Field trip 11

Rhaetian (Late Triassic) biotic and carbon isotope events and intraplatform basin development in the Northern Calcareous Alps, Tyrol, Austria

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1 Topics and geological setting

Intraplatform basin sediments of the Northern Calcareous Alps are known as one of the best sedimentary archives worldwide of significant biotic and chemostratigraphic events in the Late Triassic (Rhaetian). Continuous Triassic-Jurassic boundary sections of the Kössen Formation in the Karwendel mountain range represent the most important localities in the world for the study of the top-Triassic mass extinction event. Moreover, detailed chemostratigraphic studies in the Kössen Formation document significant changes of carbon isotope ratios which may reflect important perturbations of the carbon cycle in the Rhaetian.

The excursion is intended to give an overview of the Rhaetian intraplatform basin development and associated environmental, biotic and chemostratigraphic changes in the Rhaetian and across the Triassic/Jurassic boundary. For this purpose localities at the carbonate platform-basin transition (Steinplatte) and in the central basin (Eiberg section, Kuhjoch) will be visited.
The excursion localities of the Kössen Formation (Fig. 1) are situated within the Eiberg Basin which extends from the Salzkammergut in the east to the Lahnewiesgraben near Garmisch-Partenkirchen in the west. This basin was part of an extensive shallow marine carbonate platform at the northwestern margin of the Tethys which was bordered to the southeast by an extensive lagoon with fringing reefs (Dachstein Formation, Steinplatte reef, Adnet quarries) and to the north by a carbonate ramp (Oberrhät Limestone) (Fig. 2, 3).
Towards the southeast, the Dachstein platform facies zone passes into the open marine facies of the Hallstatt Basin at the Tethys margin. The deposits of the Eiberg Basin are today exposed as parts of the Bajuvaric and Tyrolic nappes.

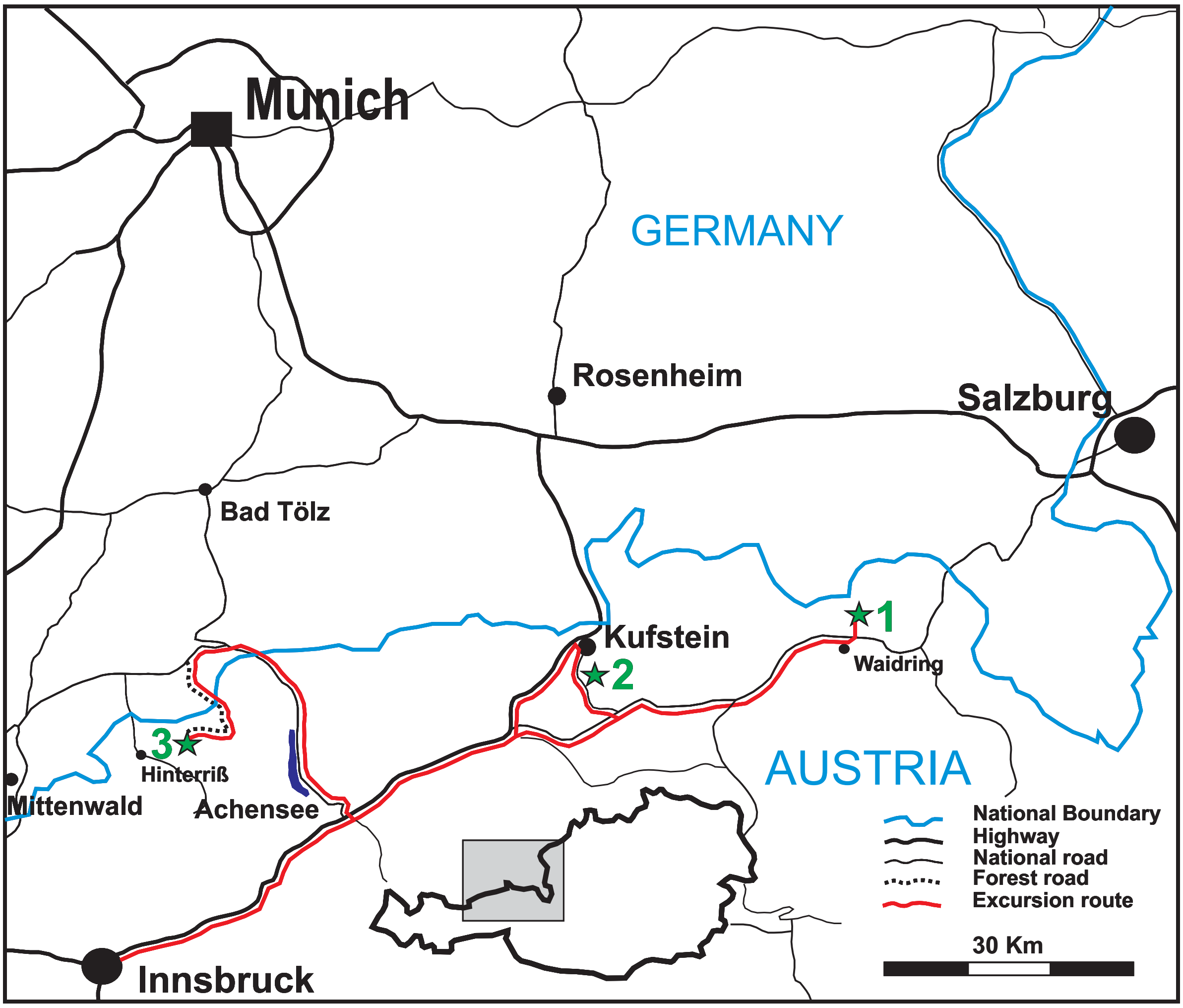


Fig. 1: Geographical map with excursion route and localities (1-3).

2 Stratigraphy of the Rhaetian

The Rhaetian stage has a long history of controverse discussions concerning the definition and duration of this time interval. It was introduced by Gümbel (1859) based on the stratigraphic range of the shallow-water bivalve *Rhaetina gregaria*. This definition was later adopted by Mojsisovics et al. (1895) although the Rhaetian itself and its lower and upper boundaries were not defined by age-diagnostic fossils. From 1979 to 1992 the Rhaetian stage was removed from the North American geologic timescale (Tozer 1979) but later established again (Visscher, 1992). Since 2008 the Rhaetian/Hettangian boundary is defined by the FAD of the ammonite *Psiloceras spelae* and the base of the Rhaetian was later determined by the FAD of the conodont *Misikella posthernsteini* (Krystyn, 2010). The Rhaetian is subdivided (Fig. 4) into the zone 1 (Lower Rhaetian), zone 2 (Middle Rhaetian) and zone 3 (Upper Rhaetian) which correspond to the ammonoid zones of *Paracochloceras suessi, Vandaites stuerzenbaumi* and *Choristoceras marshi* (Krystyn et al., 2007, Krystyn, 2008, Maslo, 2008). For Tethyan pelagic sequences between the Alps and Timor these substages were correlated

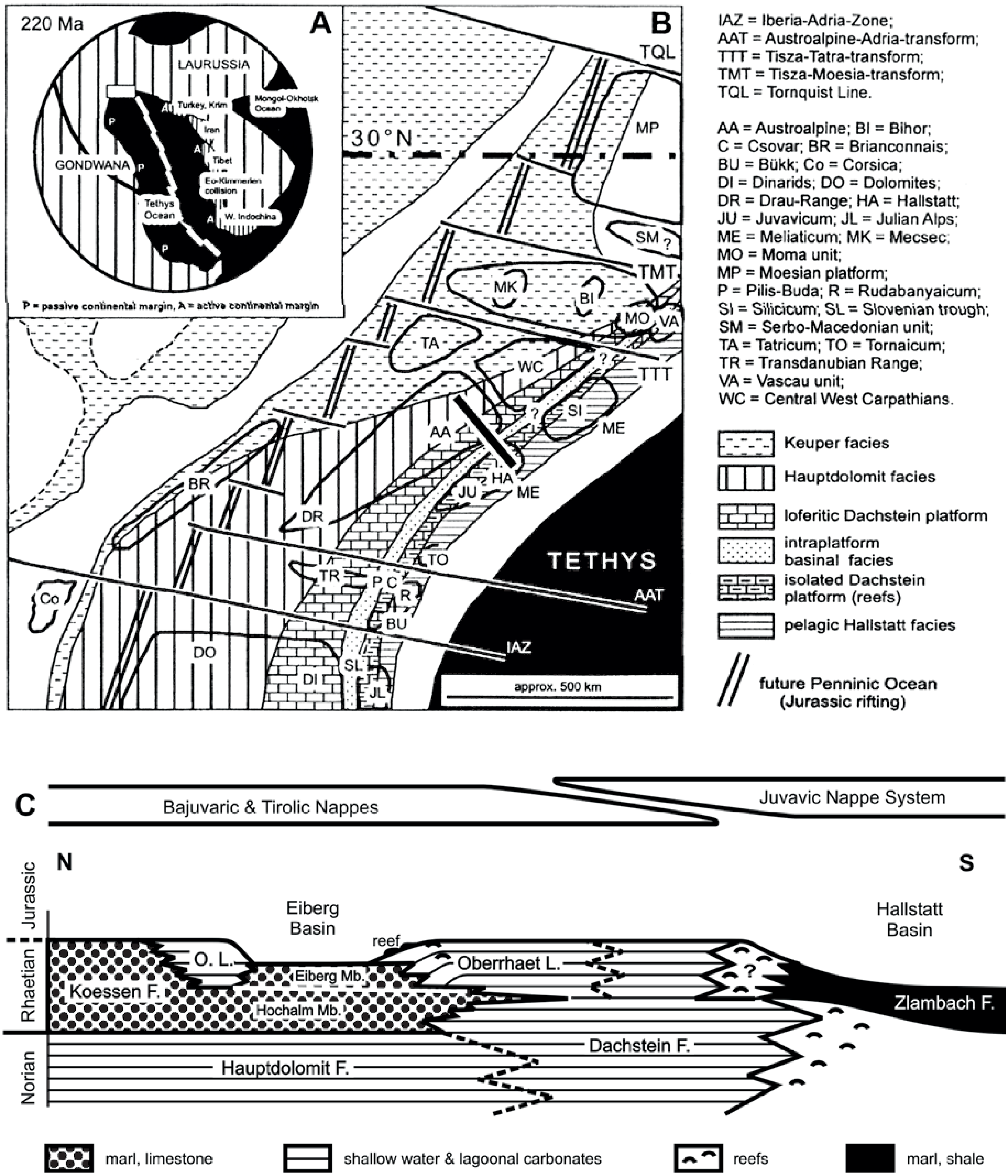


Fig. 2: Late Triassic (Norian-Rhaetian) palaeogeography and facies zones of the Northern Calcareous Alps (from Krystyn et al., 2005).

