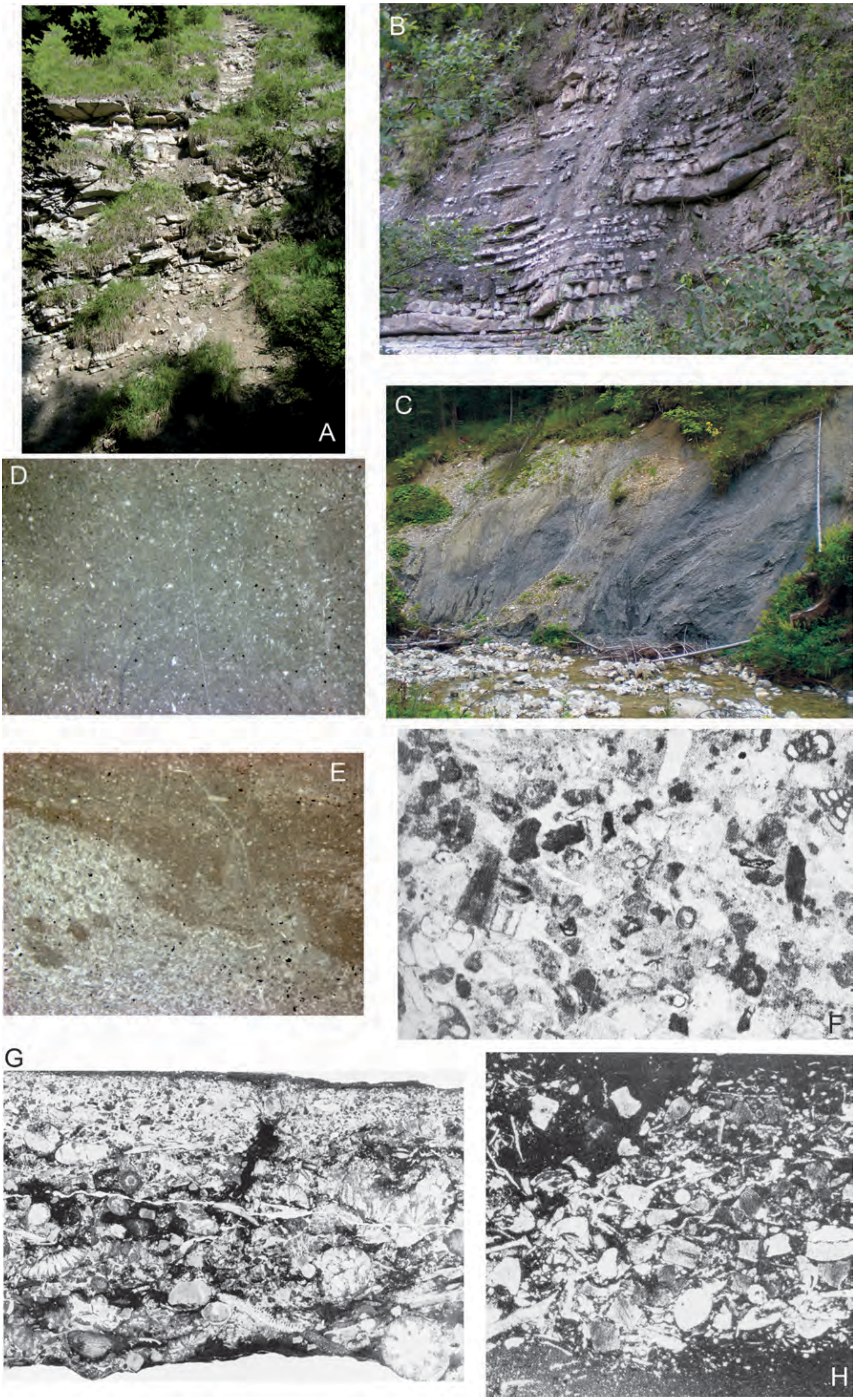


Fig. 12: Profil through the Zlambach Formation (Kleiner Zlambach) with the visited outcrop, carbon isotpe curve and important biostratigraphic markers.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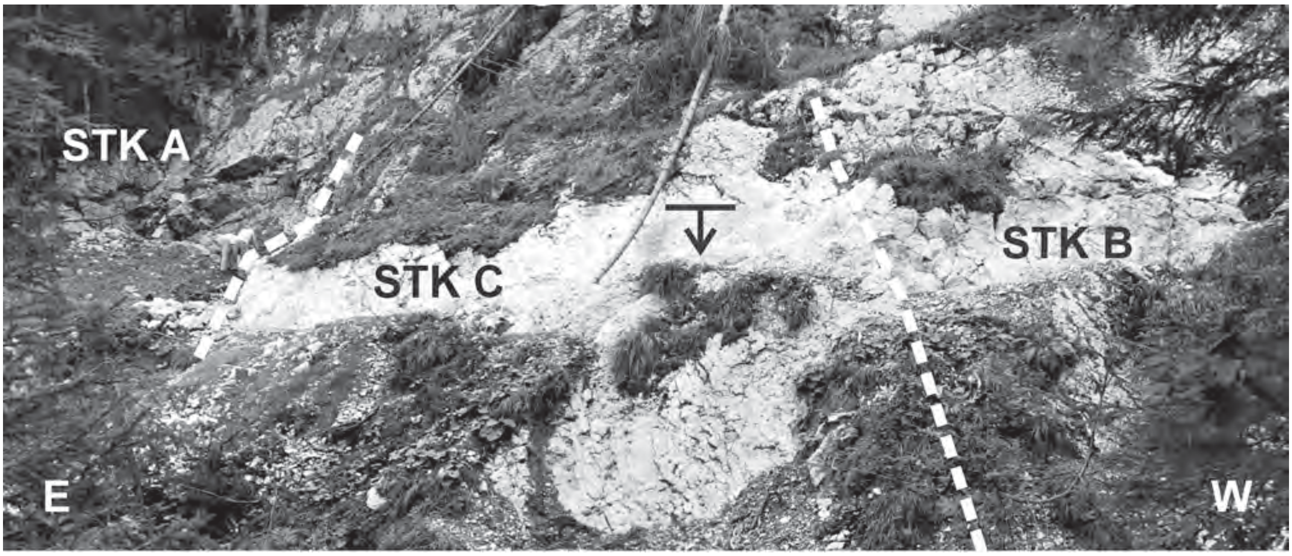


Fig. 14: Steinbergkogel quarry with sections A, C and B.

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 (Fig. 6) 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. 15) contain several layers with *Monotis salinaria*, *Heterastridium*, ammonoids, and conodonts that allow a cross-correlation with the quarry sections (Fig. 16).

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. 14, 15). About 20 beds have been studied in detail, numbered from bottom to top as 103 to 122 (Fig. 17). 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*. 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. 17). 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 the lower Rhaetian considerably (Krystyn et al. 2007a) (Fig. 18). 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 spicula, as well as poorly-preserved radiolarians and benthic foraminifers in different proportions (Fig. 19).

Fig. 13: A) Grosser Zlambach, section GZ1 - Zlambach Formation, Lower Member. Alternation of limestone and marls with distinct slumping interval (early Rhaetian). B) Grosser Zlambach, Section GZ1- 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 autochthonous wackestone highly bioturbated (Zlambach Formation Lower Member, sample L5 GZ1). F) Foraminiferal bioclastic packstone. Characteristic allochthonous 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 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).

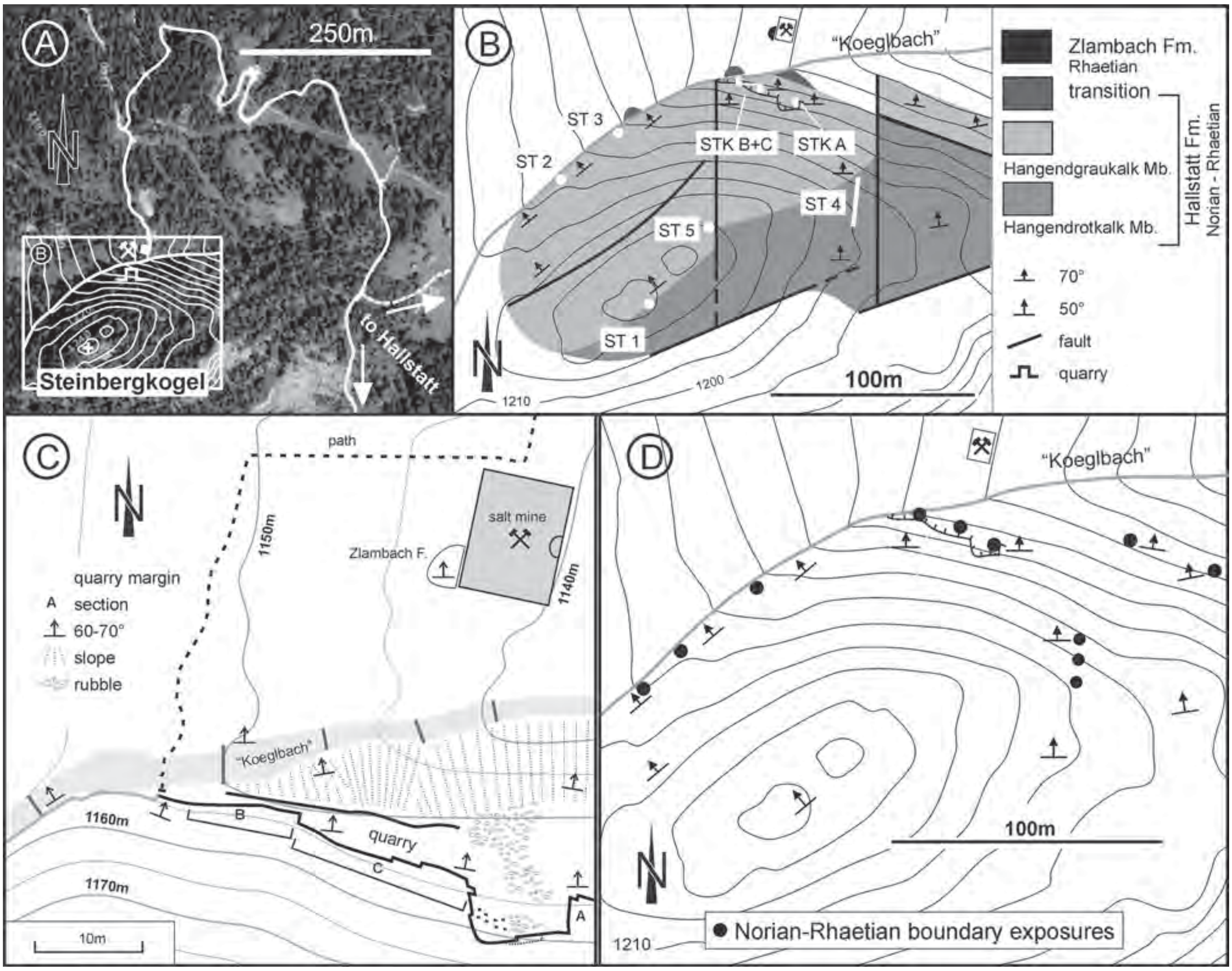


Fig. 15: Detailed Steinbergkogel maps: A) aerial view, B) geology with sections and fossil localities, C) Steinbergkogel quarry and D) location of Norian-Rhaetian boundary exposures.

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.

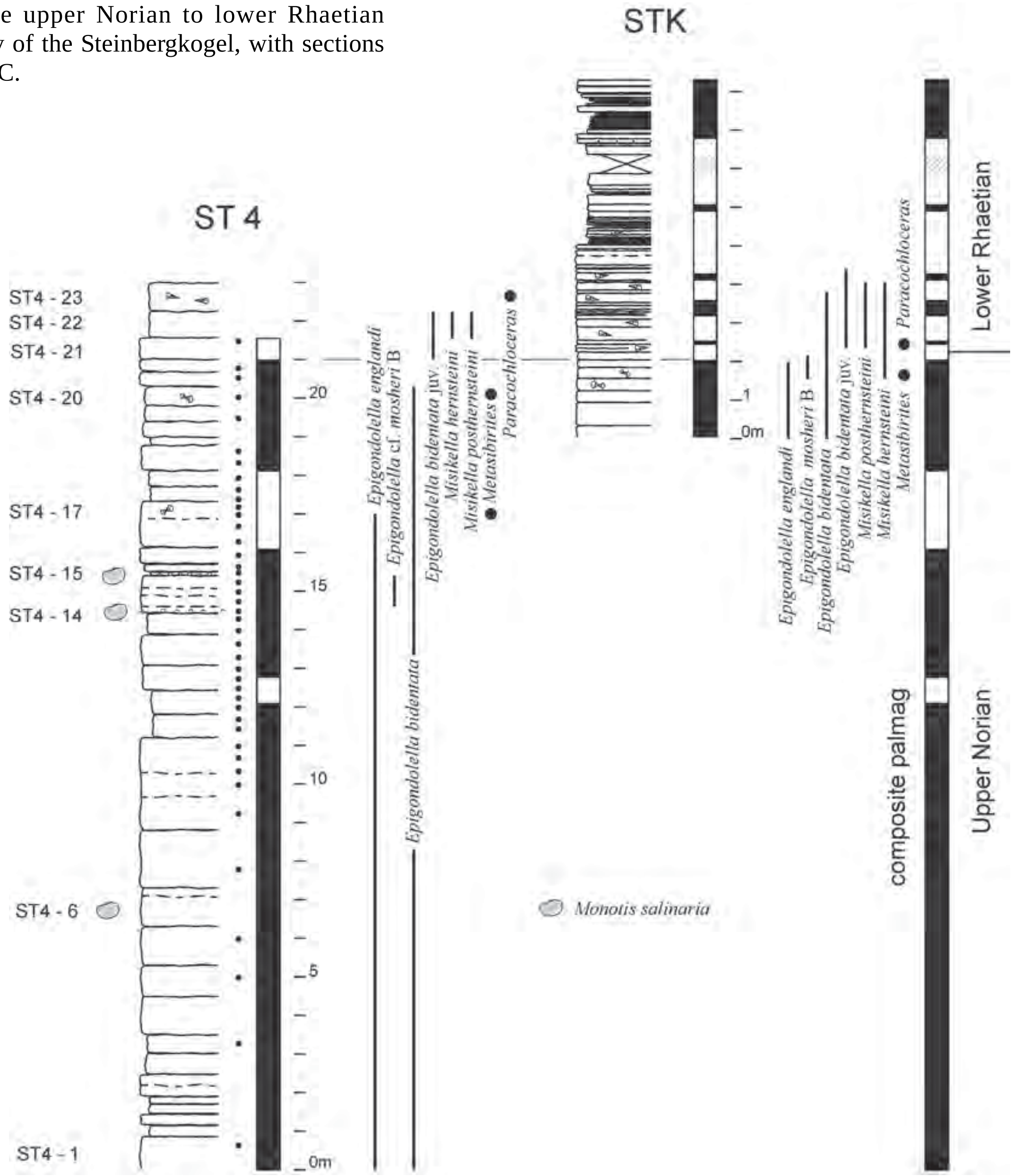
To achieve stratigraphically reliable conodont ranges at least 10 kg of limestone have been dissolved from each bed between 108 and 112. This intense search has led to p-element recoveries of 50-100 specimens per sample, with *Epigondolella bidentata* dominating up to bed 110 and replaced by a *Misikella* dominance above. *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. Bed 111A marks the FAD of *M. posthernsteini*, as phylogenetic successor of the fore-mentioned species, responsible for the 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. The initial infrequence highlights the problem of how to recognize the FAD of *M. posthernsteini* in biofacially less favourable environments 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, characterized 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 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*. Normal sized *Epigondolella bidentata* becomes rare in Zone 2 and is usually replaced by juveniles resembling the genus *Parvigondolella*.

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). Combining faunal records permits the discrimination of two ammonoid zones (Fig. 18), a lower with *Metasibirites* (bed 107 to 108) 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. A remarkable evolutionary and biostratigraphically useful change is recorded in the family Arcestidae with several species newly appearing closely below the Norian - Rhaetian boundary. 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, p. 359) and almost restricted to the Hangendrotkalk Member where they appear in several layers within an interval of 10-15 m (Fig. 16). 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

Fig. 16: Composite upper Norian to lower Rhaetian magnetostratigraphy of the Steinbergkogel, with sections ST4, STK A and B/C.



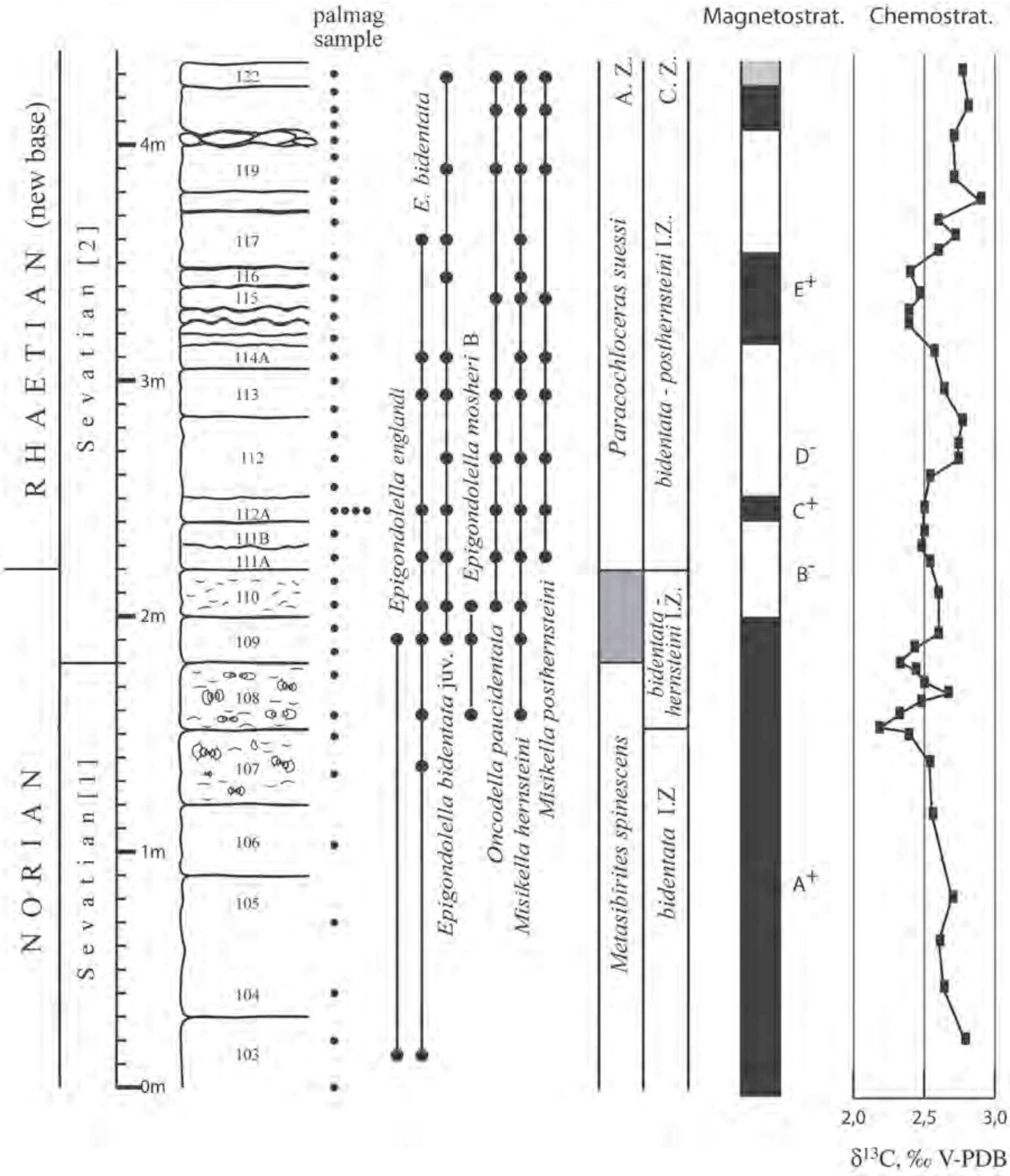


Fig. 17: Integrated bio-, magneto- and chemostratigraphy of GSSP candidate for the Norian-Rhaetian boundary section Steinbergkogel A. Note: Sevatian 1 and 2 refer to previous upper Norian classification (from KRYSTYN et al. 2007b).

