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The Global Stratotype Sections and Point (GSSP) for the base of the Jurassic System at Kuhjoch (Karwendel Mountains, Northern Calcareous Alps, Tyrol, Austria)

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The Global Stratotype Section and Point (GSSP) defining the base of the Jurassic System Lower Jurassic Epoch and Hettangian Stage is situated at the Kuhjoch pass, Karwendel Mountains, Northern Calcareous Alps, Austria (47°29'02"N/11°31'50"E). The Triassic-Jurassic (T-J) boundary is exposed at Kuhjoch West and at Kuhjoch East, and corresponds to the first occurrence (FO) of the ammonite Psiloceras spelae tirolicum. *The "Golden Spike" was fixed at Kuhjoch East. The section displays a high and continuous sedimentation rate with a constant facies trend across the boundary level. Other bio-events include the FO of the aragonitic foraminifer* Praegubkinella turgescens, *and of diverse ostracod species 1.0-3.40 cm below the FO of* P. spelae *and 3.2 m below* P. spelae *occurs the continental palynomorph* Cerebropollenites thiergartii. *Because of the lack of other terrestrial microfloral events this is yet the FO event closest to the FO of* P. spelae *and allows a correlation with nonmarine sediments. The* $\delta^{13}C_{org}$ *record shows a strong initial negative excursion at the boundary between the Kössen and Kendlbach formations, 5.8 m (Kuhjoch W) below the T-J boundary, a shift to more positive* $\delta^{13}C_{org}$ *in the Schattwald Beds and a gradual decline to more negative values at the transition of the Schattwald Beds to the proximate Tiefengraben Mb. The stratotype point lies within a zone of smaller negative and positive* $\delta^{13}C_{org}$ *peaks, which is superimposed on a longer lasting main negative shift. According to recent investigations, the radiometric age of the T-J boundary is about 201,3 Ma.*

Introduction

The Global Stratotype Section and Point (GSSP) defining the base of the Jurassic System, Lower Jurassic Series and Hettangian Stage is situated at the Kuhjoch pass, Karwendel Mountains, Tyrol, Austria (47°29'02"N/11°31'50"E) (Figs. 1-4). This boundary has recently been defined by decisions of the International Subcommission on Jurassic Stratigraphy (ISJS) in June 2008, by the International Commission on Stratigraphy (ICS) in May 2009 and ratified by the Executive Committee of the International Union of Geosciences

Figure 1. Geographical location of the Triassic-Jurassic boundary sections in the eastern part of the Northern Calcareous Alps. Orange-coloured area Fig. 2.

(IUGS) in April 2010. The inauguration of the GSSP took place August 2011 (Morton, 2012).

Considering the long history of research on the Triassic and Jurassic, this may seem surprising, but a major extinction event during this interval strongly affected the traditional fossil biomarkers (ammonoids, conodonts) and a large global sea level drop associated with tectonic and volcanic events resulted in a paucity of sections with continuous marine sequence containing key fossils.

The Northern Calcareous Alps (NCA) of Austria have been known since more than 100 years as a major source of Tethyan (i.e. tropical) Hettangian ammonites (e.g. Wähner, 1882-1898; Lange, 1952; Blind, 1963; Kment, 2000) occurring in sequence with their presumed Triassic precursors (Mojsisovics, 1893; Wiedmann, 1970). The latter are missing in northwestern Europe and are only reported from a few places globally (Tibet: Yin et al., 2007; North America: Tozer, 1979,

1994; South America: Prinz, 1985; Hillebrandt, 1994). Investigations in North America (Guex, 1980, 1995; Guex et al., 1998) demonstrated that morphologically different psiloceratids appear distinctly earlier than the traditional *P. planorbis* and may be missing in the epicontinental sea of Northwestern Europe due to shallow marine environments. *Psiloceras spelae*, described by Guex et al. (1998), and *P. tilmanni* (= *P.* cf. *tilmanni* sensu Hillebrandt and Krystyn, 2009) from Nevada, are the oldest representatives of *Psiloceras* in North America. The occurrence of *P. spelae* below *P.* cf. *tilmanni* in Peru and Austria makes it to a global form and thus a suitable biomarker for the base of the Jurassic.

The proposed sections (Kuhjoch, Austria; Kunga Island, Canada; New York Canyon, USA; Waterloo Bay, Northern Ireland and St Audrie's Bay – Doniford Bay, England) for the definition of the base of the Jurassic System and the Hettangian Stage at a Global Stratotype Section and Point (GSSP) were published in the ISJS Newsletter 34(1), edited by Paul Bown, Nicol Morton and Jackie Lees, July 2007 and 35(1), 2008, edited by Nicol Morton & Stephen Hesselbo, December 2008 [http://jurassic.earth.ox.ac.uk/newsletters]. The International Subcommission on Jurassic Stratigraphy (ISJS) first made a choice between different primary markers: the ammonoid *Psiloceras spelae* (at Ferguson Hill section, New York Canyon, Nevada, USA and at Kuhjoch section, Karwendel Mountains, Northern Calcareous Alps, Tyrol, Austria), the ammonite *Psiloceras planorbis* (at St. Audrie's Bay section, Somerset, England, UK and at Waterloo Bay section, Larne, Northern Ireland), a major evolutionary change of radiolarian faunas (at Kunga Island section, Queen Charlotte Islands, British Columbia, Canada), and a carbon isotope excursion at Ferguson Hill section. The vote of the Subcommission was clearly in favor of *Psiloceras spelae*: *Ps. spelae* 53.7%; *Ps. planorbis* 19.4%; carbon isotope excursion 16.4%; radiolarian turnover 10.5%. Kuhjoch was then selected as GSSP for the base of the Jurassic System, Lower Jurassic Series and Hettangian Stage (Kuhjoch section 56.1%; Ferguson Hill section 31.6%; abstain 12.3%). The section was chosen because, beside its continuous sedimentation, it contains the richest known marine fauna in the world for this time period and an abundant microflora allowing a cross-correlation with the continental realm and a low diagenetic overprint, which allows chemical proxies to be applied. A well preserved species of *Psiloceras* (*P. spelae tirolicum*) (Hillebrandt and Krystyn, 2009) within the lower Tiefengraben Member correlates with and is comparable with the oldest *Psiloceras* (*P. spelae spelae*) in North America (Muller Canyon, Nevada, USA), but it is much better preserved (e.g. aragonitic shell, phragmocone and body chamber, whorl section and complete suture line) than the crushed North American specimens, which lack the shell, an exact cross section, and the suture line.

Geographical setting

The GSSP at Kuhjoch is located on the southern flank of the Karwendel Syncline, about 25 km north-

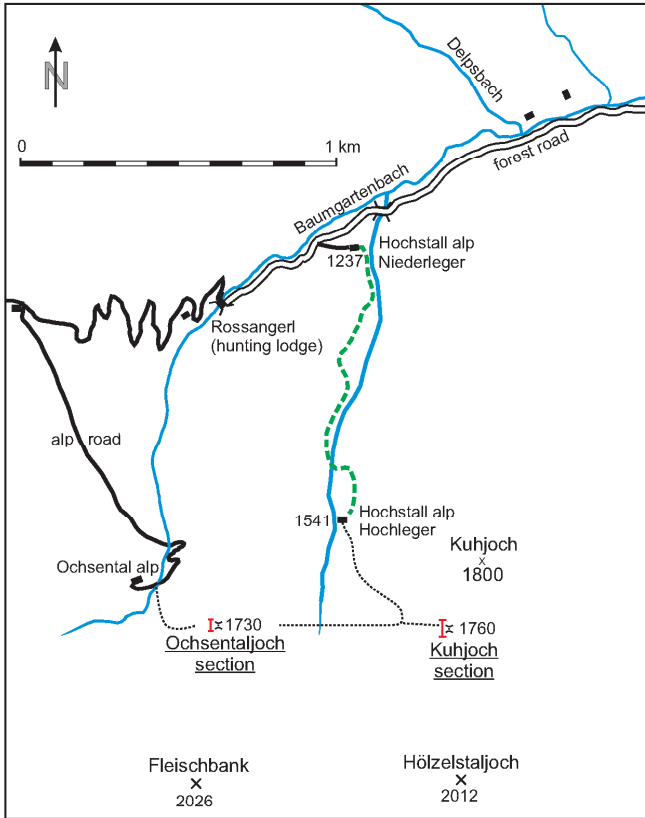*Figure 2. Geographical location of the principal Triassic-Jurassic boundary sections of the western Karwendel Syncline.*

Figure 3. Geographical location of and access routes to the Kuhjoch and Ochsentaljoch sections.

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 to 2 hours walk from the Hochstallalm Niederleger (Fig. 3). Kuhjoch (Fig. 4) [mountain pass located between Kuhjoch peak (not named on topographic map 1:50 000) and Hölzelstaljoch peak; Fig. 3] and Ochsentaljoch [located 750 m to the west (mountain pass between Ochsental and Hochstall valleys); 47°29'0"/11°31'50"], are situated within a natural reserve (Karwendel Naturpark) at altitudes of 1700-1800 m, i.e. beyond the main tree and bush growth zone (Figs. 4, 7) (air photographs and topographic maps: *http://tiris.tirol.gv.at/web/index.cfm;* search for place name: Hochstall-Hochleger). Sections were excavated and studied on both sides of the pass (Kuhjoch West and Kuhjoch East) (Fig. 8). The "Golden Spike" (Fig. 9) was fixed at Kuhjoch East because a higher guarantee of conservation (steep slope at Kuhjoch West and flat slope at Kuhjoch East). This guarantees long-term exposure and conservation with respect to protection status. There is enough space to extend, mainly at the western side of the pass, at any time fresh outcrops of the weathering marls. For reasons of protection, the section Kuhjoch East was fenced in by a wooden hoarding (Fig. 9).

Geological Setting

Expanded and highly fossiliferous sedimentary successions across the Triassic-Jurassic (T-J) boundary in the NCA are mainly found in the so-called Eiberg Basin, a Rhaetian intraplatform depression, which can be traced over 200 km from the Salzkammergut (Kendlbach, Upper Austria) in the east to the Lahnewiesgraben valley (northwest of Garmisch-Partenkirchen, Bavaria) in the west (Fig. 1). In the western part of this basin, the Karwendel Syncline is a local, East-West trending synclinal structure, approximately 30 km long, within
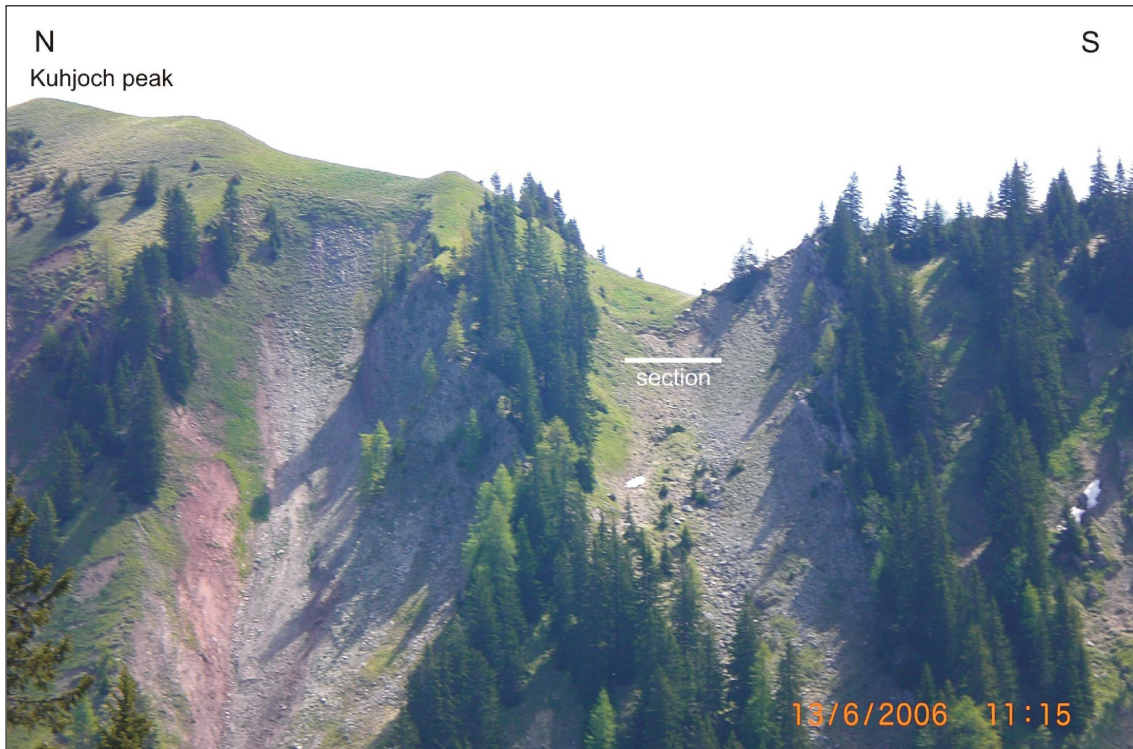
north-east of Innsbruck and 5 km east-north-east of the village of Hinterriss. On the 1:50.000 scale topographic map of Austria (sheet 118: Innsbruck); the coordinates are 47°29'02"N/11°31'50"E. It is

Figure 4. Photograph of Kuhjoch mountain and Kuhjoch pass with location of Kuhjoch West section indicated by white line.

the Inntal nappe of the western Northern Calcareous Alps. It is wide and relatively flat near the Achensee in the east (Fig. 1) and narrows towards the west with increasingly steep to overturned flanks at its western end close to Mittenwald (Fig. 2) – see Geological map 1:75000, sheet 29, Innsbruck und Achensee by Ampferer and Ohnesorge (1912) (out-of-print); Geological map (Geofast) 1: 50000, sheet 118: Innsbruck, compilation by Moser (2008), Geologische Bundesanstalt (2008/09); Geological map 1:10000 by S. Schütz (1974) (unpublished) (Figs. 5, 6)

T/J boundary sections east of the Karwendel Syncline are classical localities and have been studied by various authors (references in Kürschner et al., 2007). The boundary sections of the Karwendel Syncline, belonging to the western part of the Eiberg Basin, have been much less studied and detailed biostratigraphic information about the Tiefengraben Member is is only known recently. Most of the recently studied outcrops are situated on the southern flank of the Karwendel Syncline, and at least five of them (Hochalplgraben, Rissbach, Schlossgraben, Ochsentaljoch and Kuhjoch; Fig. 2) have become important as a result of the findings of new psiloceratids distinctly older than the well-known earliest *Psiloceras* of England (*P. erugatum, P. planorbis*) and the Alps (*P. calliphyllum*). The ammonites of the bed with *P. calliphyllum* can be compared with the earliest Psiloceras in England (Bloos, 2004, Page, 2003, Page et al.,

2010) and are found at the GSSP about 18.5 m above the horizon with *P. spelae.* (Hillebrandt and Krystyn, 2009).