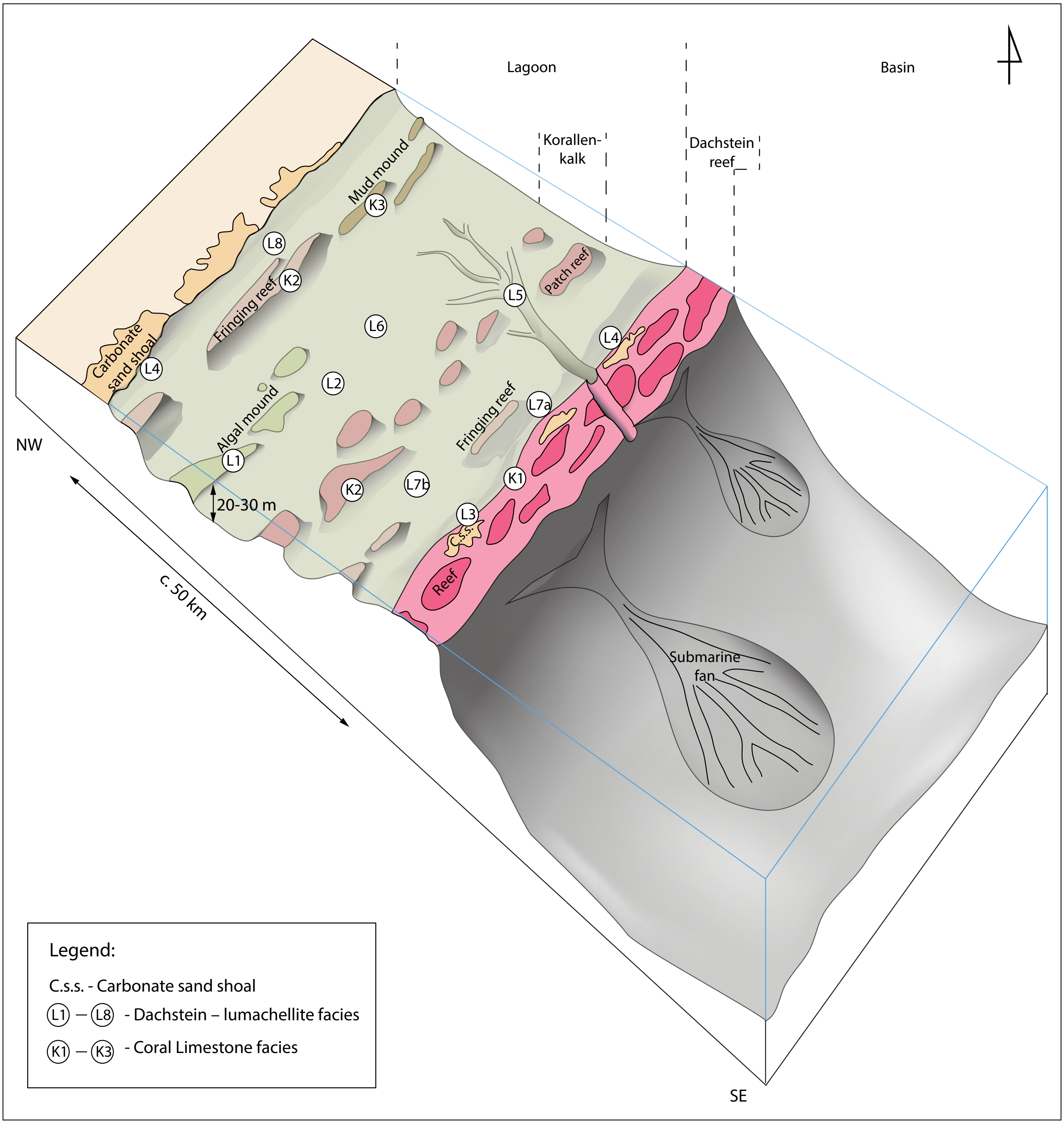


Fig. 3: 3D model of the shallow-water Eiberg Basin for the Lower and Middle Rhaetian (Hochalm Member) after Rizzi et al. (in prep.). The different facies are reported here in their depositional context. Abbreviations: L1 – Laminated algal bindstone; L2 - Peloidal pack/grainstone; L3 - Bioclastic grainstone; L4 - Oolite facies; L5 - Foraminiferal wacke/packstone; L6 - Mudstone facies; L7a - Proximal tempestite facies; L7b Distal tempestite facies; L8 - Oncoid-detritus facies; K1 - Coral detritus mud facies; K2 - Biostrome facies; K3 - Mud mound facies.

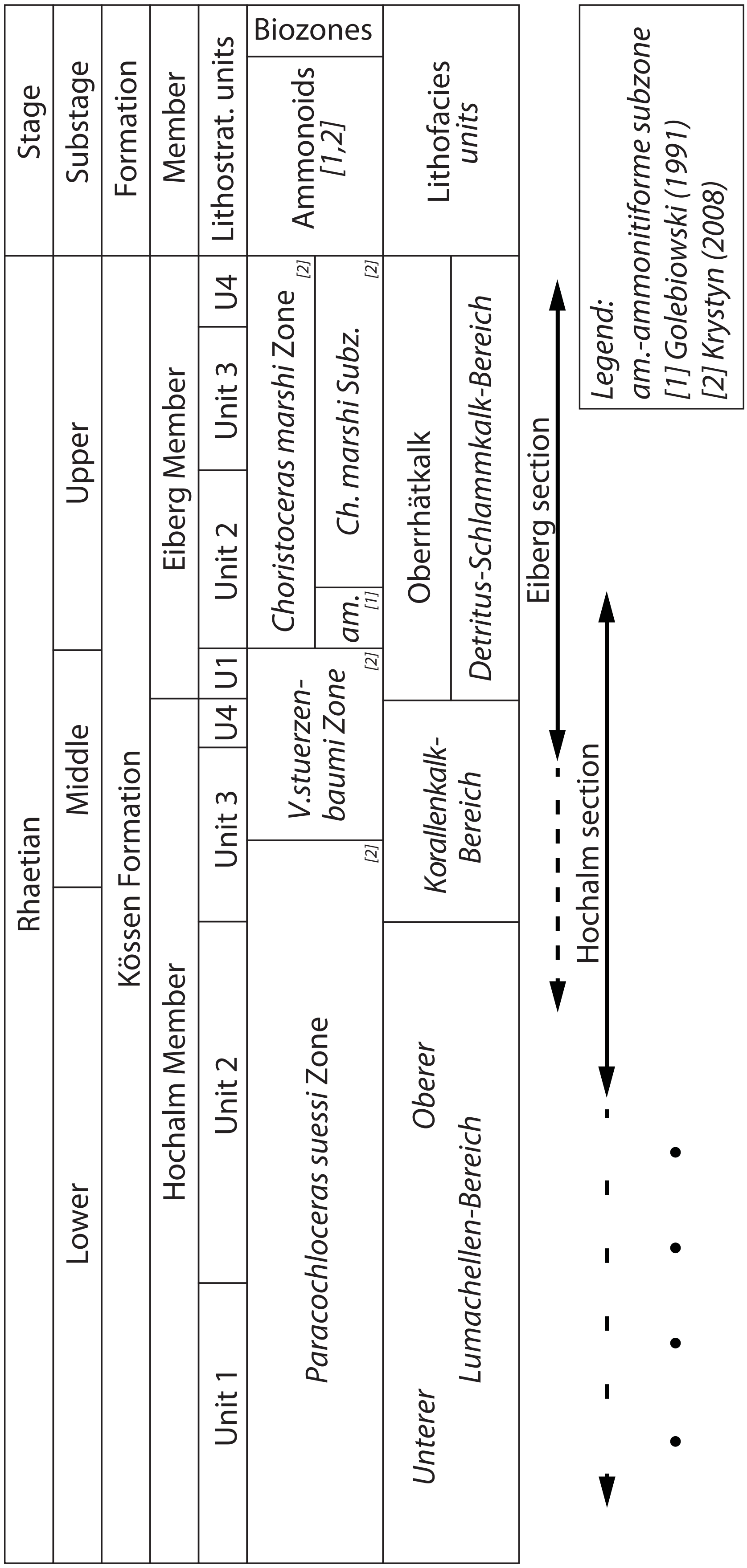


Fig. 4:
Lithostratigraphy and biozonation of the Rhaetian in the Northern Calcareous Alps (modified after Golebiowski, 1991 and Mette et al., 2012). Arrows indicate the stratigraphic extent of the sections. The dashed part of the arrow indicates the part of the Eiberg section which is currently very poorly exposed. The dashed and dotted lines indicate the part of the Hochalm section which has not been studied by Rizzi et al. (in prep.).

with the conodont zones of *Epigondolella bidentata – Misikella posthernsteini* (Rhaetian 1), *M. posthernsteini – M. hernsteini* (Rhaetian 2), *M. rhaetica* (upper Rhaetian 2 – lower Rhaetian 3) and *M. ultima* (upper Rhaetian 3) (Krystyn, 2008).

The duration of the Rhaetian is currently not clear. There is little controversy about the age of the Rhaetian/Hettangian boundary which was recently dated as 201.36 Ma (Wotzlaw et al., 2014). But there are very different age determinations for the Norian/Rhaetian boundary ranging between between 210 Ma (Hüsing et al., 2011) and 205.5 Ma (Wotzlaw et al., 2014).

3 Field trip stops

3.1 Locality 1, Steinplatte

3.1.1 Local geology

The Steinplatte carbonate complex is located south of the Unken syncline near Waidring (Tyrol) (Figs.1, 5a, b). Palaeogeographically, the Steinplatte is situated at the southern margin of the Eiberg Basin. It shows the tectonically undeformed transition from the Dachstein platform to the Kössen Basin (Fig. 6a, b). The transitional unit is a northward inclined distally steepened carbonate ramp and slope. The absence of vertical tectonic displacement between the ramp and the basinal successions allows the reconstruction of the original basin bathymetry. The data in Krystyn et al. (2005) suggest a maximum water depth of 150-200 m for the middle and upper Eiberg Member of this locality. The descriptions and illustrations of the following outcrops are largely adopted from Richoz et al. (2012).

Stop 1: Kammerköhr Inn tourist trail

This trail exposes toe-of slope calcarenites (bioclastic pack– and grainstones rich in crinoid bivalve debris with Rhaetian microfauna, (Turnsek et al., 1999), followed to the south by different types of platform carbonates respectively and reef facies types (of the Oberrhät Limestone) (Fig. 5b). The major part of the margin is not formed by reef framework (Stanton and Flügel, 1989, 1995) but by fine bioclastic limestones and coral fragments. Its top is partly overgrown by large bushlike corals (Capping Beds). Coral growth of the capping facies stopped in the latest Rhaetian, whereas the palaeorelief of the carbonate platform persisted until the Middle Liassic (Figs.6a, b).

Stop 2: Fischer`s Coral Garden

On top of the Oberrhät Limestone occur abundant corals of large *Thecosmilia* which are partly preserved in life position but mostly lying on the side or upside down (Fig. 7). There is however no evidence of a skeletal framework structure. The coral growth stopped in the latest Rhaetian and the capping facies is covered by an oncoid bearing layer with reworked megalodont shells indicating a latest Rhaetian sea level drop.

Stop 3: Steinplatte summit

Steinplatte summit with view to lagoonal sediments (Loferer Facies) forming the "Loferer Steinberge", "Leoganger Steinberge" and "Steinernes Meer" in the southeast and to the Wilder Kaiser (Wetterstein Limestone) in the west.

Stop 4: Capping Beds

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 stopped during end-Triassic, whereas the palaeorelief of the carbonate platform still existed until the Middle Liassic.

Stop 5:

At the northern slope of the Plattenkogel sponge-stromatactis–biomicrites of Lower Liassic age are preserved in a syn-tectonic depression of the former Triassic reef surface (Fig. 7). Due to the striking facies similarity with beds from the Adnet reef slope, the succession is attributed to the Schnöll Formation (Böhm et al., 1999). Non-rigid sponges formed spicular mats during starved Liassic sedimentation. Skeletal remains and adjacent micrites where partly fixed by microbially induced carbonate precipitation due to the decay of sponge organic matter (Krystyn et al., 2005). Syngenetic stromatactis cavities are attributed to regular compaction as well as volume reduction during microbialite formation.