STK-B/C (Fig. 18). This is 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*, in a predominantly reversed polarity subchron (KRYSTYN et al. 2007a, b), 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.

3.2. The Dachstein Reef, its lagoon and its margin

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 (ooid 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.

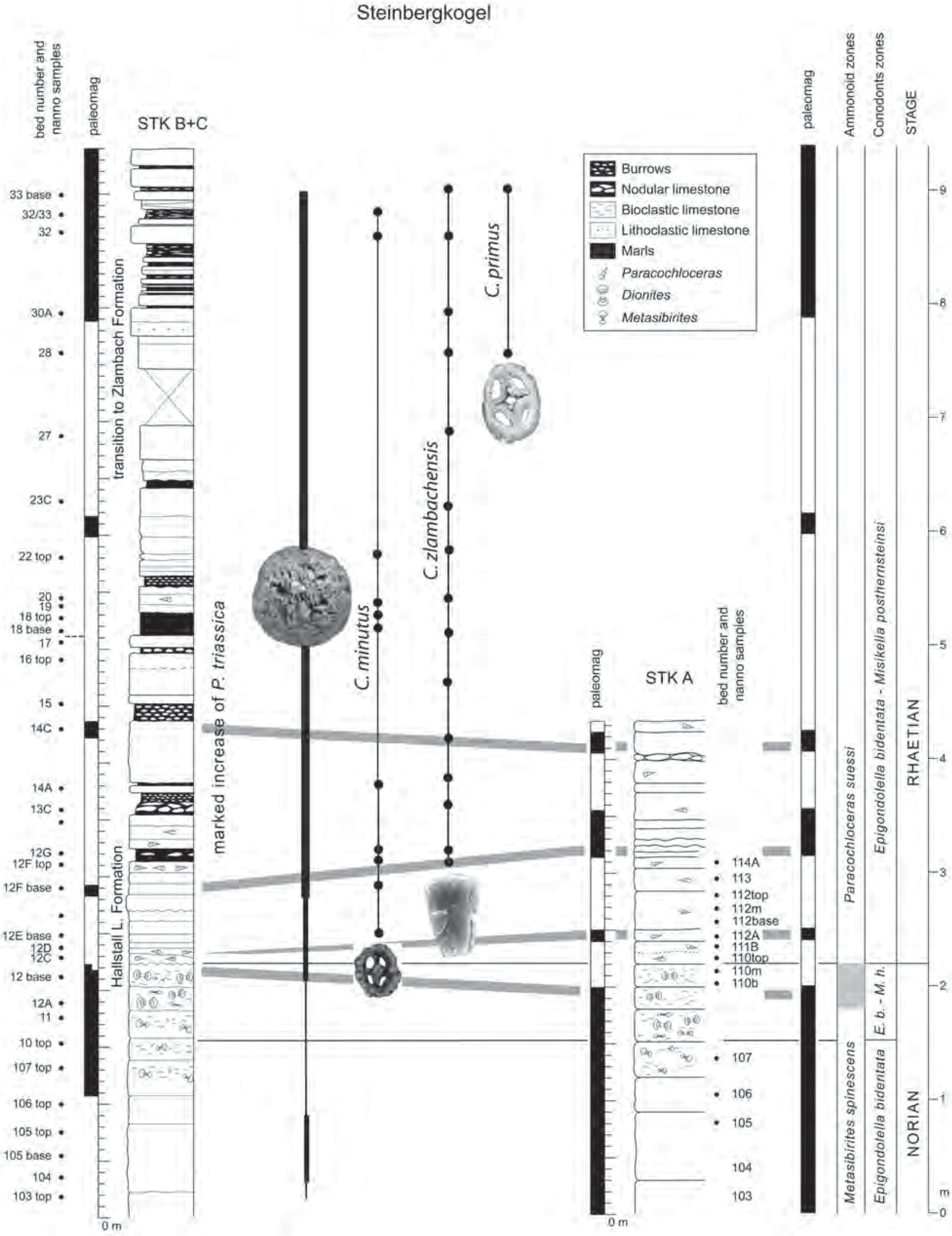


Fig. 18: Steinbergkogel A and B + C section, GSSP candidate for the Norian-Rhaetian boundary. Schematic lithology, sample location, magnetostratigraphy (black is normal polarity, white is reversed polarity) and most important calcareous nannofossil bio-events (from Gardin et al. 2012).

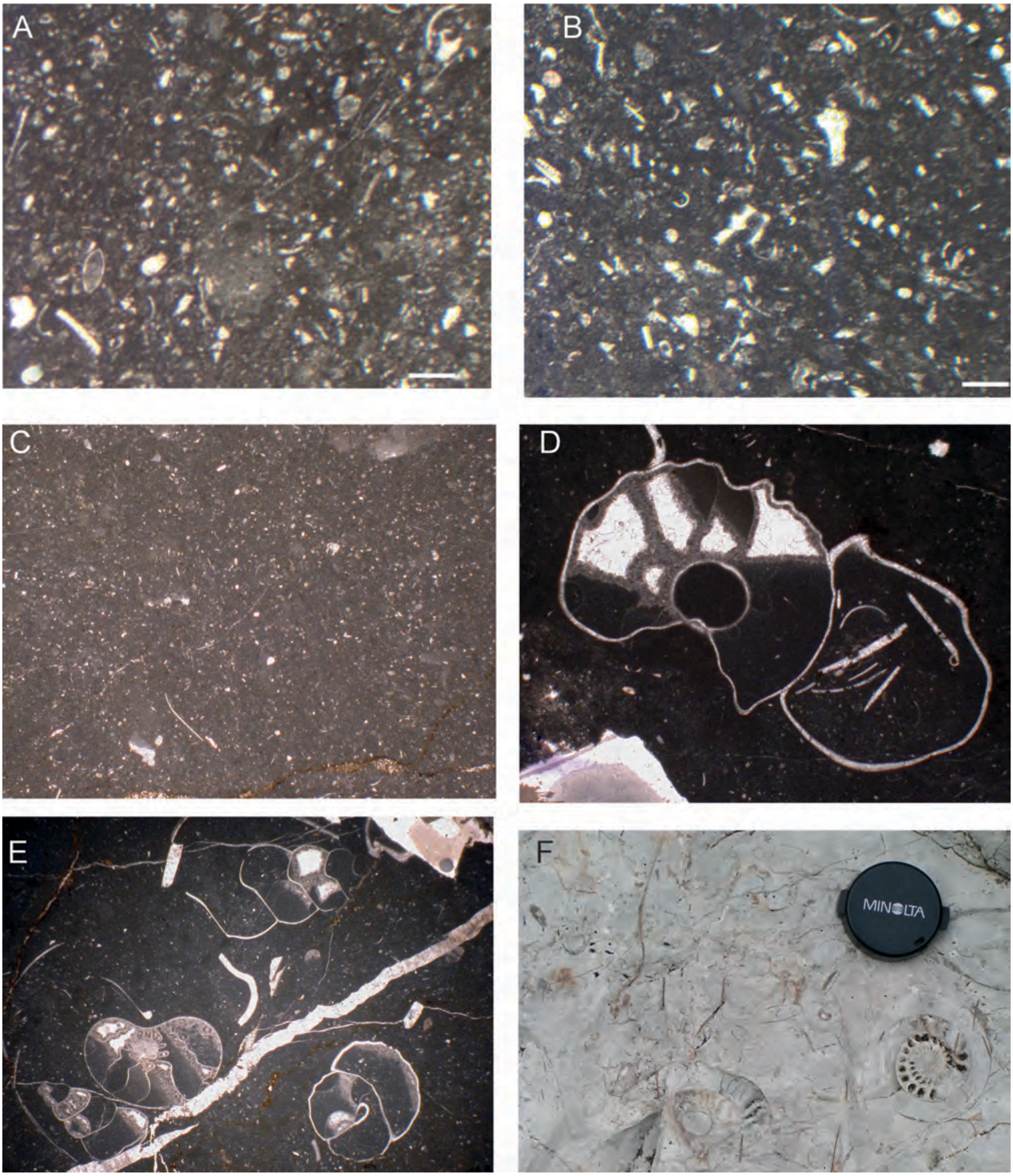


Fig. 19: A) and B) Bioclastic Wackestone with predominantly echinoderms and shell fragments (Norian, sample STK A/105, scale bar: 100 µm, Gardin et al. 2012). C) Profil bioclastic wackestone with predominantly sponge spicules and radiolarians (Rhaetian, sample STK B/12E, magnification x 5). D) Bioclastic wackestone with cross section through geopetaly filled Ammonoid (*Metasiberites*, approximately one centimetre) with geopetal filling (latest Norian, sample STKC/11). E) Wackestone with silicious sponge spicules and cephalopods (trochospiral *Paracolocheras* approximately one centimetre - *Megaphyllites* rich in geopetal fillings (earliest Rhaetian, sample STKC/12). F) Bioclastic limestone surface with multiple cephalopods cross-sections (Bed STKB/10, scale 5 cm).

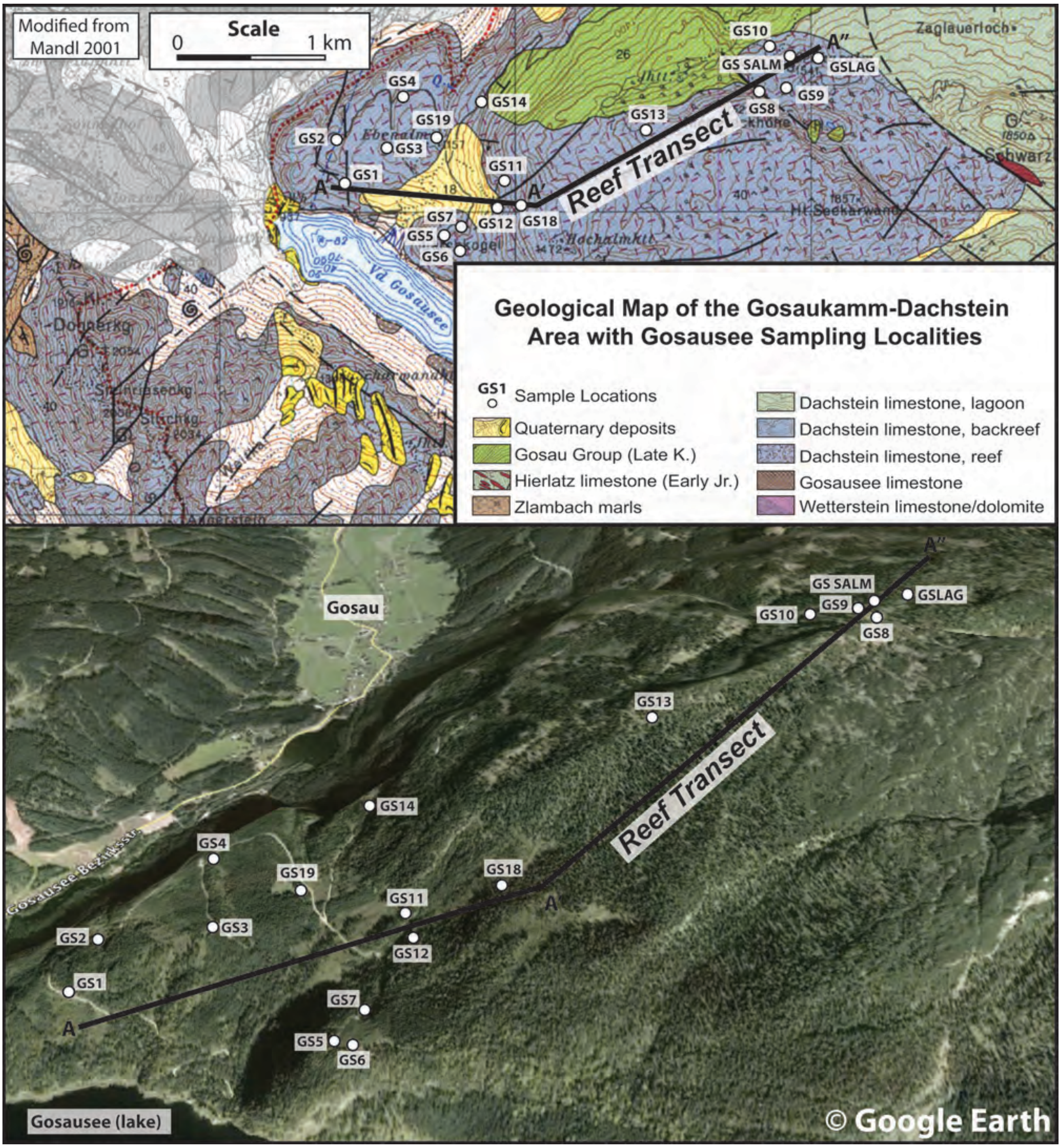


Fig. 20: The Gosausee margin of the Dachsteingebirge and sample localities from this study (transect A-A'-A" refers to reef cross section). A) Geological map of the Gosausee region, (modified from Mandl 2001), with sample localities. B) Google Earth image of the Gosausee margin of the Dachsteingebirge, forest road visible.

3.2.1. Route

From Gosau (Fig. 7) 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. From here, we will drive up a forest road taking us from the lake, up the Dachstein. We will stop at the base of the Gosausee reef (Fig. 20), 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 through the Pass Gschütt to the small town of Werfen. From there we take a 5 km road to the "Eisriesenwelt" car-park. Close to the lower cable car station we will view the initial reef facies. Coming back we will take the national road in direction of Salzburg. 30 km North of Werfen we will stop at Pass Lueg, located along the street. The rest of day 2 is described in chapter 3.3.1.

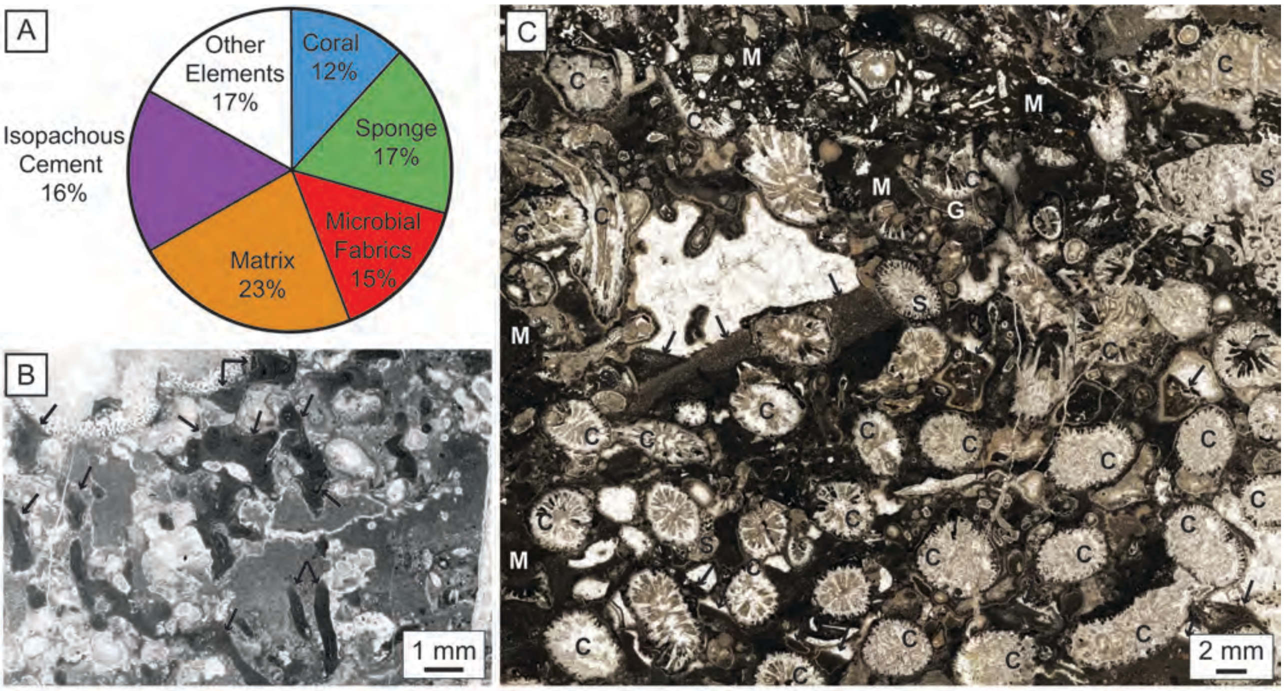


Fig. 21: The Gosausee fore reef facies. A) Fore reef facies composition based on mean values from point counting data (GS1, GS2, GS3, and GS4). B) "*Tubiphytes*" epibionts (best examples indicated by arrows), sample from site GS1, thin section photomicrograph (plane polarized light). C) Coral pillarstone 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 polarized light).

3.2.2. Locality 4 Gosausee: The Dachstein margin at Gosaukamm

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), 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. 20). Reefal units (Dachsteinriffkalk) are specifically well exposed along the forest road and are well constrained biostratigraphically; at the base of the Dachsteinriffkalk (approximately site GS1, Fig. 20), 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 *Oncodella 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 with pelagic Donnerkogel limestone (Donnerkogelkalk).