The Eiberg Basin was an intraplatform trough bordered to the southeast by a broad Rhaetian carbonate platform (Dachstein Lagoon) with, locally, fringing reefs and, further southeast, an outer shelf (Hallstatt Basin) transitional to the Tethys Ocean (Brandner and Gruber, 2011). Another partly terrigeneous-influenced carbonate ramp (Oberrhaet limestone lagoon) of the Lechtal and Allgäu nappes existed north of the Eiberg Basin. Within this unit, intraplatform depressions with sedimentary successions across the Triassic-Jurassic (T-J) boundary similar to those of the Eiberg basin are also found (e.g. Restental, Upper Austria; NE Aschau, Chiemsee, Bavaria; Tannheim, Allgäu; Lorüns, Vorarlberg). Earliest Jurassic ammonites are not found but a biostratigraphic correlation is possible with foraminifers (*Praegubkinells turgescens*). 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 Hauptdolomite Lagoon with subtidal mixed limestone and clay bearing bioclastic rocks. The sedimentary facies of the Rhaetian Kössen Formation changed around the Middle to Late Rhaetian boundary (base of marshi Zone) with the onset of a basinal facies (Eiberg Member) above the underlying shallow water sequence of the Hochalm Member
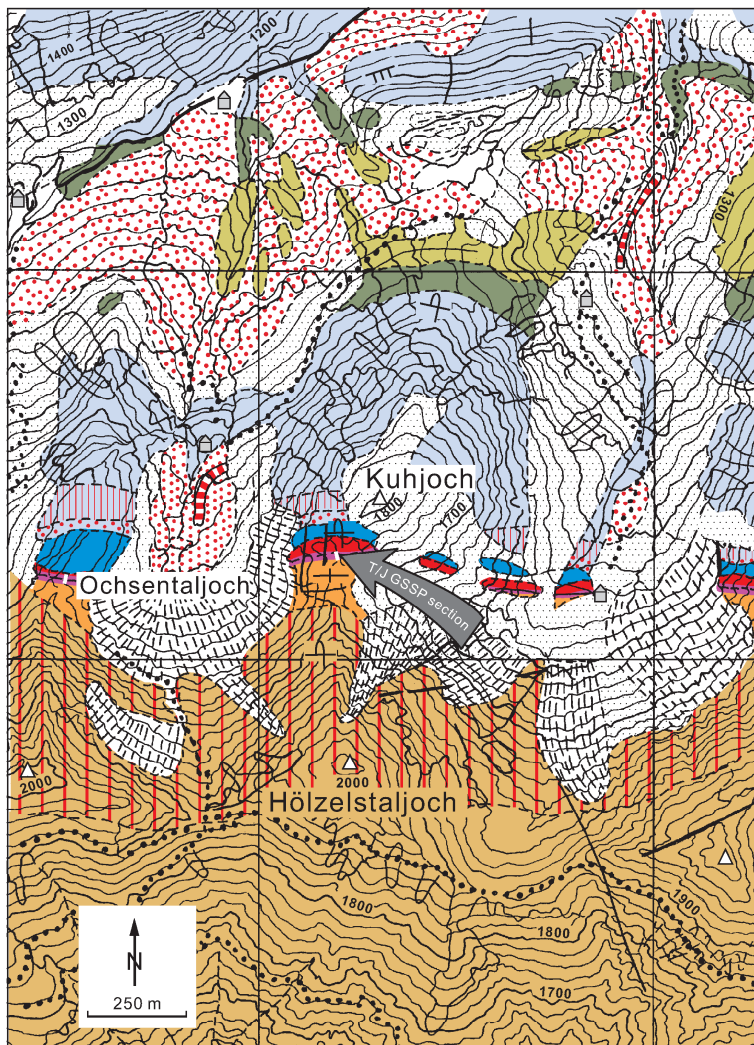

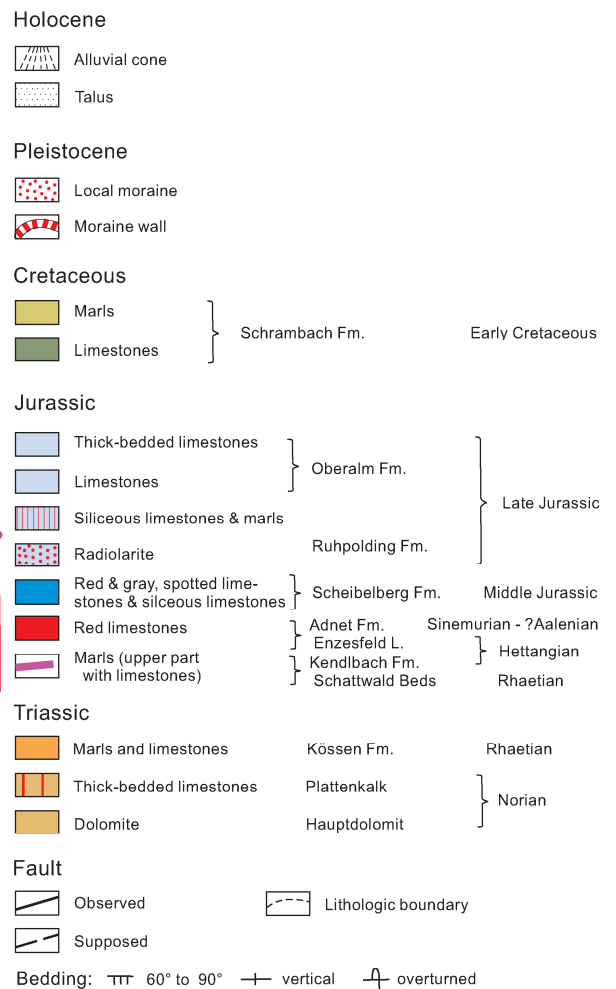**Figure 5. Geological map of the Kuhjoch area (Schütz, 1974).**

Figure 6. Key to the geological map of the Kuhjoch area.

Figure 7. Section Kuhjoch West, outcrop situation June 2006. E.M./T.M. boundary Eiberg Member/Tiefengraben Member (see also Fig. 20A); **P. spelae** *with arrow = horizon with* **Psiloceras spelae tirolicum;** *third person from left = level with* **Psiloceras pacificum;** *leftmost person (L. Krystyn) approx. first arenitic beds.*
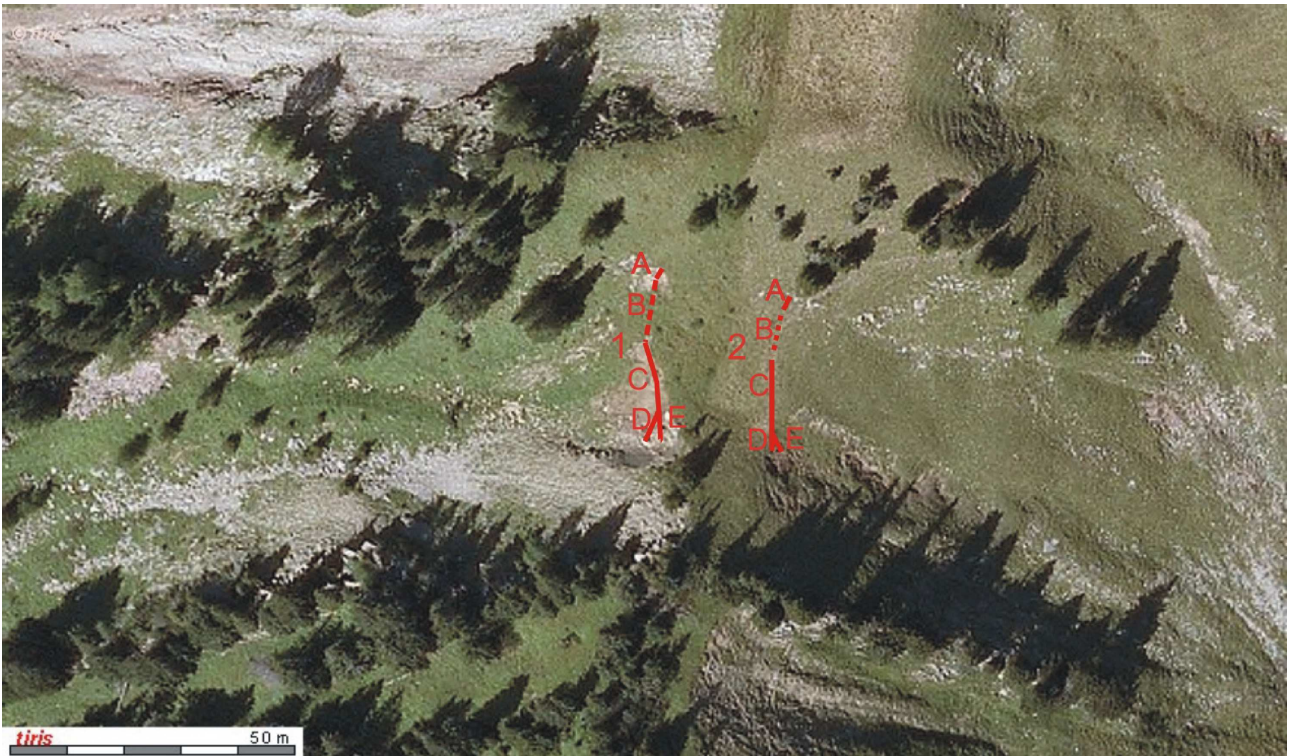

Figure 8. Air photograph (taken 2009, before Kuhjoch East was excavated) of Kuhjoch pass with sections Kuhjoch West (1) und East (2).

started at the end of the Kössen Formation 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). McRoberts et al. (2012,fig. 5) assume the lowest point of sea level fall in the uppermost part of the Eiberg Member (sensu McRoberts et al., 2012) followed by a continuous sea level rise from the Tiefengraben Member upwards. The Kendlbach Formation is replaced up-section by Early Jurassic carbonates of both increasing water depth and pelagic influence (Adnet Formation).

Within the Eiberg Basin between Kendlbach (Lake St. Wolfgang) and Garmisch-Partenkirchen (Fig. 1), all sections show the same sedimentary record across the T-J 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 Alpine and worldwide marine sections. Among the diverse T-J boundary sections of the western Eiberg Basin, therefore, the Kuhjoch Pass was selected as GSSP for the base of the Jurassic because it presents the best continuously available and most complete T-J boundary sections of the area. Only the topmost part of the boundary sequence, with the transition to the *P. calliphyllum* horizon, 10 to 18 m above the GSSP level, has been studied in more detail at a neighbouring locality (Ochsentaljoch) about 750 m to the west of Kuhjoch (Fig. 3), where this interval is better exposed and suggest a clearer presentation.

Stratigraphy

Position of main boundary-relevant ammonite levels 1 to 7 (Fig. 10)

Three new ammonite levels (levels 2, 3 and 4) have been found at GSSP Kuhjoch West which are located between the widely distributed and long-known *Choristoceras marshi* found up to the uppermost beds of the Upper Rhaetian Eiberg Member (level 1) and the also long-known Lower Hettangian limestone bed with *Psiloceras calliphyllum* (level 5) (Fig. 10) of the Breitenberg Member. Between the Eiberg and Breitenber Members is positioned the 22 m thick, continuous succession of marls and marlstones of the Tiefengraben Member with the T-J boundary interval and following ammonite levels:

> **ammonite level (2)** with *Psiloceras spelae tirolicum* from 5.80 to 6.20 m;
> **ammonite level (3)** with *Psiloceras ex gr. tilmanni* at 7.6-8.0 m;
> **ammonite level (4)** with *Psiloceras cf. pacificum* at 12.0-12.4 m above the base of the member (Hillebrandt and Krystyn, 2009).

The base of the level with *Psiloceras spelae tirolicum* was found at Kuhjoch East 6.30 m above the top of the Kössen Formation (Eiberg Member). Levels (3) to (5) were also found in Ochsentaljoch (Fig. 10).