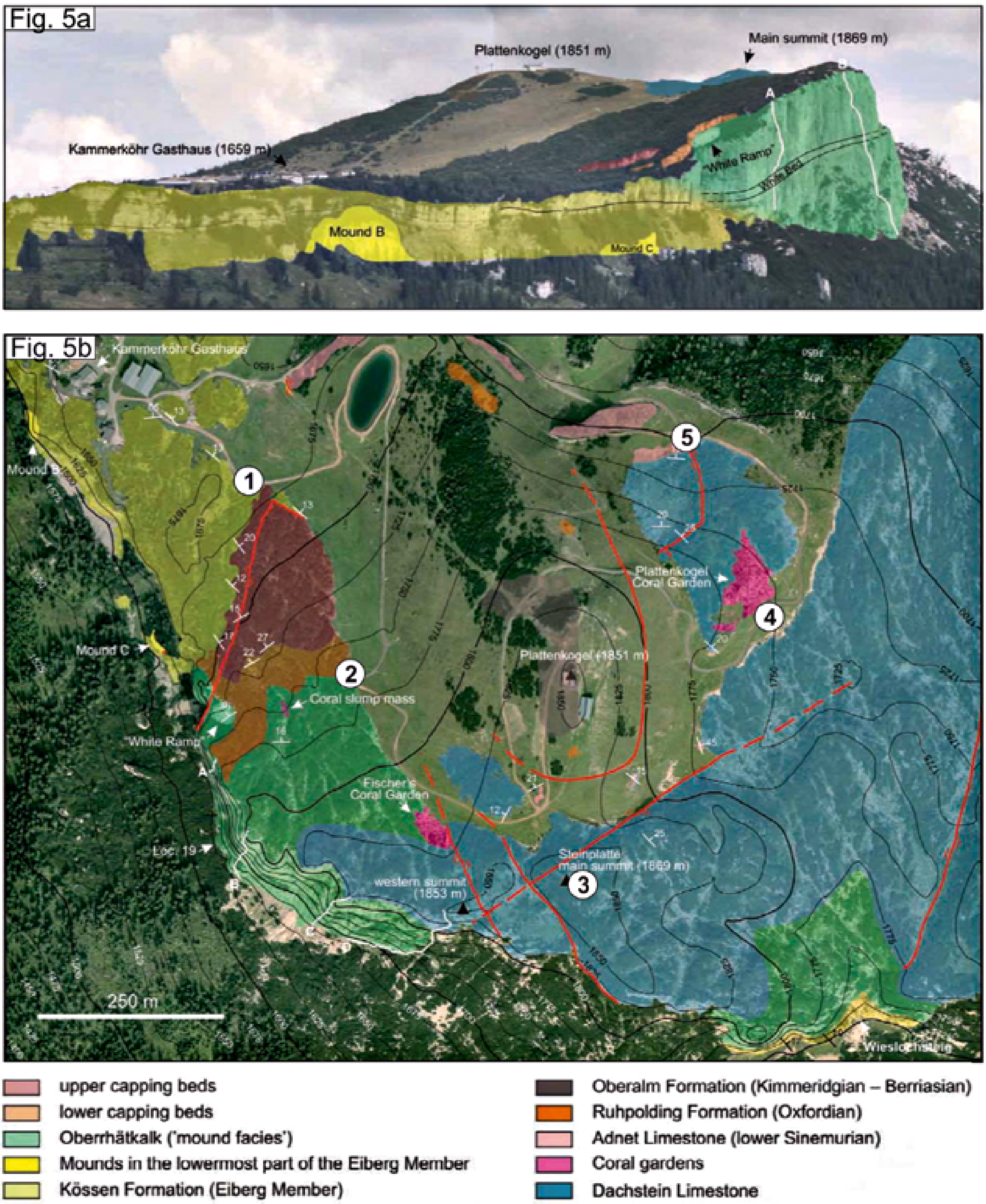


Fig. 5a: View to the Steinplatte carbonate complex from ESE; Upper Triassic lithostratigraphic units are indicated by colours; 5b: Geological map of the Steinplatte area (modified after Richoz et al., 2012).

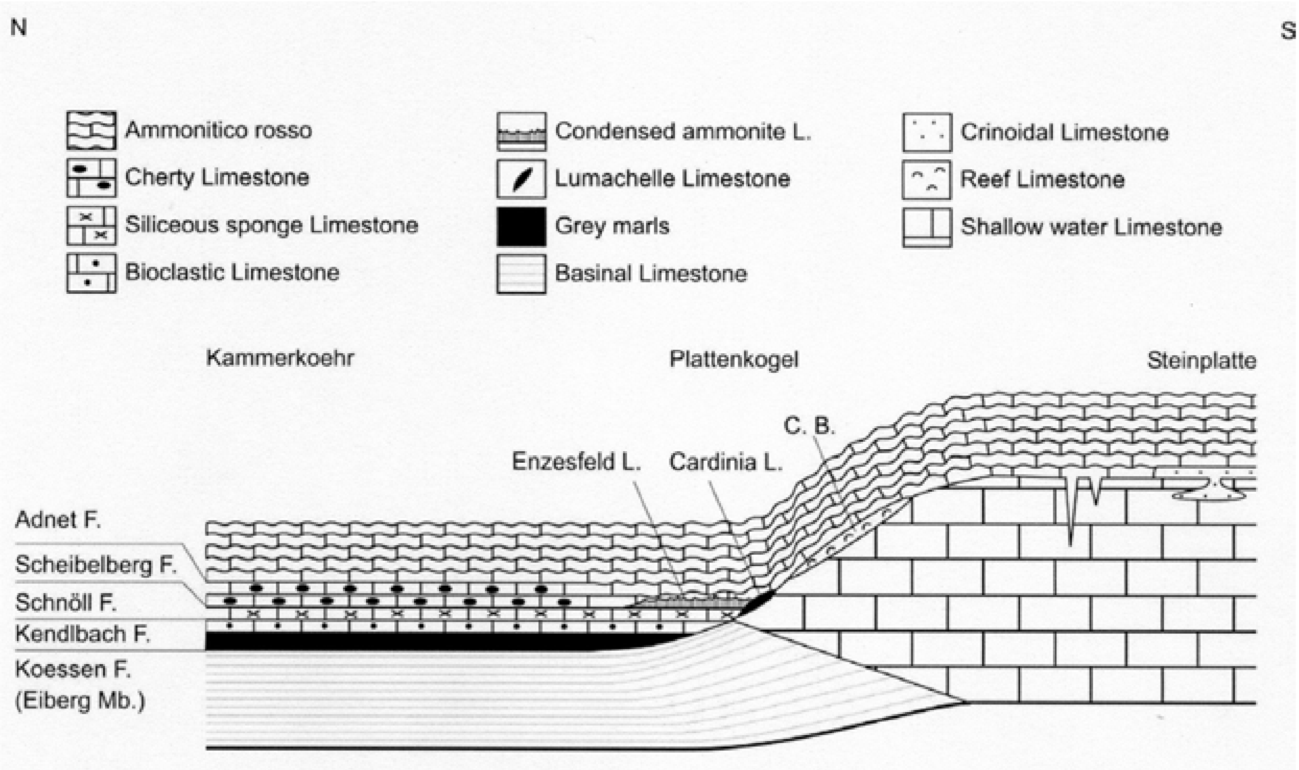


Fig. 6a

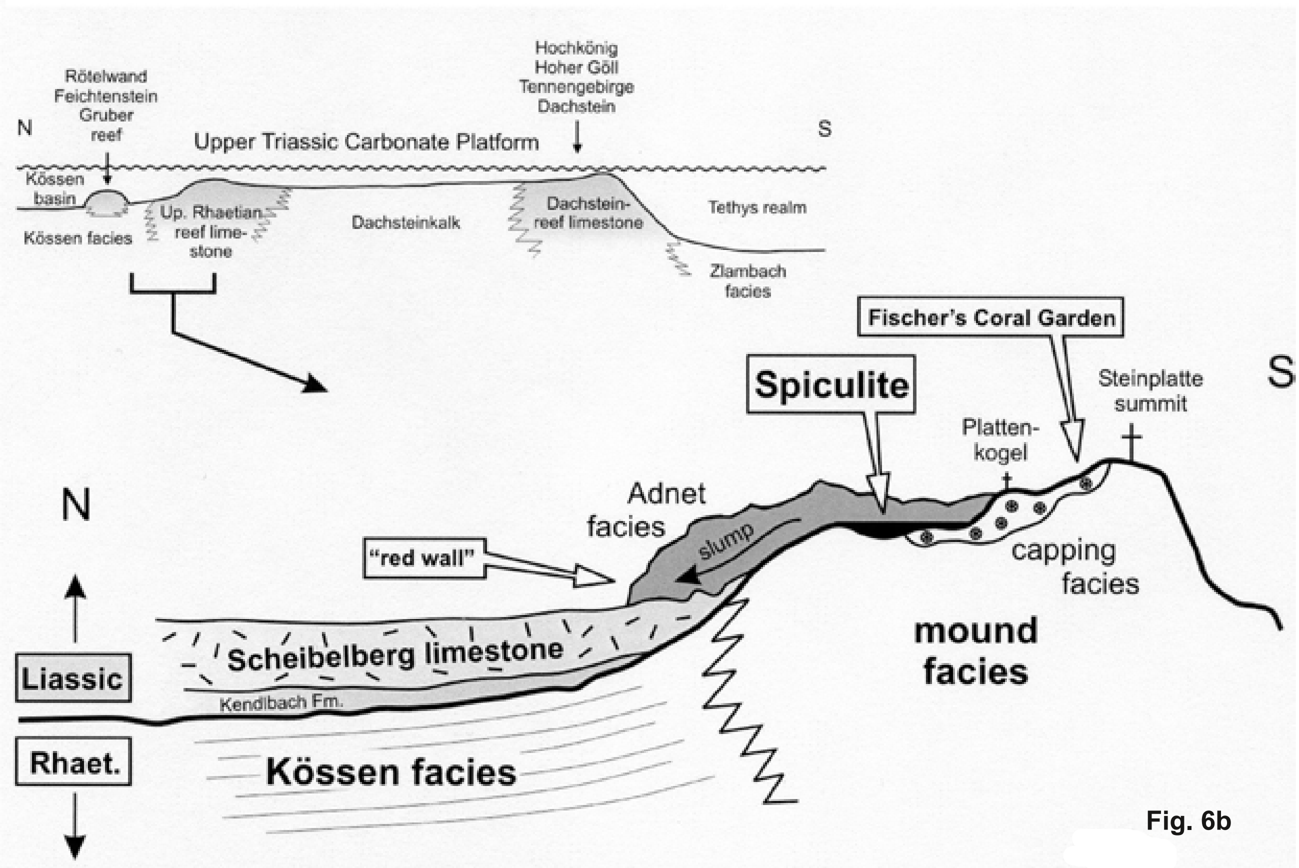


Fig. 6b

Fig. 6a: Schematic cross-section from the Steinplatte Platform to the Eiberg Basin and reconstruction of Upper Triassic and Lower Jurassic depositional sequences (C.B.=Capping Beds) (modified after Krystyn et al., 2005); 6b: Northern slope section of the Steinplatte "Reef" (N of Waidring, Austria) and reconstruction of Rhaetian to Lower Jurassic depositional history (modified after Krystyn et al., 2005).

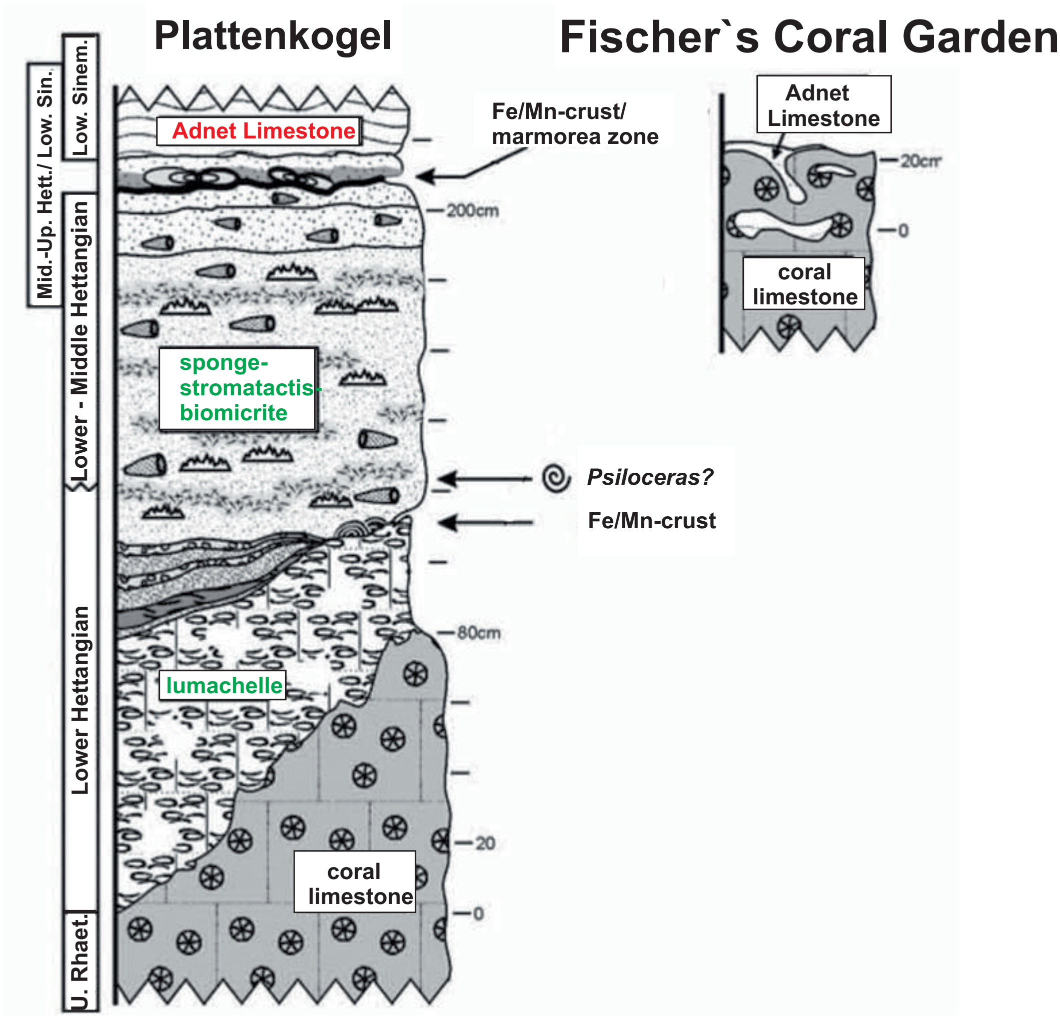


Fig. 7: Triassic-Jurassic transitional sequence at Plattenkogel hill and "Fischer`s Coral Garden" (modified after Krystyn et al., 2005).