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. submitted a): the fore reef (Fig. 21), 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) characterize the deepest fore reef (Fig. 22), particularly site GS1 (47° 32.121' N, 013° 30.044' E, 1006 m above sea level) where we will stop (Fig. 21). As the reef shallows, muddy sediments decrease in abundance and are replaced by microbial fabrics, corals, and cements (Fig. 22). At GS4 (47° 32.370' N, 013° 30.469' E, 2190 m above sea level), look for thick cements coating the skeletons, this is typical of sediments from higher in the reef and may indicate that the sediments at GS4 were transported (either by synsedimentary transport of reef blocks, or by later tectonic movement).

At GS19 extremely well preserved coral fragments on the

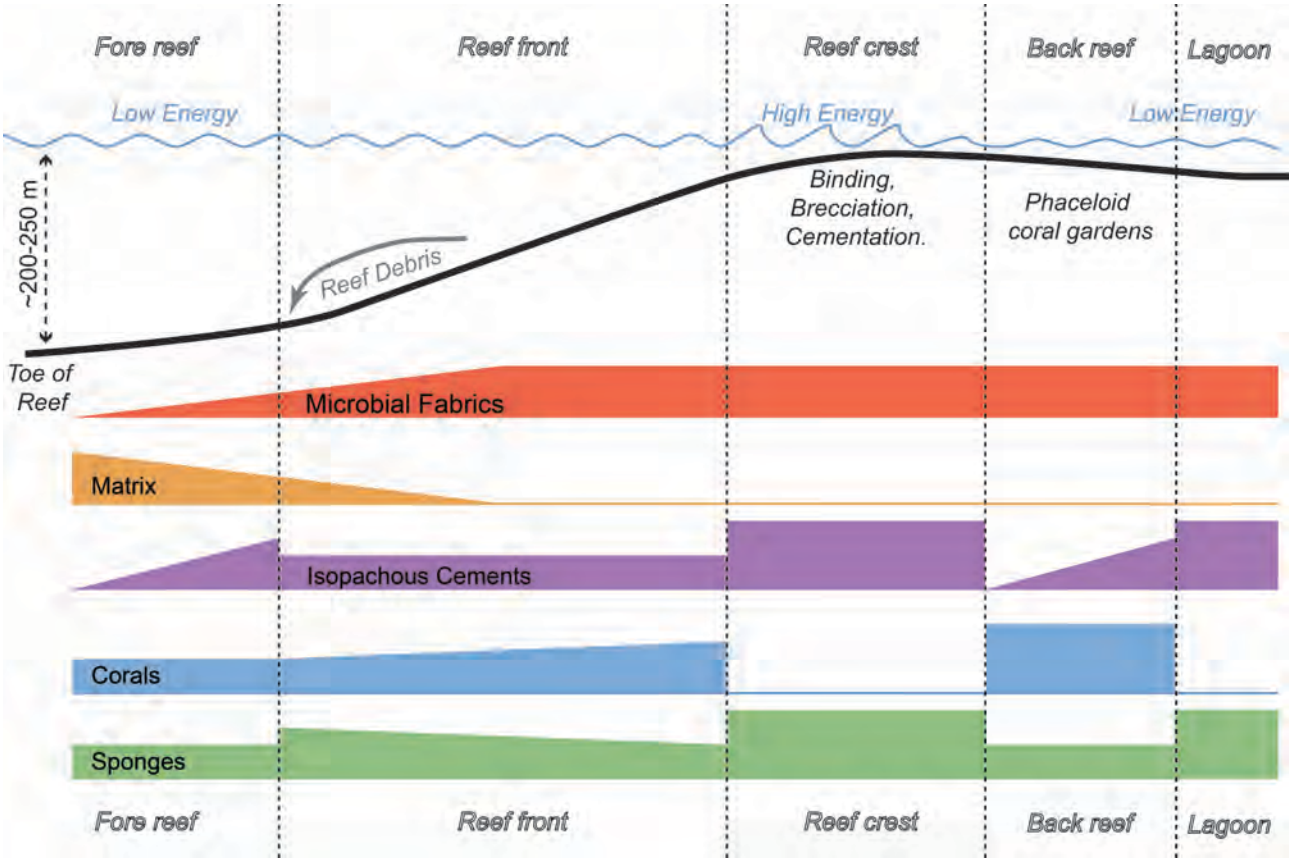


Fig. 22: Idealized transect of the Gosausee reef showing the trends in microfacies composition in different reef facies; fore reef = GS1-4; reef front = GS5-7, GS11-12, GS14, & GS18-19; reef crest = GS8 & GS13; back reef = GS9-10 & GS SALM; lagoon = GSLAG.

karst limestones are typical of the upper reef front (Fig. 23). 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. 20), whereas microbialite-coated phaceloid corals are dominant in the back reef facies (between the fault scarp and the Seekaralm, GS9 and GS10 in Fig. 20), which grades into heavily cemented oncoids or microbial-sponge bindstones of the lagoon (to the northeast of the Seekaralm (Fig. 22). 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. submitted a). 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. submitted a). 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.

3.2.3. Locality 5: Tennengebirge – Eisenriesenwelt. Initial start of the reef

The Tennengebirge is an impressive mountain range belonging to the Stauffen-Höllengebirge nappe of the Tirolicum. Its huge southwestern cliff is mainly made of cyclic meter-sized bedded Dachstein Limestone (Fig. 24). On the Tennengebirge, we will see the initial reef buildups (Site A and B in Fig. 24) overlain by subtidal, near-reefal oncolitic Dachstein Limestone (the base of Seilbahn to its top Fig. 24). The carbonate facies we will see are found on the path to the Werfen Eisriesenwelt cave at the southwestern edge of the Tennengebirge, Salzburg, Austria. The trail leads from the Eisriesenwelt welcome centre (well-bedded dolomites of middle late Carnian (Tuvalian 2) age dated by conodonts, *Paragondolella polygnathiformis* fauna) to the ice cave (Fig. 24).
Site A (fore-reef facies, latest Carnian in age (Tuvalian 3/II), *Gonionotites italicus* subzone of the Tethyan scale) is located between the upper entrance of the mountain tunnel and the wooden bridge. Site B extends from the bridge to just before (~50-100 m) the base of the cable car and is earliest Norian in age (*Guembelites jandianus* zone); the pinnacle reef at site B is just before the trail turns the corner. The path continues up the Tennengebirge and the top cable car station is also early Norian in age, oncolitic, well-bedded member of subtidal reef-near lagoonal facies

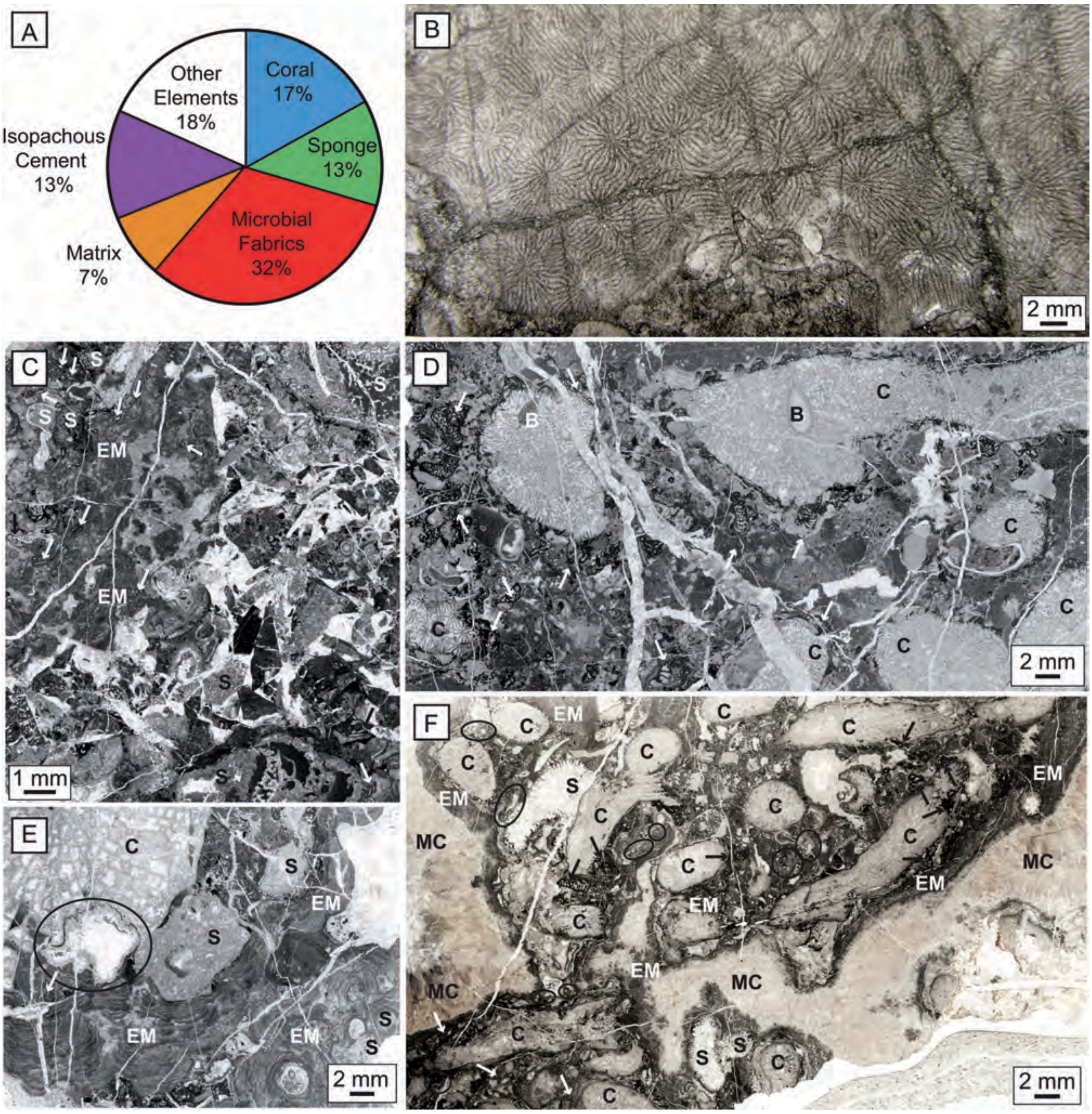


Fig. 23: The Gosausee reef front facies. A) Reef front facies composition based on mean values from point counting data (GS5, GS6, GS7, GS11, GS12, GS14, GS18, and GS19). B) Unnamed thamnasterioid coral (Genus 1) from site GS19. C) Brecciated microbial-sponge bindstone; many different sponges (S) occur 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 polarized 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 polarized 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 polarized 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-coloured marine cements (MC), sample from GS11, thin section photomicrograph (plane polarized light)

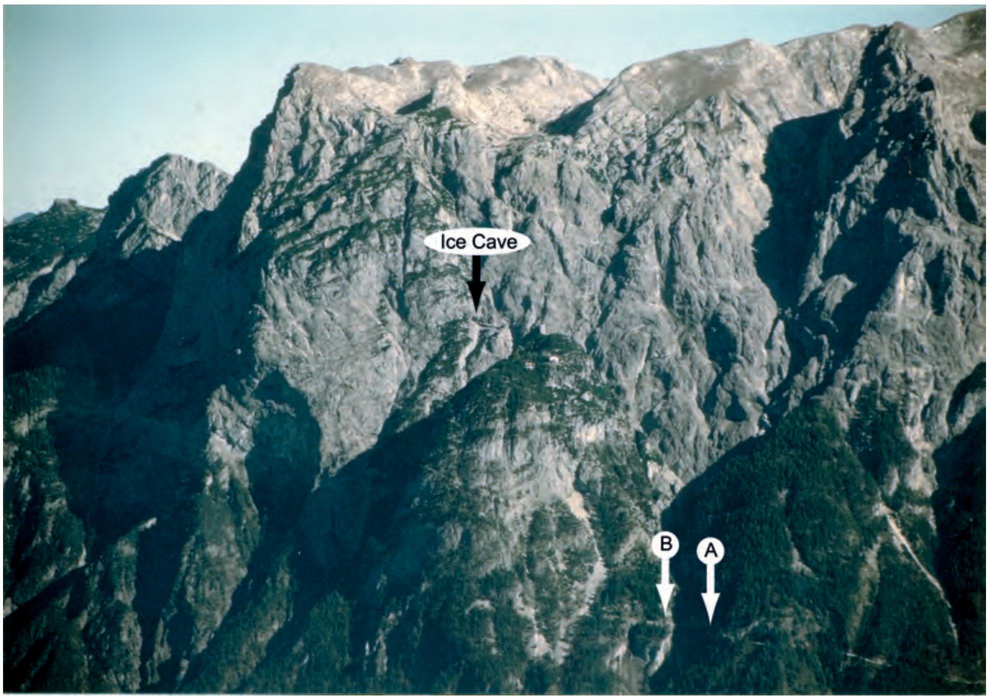


Fig. 24: The Dachstein limestones on the Tennengebirge. The locations of sites A and B and the Eisriesenwelt ice cave are marked with arrows, height is roughly 1.5 km from A to the top of the mountain.

(Martindale et al. submitted b). The Upper Carnian - Lower Norian sediments along the Eisriesenwelt trail represent fore reef to near-reef lagoonal environments with substantial amounts of microbial binding (>35% of samples determined via point counting thin sections).

The core of the small (roughly 10-15 metres wide and 5 metres high), unique pinnacle reef (Fig. 25) is constructed by tall (3-4 m), narrow (<1 m) *Retiophyllia* corals colonies; *R.* cf. *aranea* and *R.* aff. *fenestrata* (Fig. 26). In places it is clear that these colonies initiate in one location and the coral branches that were growing on the sides of the colony only grew ~30-50 cm in length, while the branches on the top of the colony grew ~2-4 m in length. The best coral colony cross sections (box in Figs. 25, 26) demonstrate that the phaceloid branches on the top of the colony grew substantially longer than those that grew on the side of the colony. These "pinnacle" coral colonies are occasionally bored (shape of boring is indicative of lithophagnid bivalves), are usually encrusted by microproblematica (Microtubus communis and "*Tubiphytes*"), sponges (*Celyphia*, *Uvanella*, and Radiomura), microbialite fabrics, and occasionally serpulid worm tubes (Fig. 27), and had several meters of elevation above the sea floor (based on the thick, isopachous cements that can be identified in outcrop). The phaceloid corals appear to exhibit phototropic growth patterns (the phaceloid branches on the top of the

Fig. 25: The pinnacle reef at site B (Lower Norian). Black sketches overlying the photo indicate the approximate size, location, and shape of the phaceloid corals that are visible in outcrop. Field assistant is roughly 2 m tall (roughly 2 m), white dotted box represents the outline of the pinnacle coral in the next figure.

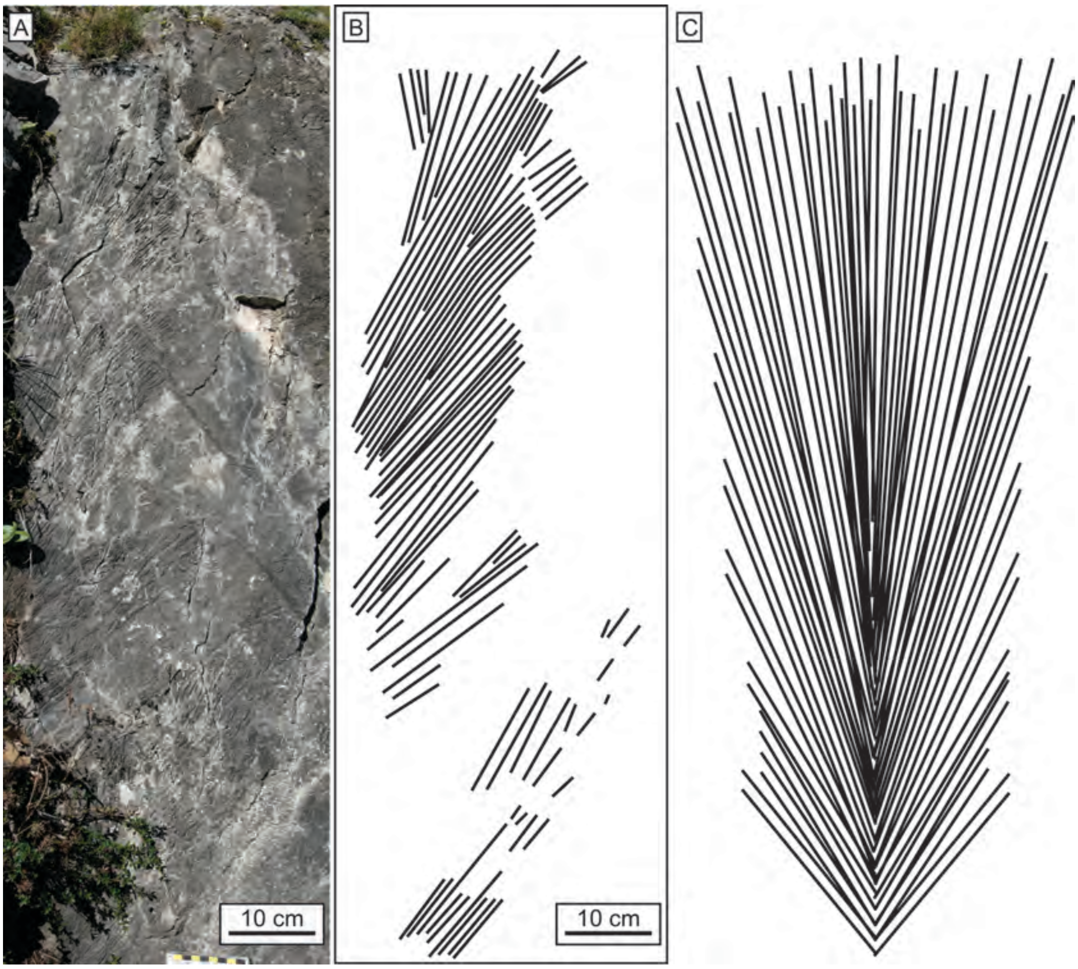


Fig. 26: Detail of a cross section through one of the pinnacle corals at site B (see previous figure for the location of this coral in the pinnacle reef). Note how the upper "branches" of the phaceloid coral are substantially longer than the branches on the side of the colony. A) Cross section through the right half of a coral colony (linear features are the phaceloid coral branches). B) Trace of the phaceloid coral colony, lines represent the phaceloid branches. C) Idealized cross section through a complete pinnacle coral colony (left and right sides).

coral colony grew substantially longer than the branches on the side of the colony, likely because they were better exposed to sunlight). The phototropism exhibited by these pinnacle corals implies that these corals had zooxanthellae symbionts, allowing the portion of the colony exposed to the greatest sunlight to grow faster and better than the rest of the colony. These pinnacle corals also grew near or at the maximum flooding surface of the first Norian 3rd order cycle, which can be identified in the coeval pelagic basin facies (GAWLICK & BOEHM 2000). If the water depth of this region was increasing, these corals could be growing as pinnacles in order to keep up with the base of the euphotic zone (or photic floor). These corals are essentially small-scale "keep up" reefs (sensu NEUMANN & MACINTYRE (1985)) that grew taller as accommodation space increased.