The clays and marls of the Tiefengraben Member were formerly called "Rhaetische Grenzmergel" [type locality Marmorgraben, western Karwendel Syncline (Fig. 2)] (Fabricius, 1960, 1966) and
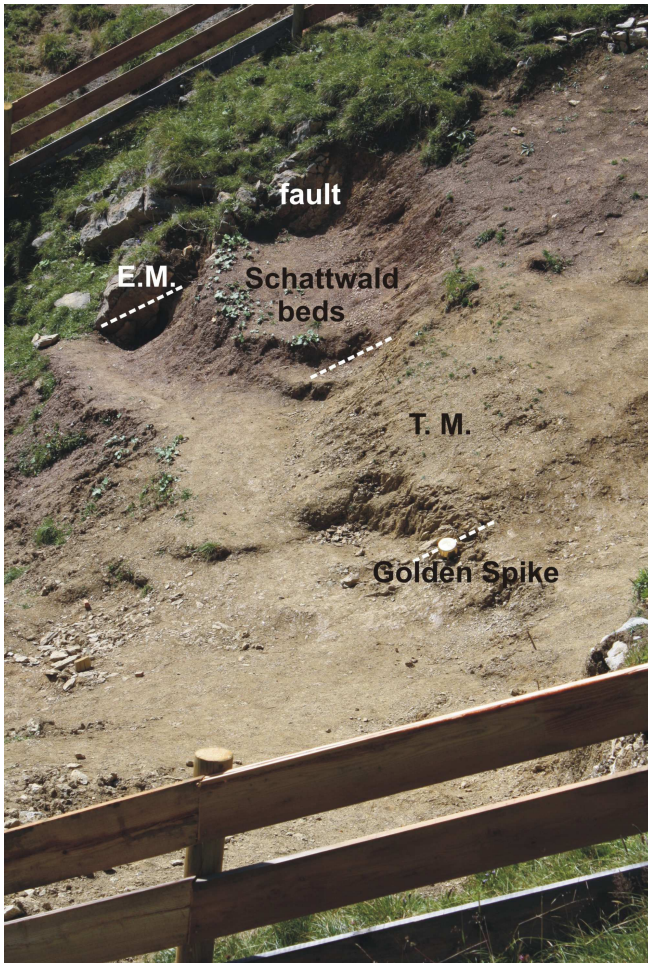

Figure 9. Section Kuhjoch East (taken August 2011) with "Golden Spike" at the Triassic-Jurassic boundary. View from North to South, beds vertical to slightly overturned; Fault = fault surface; E.M. = Eiberg Member; T.M. = Tiefengraben Member.

(Golebiowski, 1989). 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 widespread and longer-lasting emersion of the surrounding shallow water areas. 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 Fm. took place (Tiefengraben Mb., corresponding to the British pre-Planorbis Beds), which is interpreted as a result of this sea level drop. The change is said to be connected with the start of the volcanism of the Central Atlantic Magmatic Province (CAMP) whose record in the Eiberg Basin was recently evidenced by Pálfy and Zajzon (2012) from elemental geochemistry and mineralogy for the bituminous topmost layer of the Kössen Formation at Kendlbach.

The drastic lithological change was interpreted during recent decades as the T-J boundary (Golebiowski, 1990; Hallam and Goodfellow, 1990) because it coincides with the disappearance of typical Triassic fossils such as ammonoids and conodonts. New studies demonstrate, however, that the lowest meters of the Tiefengraben Mb. (= "Rhaetische Grenzmergel" sensu Fabricius, 1960, 1966 – including the reddish Schattwald Beds) still yield a Triassic micro- and nannoflora (Kürschner et al., 2007). The regression was fast; it

correspond in current nomenclature to the Tiefengraben Member of the Kendlbach area where the member differs by additional marly limestone intercalations. The overlying Breitenberg Member (named "Liasbasiskalk" by Ulrich, 1960 in the Karwendel Syncline) is rather uniformly developed and consists of a 2-3 m package of limestones with ammonite level (5) close to the top. As ammonites of several distinct biohorizons (*P.* c*alliphyllum/costosum* and *P. naumanni* horizons) occur closely together, level (5) may be condensed and is thought to correlate with a major part of the Planorbis Zone of Northwestern Europe (Fig. 22; Bloos, 2004). Levels 6 and 7 (Kuhjoch) (Fig. 10) are also condensed and can be correlated with the Middle Hettangian Alpine Megastoma and the Late Hettangian Alpine Marmoreum zones (Hillebrandt and Kment, 2011).

Lithostratigraphic description of the type sections (Kuhjoch and Ochsentaljoch)

a) Kuhjoch

On the south to north orientated crest of Kuhjoch, a steeply dipping continuous sequence of more or less overturned Rhaetian (Kössen Fm.) to Upper Jurassic sediments (Ruhpolding Radiolarite Fm.) is exposed (Schütz, 1974), perpendicular to the crest and bedding strike. A narrow topographic depression, visible both on the maps and in the field (Figs. 4, 5, 8), corresponds to the documented sections. The first samplings (2005 to 2009) were mainly carried out on the western side of the Kuhjoch pass (Fig. 8; section 1A-E). The first micropalaeontological samples from the transition of the Eiberg Member to the Schattwald Beds and Tiefengraben Member (section 1D) were taken some meters downslope section 1E. The samples studied by Bonis et al. (2009) for palynology come from section 1D. A small local fault in the uppermost part of the Schattwald Beds of section 1E results in a short sedimentary hiatus as is evident by a sharp shift in the C-isotope curve and the lack of a pollen assemblage zone (Bonis et al, 2009; Ruhl et al., 2009) (Figs. 19, 23, 24). The natural outcrop Kuhjoch East section (Fig. 8; 2A-D and E; Fig. 9), 20 m eastward from Kuhjoch West, was enlarged in 2010 and 2011 by an excavator (transported by helicopter) to the lower and middle part of the Tiefengraben Member. Section 2D ends with a fault against the Kössen Formation. Section 2E shows an undisturbed transition from the Eiberg Member to the Tiefengaben Member and no fault at the top of the Schattwald Beds. The level with *P. spelae tirolicum* is found 6.30 m above the uppermost Kössen Formation (T-Bed). This means that Kuhjoch West (Fig. 8; section 1 E) lacks approx. 0.5 m of upper Schattwald Beds. It is difficult to prove if the fault at Kuhjoch West (uppermost part of Schattwald Beds) is the same fault at Kuhjoch East (basis of the Schattwald Beds).

Kuhjoch West

The Kuhjoch West section starts 3.8 m below the top of the Kössen Formation/Eiberg Member with a package of well bedded and variably thick (up to 50 cm) bedded grey bioturbated limestones (bioclastic wackestones) overlying 5 m of black marls with pyrite nodules and rare thin (5-10 cm) limy mudstone intercalations (Fig. 15). The 20 cm thick topmost bed (= T-Bed in Fig. 20a,b) of the Eiberg Member differs by darker colour and platy weathering. Due to an increased clay content it is softer than the pure limestones below and thinly

laminated in its upper half. The top of this bed (~ 1 cm thick and mm-laminated) is black and bituminous, rich in bivalves and fish remains (scales) indicating an anoxic event and a first regression [T-Bed is employed differently by McRoberts et al. (2012) by restricting it to the bituminous very top of T-Bed sensu Hillebrandt et al. (2007). The original definition is retained here because of the lithologic and faunistic uniformity of the whole bed]. Above, the Kendlbach Formation is divided into the lower 22 m thick terrigeneous Tiefengraben Member and above the following 3 m thick calcareous Breitenberg Member.

Grey to brownish clay-rich 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, silty clays approximately 2 m thick (Figs. 9, 19, 20a,b),These are comparable with also reddish, silty clays known as Schattwald Beds in the Allgäu nappe in the north between Schattwald and Pfronten (Allgäu mountains, type region of the Schattwald Beds). Sections with Schattwald Beds of the Allgäu nappe were also studied at Aschau, Chiemsee (Bavaria) and Restental, Upper Austria (Golebiowski, 1990) as also the Lechtal nappe (e.g. Peischelspitze south of Lechtal valley) and western NCA (e.g. Lorüns, Vorarlberg; McRoberts et al., 1997). Grey intercalations characterize the transition to the overlying main part of the Tiefengraben Member, 19.5 m thick. Ammonite level (2) with *P. spelae tirolicum* is located 3.2 m above the Schattwald Beds, ammonite level (3a) with *P.* ex gr. *P. tilmanni* 2 m higher than (2) and ammonite level (4) with *P.* cf. *pacificum* 4 m higher up in the section than (3a) (Hillebrandt and Krystyn, 2009).

Approx. 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; see below).

The exposed part of the Breitenberg Mb. consists at Kuhjoch West and East (Fig. 8: 1A, 2A; 10) of grey thin-bedded 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 rich in ammonites partly preserved as limonitic steinkerns. 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 succession of ammonites of Middle and Late Hettangian age (Kment, 2000; Hillebrandt and Kment, 2009, 2011). At Kuhjoch, there 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 gray limestone clasts and *Alsatites* cf. *liasicus* of Middle Hettangian age (= Enzesfeld limestone) (8 cm thick) and a brownish, sparitic limestone (15 cm thick) with a limonitic crust at the top and *Alpinoceras haueri* (Marmoreum Zone) of Late Hettangian age. On the western slope of Kuhjoch, the limonitic crust of this bed yielded Middle Hettangian ammonites (*Megastomoceras megastoma* and *Alsatites proaries*). On the eastern slope, a loose block of the Enzesfeld limestone (10 cm thick) contained Middle Hettangian ammonites (e.g. *Megastomoceras megastoma* and *Storthoceras frigga*). Nodular limestones of the Adnet Formation of Sinemurian age follow above.
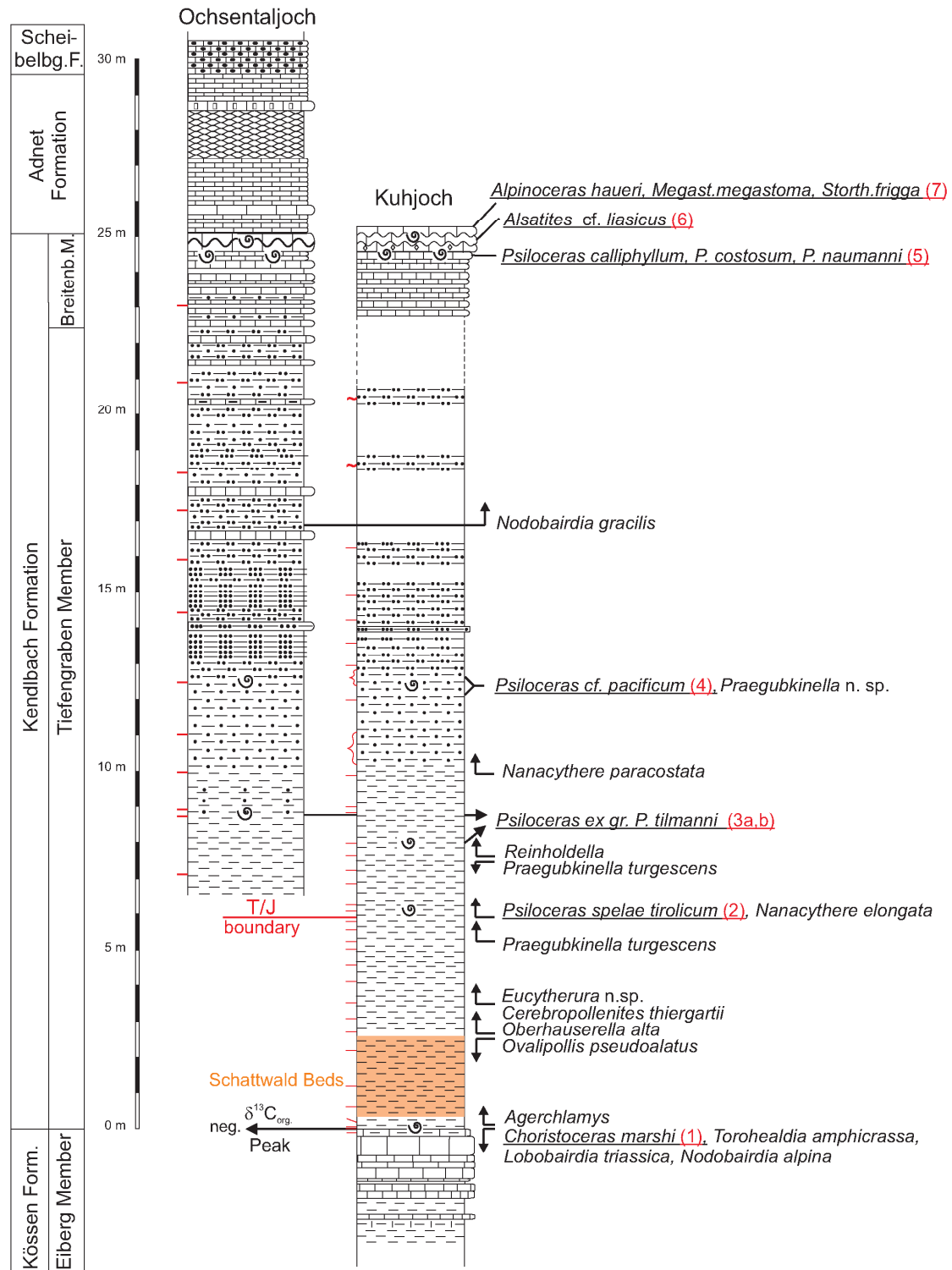
Figure 10. First and last occurrences of biostratigraphically important fossils from the Triassic-Jurassic GSSP (Kuhjoch West).