North of stop 3 the tourist trail passes a large wedge of red Sinemurian-Toarcian red pelagic carbonates (of the Adnet Formation). The succession shows slump folds and megabreccias formed by a mass flow along the palaeoslope onto grey limestones of the Scheibelberg Formation (Garrison and Fischer, 1969; Wächter, 1987) (Fig. 6b).

3.2 Locality 2, Eiberg section

3.2.1 Stratigraphy

The section at Eiberg quarry, a cement factory (SPZ Zementwerk Eiberg GmbH) located 3 km south of Kufstein (Tyrol), represents one of the most complete successions of the Kössen Formation. This section includes the middle and upper part of the Hochalm Member (upper Unit 2 - Unit 4) and a complete Eiberg Member at its type locality (Fig. 8). Based on ammonite and conodont data, Golebiowski (1989) has correlated the succession with Tethyan biozonation of the Hallstatt and Zlambach facies (Fig. 4). The Hochalm Member (Unit 1 to lower Unit 3) was attributed to the *Paracochloceras suessi* zone. The upper Hochalm Member (upper Unit 3 to Unit 4) and the lowermost Eiberg Member (Unit 1) was assigned to the *Vandaites stuerzenbaumi* zone. Eiberg Member 2 to 4 corresponds to the *Choristoceras marshi* zone. The maximum thickness of the Koessen Formation is 270 m (Golebiowski, 1989). The

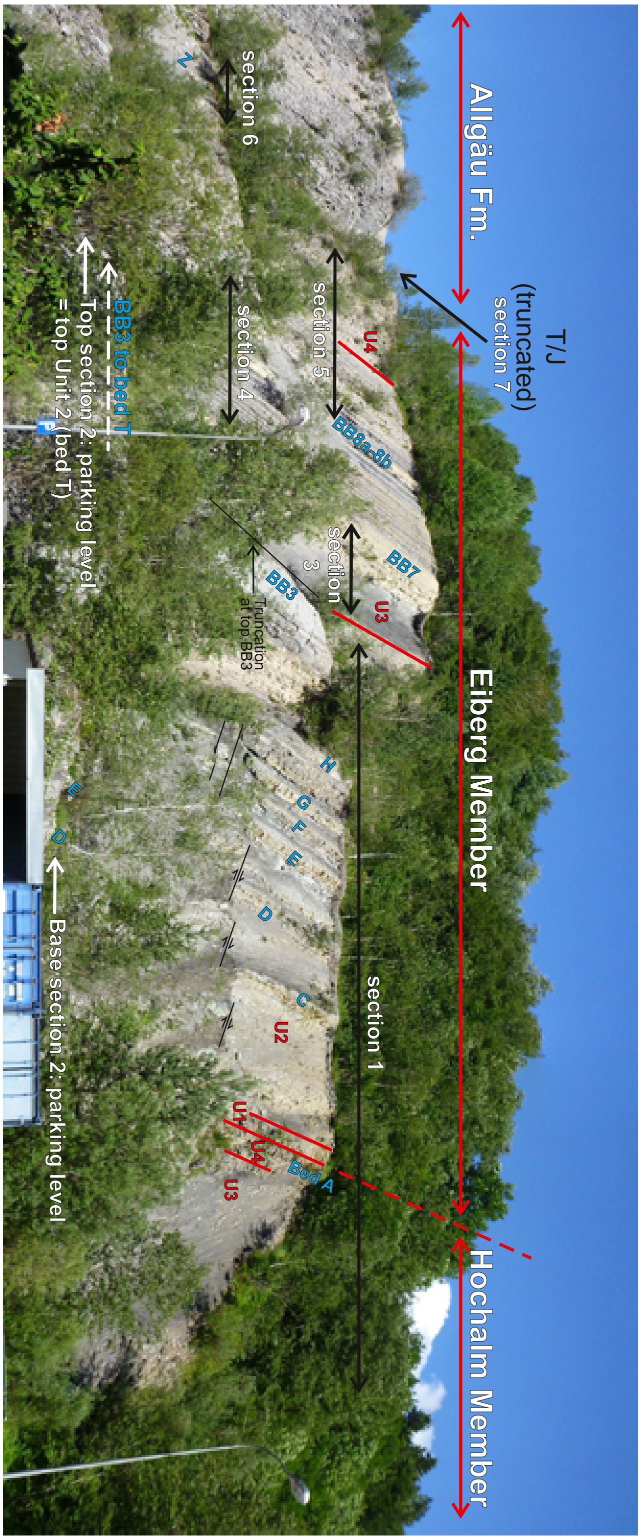


Fig. 8: Panorama of the Eiberg outcrop at the Eiberg quarry (after Thibault et al., in prep.).

succession exposed at the Eiberg quarry has a total thickness of ca. 82 m from the well-exposed topmost part of Unit 3 of the Hochalm Member to the latest Rhaetian event bed at the top of Unit 4 of the Eiberg Member. The base of the Kössen Formation (transition to the Plattenkalk) is not exposed. The contact with the Early Jurassic strata (Allgäu Formation) is disturbed by a major fault so that a major part of the Grenzmergel (uppermost Triassic) and the Kendlbach Formation (lowest Liassic) including the Triassic/Jurassic boundary are missing.

The succession at Eiberg section consists of various bioclastic and micritic limestones intercalating with marls and shales. Several distinct brachiopod beds (BB) and horizons with abundant trace fossils (Figs. 8, 9) occur. The section was recently re-logged in detail (Fig. 9; Thibault et al., in prep.) coinciding with the synthetic log by Mette et al. (2012). Both logs point toward the absence of the topmost 11 m of Eiberg Member Unit 2 in the log of Holstein (2004) (also represented in Fig. 34 of Richoz and Krystyn, 2015 although it is cited as Golebiowski, 1991 in the latter reference). The top of the succession as exposed in section 1, higher up in the quarry, is truncated by a fault that is sub-parallel to the stratigraphy at the top of brachiopod bed 3 (BB3, Figs. 8, 9). At the parking level, section 2 exposes a similar succession as section 1 but the bed-to-bed correlation of the two sections shows the exposure of an additional 11 m of sediments with wavy bedding, right above the hardground that marks the top of Unit 2 in Holstein (2004). In our log, this interval corresponds to the succession from BB3 to bed T, above which a few meters of calcareous clays mark the base of Unit 3 (Figs. 8, 9).

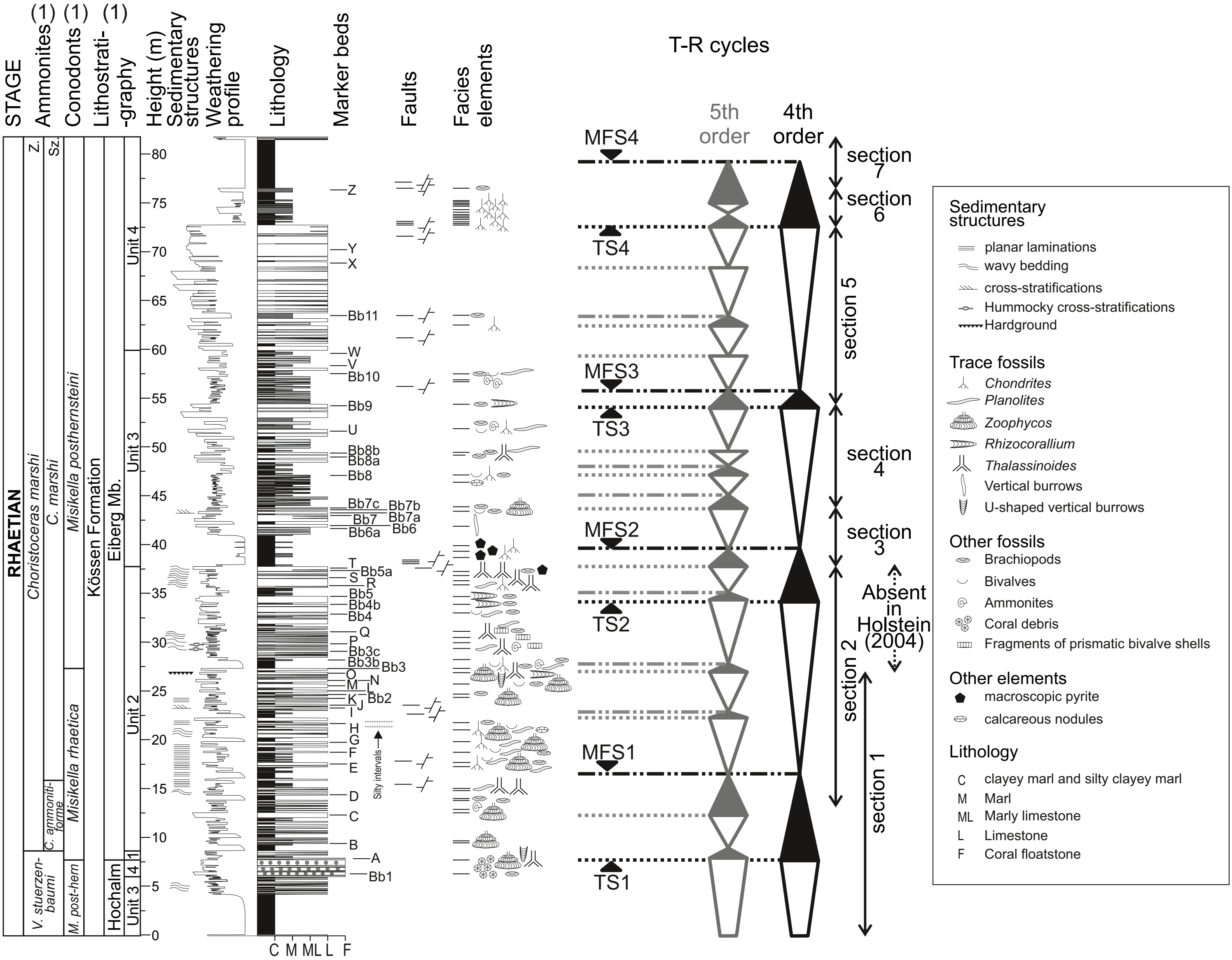


Fig. 9: Sedimentologic log of the Eiberg outcrop. Sections 1 to 7 refer to where the section was logged and sampled in 2012, 2013 and 2014. Note the presence of the upper 11 m of the Eiberg Member Unit 2 which are lacking in the Holstein (2004) log. A stratigraphic sequence interpretation proposed is based on shallowing-upward trends (after Thibault et al., in prep.).

3.2.2 Discussion: Basin development and palaeoenvironments

The Kössen Formation is characterized by several sedimentary cycles which were interpreted as shallowing upward cycles (Golebiowski, 1989, 1991, Holstein, 2004, Mette et al., 2012). The short-term cyclicity is superimposed by a long-term transgressive-regressive development with shallow marine conditions prevailing in the Lower and Middle Rhaetian part (Hochalm Member) (Fig. 3, 10) and a distinct deepening in the Late Rhaetian part (Eiberg Member) leading to a deeper neritic environment (>150m) below the storm wave base (Fig. 10). The uppermost part of the formation displays a significant sea level fall, which is indicated by upward-increasing bioclastic content and a thin, possibly condensed, hardground layer at the top (Krystyn et al., 2005).