Additionally, the Tennengebirge early Norian reef organisms exhibit distinct similarities to those from the late Carnian (encrusting sponges, "Carnian style" microbial crusts, and "*Tubiphytes*"), which suggests that the transition from sponge and encruster-dominated Carnian reefs to large coral and sponge dominated Norian reefs either did not occur until the middle Norian or occurred incrementally through the lower to middle Norian without dramatic turnover. The cause of the ecological transition is hindered by a lack of robust temporal correlations of Norian reef ecology and remains enigmatic.

3.2.4. Locality 6: 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 recognized 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 The main sediment is a light-coloured limestone; (layer C, thickness

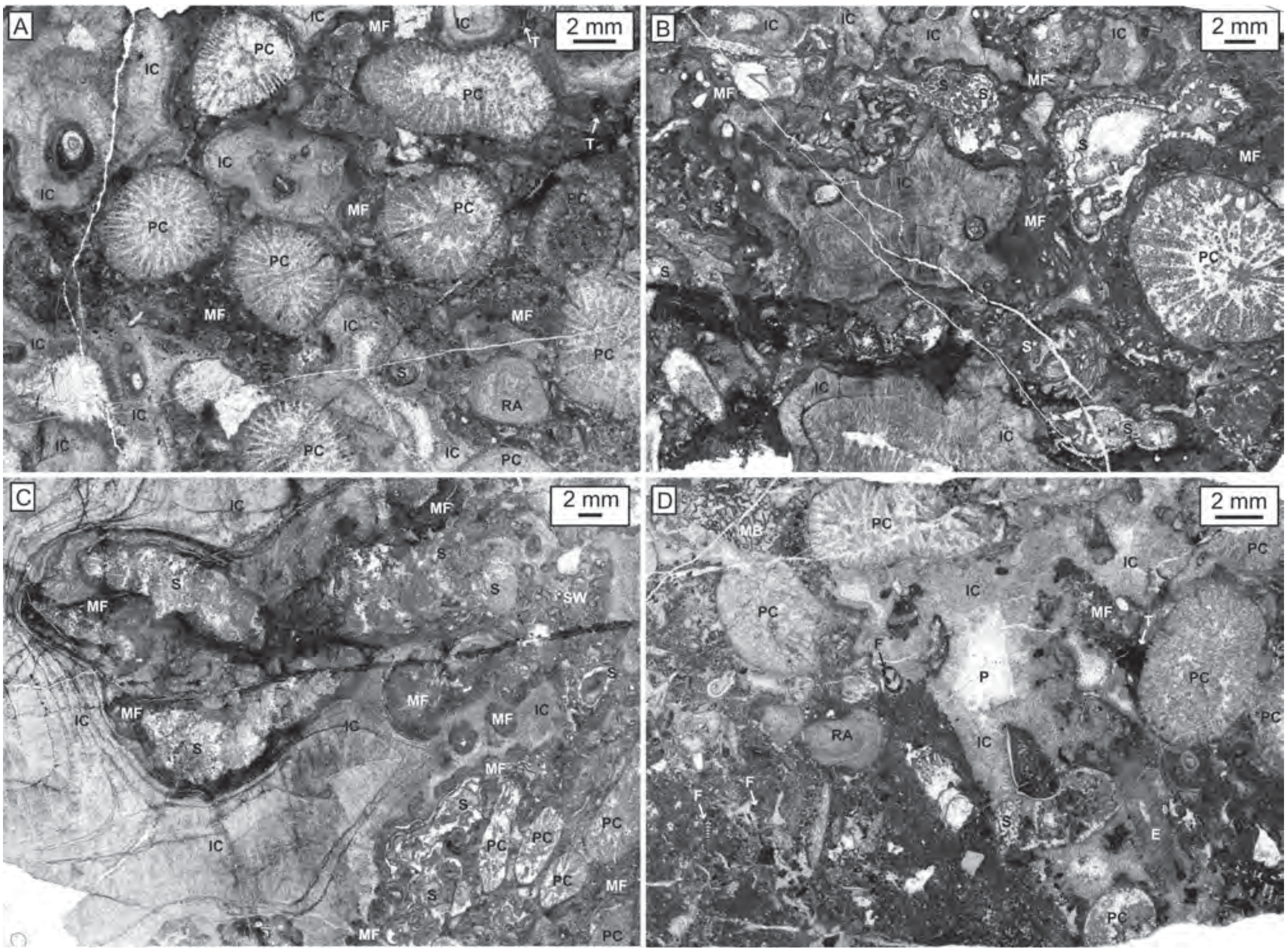


Fig. 27: Photomicrographs of the lower Norian Tennengebirge pinnacle reef facies (site B); important elements identified by letter annotations (all plane polarized photomicrographs). A) Coral pillarstone with microbial binding, note the thick microbialite fabrics and isopachous cements forming supports between phaceloid coral branches. B) Microbialite-sponge bindstone on the edge of the pinnacle corals, of note are the multiple generations of sponge and microbial encrusters growing on the phaceloid coral and coated with isopachous cements and the Antalythalamia sponge in the lower right portion of the photomicrograph. C) Microbialite-sponge bindstone on a pinnacle coral or pillarstone, there are again multiple generations of sponge and microbial encrusters growing on the phaceloid coral, and this sample is heavily cemented (see left side of photomicrograph). D) Microbialite-bound skeletal rudstones between phaceloid coral colonies. In top left hand corner are “Carnian-style“ (irregular) microbial crusts, phaceloid coral is *Retiophyllia* aff. *R. fenestrata* and foraminifers in far left corner is an *Ammobaculites rhaeticus*. PC = phaceloid coral; MF = microbialite fabrics; IC = isopachous cements; RA = red (solenoporacean) algae; S = sponge; S* = sponge, *Antalythalamia*; SW = serpulid worm tubes (?); E = echinoderm fragment; T = “*Tubiphytes*“; F = foraminifera.

up to some meters), containing oncoids, dasycladacean and codiacean algae, foraminifera, bryozoa, 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 birdseye 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

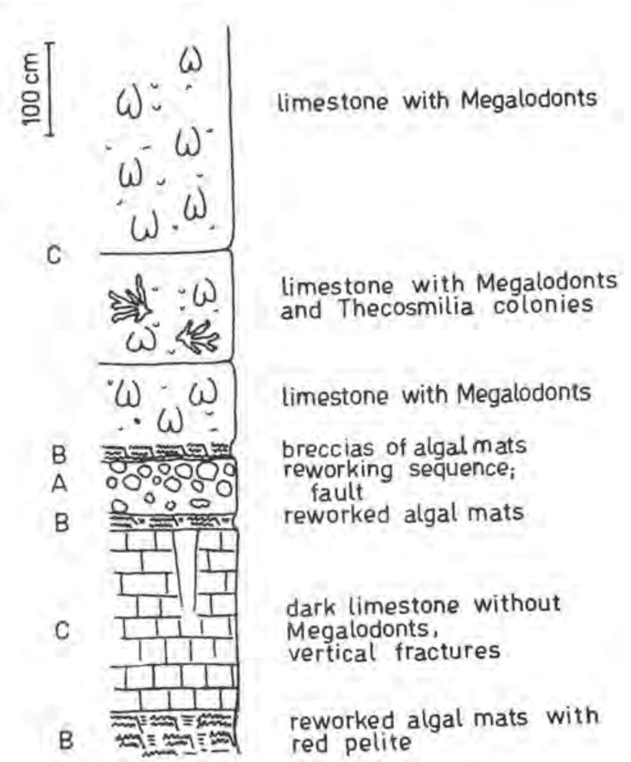


Fig. 28: Lofer Cyclothem at Pass Lueg (from Flügel et al. 1975).

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 karstifcation. 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 summarized:

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

- Facies A is reddish or greenish, argillaceous, 1 mm to 10 cm 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 paleosoils 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. 28). Several species of *Megalus, Parmegalus, Conchodus* have been described, but each levels are usually rich in individuals but poor in species number (Flügel et al. 1975).

3.3. The fringing reef

During the Late Triassic, and for the first time in earth history, scleractinian corals dominated reef ecosystems. The drowning history of Rhaetian coral builds-up is superimposed by the end-Triassic mass extinction and

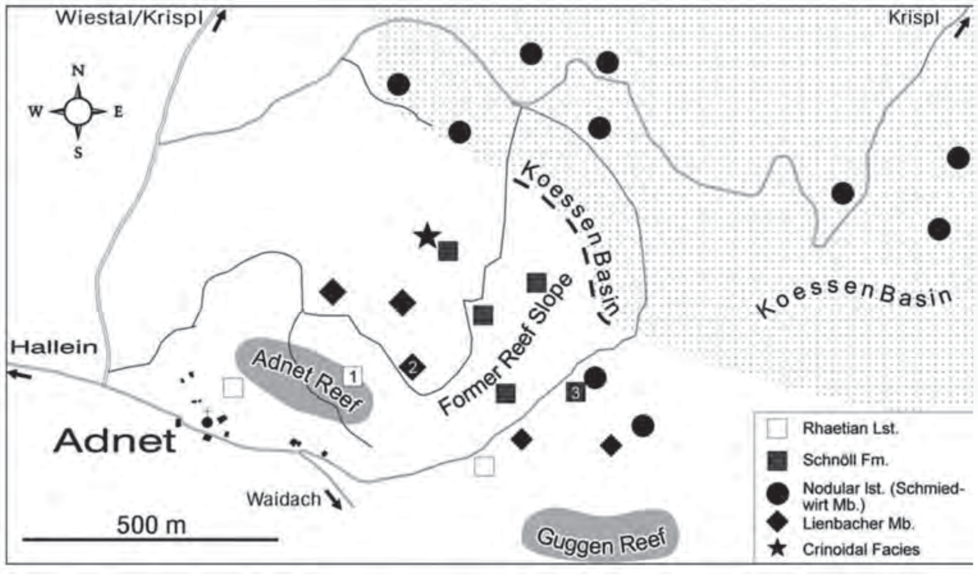


Fig. 29: Detail map of the Adnet quarries with facies distribution (from Krystyn et al. 2005 after Böhm 1992).

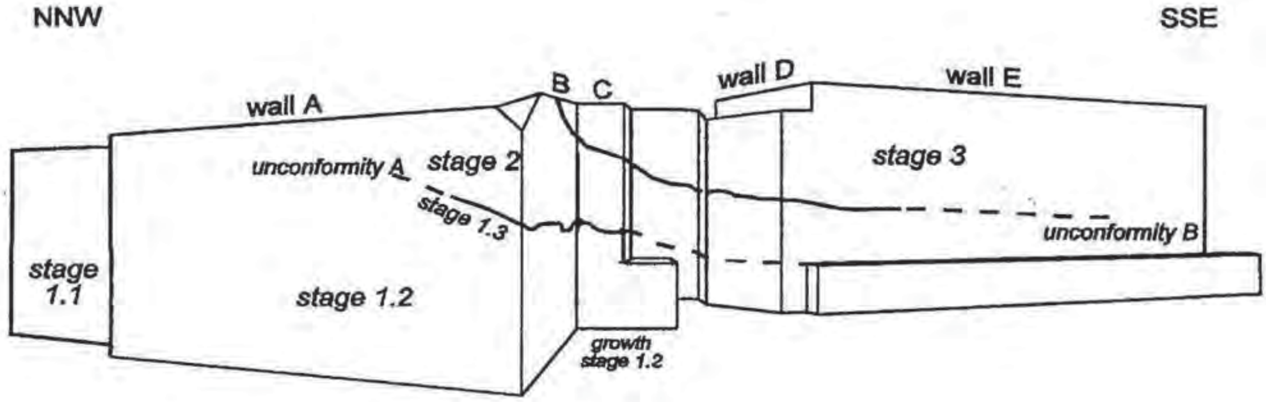


Fig. 30: Sketch of the Tropf quarry walls as seen during the early 1990s, indicating the reef growth stages and erosional unconformities (from Bernecker et al. 1999).

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.

3.3.1. Route

On day two we will go further north in the direction of Salzburg. Near the city of Hallein, we will drive through the village of Adnet and up to the quarries. In the evening we will drive through Berchtesgaden (Germany) to the Steinplatte. We will stay overnight on the Steinplatte

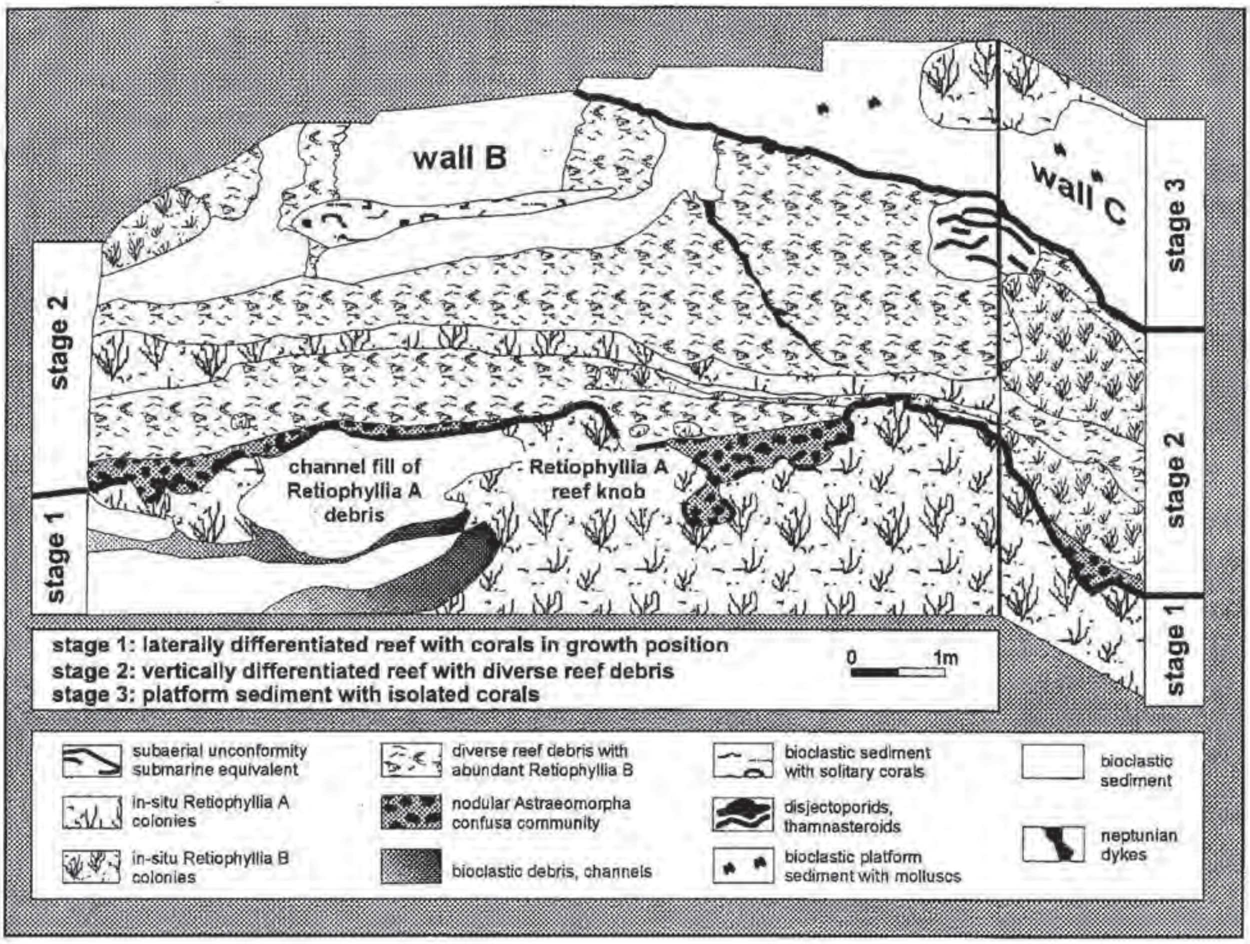


Fig. 31: Detailed facies distribution on walls B and C (Fig. 30) and positions of unconformities A and B. Note pronounced relief unconformity A (up to 4 m), Unconformity B is less pronounced (from Bernecker et al. 1999). Notice that the capping beds of Steinplatte, locality 8, correspond to the stage 1 to 3 here and the coral garden to stage 2.

plateau so that we can be ready to go on to the outcrop the following morning.

3.3.2. Locality 7: Adnet

The quarries of Adnet, located in the northwestern Osterhorn Block, southeast of the city of Salzburg (Figs. 1, 29) 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 7.1 and 7.2) to the aphotic deep-water hemipelagic sedimentation of the Jurassic (Stops 7.2 and 7.3). If both Adnet and Steinplatte have been described as typical warm-water photic-zone reefs (e.g., Stanton & Flügel 1989, 1995, Bernecker 2005), Stanton (2005) proposed rather a nutrient rich water favourable to heterotroph corals. Intermediate reef drowning stages of the Hettangian are nicely exposed in the lower slope sections (Stop 7.3). 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.