Kuhjoch East

Only the uppermost beds of the Kössen Formation crop out. The band of well-bedded and variably thick (up to 50 cm) gray, bioturbated limestones yielded *Choristoceras*. The transition from the Eiberg Member to the Tiefengraben Member is only complete at the partial section 2E (Fig. 8) [left part with E.M. (Eiberg Member) on Fig. 9] where the T-Bed (as originally defined) with its bituminous top is

present. The following yellowish marls are strongly weathered and pass into the Schattwald Beds. At partial section 2 D (Fig. 8: 2D the Schattwald Beds are faulted against a limestone bed of the uppermost Kössen Formation (right part with "fault" on Fig. 9). The Schattwald Beds are 2.8 m thick and pass into the Tiefengraben Member. An inner whorl of the first *P. spelae tirolicum* was found 3.2 m and poorly preserved fragments and specimens 3.6 to 3.7 m above the Schattwald Beds. A fragment with inner nodes of Psilo*ceras tilmanni* group was

found 4.7 m and shell fragments with suture lines of ?*Psiloceras* in samples 6.2 and 8.4 m above the Schattwald Beds. The marls of the Tiefengraben Member are usually more strongly weathered than those from Kuhjoch West. Aragonitic shells and in part also calcitic shells tend to be dissolved. *Reinholdella* n.sp. in some samples is very frequent in the upper part (Fig. 12). A first arenitic bed (15 to 20 cm thick) occurs at 12 m above the Schattwald Beds followed by a second one 50 cm above the first arenitic bed. The outcrop ends in the arenitic interlayers of the Tiefengraben Member due to a meter thick moraine that covers the interval to the Breitenberg Member.

b) Ochsentaljoch

Better exposures of the upper half of the Tiefengraben Member have been found at Ochsentaljoch. A mountain trail crosses the steeply dipping sequence, which starts with the same grey marls as at Kuhjoch. An exact correlation with the latter is possible by the presence of ammonite level (4) 4 m above the base of the measured section. Higher up in the section follow sandy marls (1.5 m) with rare thin arenitic layers (at Kuhjoch too weathered and therefore not identified) and at the top a thicker arenitic bed (20 cm) that matches the first arenitic bed of the Kuhjoch sections. The following 2 m are composed of marls, with some silty arenitic beds up to 15 cm thick, overlain by a fine-grained limestone bed (20 cm) with bivalves and brachiopods at the base. Grey, partly silty marls continue for another 4.3 m with 2 marly limestone beds (each 15-20 cm) at 0.9 m and 3.3 m above the bed with bivalves and brachiopods. The Breitenberg Member starts with a pure limestone bed (15 cm) overlain by dark grey marls (0.3 m) that are followed by thin hard intercalations of marlstones between wavy bedded, grey bioclastic limestones (2 m). No fossils have been collected in the overlying *Calliphyllum* bed and the Middle to Late Hettangian condensed layers, which are identified by lithological affinity with the Kuhjoch counterparts. Platy to nodular red limestones of the Adnet Formation (4.5 m) form the top of the section up to the cherty limestones of the Late Sinemurian Scheibelberg Formation.

Palaeontology of the Kuhjoch and Ochsentaljoch Sections

The palaeontological record at Kuhjoch is clearly marked by the end-Triassic mass-extinction coincident with the top of the Kössen Formation (top of T-Bed) (Kürschner et al., 2007; Hillebrandt and Kment, 2011; McRoberts et al., 2012). The top of the T-Bed records the onset of the main extinction pulse. The lowermost 0.3 meter (Fig. 20a, b) (0.4 m at Schlossgraben section) of the Tiefengraben Mb., called Grenzmergel s. str. (Hillebrandt and Kment, 2011) or initial phase of extinction (McRoberts et al., 2012), records opportunistic species of bivalves and further levels of foraminifer and ostracod extinctions. The Schattwald Beds yield almost no micro- or macrofossils and represent the peak phase of extinction (McRoberts et al., 2012).

The extinction (e.g. Hallam and Wignall, 1999; Hautmann, 2004) affected similarly the terrestrial fauna and flora (McElwain et al., 1999, 2009; van de Schootbrugge et al., 2007; Whiteside et al., 2007). The Central Atlantic Magmatic Province (CAMP) is the most often cited cause for this extinction (e.g. Palfy et al., 2000, Marzoli et al., 2004, Payne and Kump, 2007; van de Schootbrugge et al., 2009;

Schoene et al., 2010). Injection of methane to the atmosphere (Ruhl and Kürschner, 2011; Ruhl et al., 2011) has also been inferred, but has been challenged by Lindström et al. (2012). Whatever the cause, the subsequent longer lasting greenhouse effect led to further biotic decimation (McElwain et al., 1999). A phase of slow regeneration followed during which mainly new Tethyan faunal elements immigrated to the Eiberg Basin.

A broad spectrum of marine invertebrate groups is recorded, although brachiopods are rare. Macrofossils (Fig. 11.1-11.6) are represented by biostratigraphically (ammonites) as well as palaeoecologically important groups (bivalves, echinoderms). Microfossils (Figs. 11.7-11.11, 12, 13) constitute a major part of the calcareous biomass except for the Schattwald Beds where only a depauperate foraminifer record is present. Ostracods (Fig. 15) are usually less frequent than foraminifers. Calcareous nannofossils (Figs. 16, 17) are present in many samples, though they are unfortunately very rare and extremely small. Most samples were rich in well preserved palynomorphs (Figs. 23-26), 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 (Kürschner et al., 2007).

1. Macrofossils

a) *Ammonites* (cf. Hillebrandt and Krystyn, 2009) (Figs. 10, 11, 22)

Low ammonite diversity, sporadic occurrence of determinable specimens and restriction to certain levels are characteristics of the sections, though shell fragments were frequently found in samples for micropalaeontological studies (Figs. 12, 13). The limestones of the upper Eiberg Member contain relatively common fragments of *Choristoceras,* but the last pure limestone bed shows only cross-sections of unextractable specimens. Rare, compressed and flattened *Choristoceras marshi* (Fig. 11.6) are found in the uppermost part of the T-Bed, representing the last occurrence not only of the genus *Choristoceras* but of Triassic ammonoids and conodonts at all in the section. Choristoceratids are the only common cephalopods in the Eiberg Member. The reported presence of another group (*Rhaetites,* a gigantogaleat arcestid) in the T-Bed of the Möserer Alm near Steinplatte (Bökenschmidt and Zankl, 2005) is thus an extremely rare and sensational exception.

Ammonite level (2), located from 5.8-6.2 m above bed T at the Kuhjoch West section, contains mostly flattened and small (rarely > 2 cm) specimens, which are easily visible due to their white aragonitic shell. Rare, originally pyritic and now mostly limonitized, undeformed phragmocone specimens allow an exact illustration of the cross-section and the suture line. The specimens belong to an involute species of *Psiloceras* with predominating psiloceratid characters (mainly inner whorls with well developed "Knötchenstadium"). The suture line with a lituid internal lobe is evolutionarily still related to Triassic phylloceratids. Other Triassic phylloceratid features are the high ovate whorl section with well developed umbilical wall and similar growth lines.

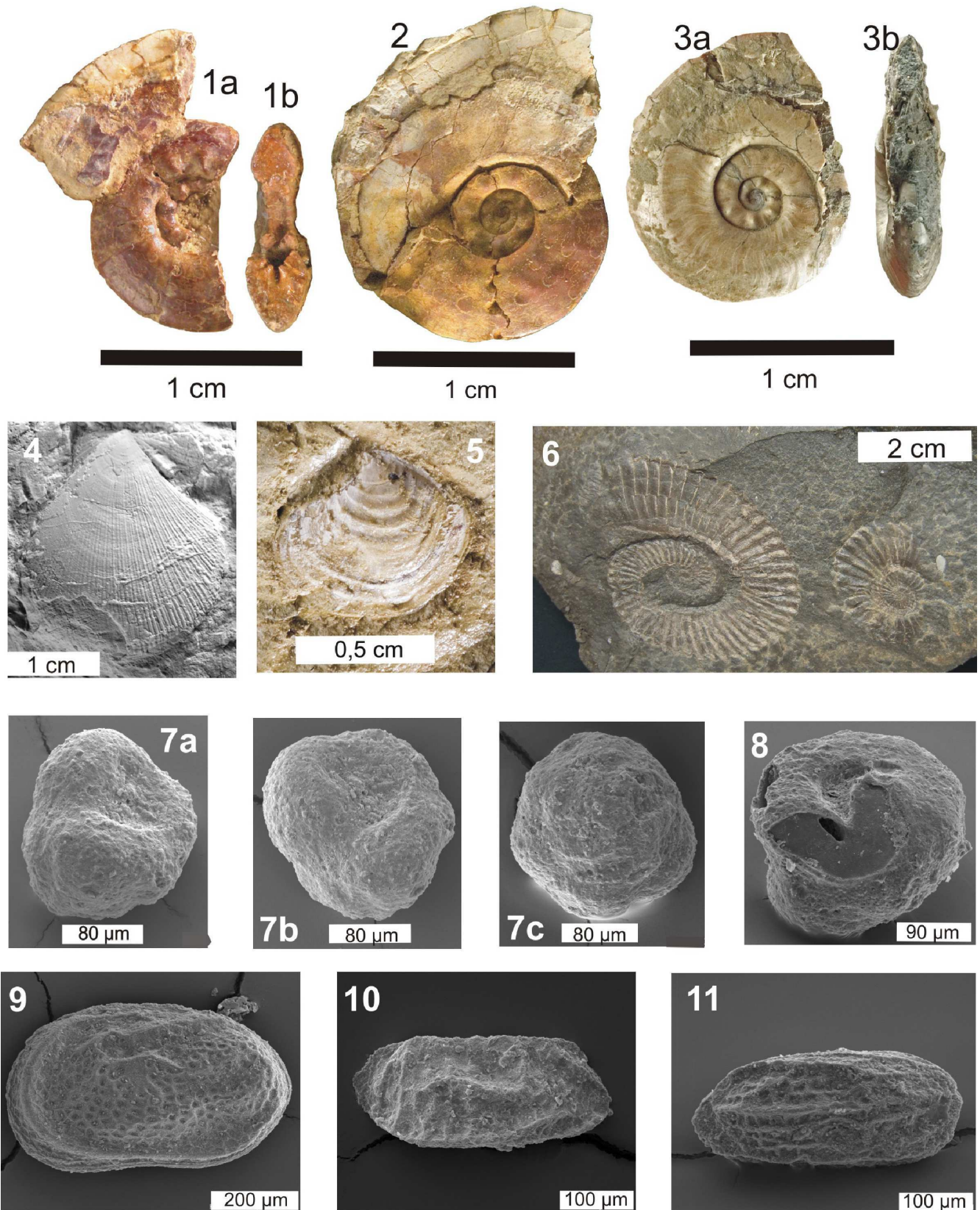The Alpine specimens were originally determined as *P.* cf. *spelae*

Figure 11. Important guide fossils from the Triassic-Jurassic boundary of GSSP Kuhjoch. 1-3: **Psiloceras spelae tirolicum** *Hillebrandt and 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; 8:* **?Reinholdella** *sp., Kuhjoch, cf.* pacificum *horizon; 9:* **Cytherelloidea buisensis** *Donzr, 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.*

(Fig. 8 in Hillebrandt et al., 2007), because only one specimen was figured from Nevada, which does not show all the characters present in *P. spelae* from the Alps. Moreover, the variability of the Alpine species was not well known. A later published specimen of *P. spelae* from Nevada shows the end of the body chamber with a sculpture comparable with that in *P. spelae* from the Alps. In the meantime *P. spelae* from Nevada and the Alps could be compared directly. J. Guex and the first author (as well as G. Bloos, Stuttgart) concluded that *P. spelae* from Nevada and from the Alps belong to the same species but can be distinguished as regional subspecies: *Psiloceras spelae spelae* and *Psiloceras spelae tirolicum* (Figs. 11.1-3). The two subspecies are closely related phylogenetically and in time. They characterize the ammonite biohorizon of *P. spelae,* which is the earliest ammonite biohorizon of Jurassic aspect. A detailed description on the basis of more than 100 specimens is found in Hillebrandt and Krystyn (2009). The new subspecies has a nodose stage very similar to that of *P. spelae spelae*. *P. spelae spelae* has more sculptural elements (nodes) per whorl (12) than *P. spelae tirolicum* (7 to 8) and the sculpture with elongated nodes persists up to an umbilical diameter of 3.5 mm (2.0 to 2.4 mm in *P. spelae tirolicum*). The original whorl section of *P. spelae spelae* is insufficiently known, so an original subtriangular whorl section cannot be excluded. The suture line, the beginning of the nodose stage and the innermost whorls of *P. spelae spelae* are also unknown. The differences between both subspecies are probably caused by palaeobiogeographic separation. Korte and Kozur (2011) postulate a 100 ky younger age of *P. spelae tirolicum* against *P. spelae spelae* from Nevada on the basis of an extremely fine-tuned C-isotope correlation between NYC (New York Canyon) and Kuhjoch. In our opinion, this implied accuracy and correlation are not justified. Co-occurrence of *P. spelae spelae* and *P.* cf. *tilmanni* in Nevada more likely points to the opposite, i.e. a slightly younger age of the Nevadan occurrence because *P.* cf. *tilmanni* appears in the NCA above *P. spelae tirolicum.*

Anaptychi of *P. spelae tirolicum* and a fragment of *Togaticeras* cf. *goisernense* (Hillebrandt and Krystyn, 2009, fig. 10.16) are also known. A small specimen (diameter 1 cm) (Kuhjoch West section) of a phylloceratid was found in 2008 by Stefan Gräbenstein (Bodelshausen, Germany). As the specimen is more involute than Triassic phylloceratids and the cross section and involution is similar to that of *P. chilense* from the Hettangian of South America it is determined as *Phylloceras* cf. *chilense*. Similar specimens are also recently found in the *spelae* horizon of the Zlambach area.