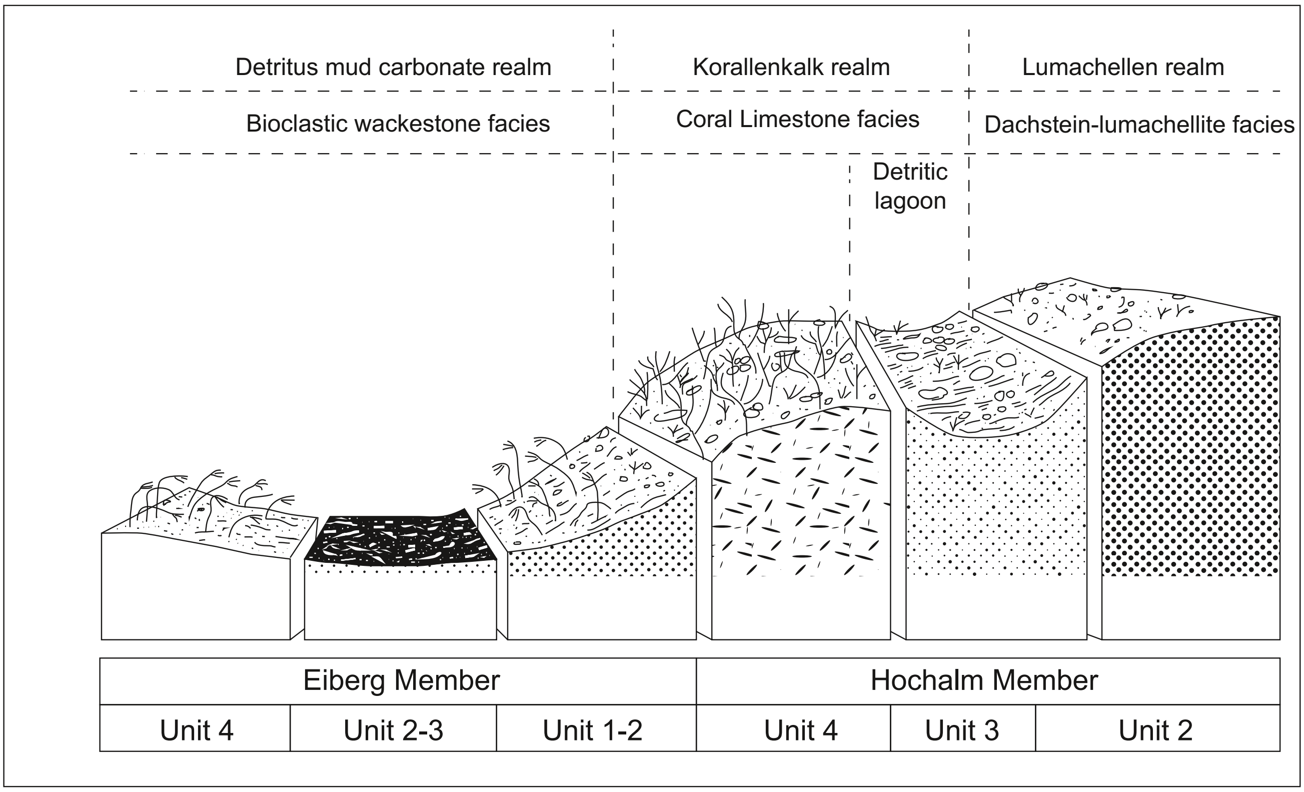


Fig. 10: Paleoenvironmental changes in the Kössen Formation through time based on the lithofacies and ecological stratigraphy of the brachiopods (modified after Golebiowski, 1991).

Marine conditions prevailed in the Eiberg Basin during the latest Rhaetian sea level fall whereas the surrounding shallow marine platform areas were probably affected by widespread emersion.

The Eiberg section is located in the central part of the Eiberg Basin. The litho- and biofacies development (Golebiowski, 1989) as well as palynomorph associations (Holstein, 2004) are indicative of a general upwards deepening trend which was interrupted by several subordinate shallowing upwards events. The sea level fluctuations were accompanied by changes in water oxygenation as indicated by significant variations of microfossil and microfloral assemblages and high abundance of framboidal pyrite in the lower part of the sedimentary cycles (Holstein, 2004, Mette et al., 2012). The upper Hochalm Member (Unit2), which is currently poorly exposed in the quarry (Fig. 8) was deposited in a shallow and restricted environment of less than 20 m water depth as indicated by abundant distal tempestites, laminated mudstones and marls as well as eurytopic bivalve associations (Golebiowski, 1989, 1991) and high abundance of marine euryhaline ostracods (Mette et al., 2012). A deepening below the storm wave base has been reported by Golebiowski (1989) for the Hochalm Member Unit 3 due to the absence of distal tempestites and changes in bivalve and brachiopod associations. In the Eiberg Basin, the top of the Hochalm Member (Unit 4) is marked by the "*Lithodendron* Limestone" which however, is not very prominent at the Eiberg section (< 2 m thick).

A further deepening occurs in the Eiberg Member Unit 1-3 indicated by a litho- and biofacies change (e.g. disappearance of terebratulid brachiopods, appearance of spiriferid brachiopods, dominance of the basinal bivalve *Oxytoma*) as well as by microfossil data (e.g. disappearance of shallow water ostracods). Unit 3 is dominated by a monotonous alternation of micritic limestones and marls with very low fossil content. The high abundance of pelagic ammonoids and conodonts in the Eiberg Member suggests a connection between the Eiberg Basin and the open Tethys during the Late Rhaetian. In the upper

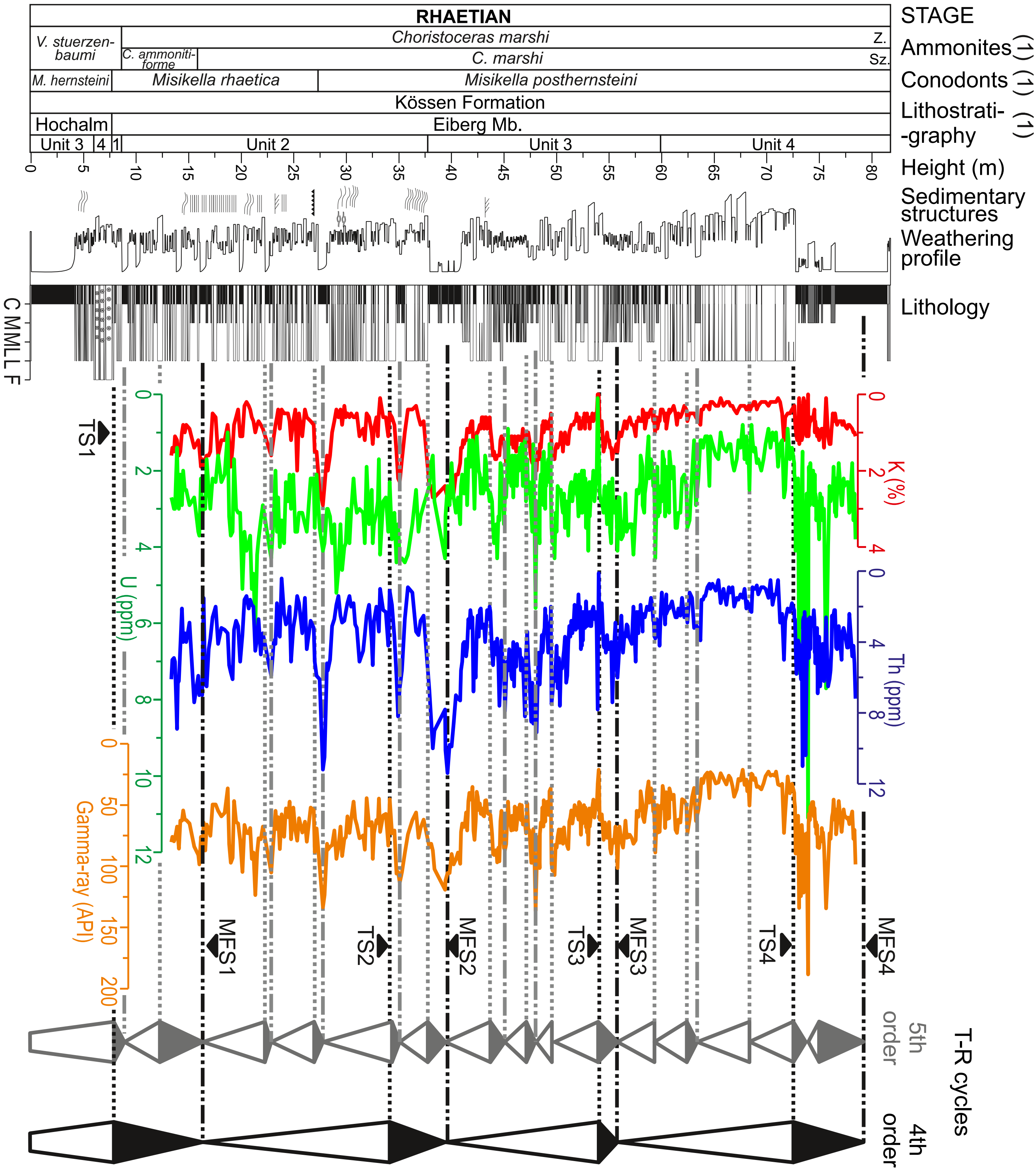


Fig. 11: Gamma-ray variations through the Eiberg section and corresponding sequence stratigraphic interpretation (after Thibault et al., in prep.).

Eiberg Member, a succession of medium to thick limestone beds with increasing bioclastic content, and the re-appearance of shallow water bivalves (*Palaeocardita*) and brachiopods (*Fissirhynchia*) indicate a gradual regressive trend that characterizes Unit 4 (Golebiowski, 1989, Krystyn et al., 2005). At the top of the Kössen Formation the limestone sequence of Unit 4 is overlain by ca. 9 m of marly limestones and marls (sections 6 and 7, Figs. 8 and 9) which include the interval of the late Rhaetian environmental perturbation associated with the mass extinction (Ruhl and Kürschner, 2011). The interval where the perturbation is recorded is hardly accessible in the quarry, situated at the top of a steep and slippery gully (section 7, Figs. 8 and 9).

Gamma-ray data were generated by a hand-held gamma-ray gun for a succession of the Eiberg section starting a few meters above the "*Lithodendron* Limestone" and extending up to the topmost calcareous clays (Fig. 11). Maxima in the gamma-ray correspond to maxima in the detrital component which are interpreted as maximum flooding surfaces (MFS), whereas sudden, sharp changes from low to high gamma-ray values are interpreted as transgressive surfaces (TS). Together with the sedimentology, these results allow for the identification of a number of T-R sequences in the order of 2-5 m long (5th order) that combine into 4 main sequences of 15-25 m (4th order). This interpretation is in agreement with the shallowing-upward trends of Golebiowski (1991) and Holstein (2004).

3.3 Locality 3, Kuhjoch section

The Kuhjoch section has been elected as the Global Boundary Stratotype Section and Point (GSSP) for the Triassic/Jurassic boundary (Hillebrandt et al., 2013). The main reasons for this decision is that this boundary section shows a relatively high sedimentation rate, continuous sedimention, well-oxygenated open marine environment, no vertical facies change, a global biomarker with short vertical range, a good microfossil record and terrestrial palynomorphs which may be used for correlations with the non-marine realm. And finally it shows a $\delta^{13}C_{org}$ curve with two distinct negative excursions which provide additional information for regional and global stratigraphic correlations. The section is moreover one of the best worldwide for the study of the end-Triassic mass extinction event.

The Kuhjoch section is located about 5 km east-north-east of the village Hinterriss on the southern flank of the Karwendel syncline as part of the Inntal nappe (Fig. 12a, b) and consists of two parallel outcrops on the western (Kuhjoch west) and eastern (Kuhjoch east) side of the Kuhjoch mountain pass (Figs. 12b, 13). The section comprises a steeply inclined and overturned succession of the Upper Rhaetian Kössen Formation and the uppermost Rhaetian – lowermost Liassic Kendlbach Formation. It is part of a continuous Rhaetian (Kössen Formation) – Upper Jurassic (Ruhpolding Formation) succession which crops out at the crest of the Kuhjoch.

Beside the Kuhjoch section there are a few other T/J boundary sections (e.g. Hochalplgraben, Schloßgraben) occurring in the Karwendel syncline within a distance of a few kilometers. The Kuhjoch section is however the most complete and best accessible of all P/T boundary sections in the Eiberg Basin. The following description is largely adopted from Hillebrandt et al. (2013) and includes some observations of the present authors.