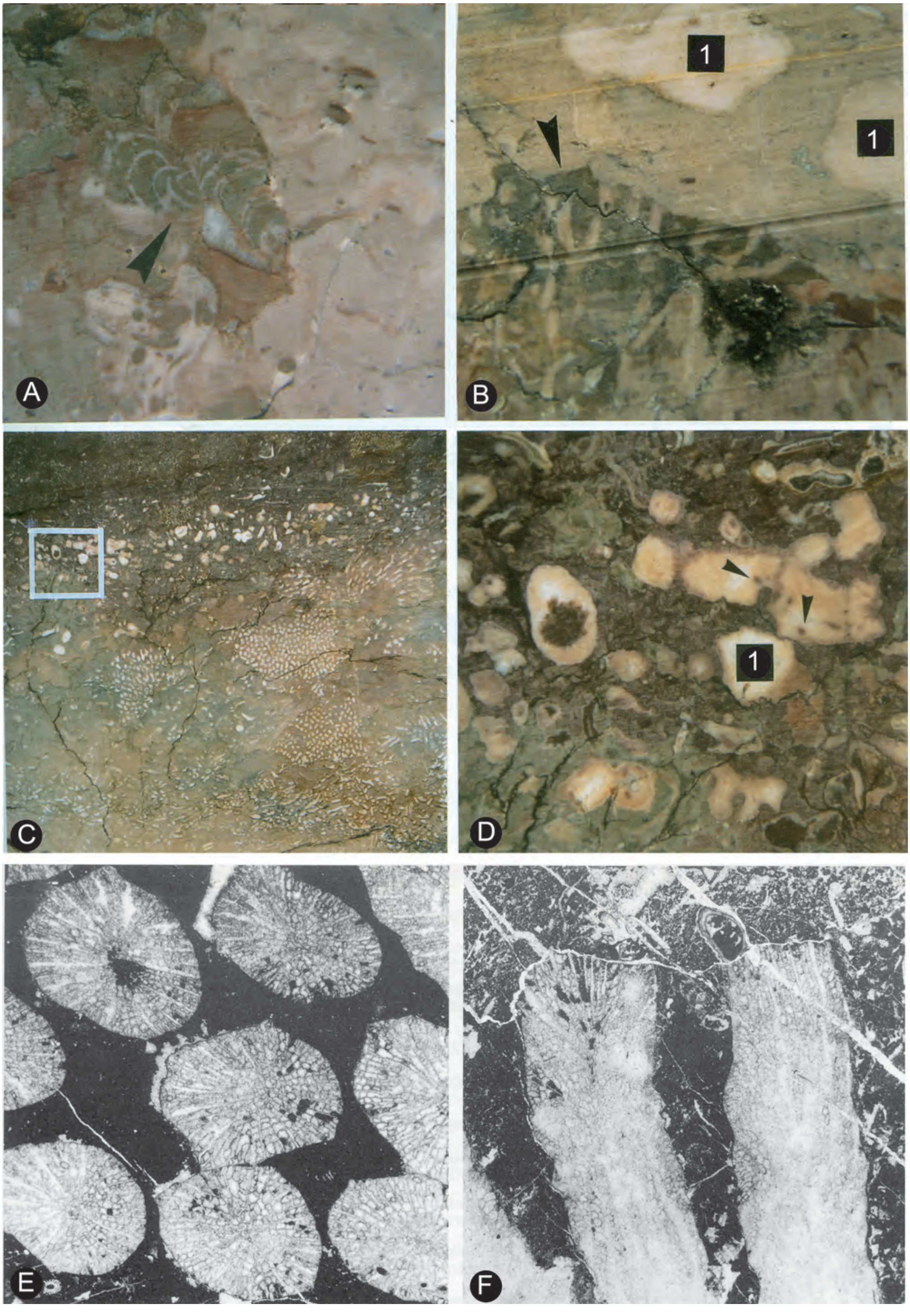
Fig. 32: Transect from growth stage 1 to stage 2 at the Tropf quarry. Small arrow point to the distinct disconformity surface between the “Large *Retiophyllia* A community“ and the thinner *Retiophyllia* B colonies. Wall B, width 1.70 m, height 2.50 m (from Bernecker et al. 1999).

3.3.2.1. Outcrop 7.1: Tropf quarry

The Tropf quarry /47° 41.7819’N 13° 8.2109’E, Fig. 29) 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. 30, 31, 32) belong to the 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. 30, 31). Megalodont bivalves are common in this layer. At the very top of the outcrop coral colonies occur again, although less frequently (Fig. 31). Possibly correlative sediments of Stage 3, exposed in the Lienbacher quarry (Stop 7.2), continue up to the Triassic-Jurassic boundary.

Bernecker et al. (1999) found two unconformities with distinct relief cutting through the reef and showing signs of erosion and karstification (Figs. 31, 33). A third unconformity marks the Triassic-Jurassic boundary, which is exposed in the Lienbacher quarry (Stop 7.2). 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 Rhaetian, when the higher parts of the platform

Fig. 33: 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).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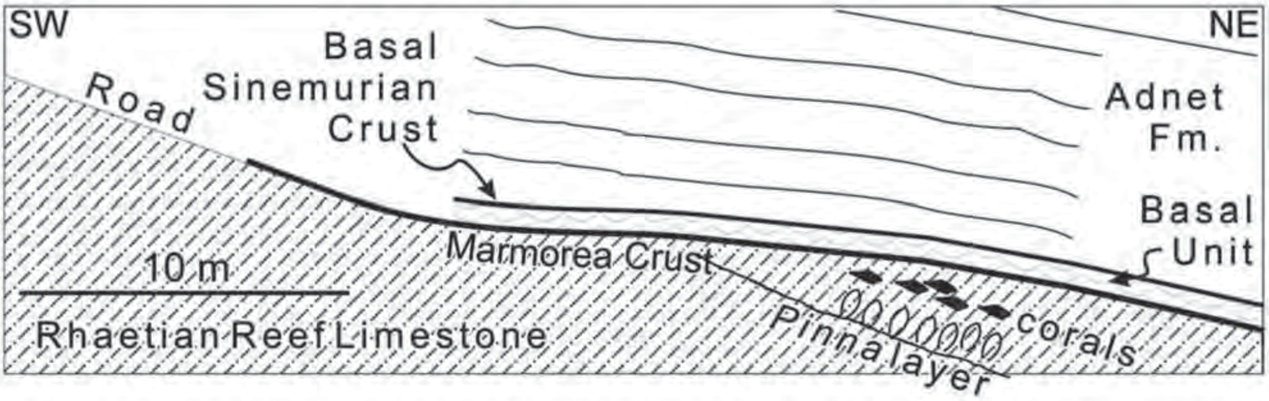

Fig. 34: Slightly exaggerated sketch of the depositional small-scale relief as exposed in the NW part of Lienbacher quarry. The upper Hettangian Marmorea Crust covering the underlying massive Rhaetian reefal limestone is shown as a thick line. It forms the pavement of the road at left. It is overlain 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. Bivalves and coral fragments in the Rhaetian limestone indicate depositional surfaces dipping steeper to the NE (from KRYSTYN et al. 2005 after BÖHM 1992).

south of the Eiberg Basin were exposed and reef deposition moved down the slopes.

3.3.2.2. Outcrop 7.2: Lienbacher quarry

The Lienbacher quarry (47° 41.8202'N 13° 8.2572'E, Fig. 29), 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 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 100 m 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

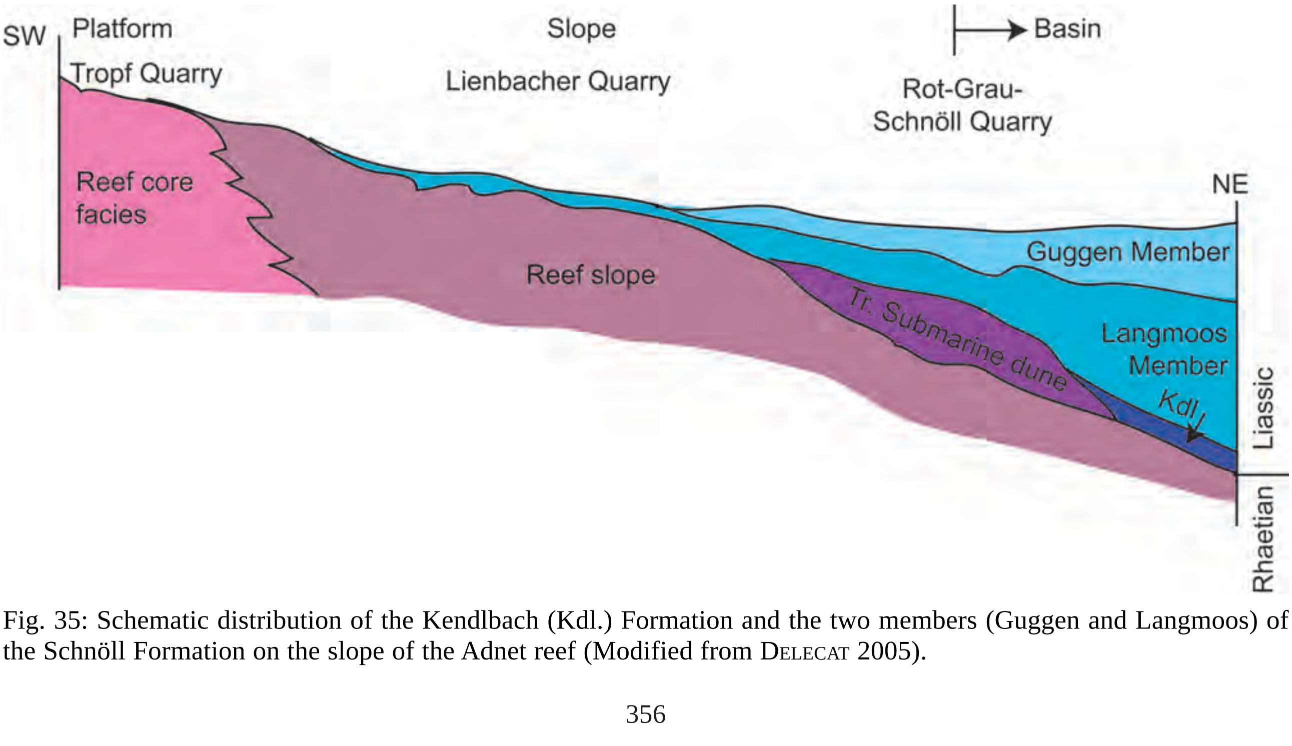

Fig. 35: Schematic distribution of the Kendlbach (Kdl.) Formation and the two members (Guggen and Langmoos) of the Schnöll Formation on the slope of the Adnet reef (Modified from DELECAT 2005).

terrace in the NW quarry corner (Fig. 34). 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 the Triassic. Red limestones of the Adnet Formation follow above the *Marmorea* Crust. They already belong to the late Sinemurian obtusum zone.

3.3.2.3. Outcrop 7.3: Rotgrau-Schnöll quarry

The RGS quarry (47° 41.8029'N 13° 8.5872'E, Fig. 29) 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). This is the type locality of the peculiar Hettangian Schnöll Formation, which represents the recovery of carbonate 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. 35). 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 northeastern part of the quarry to only about 1 m in the southwestern 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 1 m of 10 m in total. Sponges are very common and the occurrence of stromatactis points to early microbial diagenesis. The lowest exposed layer is rich in radiolaria (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 Sinemurian age.

3.3.3. Locality 8: 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. Just above the Steinplatte inn, there is a panoramic view of the Steinplatte Mountain (Fig. 36). 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, at stop 8.2, Fig. 37). Small separated mounds exposed at the base of the crest are interpreted as initial growth stages. They are not visible from Kammerkoehr Inn and are only accessible by climbing or via steep hiking trails.

3.3.3.1. Outcrop 8.2

East of Kammerkoehr inn a tourist trail (Fig. 37) exposes toe-of-slope calcarenites (bioclastic pack and grainstones rich in crinoid and bivalve debris with Rhaetian microfauna and rare brachiopods; Turnsek et al. 1999) followed to the south by different platform carbonates respectively reef facies types (Fig. 38). 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, stop 8.5). Coral growth of the capping facies stopped during end-Triassic time, whereas the palaeorelief of the carbonate platform still existed until the Middle Liassic (Fig. 39). A

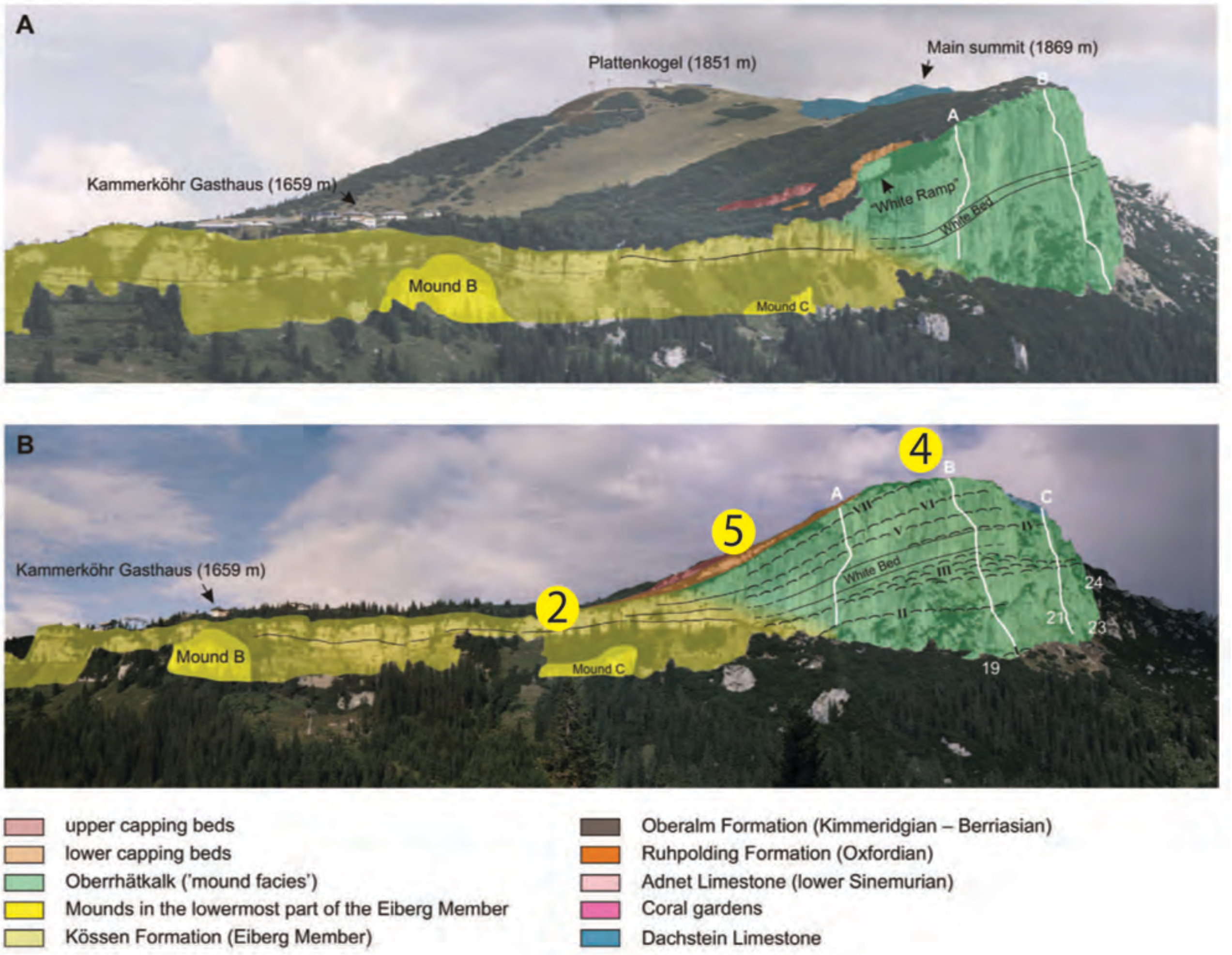

Fig. 36: The Steinplatte complex from two different perspectives and with visited outcrop. A) Looking ESE from near Brennhütte. B) Looking ENE from Grünwaldkopf. Flat-lying Kössen Beds (yellow) grade laterally into up to 36° ("White Ramp") inclined Oberrhätkalk (green). Width of outcrop is ca. 1000 m. 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).

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

3.3.3.2. Outcrop 8.3

"The Fischer's Coral Garden" is an area of abundant corals which consists 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 on the side or upside down. None has been found growing upon another, so evidence for any rigid skeletal framework is missing (Stanton & Flügel 1989). The "matrix" is a bioclastic wackestone with predominantly miliolid foraminifera, some dasycladacea (*Diplopora*) burrow with larged bored and encrusted gastropod and plecypod shells and echinoderms. Some layered pack to grainstone with rounded lithoclasts and coral debris, duostominid foraminifera indicate occasional higher energy events. The coral heads have frequent microbial crust, *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.

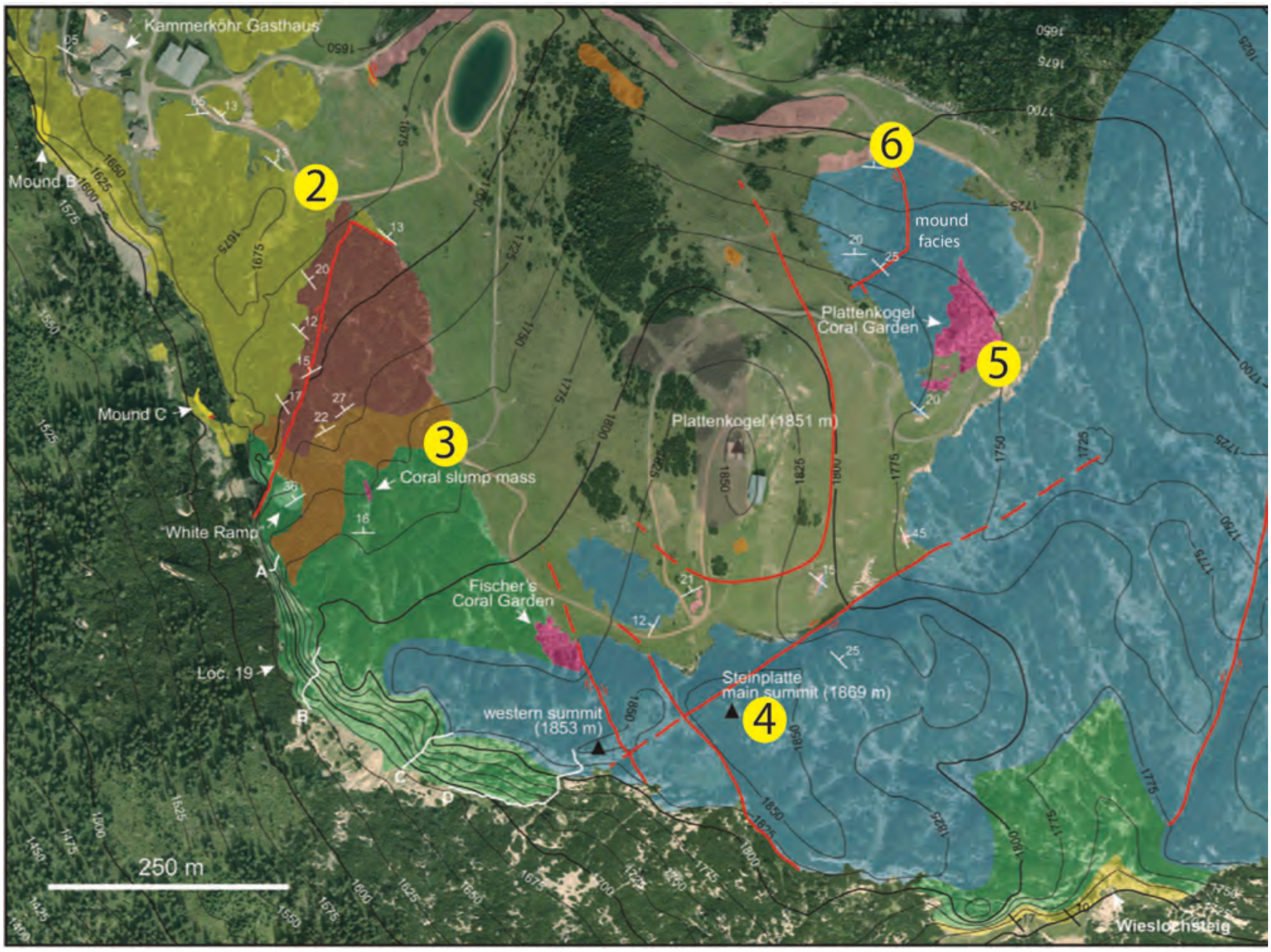

Fig. 37: Locality and geological map of the Steinplatte area with visited outcrops. A-D = Cliff sections of STANTON & FLÜGEL (1989). Red lines = major faults. For legend see Fig. 36, (from KAUFMANN 2009).