Ammonites from level (3a) (Kuhjoch West section) have been detected in the residue of a washed sample containing 20 limonitic casts of inner whorls (< 1.7 mm), One compressed specimen (3 mm) and a whorl fragment (Wh 2.5 mm) with suture lines can be placed within the *P. tilmanni* group (Hillebrandt and Krystyn, 2009, figs. 13.1-4). A similar level (3b) was found in the Ochsentaljoch section 3.5 m below ammonite level (4) (Figs. 9, 10).

Ammonite level (4), located 4 m above level (3a) and 6 m above ammonite level (2), has yielded several shell fragments and one poorly preserved specimen in the Kuhjoch section. Four specimens from the Hochalplgraben section are illustrated in Hillebrandt and Krystyn (2009) (figs. 10.11-14). Two tiny juveniles and two larger forms (up to 15 mm in diameter) with relatively wide umbilicus are determined as *Psiloceras* cf. *pacificum*, a species described from Nevada (North America) (Guex, 1995) and also found in Peru (South America) (Hillebrandt, 2000a).

Ammonite level 4a (Hochalplgraben) yielded a fragment (whorl height 16 mm, whorl width 10 mm) of a *Psiloceras* with a smooth body chamber (*Psiloceras* sp. A in Hillebrandt and Krystyn, 2009, figs. 5, 11.6a,b) which probably belongs to the *P. erugatum/ minillaensis* group.

In ammonite level 4b (Rissbach section across Hinterriß) *Psiloceras* cf. *planorbis* and a new species of *Psiloceras* (possibly related to *Psiloceras* spelae) were found in a limestone bed at the boundary between the Tiefengraben Member and the Breitenberg Member.

Ammonite level (5), rich in ammonites in the Kuhjoch section, follows 12 m above level (4) near the top of the Kendlbach Formation. A single limestone bed here contains large sized *Psiloceras calliphyllum*, *P. costosum* and *P. naumanni* (Fig. 10). The level is condensed, containing species of at least 2 ammonite horizons of the Calliphyllum Zone.

Ammonite level (6) is a limestone bed (18 to 20 cm thick), with rare ammonites in the Kuhjoch section, contains *Alsatites* cf. *liasicus*, *Megastomoceras megastoma,* and *Storthoceras frigga* of the Middle Hettangian Megastoma Zone (Hillebrandt and Kment, 2011).

Ammonite level (7) is in a limestone bed (20 cm thick) and the uppermost bed of the Breitenberg Member in the Kuhjoch section. It contains rare ammonites, *Alpinoceras haueri* of the Late Hettangian Marmorea Zone (Hillebrandt and Kment, 2011).

b) *Bivalves* (written by C. McRoberts) (Figs. 11-13)

Bivalves occur throughout the GSSP interval at Kuhjoch and nearby sections at Ochsentaljoch. From Kuhjoch west, the uppermost Kössen carbonates of the Eiberg Member (below the T-Bed sensu McRoberts et al., 2012) yielded the typically Triassic bivalves *Cassianella* sp. and *Lyriochlamys valoniensis.* The T-Bed itself and the lower centimetres of the Tiefengraben Member contain *Agerchlamys textoria* and rare *Pseudolimea* cf. *hettangiensis* that are concentrated in the bituminous layer at the top of the T-Bed. Tens of centimetres above the T-Bed and into the lower Tiefengraben Member occurs *Cardinia hybrida.* The grey marls of the Tiefengraben Member also provide at different levels small nuculids and different species of *Cardinia*: *C.* cf. *listeri* and *Astarte* sp. (Fig. 11.5) were found in ammonite level (2) and *Cardinia* cf. *ingens* 7.45 m above the T Bed. The residues of washed microfossil samples often contain juvenile specimens (mostly steinkerns) or fragments of bivalves, mostly pectinids and nuculids (Figs. 12, 13). Higher in the sequence, the first limestone bed, 4 m above ammonite level (4) in the Ochsentaljoch section, yielded *Modiolus*, *Liostrea* and additional examples of *Agerchlamys* (Fig. 11.4).

c) *Gastropods and scaphopods* (written by A.v. Hillebrandt)

Tiny and juvenile gastropods (mainly steinkerns) were often found in the residue of washed samples for microfossils (Figs. 12, 13), but determinable specimens are very rare. Fragments of scaphopods appear in the residue of some samples.

d) *Brachiopods* (written by A. Tomāsových)

A last Triassic brachiopod, the giant spiriferid *Oxycolpella oxycolpos*, occurs in the bed below as well within the T-Bed. Brachiopods are rare in the lower part of the Tiefengraben Member and restricted to a few beds. A layer with compressed multicostate

rhynchonellids occurs in the lower part of the Schattwald Beds of the Kuhjoch section. Although these specimens are the stratigraphically earliest (after the last *Choristoceras*) rhynchonelliformean brachiopods found in the Eastern NCA, their taxonomic relation is uncertain owing to their poor preservation.

The biomicritic limestone bed in the Ochsentaljoch section, about 4 m above the level with *Psiloceras* cf. *pacificum* in the upper part of the Tiefengraben Member, contains well-preserved rhynchonellids of the exclusively Hettangian species *Tetrarhynchia inopinata* (Siblík, 1999). This species is also abundant in the Breitenberg Member of the Hochleitengraben section (type locality, Siblík, 1999; Tomãsových and Siblík, 2007). It probably preferred low-energy habitats below storm wave base, and was able to tolerate some input of terrigenous supply. *Tetrarhynchia inopinata* is thus the first rhynchonelliformean brachiopod that colonized sea-floors during deposition of the Tiefengraben Member after the T-J boundary because an increase in abundance and diversity of Hettangian brachiopods in the Eastern NCA coincides with the onset of the Breitenberg Member (Tomãsových and Siblík, 2007). *Tetrarhynchia inopinata* represents the earliest and endemic species of the genus *Tetrarhynchia*, which was a common member of benthic communities in the Early and Middle Jurassic. Rhaetian tetrarhynchiids do not occur in the western Tethys, and ancestors of *Tetrarhynchia inopinata* thus probably migrated into the western Tethys from adjacent biogeographic regions. The specimens sampled in the Ochsentaljoch section attain 10-16 mm in length, 10-18 mm in width, and 6-14 mm in thickness. Dorsobiconvex shells possess incipient planareas, suberect/erect beak, relatively sharp beak ridges, hypothyrid/submesothyrid foramen, relatively thick deltidial plates, and 8-12 relatively rounded costae that reach to the umbo in both valves and do not show any bifurcation. The anterior margin is rounded, but rarely flattened. Smaller and larger specimens differ highly in shell shape and convexity because shell width and thickness increase in size more rapidly than shell length. Internal structures 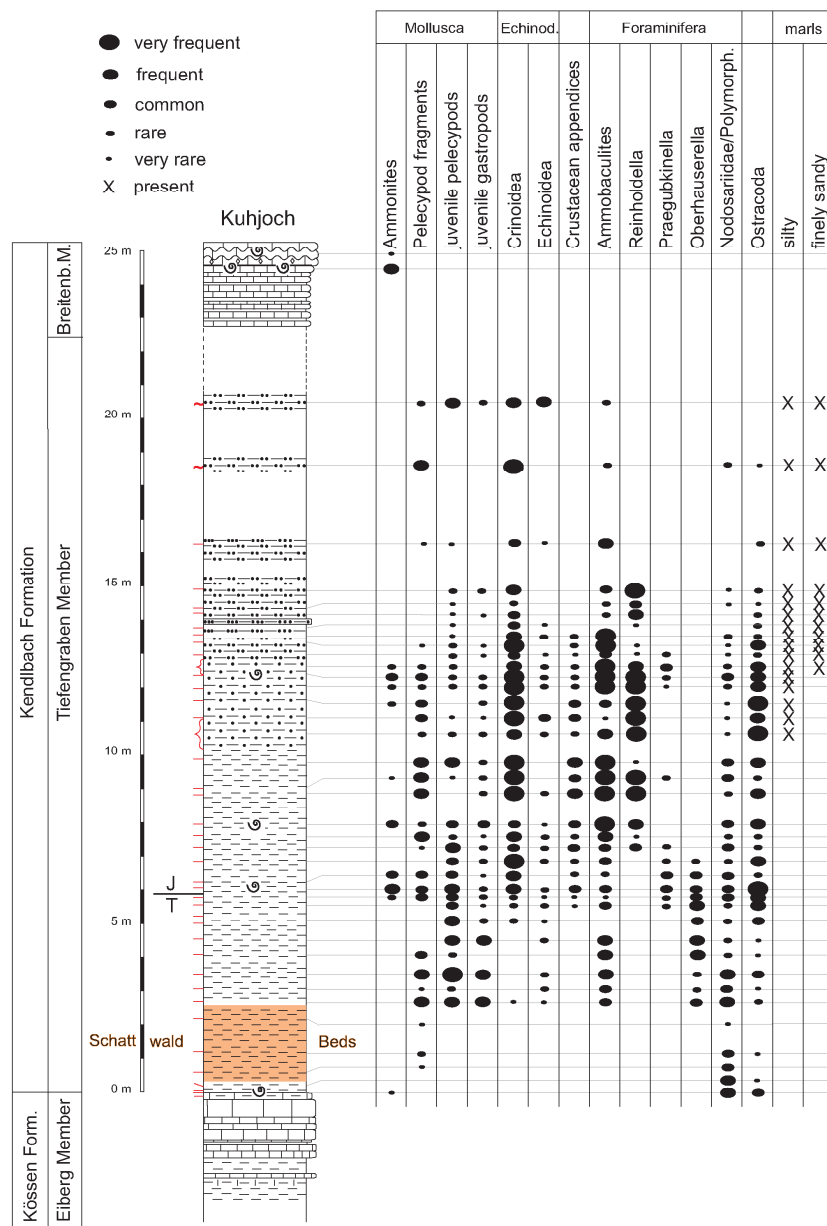of two sectioned specimens show internal shell thickenings in the umbonal parts of the dorsal valve, presence of massive median septum connected with hinge plates, and enclose a markedly pronounced notothyrial cavity.

The smooth-shelled terebratulid *Lobothyris delta* is found in the lower part of the Breitenberg Member and is frequent in one limestone bed of the Schlossgraben section. *Lobothyris* became a numerically dominant brachiopod in carbonate-rich environments of the Eastern NCA during the deposition of the Breitenberg Member and its appearance marks the onset of recovery phase of brachiopod distribution patterns to pre-extinction levels (Siblík, 1993; Tomãsových and Siblík, 2007). Members of this genus also form Hettangian shell beds in palaeobio-geographically–adjacent regions of the Western Carpathians (Tomãsových, 2008).

e) Echinoderms (written by M. Simms and in part by A.v. Hillebrandt)

Crinoid ossicles occur in the washed residue of many samples (Figs. 12, 13); fragments of echinoids are less frequent (Figs. 12, 13). Holothurian ossicles are found in some samples as well as crinoid ossicles, which can be very frequent (Figs. 12, 13). A 1 cm thick layer in the upper part of ammonite level (2) contains in the Hochalplgraben section nearly exclusively crinoids. Connected (up to 1 cm) columnals of crinoids are also frequent at ammonite level (2) with *P. spelae tirolicum* of Kuhjoch East section (GSSP).