3.3.1 Lithofacies development, fossil assemblages, environmental change and extinction patterns

3.3.1.1 Uppermost Rhaetian

The uppermost Kössen Formation (Fig. 13) consists of dark-grey marls with rare thin limestones beds overlain by medium to thick-bedded bioturbated limestones with a variable amount of bioclastic material (wackestones, mudstones) and thin marly intercalations. The microfauna includes moderately diverse foraminifera and highly diverse ostracod assemblages. The limestones also yielded a relatively diverse conodont fauna, including *Misikella posthernsteini,* and *M. ultima*.

A marly limestone at the top of the limestone succession yielded heavily sculptured Bairdiidae and other shallow marine ostracods indicating a relatively shallow water depths (unpublished data). The topmost 20 cm of the Kössen Formation are

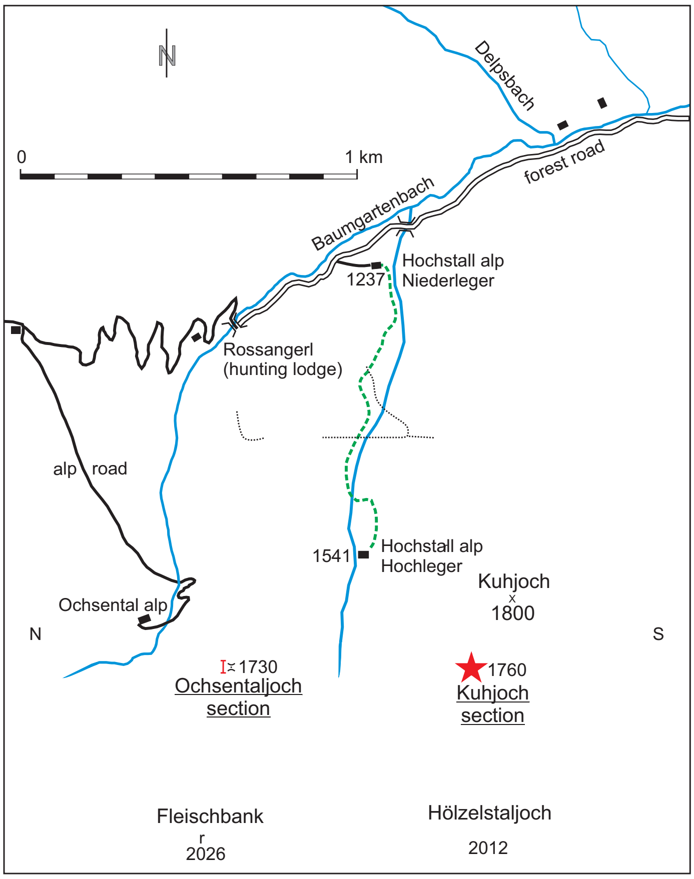
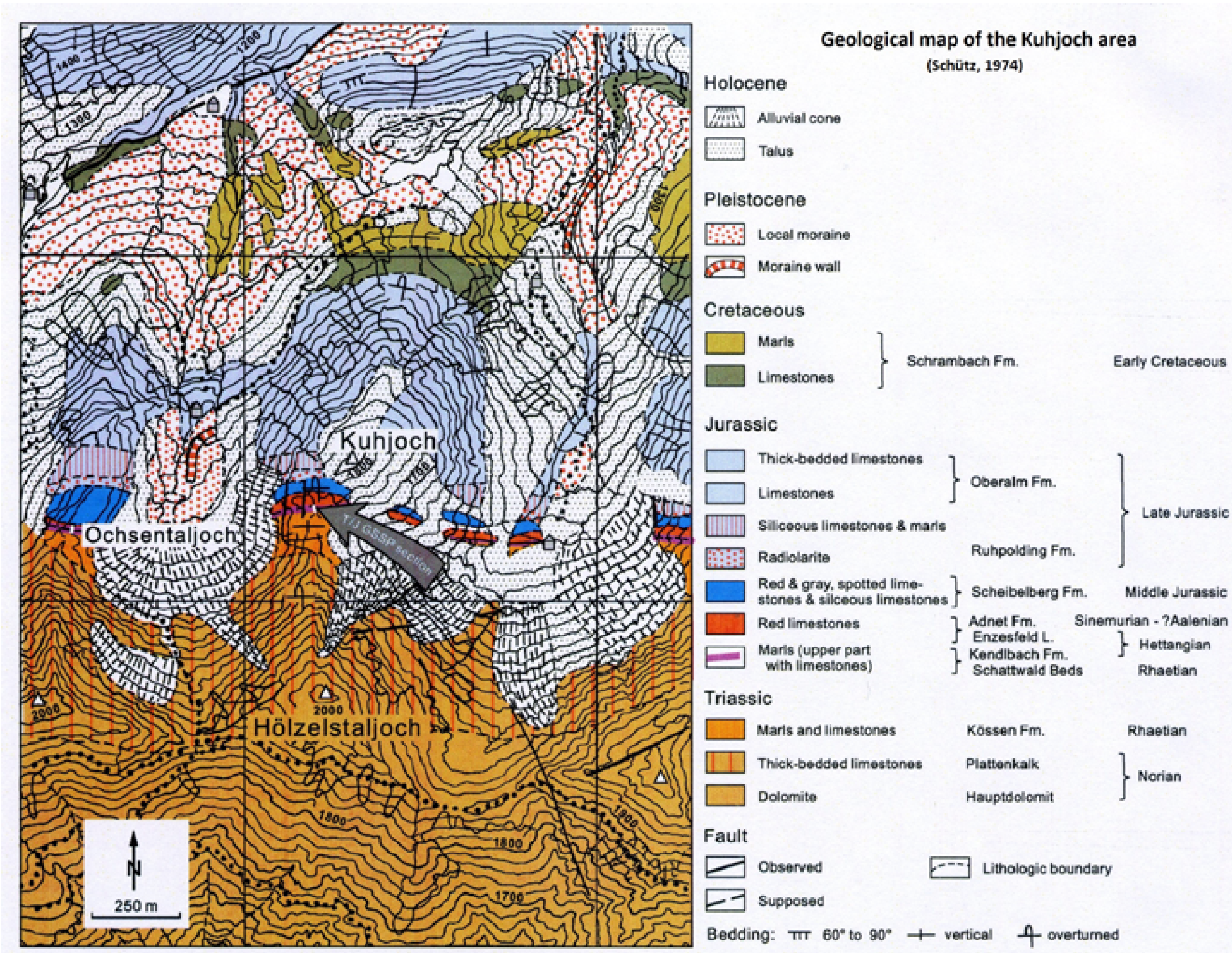


Fig. 12a: Locality map of the Kuhjoch section and Ochsentaljoch section (modified after Hillebrandt et al., 2013);
12b: Geological map of the Kuhjoch area (modified after Schütz, 1974).



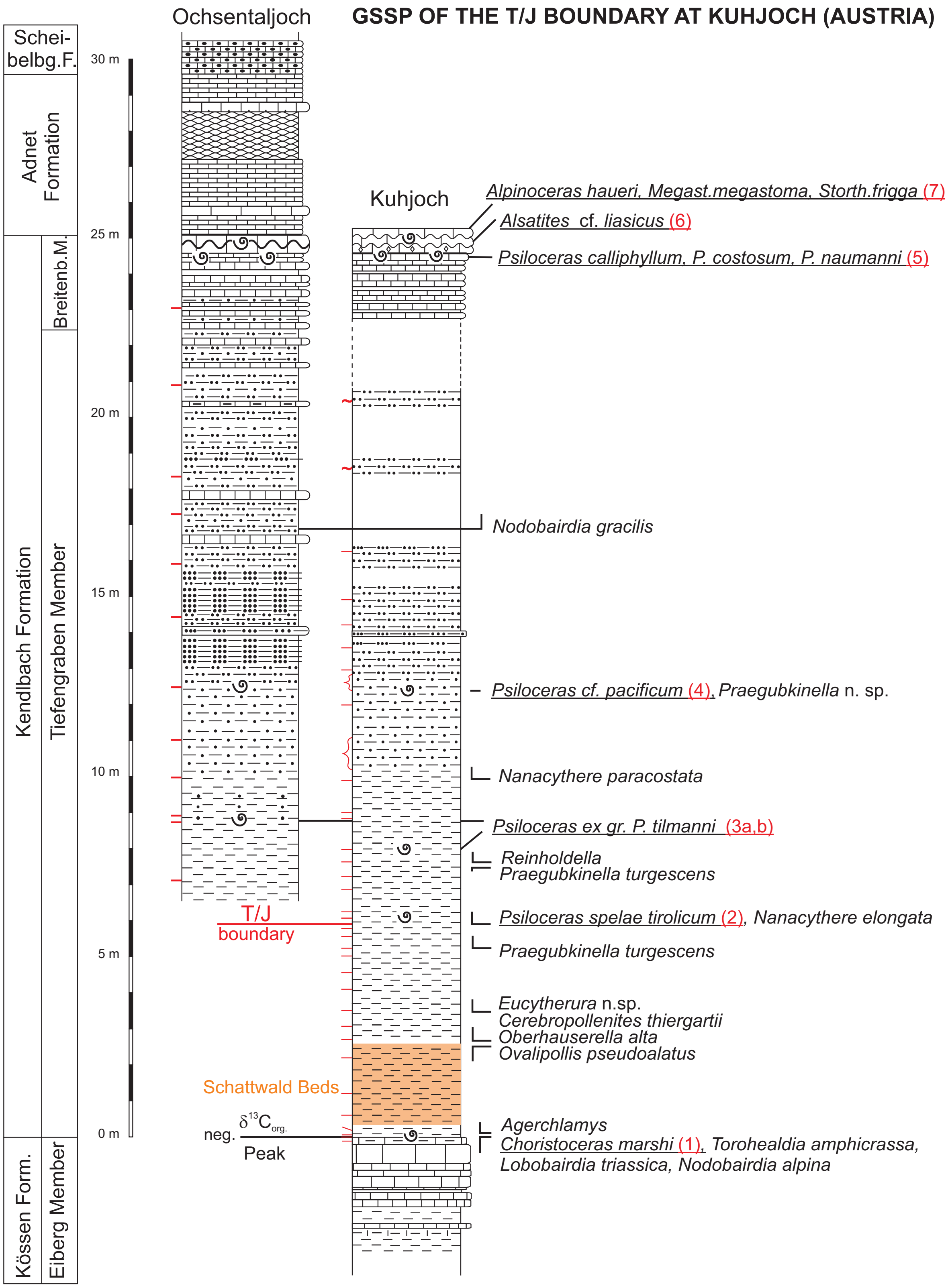


Fig. 13: Litho- and biostratigraphy of the Kuhjoch section and the nearby Ochsentaljoch section (modified after Hillebrandt et al., 2013).

represented by a dark brownish-grey and marly limestone to marlstone bed (T-Bed) without any bioturbation and a platy weathering. At Schloßgraben section abundant pyrite concretions were found in the upper part of the T-Bed. The T-Bed marks a distinct and abrupt lithologic change from basinal carbonates to marly-clayey sediments which was previously interpreted as reflecting a sea level drop. The ostracods however, do not point to a shallowing (unpublished data). At the top of the T-Bed a 1 cm thin black and bituminous layer occurs which is rich in bivalves and fish remains (scales) and is interpreted as an indicator for short-lasting anoxic conditions. Rare compressed and flattened *Choristoceras marshi* are also found representing the last occurrence of this genus in particular and of Triassic ammonites in the Kössen Formation in general. Also spiriferid brachiopods (*Oxycolpella*) were found. The top of the T-bed probably records the onset of the main extinction phase of the T/J mass extinction event as indicated by the disappearance of several macro– and microfossil taxa, particularly among ammonoids, foraminifera and ostracods (Fig. 14). This level is also characterized by marked changes of the terrestrial palynomorph assemblages (Kürschner et al., 2007) and extinction of calcareous nannofossils and change of benthic foraminiferal associations (Clemence et al., 2010).