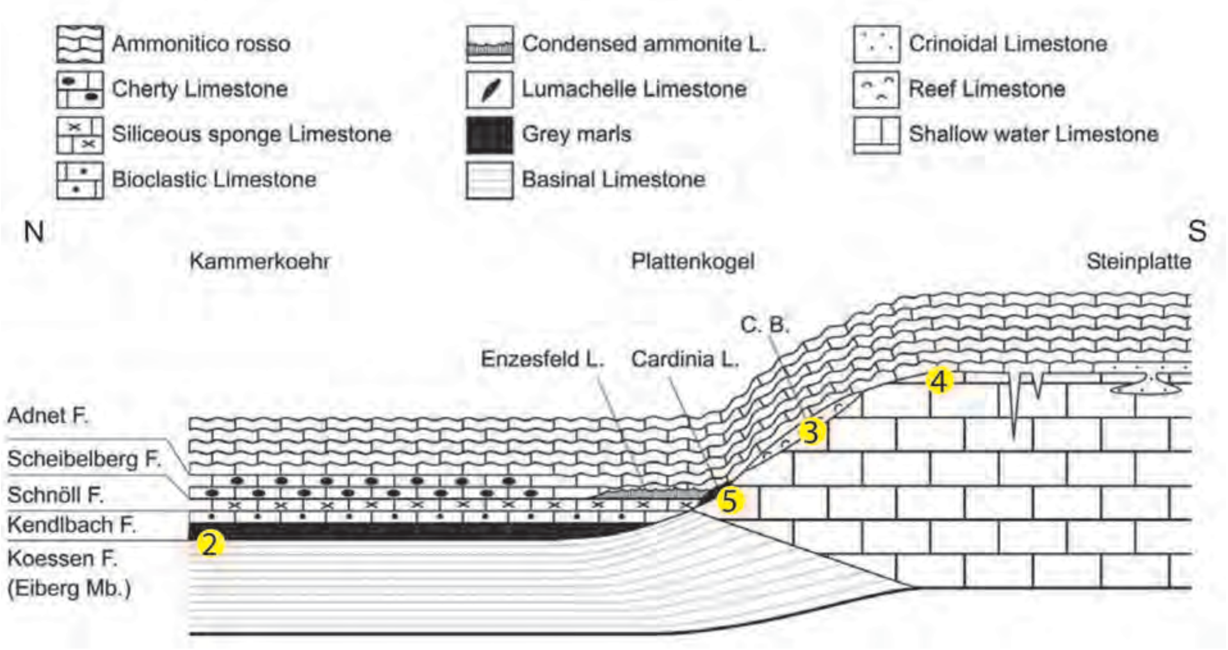

Fig. 38: Schematic Steinplatte cross-section from the platform to the basin with visited outcrops; note the lowstand position of the Capping Beds and the onlap geometries of the Hettangian rocks (Kendlbach F., Schnöll F., Enzesfeld L.) as well as the delayed platform flooding by the Adnet Formation (from KRYSTYN et al. 2005).

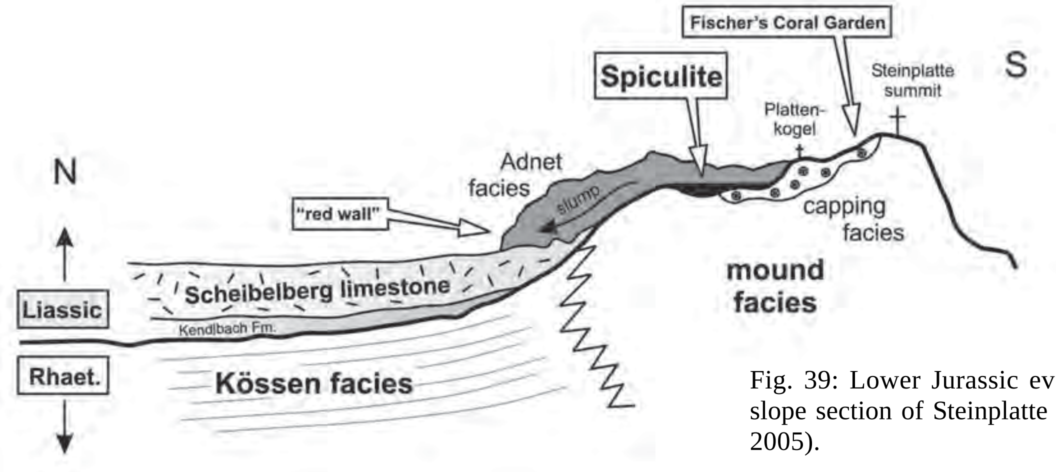

Fig. 39: Lower Jurassic events on the northern slope section of Steinplatte (from KRYSTYN et al. 2005).

3.3.3.3. Outcrop 8.4

If good weather conditions prevail, the Steinplatte summit offers a spectacular view onto parts of the Northern Calcareous Alps. Adjacent to the Southeast, lagoonal sediments (e.g., Loferer facies) form the mountains of the "Loferer Steinberge", "Leoganger Steinberge" and "Steinernes Meer". To the west faces the steep rugged ridge of the "Wilder Kaiser" Mountain built of Wetterstein Limestone (mostly Middle Triassic).

3.3.3.4. Outcrop 8.5

The top of the Steinplatte buildup is partly overgrown by large separate bush-like corals (Capping Beds) of latest Rhaetian age (KRYSTYN et al. 2005). Coral growth of the capping facies stopped during end-Triassic time, whereas the palaeorelief of the carbonate platform still existed until the Middle Liassic.

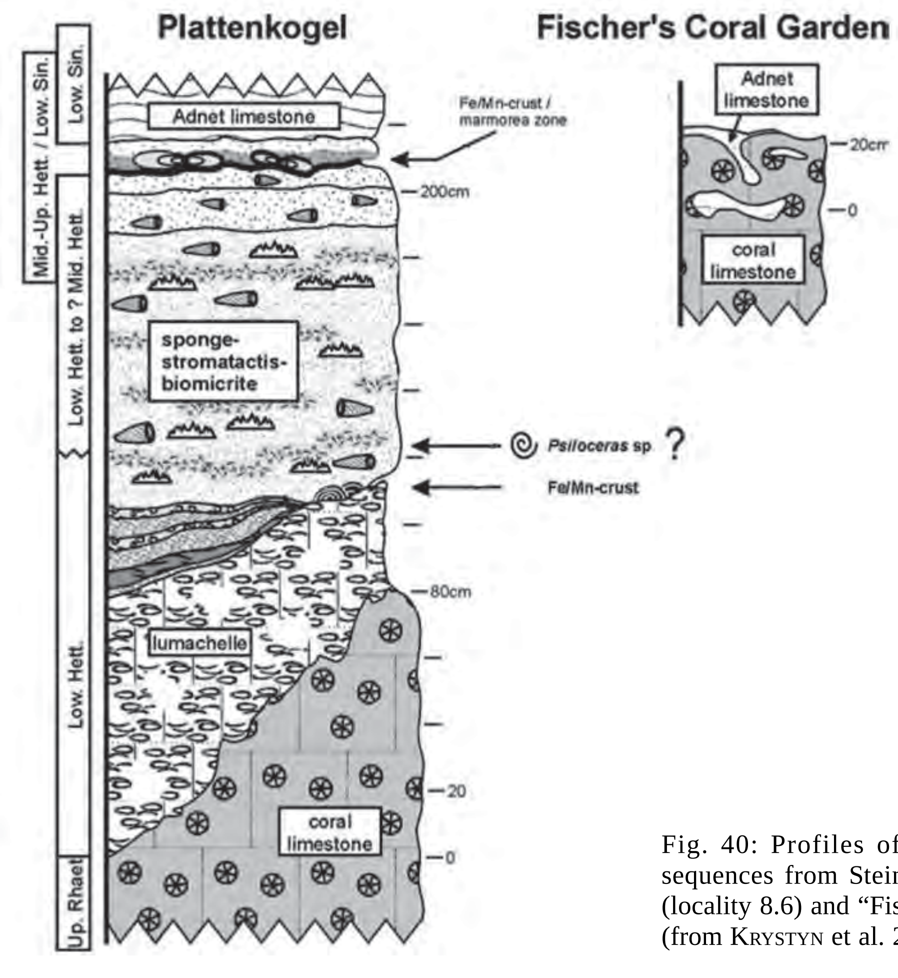

Fig. 40: Profiles of the Triassic-Jurassic boundary sequences from Steinplatte localities: Plattenkogel hill (locality 8.6) and "Fischer's Coral Garden" (locality 8.3) (from KRYSTYN et al. 2005).

3.3.3.5. Outcrop 8.6

At the northern flank of the Plattenkogel sponge-stromatactis-biomicrites of Lower Liassic age are preserved in a depression of the former Triassic reef surface (Figs. 39, 40) but pinch out laterally after a few meters. Due to the strikingly similarity of their facies with beds from the Adnet reef slope, the sequence is attributed to the Schnöll Formation (Böhm et al. 1999). Non-rigid siliceous sponges (mainly *Lyssacinosida*) formed spicular mats during starved Liassic sedimentation. 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 formation resulted in syndiagenetic stromatactis cavities. The latter are recognizable in the field as a network of white spar-filled cavities pervading the red to pink coloured host rock. Subjacent to the spiculite a sequence of allochthonous sediments that starts with a *Cardinia* 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 a 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. Between Stops 8.4 and 8.6, the loop of the tourist trail passes a large wedge of red Liassic sediments (Sinemurian-Toarcian). It is formed by a big mass flow of Adnet limestones comprising slump folds and megabreccias that slid downslope onto grey limestones of the Scheibelberg Formation (Garrison & Fischer 1969, Wächter 1987).

3.4. The Eiberg basin

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).

3.4.1. Route

From the Steinplatte, we will go further west to the Eiberg quarry near Kufstein and then to Fall (Germany), north-west from Achenkirch in Tirol (Fig.1), where we will sleep. 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. 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

Fig. 41: Eiberg quarry behind main cement factory exposing Kössen Formation with top Hochalm Member (Units 3 + 4) and lower Eiberg Member (Units 1 + 2).

hike from the Hochstallalm Niederleger (Fig. 47). Ochsentaljoch is located 750 m to the west (47°29'0"/ 11°31'50").

3.4.2. Locality 9: Eiberg

The Eiberg section (Fig. 41) is located in an active cement quarry (SPZ Zementwerk Eiberg GmbH) about 3 km south

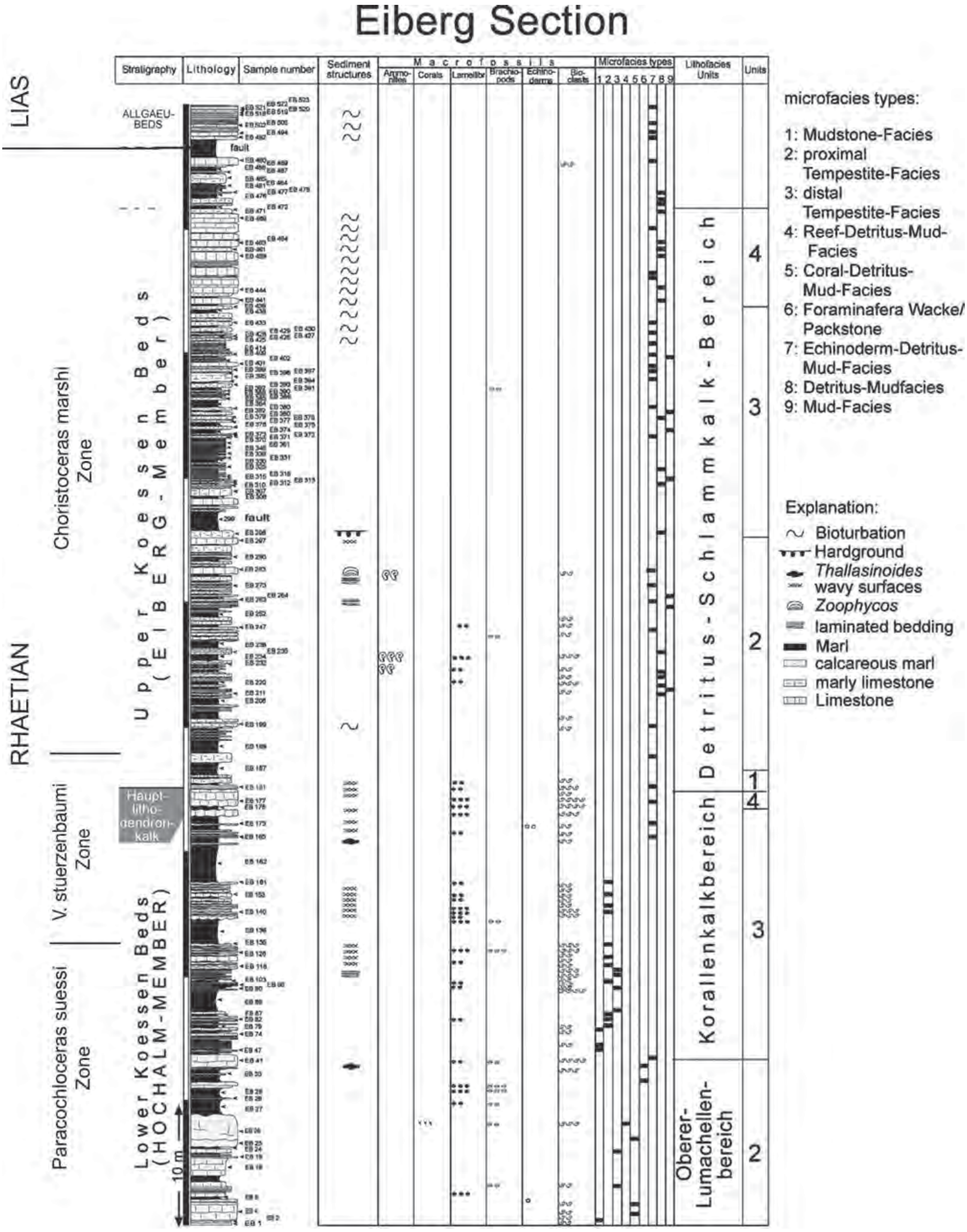

Fig. 42: Profil of the Eiberg section.

of Kufstein (North Tyrol). The upper part of the Hochalm Member (upper unit 2 to unit 4, sensu Golebiowski 1989) and the Eiberg Member are exposed. 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. 42). Particularly the association of bivalves and brachiopods studied in details by Golebiowski (1989, 1991) give indication of depth changes (Fig. 43).

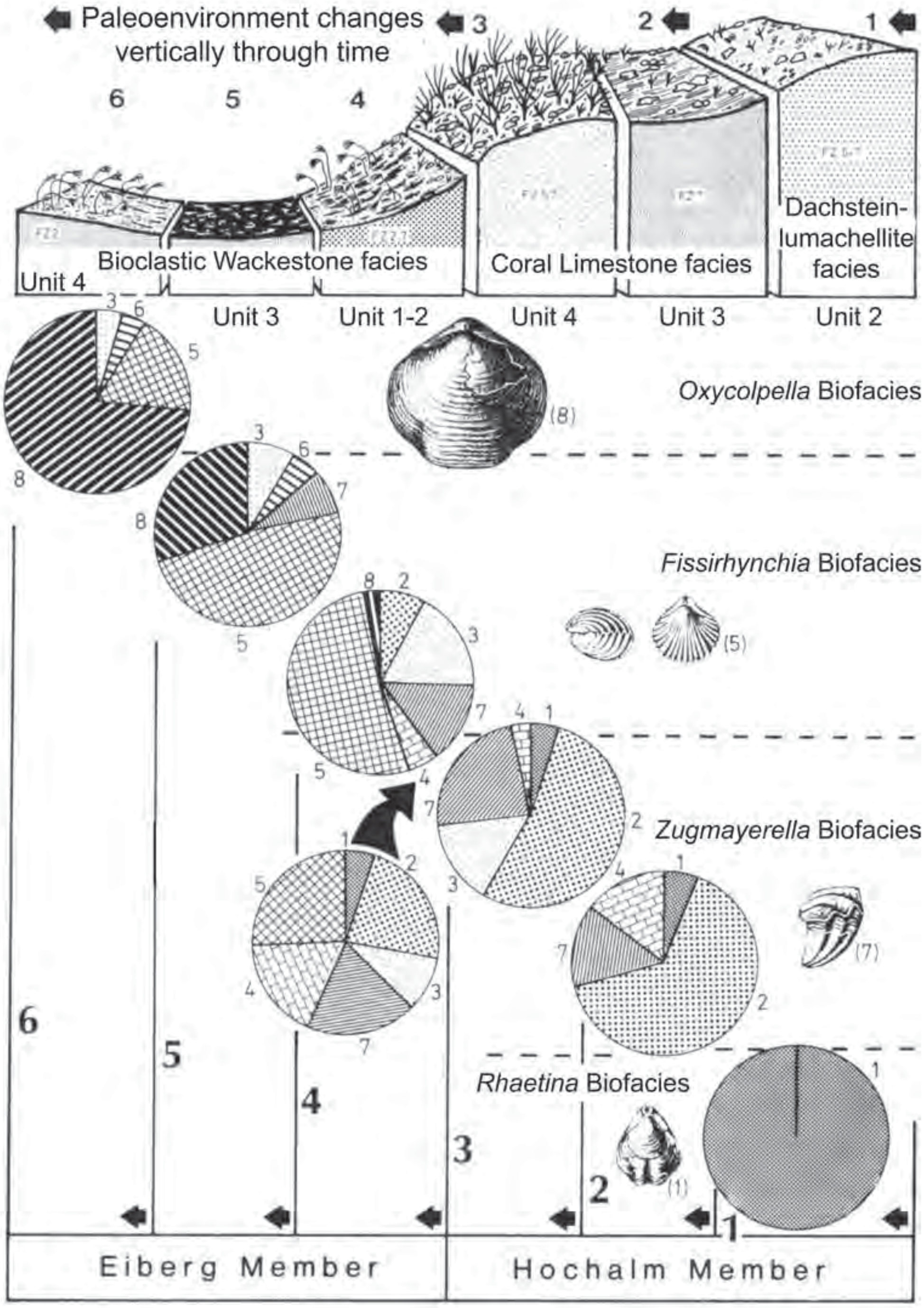

Fig. 43: Ecological stratigraphy of the brachiopods biofacies of the Kössen Formation. There are continuous changes in assemblages concomitant with the deepening of the basin. 1- *Rhaetina gregaria*, 2 - *Rhaetina pyriformis*, 3 - *Zeilleria norica*, 4 - *Austrirhynchia cornigera*, 5 - *Fissirhynchia fissicostata*, 6 - *Sinucosta emmrich*i, 7 - *Zugmayerella kössenensis* und *uncinata*, 8 - *Oxycolpella oxycolpo*s. From Golebiowski (1991).