Most ossicles are from the cirri with a few hooked terminal cirral ossicles determined so far as isocrinid. The bulk of the material comprises mainly columnals and a few brachials of isocrinids. Different types of columnals (nodals, internodals and infranodals) are found. From the relative abundances of nodal versus internodal and infranodal columnals it is estimated that the number of columnals per noditaxes averages about 6 or 7, although the longest pluricolumnal recovered has just 5 columnals. An apparently identical isocrinoid is found in the Larne section in Northern Ireland,
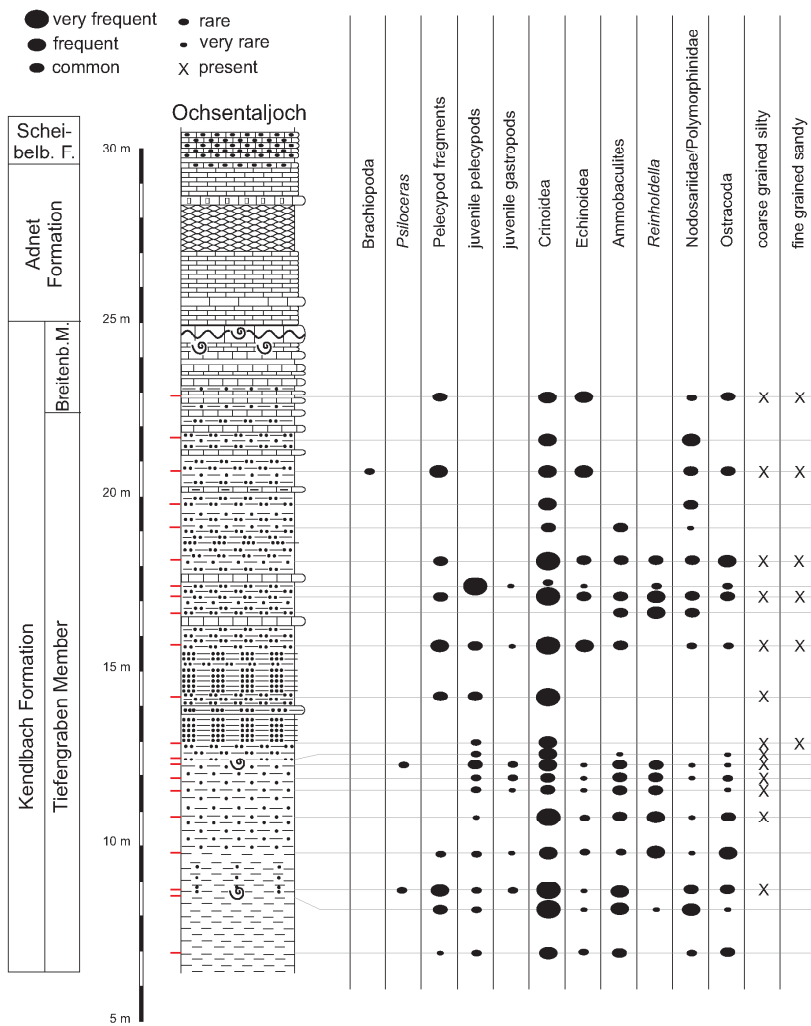

Figure 12. Occurrences and relative abundances of Microfossils from Kuhjoch West section.

Figure 13. Occurrences and relative abundances of Microfossils from Ochsentaljoch section.

2.5 m below the first *Psiloceras erugatum* (first *Psiloceras* in Great Britain). Columnal morphology and the number of columnals per noditaxis for both the Kuhjoch and Larne material corresponds closely to *Isocrinus angulatus* (Oppel). This species in the UK appears to range from the Pre-Planorbis Beds into at least the lower part of the Angulara Zone.

Spines of echinids can be frequent in the uppermost part of the Tiefengraben Member.

2. Microfossils

50 microfossil samples have been studied from the Kuhjoch West section, 30 from the Kuhjoch East section and 21 from the Ochsentaljoch section, with various fossil groups represented. Ossicles of Echinodermata are often more frequent than other microfossils (Figs. 12, 13), foraminifers usually outnumber ostracods. Small appendices of crustaceans can be common in some samples (Figs. 12, 13). Radiolaria are extremely rare.

a) Foraminifers (written by A.v. Hillebrandt) (Figs. 12-14)

(1) Kuhjoch sections (Fig. 12)

Most observations were made at section Kuhjoch West. The less

weathered marls of this section mostly contain better preserved foraminifers than those from Kuhjoch East. Black and grey marls 2.5 and 1 m below the uppermost beds of Kössen limestones (Kuhjoch East) yielded only small sized *Trochammina*, *Ammodiscus* and polymorphinids (limonitic casts). A weathered sample (Kuhjoch East) from the basal part of the T-Bed contains a diverse fauna of Nodosariidae with few Textulariina. This fauna is typically Rhaetian. The diversity decreases in the upper part of the T-Bed towards the end-Triassic mass extinction (see also Hillebrandt and Kment, 2011, Fig. 2). The beds between the Top-Kössen and the Schattwald Beds are characterized by small, mostly compressed, coarsely agglutinated *Trochammina* and an impoverished fauna of nodosariids often characterized by a large species of *Marginulinopsis* (Kuhjoch West).

Hippocrepina (a finely agglutinated siliceous foraminifer with simply constructed test) dominates the Schattwald Beds of the Eiberg Basin and is accompanied by compressed *Trochammina* and an impoverished fauna of nodosariids (especially *Marginulinopsis*). The predominance of *Hippocrepina* points to unfavourable ecologic conditions during "Schattwald time" (~ 100 kyr) amongst others unsuitable for the segregation of calcitic test due to a $CaCO_3$ precipitation crisis as proposed by McRoberts et al. (2012). *Hippocrepina* and compressed *Trochammina* still dominate the first grey marl with thin red layers at the transition from the Schattwald Beds to the Tiefengraben Member s.str. of Kuhjoch East.

Large *Ammobaculites* (species similar to that of the Kössen Fm.) are common to frequent in many samples of the marls above the Schattwald Beds.

Compressed *Trochammina* and tiny, uncompressed *Trochammina* are dominant in the lower part of the grey marls above the Schattwald Beds. *Ammodiscus* and *Glomospira* are rare and in some samples small, attached Ammodiscidae are common.

Small Nodosariidae and Polymorphinidae are mostly rare in the lower part of the Tiefengraben Member, Polymorphinidae more frequent than Nodosariidae, while the latter become more frequent from ammonite level (2) upwards. Well preserved, limonitic casts of Polymorphinidae are found in weathered samples of Kuhjoch East. *Lenticulina* can be the dominating nodosariid genus in the upper part of the Tiefengraben Member. Robertinina are represented by 3 genera (Figs. 12-14): *Oberhauserella* mostly is common; *Praegubkinella* (Fig. 11.7) may be common in the intervals around the ammonite horizons; and *Reinholdella* (Fig. 11.8) is very frequent in the middle part of the Tiefengraben Member. The specimens are usually preserved with aragonitic shell. A characteristic increase in size and evolution takes place from *Oberhauserella* (diameter ~ 0.06 to 0.12 mm) to *Praegubkinella* (~ 0.15 to 0.2 mm) and *Reinholdella* (~ 0.2 to 0.3 mm) (Hillebrandt, 2008).

(2) Ochsentaljoch section (Fig. 13)

Ammobaculites is common to frequent in most samples but disappears in the uppermost samples. *Glomospira* and attached
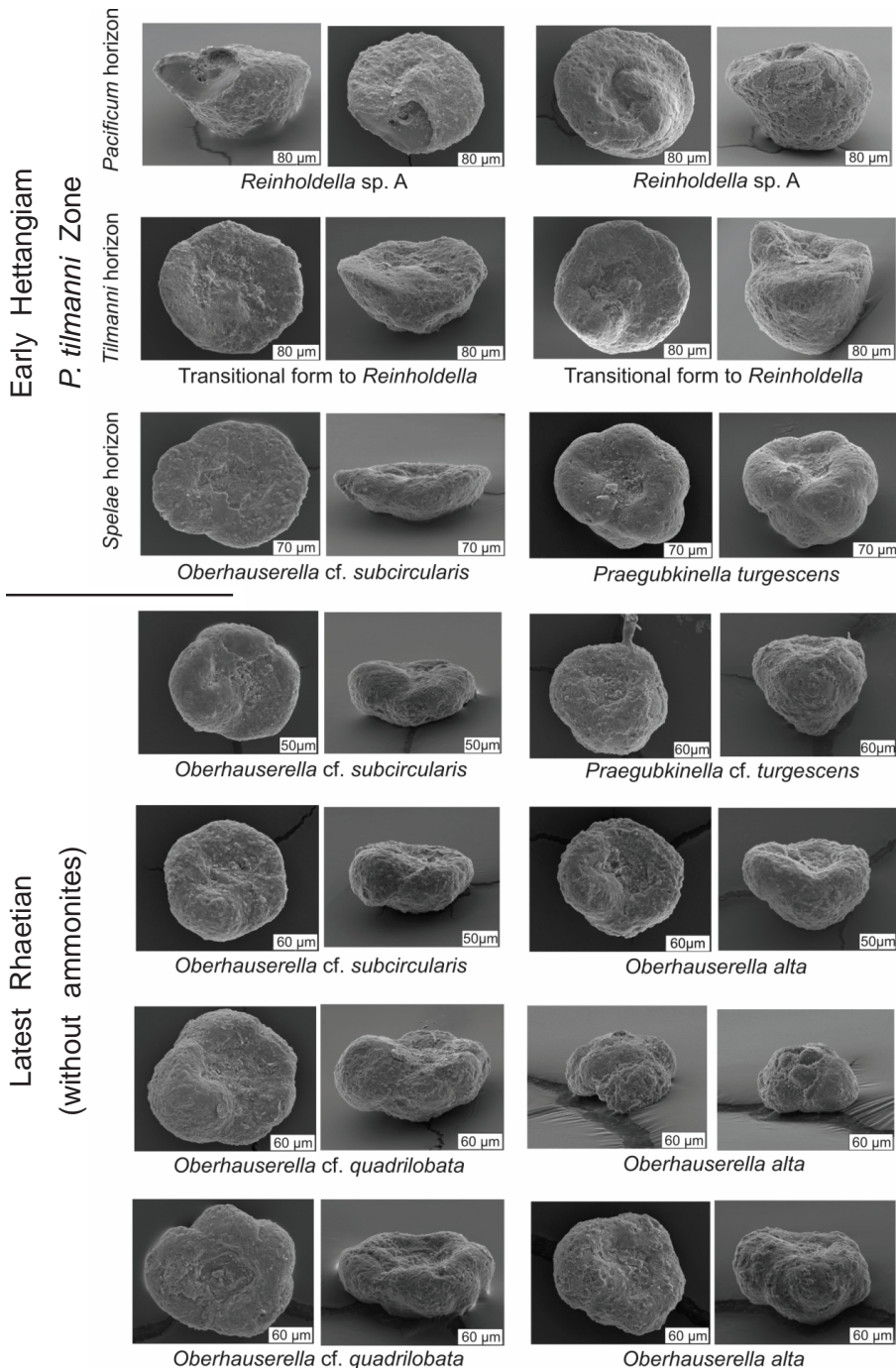
Figure 14. Stratigraphy and Evolution of Robertinina, in the western Karwendel Syncline (Hillebrandt 2010).

from adjacent localities of the Karwendel Mountains are summarized. The earlier work (Hillebrandt and Urlichs, 2008) is now updated based on additional material. From the uppermost Eiberg Member to the Tiefengraben Member (Late Rhaetian-Early Hettangian), three different groups of ostracods are distinguishable by their stratigraphic ranges (Fig. 15):

1. The dark marls 3.8-4.0 m below the top of the Eiberg Member (late Marshi Zone) contain at Kuhjoch a high-diverse Rhaetian ostracod fauna comprising 30 species (Fig. 15: species restricted to the Rhaetian are marked in red). The following rare species are missing above this layer: *Citrella*? *ampelsbachensis, C*? *bairdiiformis, Monoceratina*? *lobitzeri,* and *Triebacythere loferensis.* Other species range somewhat higher up within the Eiberg Member: *Bairdia subsymmetrica*, *Bairdia* sp. A, *Cytherelloidea plana, Eucytherura norica, Kerocythere mostleri* (at Schlossgraben), *Nodobairdia reticulata, Parariscus*? *pygmaeus,* and *Triebacythere ampelsbachensis.* Further species *Bairdiacypris* sp. B, *Signohealdia robusta, S*? *rotunda,* and *Tuberoceratina fortenodosa* continue at Kuhjoch to the base of the T-Bed, *Kerocythere hartmanni, Nodobairdia alpina,* and at Schlossgraben *N. dentata.* The earlier disappearance of some taxa at Kuhjoch may be caused by unfavorable preservation conditions, because merely low-diverse faunas consisting of preferably thickly shelled, and corroded ostracods occur there in thin marl beds. Additional species persist at Schlossgraben even to the upper part of the T-Bed: *Dicerobairdia ornata*, *Lobobairdia triassica*, *Ogmoconchella serratostriata,* and *Pseuodomacrocypris* sp. A. Together with *Choristoceras marshi* (= ammonite horizon 1 in Fig. 15), merely *Ogmoconcha trigonia, Ogmoconchella bristolensis, O. martini,* and *Torohealida amphicrassa* continue into the thin, black layer at the top of the T-Bed at Schlossgraben. The bulk of the Rhaetian species disappeared from the bottom to the top of the T-Bed. Consequently, the end-Triassic mass extinction took place within this bed. Altogether 27 of 45 Rhaetian species (= 60% of the Rhaetian ostracod species) recorded from outcrops of the Karwendel Mountains disappeared, and the ostracod fauna of the uppermost Rhaetian becomes poor and exhibits low diversity above the T-Bed and below the Schattwald Beds. Only *Eucytherura schulzi* and *Ogmoconchella bristolensis* have been recorded from this interval. The overlying Schattwald Beds are barren in ostracods, because they were obviously deposited in an environment, which is not normal marine. A high CO_2 content in the sea water probably hindered the precipitation of $CaCO_3$ (McRoberts et al., 2012).