The overlying Kendlbach Formation is represented by the Tiefengraben Member, a 22 m thick terrigenous sequence, and the 3 m thick calcareous Breitenbach Member (Fig. 13). The Tiefenbachgraben Member starts with brownish-grey marls (up to 13 cm) with pyritized worm burrows

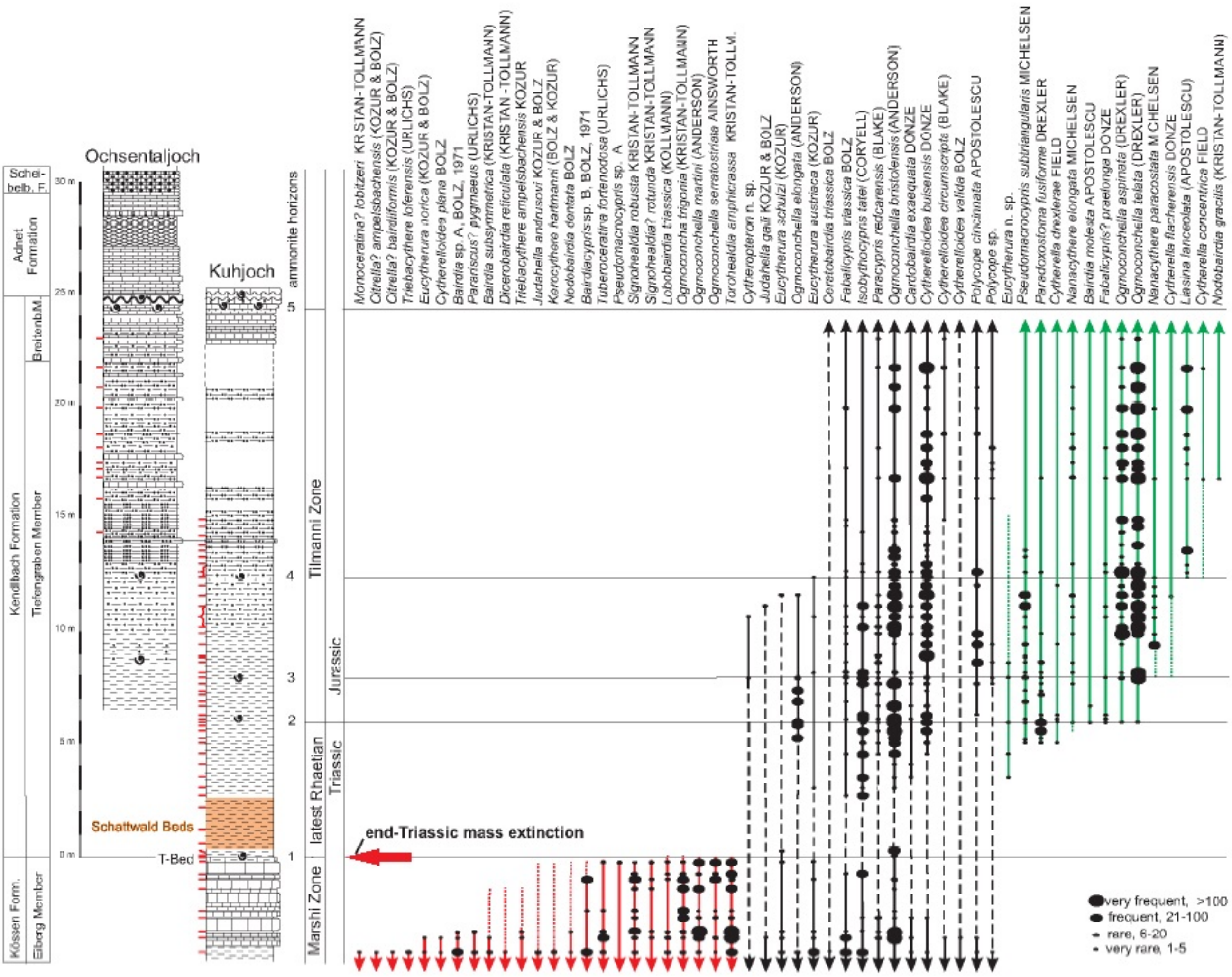


Fig. 14: Range of ostracod taxa at the Kuhjoch and Ochsentaljoch sections. The numbers 1-5 represent ammonite levels: 1= *Choristoceras marshi,* 2= *Psiloceras spelae tirolicum*, 3= *Psiloceras* ex.gr. *P.* cf. *tillmanni*, 4= *Psiloceras* cf. *pacificum* (modified after Hillebrandt et al., 2013).

and pyrite concretions. The macrofauna consists of few bivalves (*Agerchlamys, Pseudolimea, Cardinia,* small nuculids). The microfauna of this interval shows very little diversity, including few healdiid ostracods, small *Trochammina* and few nodosariids. The brownish marls pass upwards into yellowish-weathering, laminated marls (30 cm) and reddish, partly laminated silty clays (ca. 2 m) which are interpreted as an equivalent to the Schattwald Beds in the Allgäu Mountains (type locality near Schattwald). These beds are almost barren of macro- and microfossils, except for finely agglutinated siliceous foraminifera and palynomorphs, which could be due to a biocalcification crisis as proposed by Clemence et al. (2010) and Mc Roberts et al. (2012). The Schattwald Beds are also suggested to represent the maximum regression which was followed by a long-term gradual sea level rise that started already above the T-Bed. The overlying part of the marls of the Tiefengraben Member shows the reappearance of ostracod species as well as the appearance of new Liassic species (Fig. 14).

3.3.1.2 Lower Liassic

The first Liassic ammonite level with *Psiloceras spelae tirolicum* (Guex, 1998) occurs 3.2 meters above the Schattwald Beds. This level is now accepted as the biomarker for the base of the Jurassic (Fig. 13). Another ammonite level with *P. tillmanni* is found 5.2 m above the Schattwald Beds and 2 m higher an ammonite horizon with *P*. cf. *pacificum* occurs. 8 m above the Schattwald Beds the marls become more silty and at 10 m more arenitic. The Breitenberg Member consists of grey, thin-bedded limestones with thin, black marl layers, a hardground layer and a condensed ammonite horizon of the *Calliphyllum* zone at the top. The next two or three limestone beds are condensed ammonite horizons of Middle and Late Hettangian age.

3.3.1.3 T/J extinction event

There is now broad consensus that the latest Triassic global mass extinction event was primarily caused by the emplacement of the Central Atlantic Magmatic Province (CAMP) and associated with possibly catastrophic environmental changes (e.g. ocean acidification, rapid sea level drop). The possiblity of a causal relationship between these geologic and biotic events was confirmed during the last few years by integrated high-resolution stratigraphic correlation and radiometric dating of the extinction event and the earliest magmatic intrusions of the CAMP (e.g. Schoene et al., 2010, Ruhl et al., 2010, Deenen et al., 2011, Guex et al., 2012, Blackburn et al., 2013). According to Ruhl et al. (2010) the extinction interval (corresponding to the initial negative excursion) lasted for 20-40 kyr while the recovery interval (first occurrence of Jurassic ammonites) was about 120 kyr long.

4 Carbon isotope stratigraphy of the Middle Rhaetian – Lower Jurassic at the Eiberg section and at the Triassic/Jurassic boundary section (base Jurassic GSSP) at Kuhjoch (Austria)

Stable isotope ratios were analysed on bulk rocks and brachiopods from the Eiberg section (Clémence et al., 2010; Ruhl and Kürschner, 2011; Mette et al., 2012; Thibault et al., in prep.). $\delta^{13}C$ values increase from +1.5 ‰ in the Hochalm Member to +2.5 ‰ in unit 3 of the Eiberg Member. An about 1.5 ‰ negative carbon isotope excursion occurs in the lower Unit 3 culminating at BB 7 (Late Rhaetian Event sensu Mette et al., 2012). The carbon isotope values vary between +1.5 and +2 ‰ for the higher part of the Eiberg Member showing an even more pronounced negative excursion at the top of the section. The $\delta^{13}C$ values in the Early Jurassic Allgäu Formation fluctuate around +0.5 ‰. The carbon isotope variations in the Eiberg Member of the Eiberg section (Clémence et al., 2010, Ruhl and Kürschner, 2011, Mette et al., 2012) may represent important chemostratigraphic markers and these are currently further refined by high resolution datasets (Thibault et al., in prep.). The observed trends suggest that carbon cycle perturbations have existed in the Rhaetian. The oxygen isotope values – analysed on well-preserved brachiopod shells – show an about +0.5 ‰ shift towards heavier values from the top of the Hochalm Member and middle Eiberg Member and were interpreted as bottom water cooling of ~ 2.5 °C (Mette et al., 2012).

The base-Jurassic is preceded by the end-Triassic mass extinction by 100–200 kyr (Deenen et al., 2010; Whiteside et al., 2010; Hüsing et al., 2014). The end-Triassic mass extinction is marked by a major, short-lived perturbation of $\delta^{13}C$ records from marine and terrestrial organic matter and calcite, which has been observed in sedimentary basins worldwide (Hesselbo et al., 2002; Palfy et al., 2007; Korte et al., 2009; McElwain et al., 2009; Ruhl et al., 2009; Korte and Kozur, 2011; Ruhl et al., 2011; Bartolini et al., 2012) (Fig. 15). This short-lived excursion is succeeded by a return to pre-excursion values and followed by a second shift to ^{13}C depleted carbon isotope values that continues throughout the Hettangian stage. The $\delta^{13}C$ values only return to upper Triassic levels in the Early Sinemurian.

The negative carbon isotope excursion (CIE) at the end-Triassic mass extinction has long been linked to the onset of CAMP volcanism. Paleomagnetic and bio-, chemo- and cyclostratigraphic correlation, combined with radiometric dating now reliably links (at high precision) the first major CAMP basalt flows in Morocco and eastern North America with the marine extinction event and coeval global carbon cycle perturbation (Deenen et al., 2010; Whiteside et al., 2011; Blackburn et al., 2013; Dal Corso et al., 2014; and references herein). The major phase of CAMP volcanism, however, continued for up to a million years into the Early Jurassic, impacting (doubling to quadrupling) atmospheric pCO_2 (McElwain et al., 2009; Schaller et al., 2011). The negative $\delta^{13}C$ perturbation at the end-Triassic mass extinction event was, however, short-lived (50–100 kyr) (Deenen et al., 2010; Hüsing et al., 2014), much shorter than the duration of CAMP emplacement. This observation suggests that an additional volume

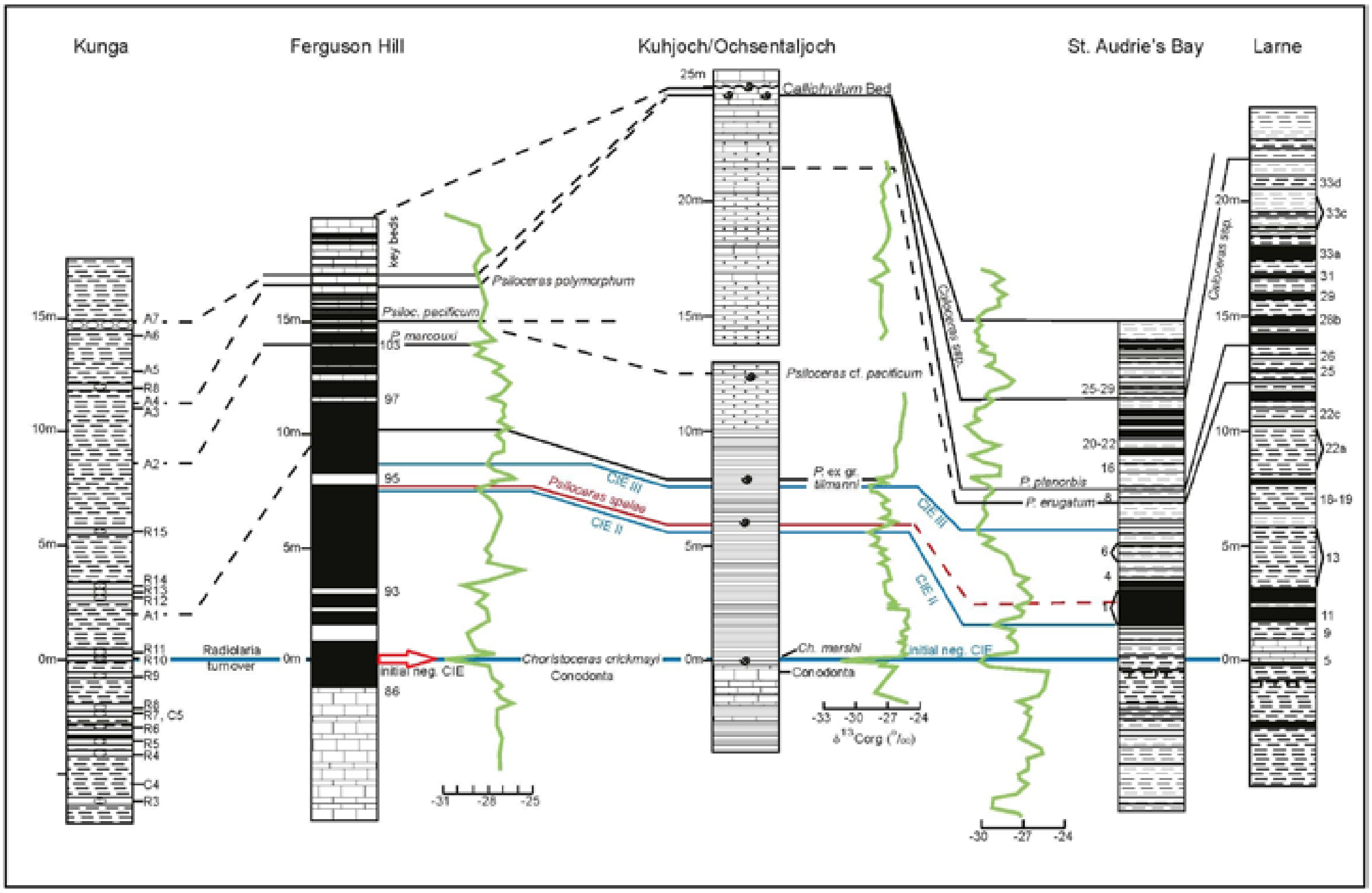


Fig. 15: Biostratigraphic and carbon isotope correlation of the Kuhjoch section with other T/J boundary sections (modified after Hillebrandt et al., 2013).