3.4.2.1. 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. 44B) are more rare 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 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 20 m 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. 44A). The Units 3 and 4 mark a deepening below the wave base (30-50 m) and a transition phase between a deep, open marine lagoon (Unit 1 and 2) and the

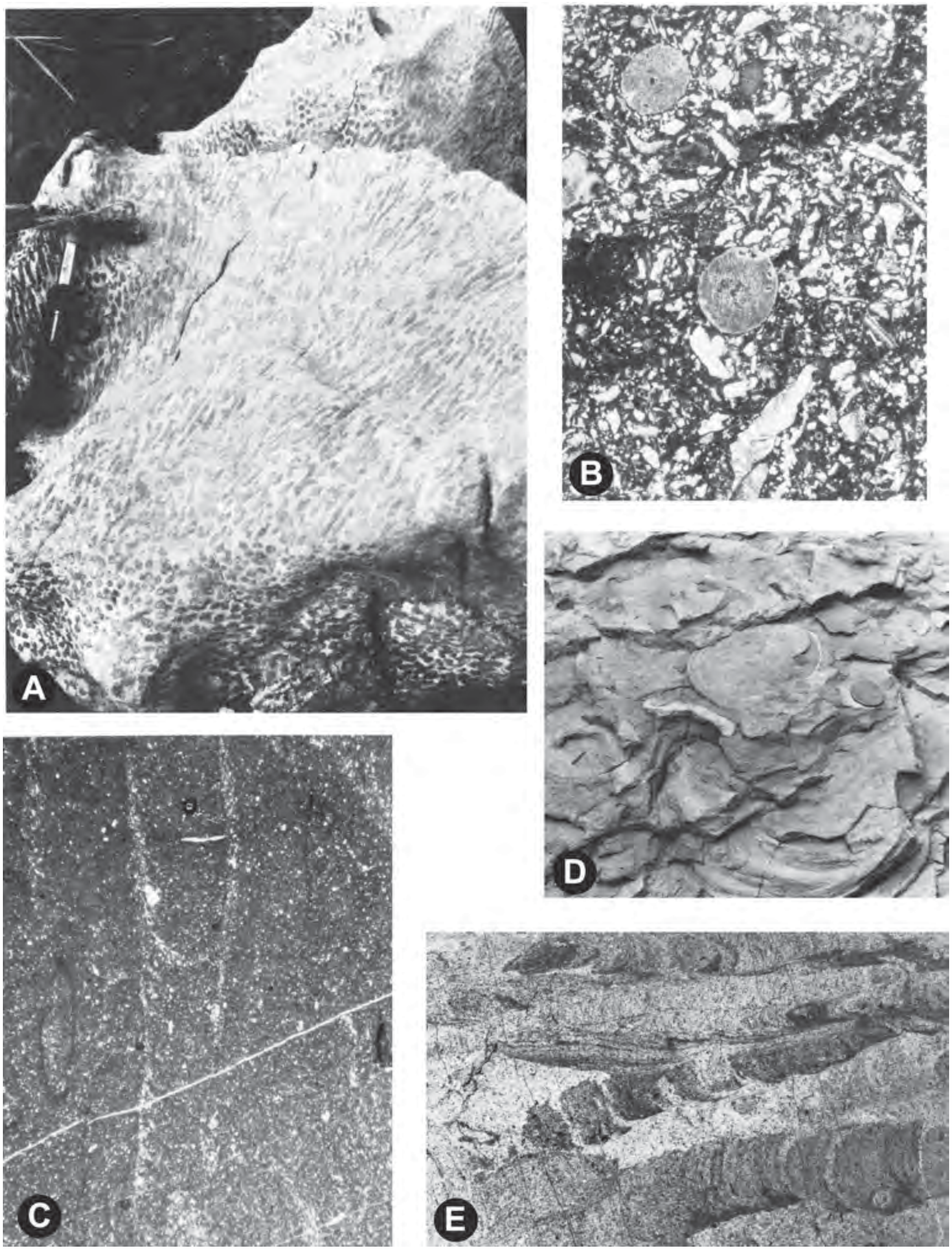

Fig. 44: A) Lithodendron Limestone (hammer for scale); B) Echinoderm bioclastic grainstone with brachiopod fragments and crinoids, x 7; C) Bioclastic wackestone with sponges spicules and bioturbation, x 4,5; D) *Zoophycos* traces within the marly sediment, x 0,3; E) Vertical section of *Zoophycos* traces, together with later burrows, x 1. B) to E) Eiberg Member. (All photos from KUSS 1983).

intraplattform basin deposition milieu of the Eiberg Member. According to Golebiowski (1991), the ammonoids and conodonts give a lower Rhaetian age for the Unit 1+2 and the base of the Unit 3 (*Paracochloceras suessi* Zone until 23 m in Fig. 42). The top of the Unit 3, the Unit 4 of the Hochalm Member and the Unit 1 of Eiberg Member belong to the liddle Rhaetian *Vandaites stuerzenbaumi* ammonoid Zone.

3.4.2.2. 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. 44C-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 basinal form *Oxytoma inaequvalve* (Golebiowski 1989, 199, Fig. 43). The ostracods record a change from warm to cold water (Urlichs 1972). These changes indicate a further deepening of the basin to about 50-100 m water depth 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 “are“ 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 upper Rhaetian *Choristoceras marshi* ammonoid Zone (Fig. 42).

3.4.3. Locality 10: The Triassic-Jurassic GSSP at Kuhjoch

This text is mainly taken from Hillebrandt et al. in prep. In 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

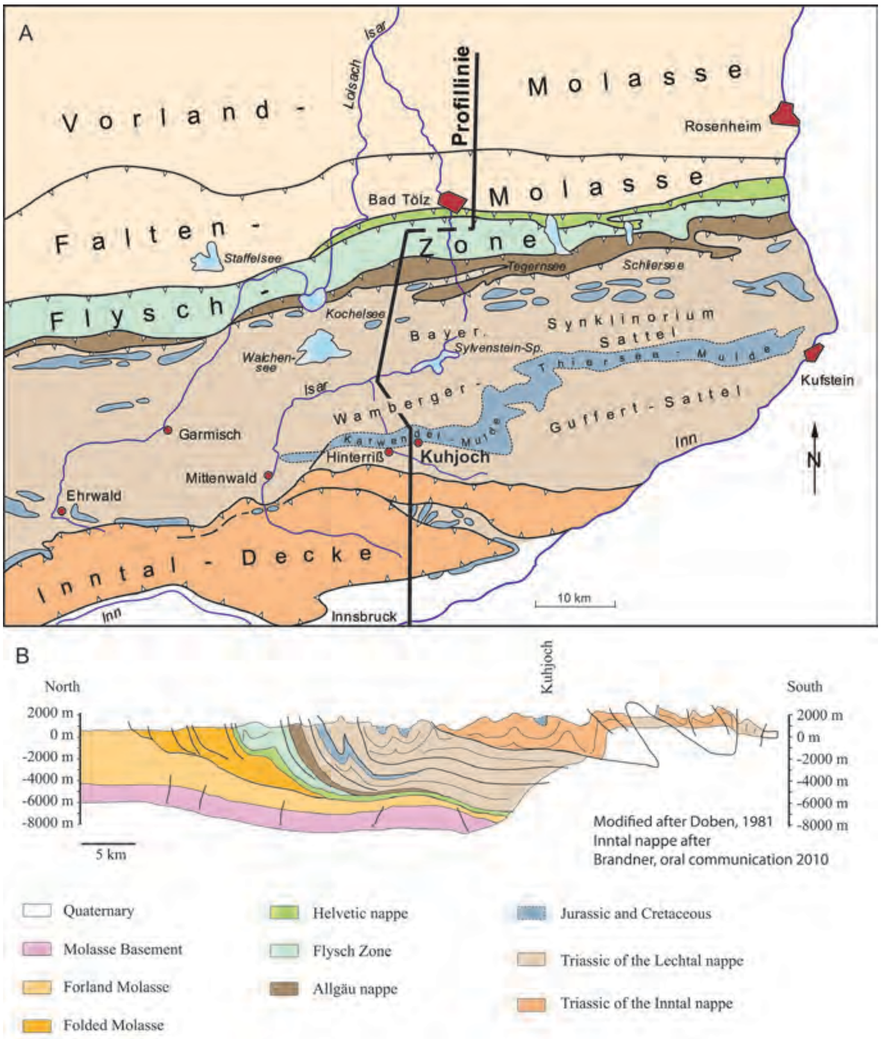

Fig. 45: Geological map and cross-section of the Karwendel mountains (modified after Hillebrandt & Kment 2009).

western Northern Calcareous Alps, extended E-W. The syncline is wide and relatively flat near the Achensee in the east (Fig. 45) and narrows towards the west with increasingly steep to overturned flanks at its western end close to Mittenwald. Triassic-Jurassic boundary sections east of the Karwendel Syncline are classical localities and have been studied by various authors (Fig. 46, 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 new psiloceratid (*Psiloceras spelae tirolicum*) distinctly older than the well-known earliest *Psiloceras* from England (*P. erugatum*, *P. planorbis*) and the Alps (*P. calliphyllum*).

Fig. 46: Triassic - Jurassic boundary sections of the western Karwendel Syncline (modified after Hillebrandt & Kment 2009).

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). Within the Eiberg basin, between Lake St. Wolfgang (Kendlbach) and Garmisch-Partenkirchen (Fig. 2) 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.

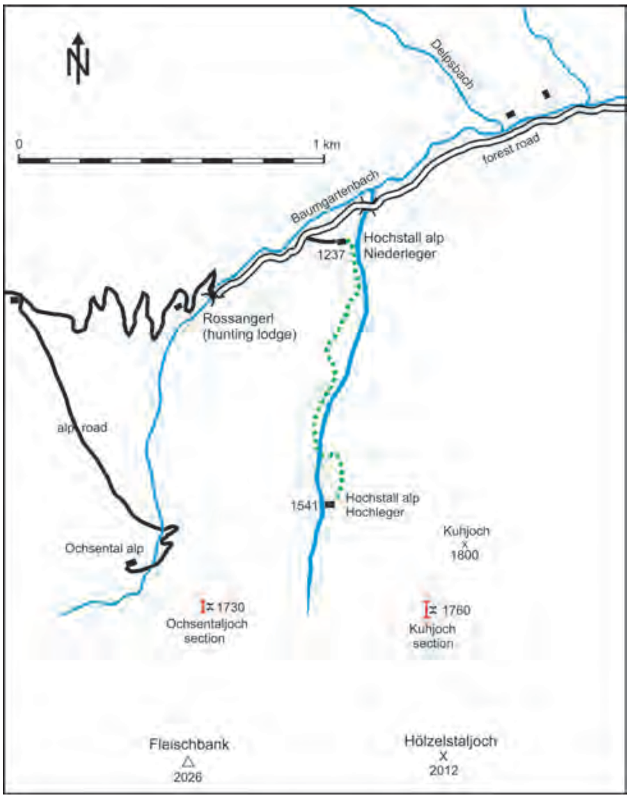

Fig. 47: Way to Kuhjoch and Ochsentaljoch sections (from Hillebrandt & Kment 2009).

Fig. 48: View to the West on Kuhjoch section with the main lithological formations.

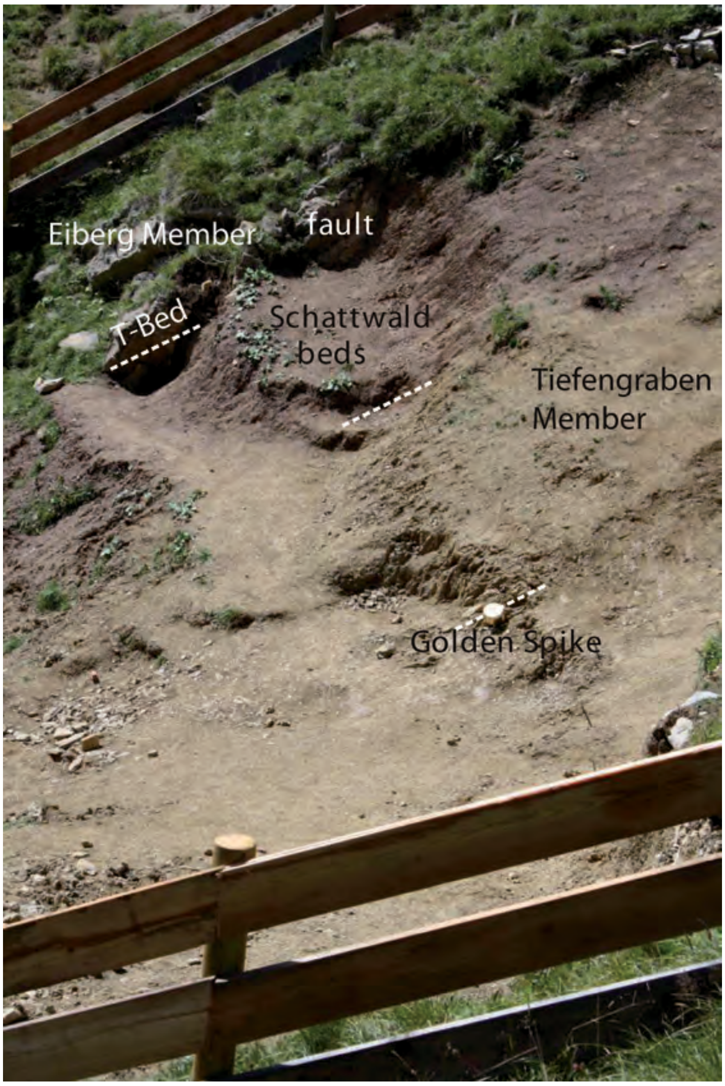

Fig. 49: Section Kuhjoch East with “Golden Spike“ at Triassic-Jurassic boundary.

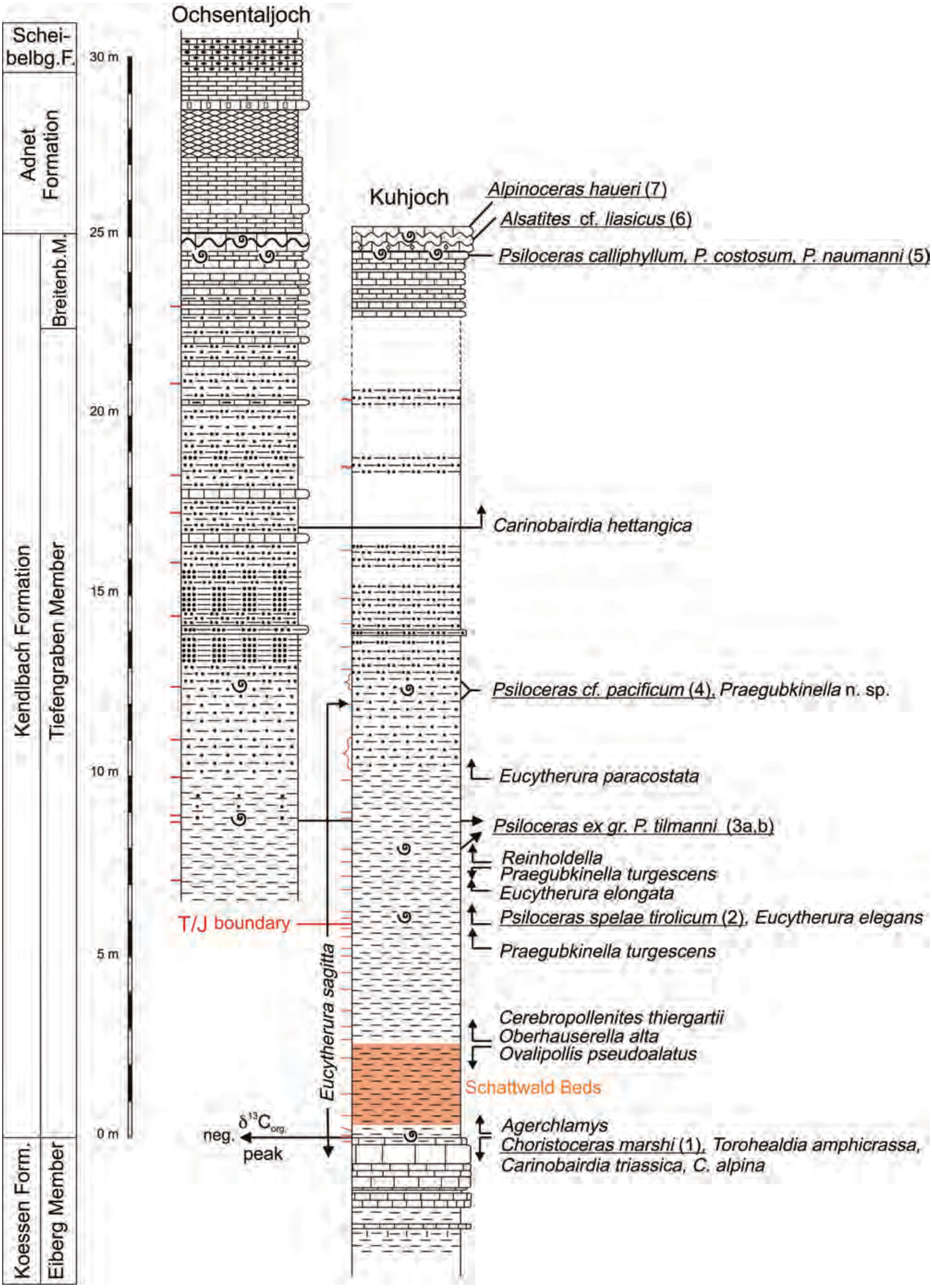

Fig. 50: First and last occurrences of biostratigraphic important fossils at GSSP Kuhjoch West (from HILLEBRANDT et al. in prep.).