2. The second group (marked in black in Fig. 15) consists of ostracod taxa, which occur already in the late Marshi Zone and

Ammodiscidae occur in some samples. *Trochammina* is restricted to the lowest samples. Nodosariidae and Polymorphinidae are very rare to frequent in the lower and middle part of the section. Polymorphinidae can be more frequent than Nodosariidae in the lower part. *Lenticulina* is the most frequent nodosariid genus in the upper part, mostly together with *Lingulina tenera. Reinholdella* is common to frequent in many samples and disappears (like *Ammobaculites)* in the upper samples.

b) Ostracods (written by M. Urlichs) (Fig. 15)

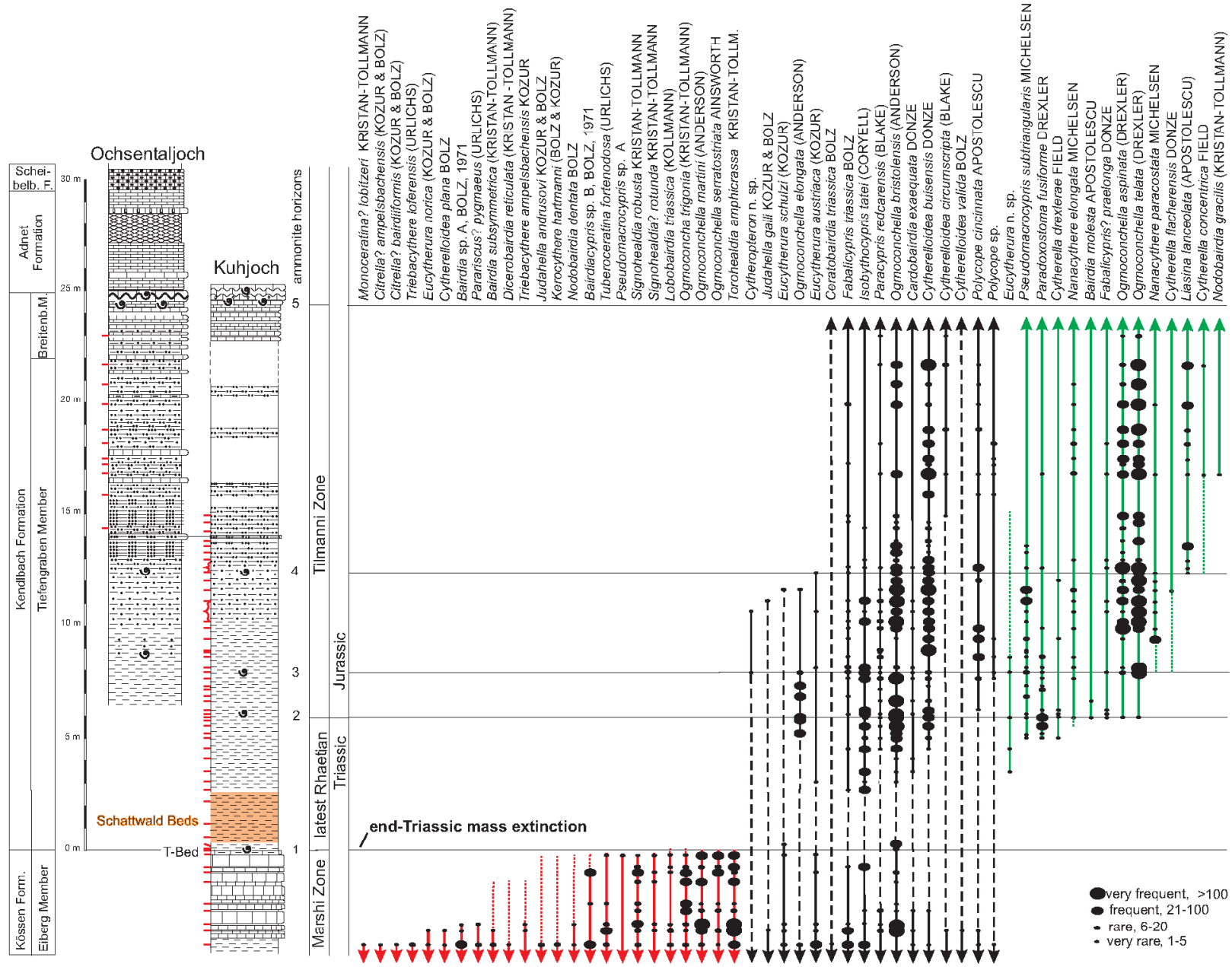The occurrences of ostracods from the GSSP Kuhjoch West and

Figure 15. Stratigraphic range chart of ostracods at Kuhjoch West and Ochsentaljoch sections (red: Triassic species; black: Triassic-Jurassic species; green:Jurassic species; ammonite levels :. 1 = Choristoceras marshi, 2 = Psiloceras spelae tirolicum, 3 = Psiloceras ex gr. P. cf. tilmanni, 4 = Psiloceras cf. pacificum).

reappear either above the Schattwald Beds in the latest Rhaetian or somewhat later within the Tilmanni Zone (earliest Hettangian). Many of them cease at Kuhjoch in this zone *Cytheropteron* n. sp., *Eucytherura austriaca, Eu. schulzi, Judahella galli, Ogmoconchella elongata* and at Hochalplgraben *Eucytherura sagitta* (Fig. 11.10), *Lutkevichinella hortonae*, and *Procytherura nannodes*. Other species continue into younger zones, at least into the Calliphyllum Zone: *Cardobairdia exaequata*, *Ceratobairdia triassica, Cytherelloidea buisensis* (Fig. 11.9), *C. circumscripta, C. valida, Fabalicypris triassica, Isobythocypris tatei, Ogmoconchella bristolensis, Paracypris redcarensis, Polycope cincinnata*, and *Polycope* sp.

3. The third group consists of strictly Jurassic ostracod taxa (marked green in Fig. 15). At Kuhjoch, the earliest Jurassic species occur in the Tiefengraben Member 1.0-2.4 m below the first occurrence of *Psiloceras spelae tirolicum* (= ammonite horizon 2 in Fig. 15 = base of the Tilmanni Zone): *Cytherella drexlerae, Eucytherura* n. sp. (Fig. 11.11), *Nanacythere elongata, Paradoxostoma fusiforme*, and *Pseudomacrocypris subtriangularis*. Other Jurassic species appear for the first time together with *Psiloceras spelae tirolicum*: *Bairdia molesta, Fabalicypris praelonga, Ogmoconchella aspinata* (= *O. ellipsoidea*), and *O. telata*. Further Jurassic species emerge at the Hochalplgraben in the horizon with *Psiloceras* ex gr. *P. tilmanni* (= ammonite horizon 3 in Fig. 15): *Nanacythere paracostata* and *Cytherella flacherensis*. Additional species appear together with *Psiloceras* cf. *pacificum* (= ammonite horizon 4 in Fig. 15) for the first time: *Liasina lanceolata* (at Kuhjoch), *Kinkelinella* sp., *Cytherella concentrica* (at Hochalplgraben), and above this horizon *Acratia* sp. B, *Nodobairdia gracilis*, and *Pustulobairdia* sp. A. (at Hochalplgraben).

In summary, some rare ostracod species disappeared already during the late Marshi Zone, and many Rhaetian ostracods became extinct at the base of the T-Bed, and a few species within or at the top of this bed. The ostracod fauna from the Tilmanni Zone (Early Hettangian) of the Karwendel Mountains comprises Rhaetian holdovers and Jurassic immigrants. A re-elaboration of Rhaetian ostracods during the Early Hettangian appears unlikely, because some species originally described from the Rhaetian occur also in the Middle and Late Hettangian (e.g. Harloff and Jäger, 1994: *Cytherelloidea valida* from the Calliphyllum Zone and *Ceratobairdia triassica* from the Megastoma Zone). The recovery of Jurassic ostracods took place gradually within the Tilmanni Zone, together with the subsequent appearances of the three ammonite species recorded above (= ammonite horizons 2-4 in Fig. 15)**.** The bulk of the Jurassic ostracod species appeared somewhat below or together with *Psiloceras spelae tirolicum* and some others together with *Psiloceras* ex gr. *P. tilmanni* or later together with *Psiloceras* cf. *pacificum*.

The significance of the stratigraphically important ostracod species is discussed in the biostratigraphy chapter.

c) *Conodonts* (written by L. Krystyn)

Since the pioneering study of Mostler et al. (1978) conodonts are known to occur widely in the Kössen Formation of the NCA. They are more common in the calcareous basinal facies of the Eiberg Member (Golebiowski, 1986) and have also been documented from the uppermost Triassic part of the Kendlbach section (Krystyn, 1980). In Kuhjoch, repeated dissolution (6 kg) of the last autochthonous limestone layer (sample KJ-2) of the Kössen Formation has produced a relatively numerous and diverse fauna dominated by specimens of

the genus *Misikella* (individual numbers in brackets): *M. posthernsteini* (26), *M. ultima* (2), *Zieglericonus rhaeticus* (2), and *Neohindeodella* sp. (4). Of these forms, *M. ultima* is the name bearer of the topmost Triassic conodont zone as found in Hungary (Kozur and Mock, 1991; Palfy et al., 2001), Turkey (Gallet et al., 2007) and Austria. Kozur and Mock (1991) distinguished above the *ultima* zone another short conodont interval (*Neohindeodella detrei* zone), which eventually could correspond to the topmost T-Bed of the Kössen Formation in Kuhjoch. This bed seems due to its high marl and silt content unsuitable for conodonts and has not been investigated. A large sample (8 kg) from a more calcareous counterpart of T-Bed on the Steinplatte slope (Tyrol) has produced a tremendous amount of insoluble residue but no conodonts.

d) *Calcareous Nannofossils* (written by P. Bown) (Figs. 16, 17)

Twenty-one samples were examined from the Kuhjoch section and all but four were nannofossiliferous. The nannofossil assemblages
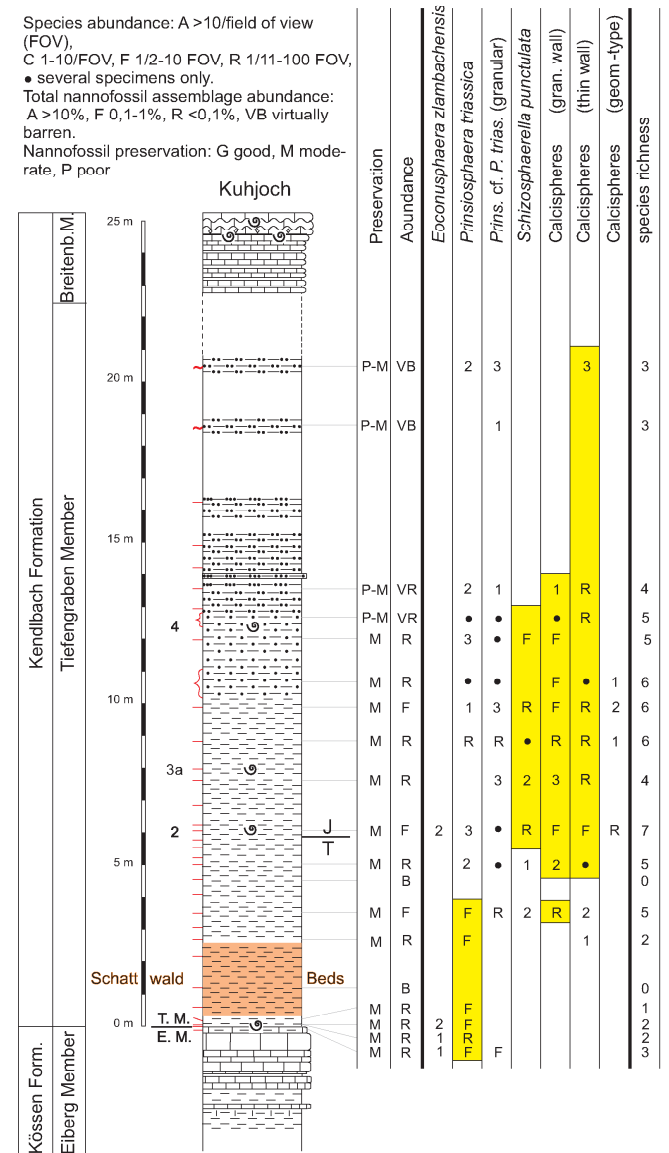

Figure 16. *Stratigraphic range chart of calcareous nannofossils from Kuhjoch West.*

Hochalplgraben

	Preservation	Abundance	Crucirhabdus minutus	Eoconusphaera zlambachensis	Prinsiosphaera triassica	Prins. cf. P. triass. (granular)	Calcispheres	Calcispheres (gran. wall)	Calcispheres (thin wall)	Calcispheres (geom.-type)	spicules	Ascidians	Species richness
	M	R				?2	F	C	F	R	2		6
	P-M	R					2			2			2
	P-M	F				?●	F	?●	C				4
	M	F				F	F	F	F	R			5
	M	F		2		R	C	F	F	R		A	7
	M	F					F		C	R		C	4
	M	F				R	R	C	C	R	2	A	7
	M	F	1	1	●	F	C	C	F	1		?●	10