of isotopically depleted carbon was introduced into the end-Triassic ocean-atmosphere system. Initial global climatic warming, initiated by the onset of CAMP volcanism and the associated release of greenhouse-gasses, may have allowed for the catastrophic release of isotopically depleted carbon from sea-floor methane clathrates (Hesselbo et al., 2002; Ruhl et al., 2011). Alternatively, thermogenic methane released by dyke and sill intrusions into organic-rich sedimentary basins, related to and underlying CAMP, may have added significant amounts of isotopically depleted carbon to the end-Triassic oceans and atmosphere.

The Triassic-Jurassic boundary sections in the Eiberg Basin are all marked by the above described perturbations in $\delta^{13}C$ records (Ruhl et al., 2009) (Figs. 16, 17). The Kuhjoch outcrop is marked by a stratigraphically short, 5-6 per mil, negative shift in $\delta^{13}C_{TOC}$ at the very base of the Tiefengraben Member, preceding the Schattwald Beds and directly following the Kössen Formation (Ruhl et al., 2009). The onset of the negative CIE in this outcrop coincides with an organic-rich black shale, with TOC >10% and a distinct change in palynoflora (Bonis et al., 2010). Organic geochemistry of the second half of the negative CIE is, however, similar to the succeeding Schattwald Beds.

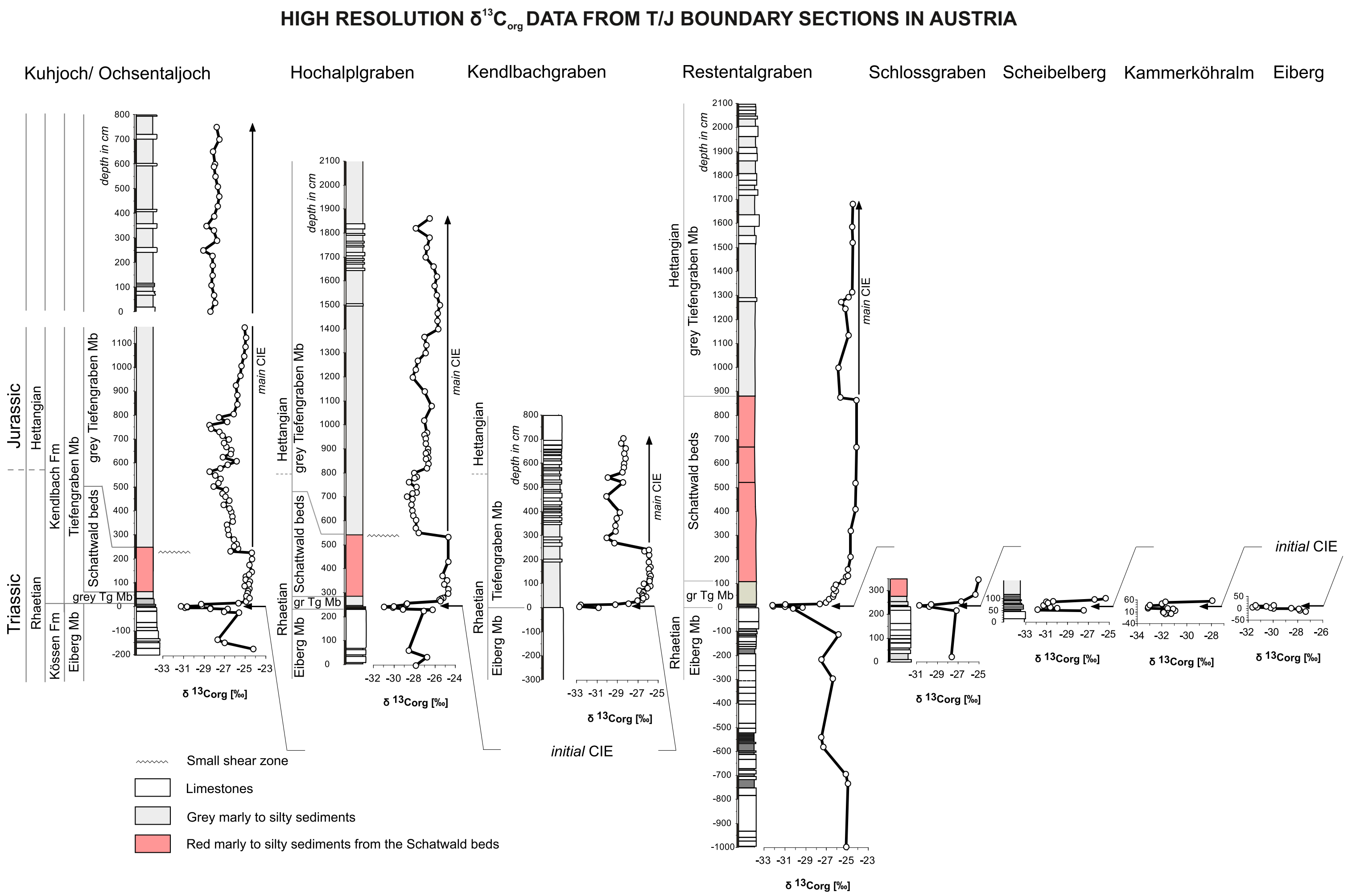


Fig. 16: Upper Rhaetian–Hettangian carbon isotope ($\delta^{13}C_{org}$) curves of the Kuhjoch section and other T/J boundary section in the Northern Calcareous Alps (CIE= carbon isotope excursion) (modified after Ruhl et al., 2009).

A second long-term, negative shift in $\delta^{13}C_{TOC}$ precedes the Triassic-Jurassic boundary (Figs. 16, 17), with the first occurrence of *Psiloceras spelae tirolicum* (Hillebrandt et al., 2013), by ~3 meters (Ruhl et al., 2009). In the Kuhjoch West section on the western side of the Kuhjoch mountain pass, the onset of this negative CIE is marked by an abrupt -1 to -1.5 per mil negative shift in $\delta^{13}C_{TOC}$. This abrupt shift in $\delta^{13}C_{TOC}$ values also marks a missing palynomorph zone and suggests a minor hiatus (Ruhl et al., 2009; Bonis et al., 2010). Coeval sediments in the Kuhjoch East section, east of the Kuhjoch mountain pass do, however, show a gradual change in $\delta^{13}C_{TOC}$ and all the palynomorph zones typical for the Triassic-Jurassic transition in the Eiberg Basin (Hillebrandt et al., 2013). Combined, the Kuhjoch West and East section, which are geographically only 10–20 m apart, do represent a continuous sedimentary sequence across the Triassic-Jurassic transition in the Eiberg Basin.

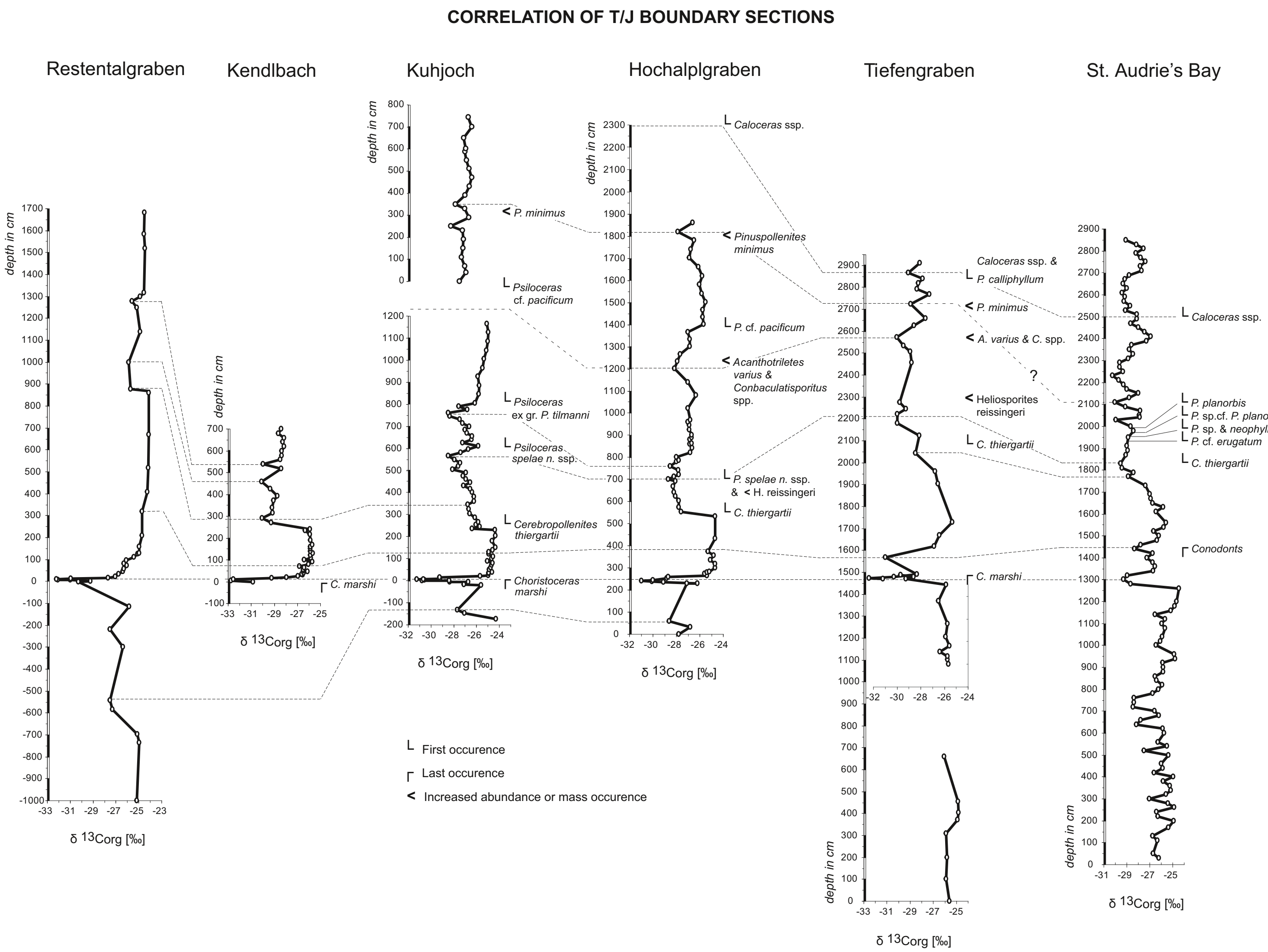


Fig. 17: Stratigraphic correlation of the Triassic-Jurassic boundary sections from the Northern Calcareous Alps and St. Audrie`s Bay based on high resolution organic C-isotope records and biostratigraphic markers (modified after Ruhl et al. 2009).

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