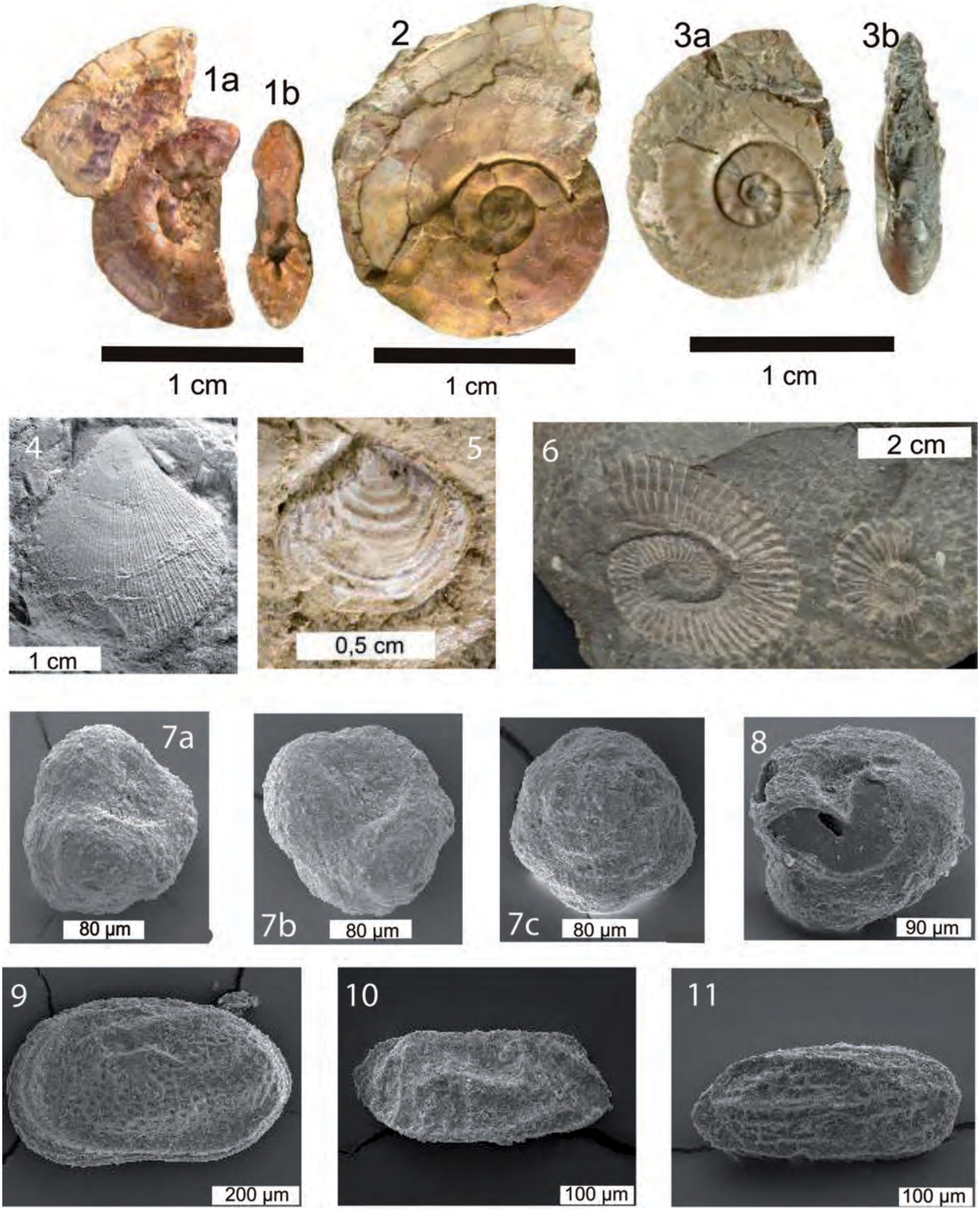

Fig. 51: Important guide fossils at the Triassic - Jurassic boundary of GSSP Kuhjoch. 1-3: *Psiloceras spelae tirolicum* Hillebrandt & Krystyn, 1a, b, 2: Kuhjoch, 3: Hochalplgraben; 4: *Agerchlamys* sp., Hochalplgraben; 5: *Astarte* sp., Kuhjoch, spelae horizon; 6: *Choristoceras marshi* Hauer, Kuhjoch, top T bed; 7a, b, c: *Praegubkinella turgescens* Fuchs, Kuhjoch, *spelae* horizon; ?*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. in prep.).

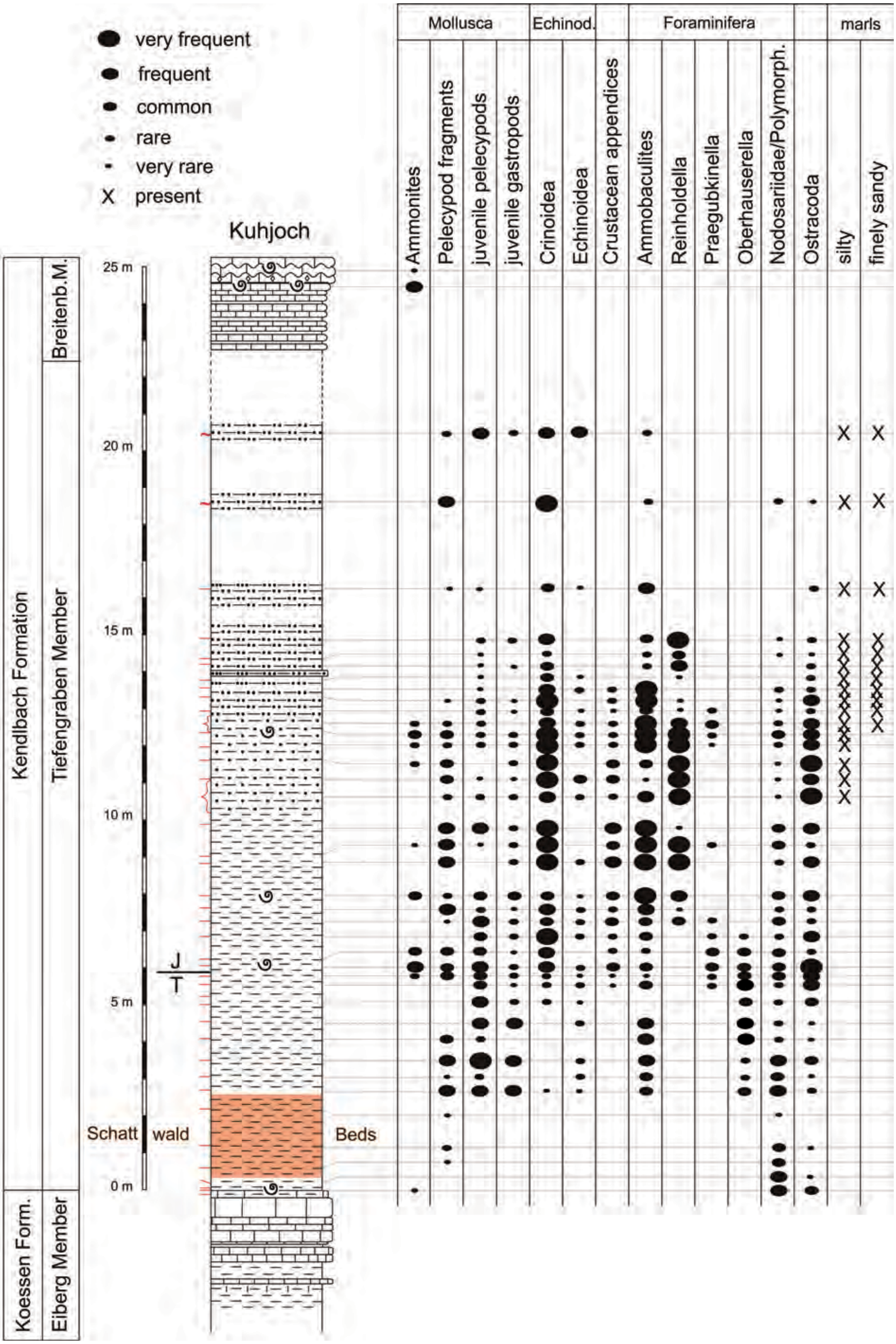

Fig. 52: Fossil at Kuhjoch section (from HILLEBRANDT & KMENT 2009).

Among the diverse Triassic-Jurassic boundary sections of the western Eiberg basin, the pass of the Kuhjoch 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 (Figs. 47, 48), where this interval is better exposed.

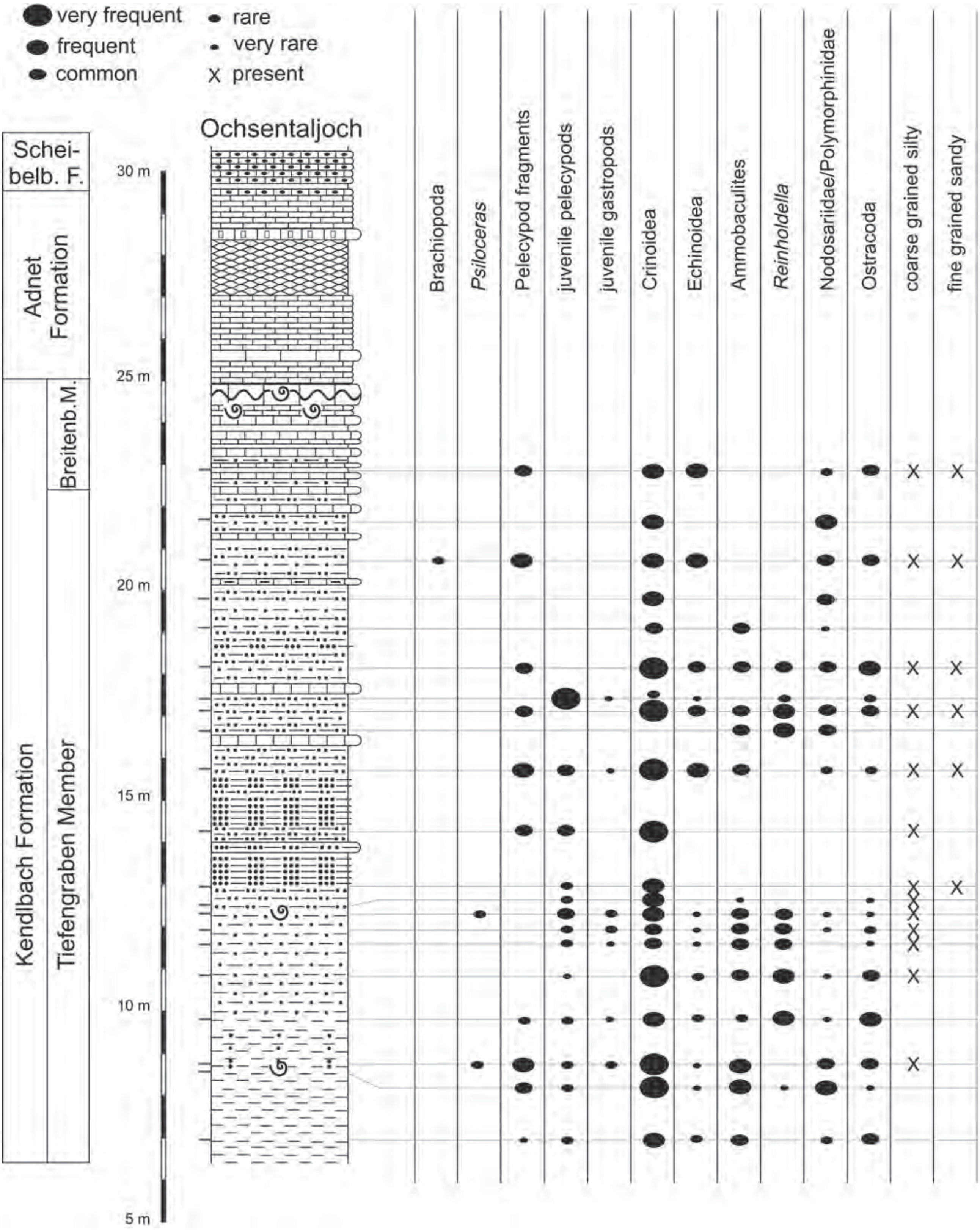

Fig. 53: Fossil at Ochsentaljoch section (from Hillebrandt & Kment 2009).

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 limestone (bioclastic wackestones) overlying 5 m black marls with pyrite nodules and rare thin (5-10 cm) limy mudstone intercalations (Figs. 49, 50). The 20 cm thick topmost bed (= T in Fig. 49) 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. 50) and comparable with also reddish, argillaceous marls which are known as

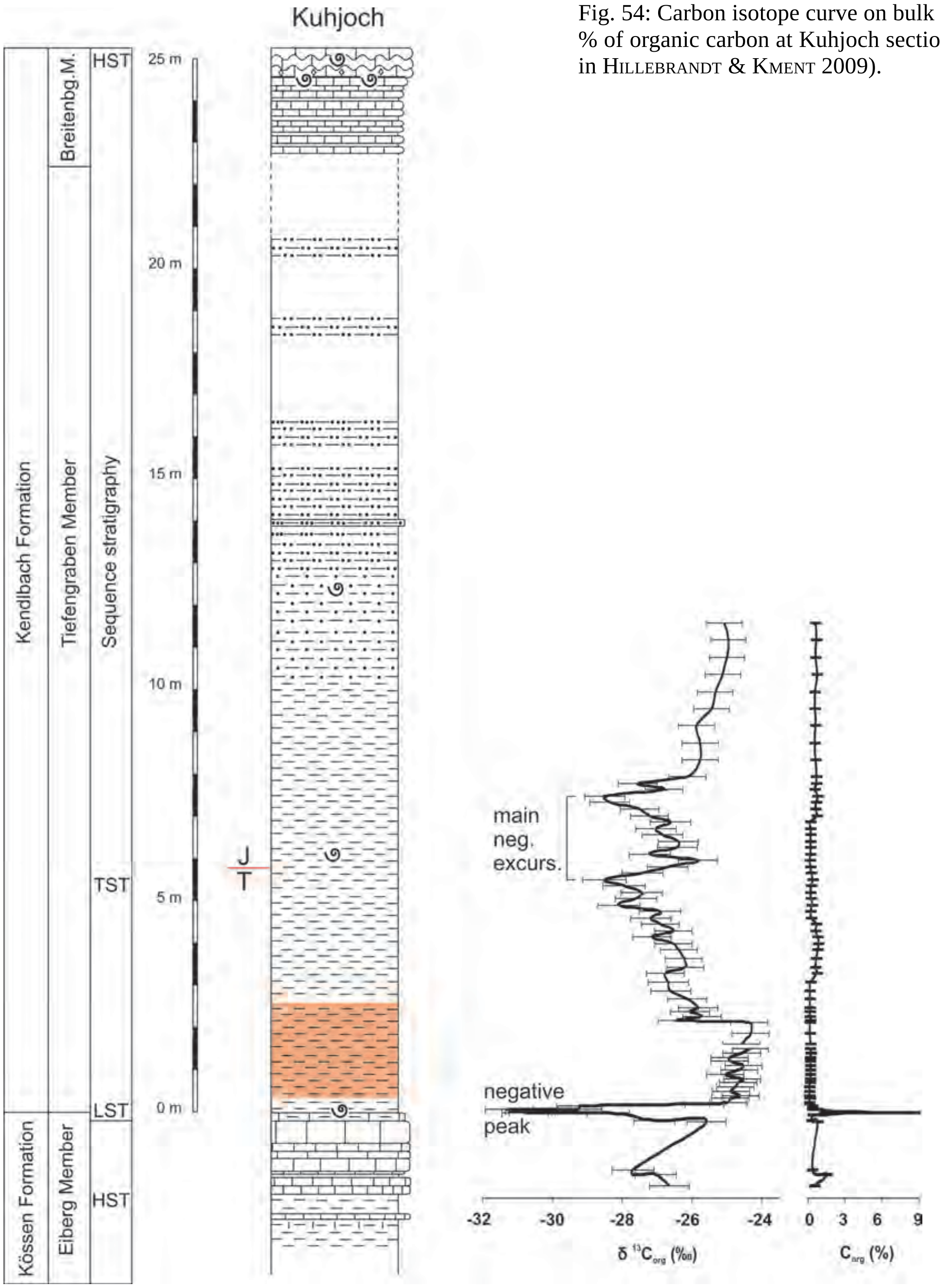

Fig. 54: Carbon isotope curve on bulk organic carbon and % of organic carbon at Kuhjoch section (from RUHL et al. in HILLEBRANDT & KMENT 2009).

Schattwald Beds. Grey intercalations characterize the transition to the overlying main part of the Tiefengraben Member, 19 m thick. Ammonite level (2) with *P. spelae tirolicum* (Fig. 51) 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).

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).

The exposed part of the Breitenberg Member consists at Kuhjoch (Fig. 50) 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 colored, 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 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.

A broad spectrum of marine invertebrate groups is recorded, although brachiopods are rare. Macrofossils (Figs. 51, 52, 53) are represented by biostratigraphically (ammonites) as well as palaeoecologically important groups (bivalves, echinoderms). Microfossils (Figs. 51, 52, 53) 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 characterized 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 foramifera (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 (Fig. 54) have been studied (RUHL et al. 2009). In addition, compound-specific C-isotope measurements (n-alkanes) have been carried out (RUHL et al. 2011).

4. Concluding remarks

The Austrian Northern Calcareous Alps allow a worldwide unique insight to latest Triassic tropical sea life and its respective sedimentary record. Various Norian and Rhaetian depositional environments (lagoon, reefs, intra-platform basin, slope, offshore pelagic plateau), all of them known to occur widespread throughout the Tethys, are facially and faunistically exceptionally developped: Norian inshore platform sediments of lagoonal Dachstein facies with typical peritidal Lofer cycles, the Dachstein barrier reef facies and the off-shore Hallstatt type facies (condensed pelagic limestone) as well as Rhaetian mixed carbonatic-terrigeneous cyclic (Kössen facies) and deep-water, partly turbiditic (Zlambach facies) sequences. The marine faunal record shows certain crisis intervals during middle Norian and early-middle Rhaetian time that culminate in the end-Rhaetian extinction event, with all three phases marked by disturbances in the carbonate productivity. Whereas the middle Norian event comes up as turnover in both the reefal and pelagic fauna, reefs are still flourishing during the early Rhaetian where the pelagic fauna has already started to decline. The Rhaetian stepwise extinction history of the pelagic fauna clearly predates the end-Triassic crisis and extinction of the shallow-water fauna which can be directly coupled with the ultimate breakdown of the carbonate factory on the platform, and is linked in major parts of the Northern Calcareous Alps with a distinct sea-level drop.

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