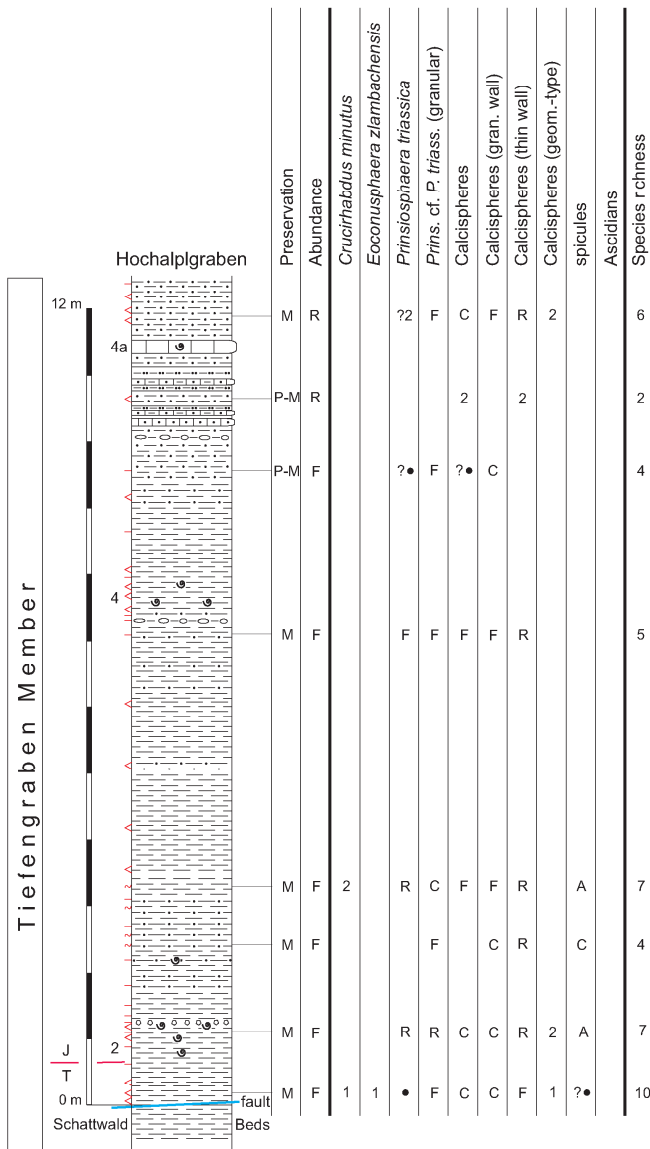Tiefengraben Member — Schattwald Beds — fault — J / T

Figure 17. Distribution of calcareous nannofossils from Hochalplgraben section.

are generally rare to frequent, of low diversity and poorly-moderately preserved. The lowermost samples (Fig. 16, 0-3.6 m) are dominated by *Prinsiosphaera triassica* but the section probably lies above the LO (last occurrence) of *Eoconusphaera zlambachensis* (the few specimens seen are most likely reelaborated). At the boundary interval (~ 6 m) there is a switch in dominance from *P. triassica* to calcispheres and *Schizosphaerella punctulata*. The FO (first occurrence) of *S. punctulata* may be coincident with the boundary level. We hope to refine the position of these bio-events with further high-resolution sampling and quantitative assemblage data. Both the LO of *P. triassica* and the FO of *S. punctulata* may be extremely useful boundary indicators as they are common, robust and globally distributed species.

e) Palynomorphs (written by W.M. Kürschner, N.R. Bonis, and M.A.N. Schobben) (Figs. 23-26)

In general, pollen and spore assemblages from the Kössen Formation are dominated by *Classopollis meyeriana* and *C. torosus* accompanied by *Ovalipollis pseudoalatus*, *Rhaetipollis germanicus*

and *Ricciisporites tuberculatus*. Marine palynomorphs such as dinoflagellate cysts *Rhaetogonyaulax rhaetica* and *Dapcodinium priscum* and some acritarchs (e.g. *Microhystridium*) are present. The palynomorph assemblages from the topmost bed of the Kössen Formation (black shale of top T-bed) are characterized by peak abundances of prasinophytes, particularly *Cymatiosphaera polypartita*. The rather monotonous sporomorph assemblages from this interval are dominated by *C. meyeriana* and *Porcellispora longdonensis*. Sporomorph assemblages from the Schattwald Beds are characterized by an increase in *Polypodiisporites polymicroforatus*, *Deltoidospora* spp. and *Calamospora tener,* while *C. meyeriana* declines. *Rhaetipollis germanicus* disappears in the lower part of the Schattwald Beds, while *O. pseudoalatus* has its highest appearance at the top of the Schattwald Beds. Algal remains in the Schattwald Beds are mainly represented by *Botryococcus* and *Tasmanites,* while dinoflagellate cysts are rare and *Rhaetogonyaulax rhaetica* disappears. Of biostratigraphic value is the lowest occurrence of *Cerebropollenites thiergartii* and *Ischyosporites variegatus* immediately above the Schattwald Beds and ca. 3 m below the entry level of *P. spelae.* For further discussion of the palynological results see paragraphs below.

Sediment diagenesis (written by A.v. Hillebrandt, L. Krystyn, and W.M. Kürschner)

At the Kuhjoch section **no** significant alteration is observable. Ammonites, bivalves, and aragonitic forams (in part hollow) are preserved with an aragonitic shell. There are absolutely no signs of regional or local metamorphism of the rocks (Kuhjoch, Hochalplgraben, Schlossgraben and also Tiefengraben and Kendlbach). From the preservation of palynomorphs, notably the colour, it is evident that this material was never heated above about 50°C (see also Kürschner et al., 2007). Conodonts also show a low CAI 1 value.

Geochemistry (written by M. Ruhl, W.M. Kürschner and S. Richoz)

Carbon isotopes of bulk sedimentary organic matter have been studied by Ruhl et al. (2009) as well as carbon-isotopes of selected micrite and shells (this study). In addition, compound-specific C-isotope measurements (n-alkanes) have been carried out (Ruhl et al., 2011). A clay mineralogy/XRD stratigraphy has been published for the coeval Kendlbach section by Zajzon et al. (2012) and Palfy and Zajzon (2012). Clay mineralogy investigation at Kuhjoch itself is going on, those of the Strontium isotopes, Rare Earth Elements, Ca/Mg are planned.

1. Carbon isotopes and organic carbon content (written by M. Ruhl and W.M. Kürschner) (Figs. 18, 19, 20b, 21, 24)

$\delta^{13}C_{org}$ data (Fig. 24) have been documented from many sections of the Northern Calcareous Alps (Restental, Hochalplgraben, Kuhjoch/ Ochsentaljoch, Kendlbach, Schlossgraben, Steinplatte/Scheibelberg, Tiefengraben) and are discussed in detail by Ruhl et al. (2009). All these records show very regularly the distinct initial isotope excursion at the transition from the Kössen Formation to the Schattwald Beds. Two sections were studied at Kuhjoch: Kuhjoch West and Kuhjoch East.
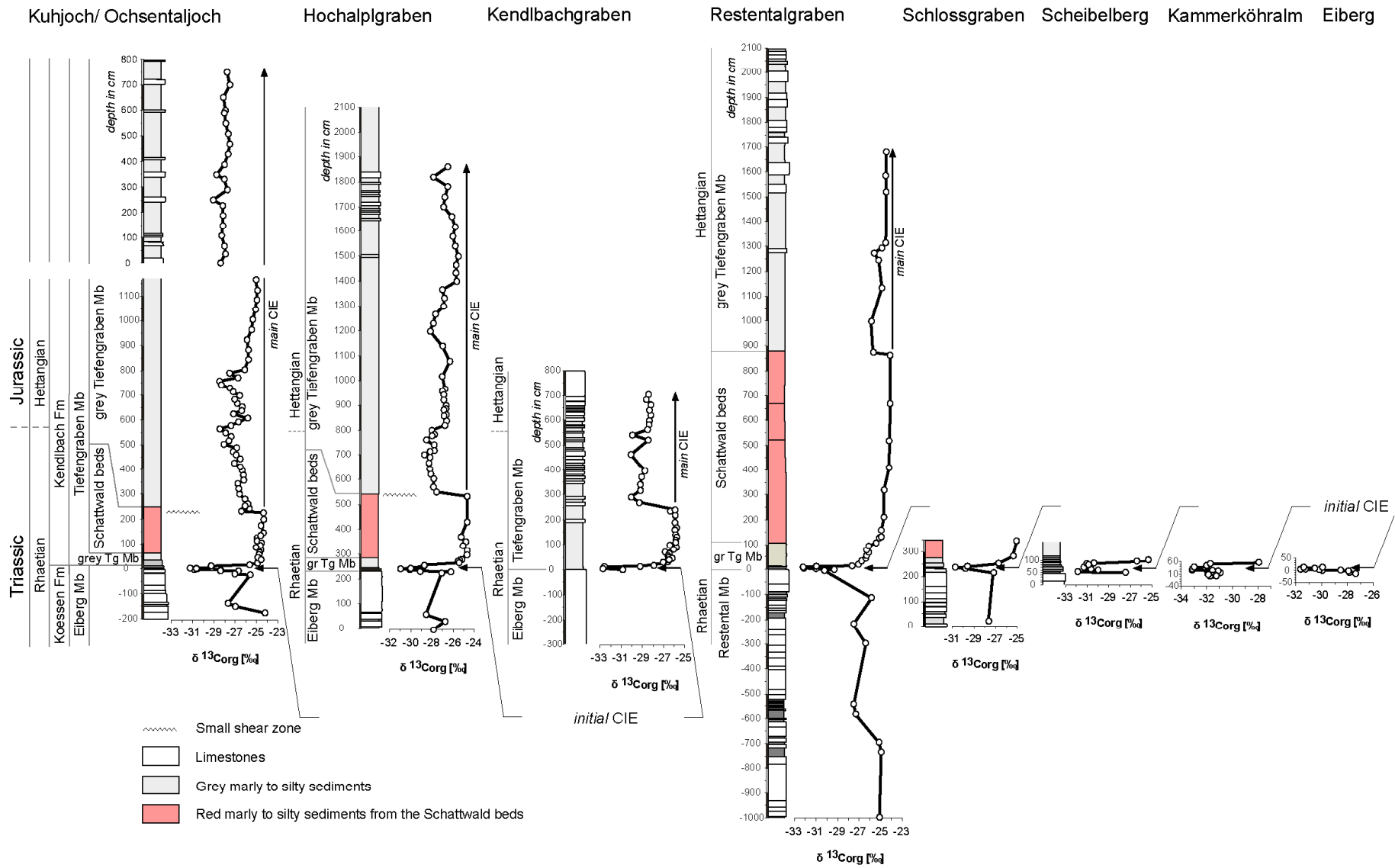
Figure 18. $\delta^{13}C_{org}$ curves for Eiberg-Tiefengraben members from Northern Calcareous Alps (Ruhl et al., 2009).

a) Kuhjoch section West (Fig. 19)

In the Kuhjoch West section the transition from the Eiberg Member to the Tiefengraben Member was sampled at a cm scale. This interval is characterized by a distinct negative C isotope excursion with a maximum of about -31‰ (Fig. 19). The onset of the $\delta^{13}C_{org}$ peak coincides with a bituminous, black siltstone layer (1 cm) at the top of the thin-bedded marly limestone (T-Bed) of the uppermost Eiberg Member. The upper half of this negative carbon isotope excursion coincides with the top of the brownish marls with *Pseudolimea*, concretions of pyrite and worm-shaped traces. The C isotope curve turns to more positive values of about -25‰ within the lowermost 20 cm of the Schattwald Beds and remains rather stable within this interval. An abrupt ~2‰ negative shift (from ~ -25 to ~ -27‰) occurs at the top of the Schattwald Beds at ~ 2.5 m height in the section. This shift is related to a minor fault in the sedimentary record, marked by a ~ 10 to 20 cm thick and tectonically deformed clay horizon (Fig 19). The break in the sedimentary succession is also confirmed by a hiatus in the palynological record (see palynostratigraphic paragraph below, Fig. 24). In the Tiefengraben section this zone is characterized by a gradual negative trend from -26‰ to -28‰ (Kürschner et al., 2007). The minor sedimentary hiatus in the Kuhjoch West record is succeeded by gradually decreasing $\delta^{13}C_{org}$ values, from ~ -27 to ~ -28.5‰, similar to the observed negative

trend in the Tiefengraben $\delta^{13}C_{org}$ record. This long-term gradual negative shift is interrupted by a significant positive shift (to -26‰) at the level of the first ammonite horizon. This minor positive excursion is followed by less negative values and subsequently more depleted values at the top of the studied record.

b) Kuhjoch section East (Fig. 19)

To get the completeness of the Schattwald sedimentary record at Kuhjoch, a combined palynological and bulk C-isotope study has been carried out at Kuhjoch West as well at Kuhjoch East.

C-isotope values (Fig. 19) of the lower part of the Schattwald Beds, between the base of the sampled section and about 260 cm height, remain rather stable at around -25‰. Between 260 cm and 330 cm C-isotope values turn gradually to more negative values with a minimum of -27‰ at 330 cm and increase gradually again to less negative values of -26‰ towards the top of the section studied (at 400 cm).

C-isotope analysis of the Schattwald Beds of the Kuhjoch section at the east side reveals no abrupt shifts (jumps) but a steady decline to more negative values. These values correspond to the jump in C-isotope values at 230 cm at the west side of the Kuhjoch section and support the presence of a small hiatus at this level, caused by a minor fault (Ruhl et al., 2009; Bonis et al., 2009), while the sedimentary succession at the east side is complete in this interval.

2. Total Organic Carbon (TOC) (written by M. Ruhl and W.M. Kürschner) (Fig. 20b)

The TOC curve shows a sharp maximum of about 10% at the black, bituminous layer, which coincides with the initial $\delta^{13}C_{org}$ minimum, while the rest of the section shows only minor variations between 0 and 1%. A similar pattern has been found throughout the Eiberg Basin.

3. Kerogen analysis (written by M. Ruhl and W.M. Kürschner)

Rock Eval pyrolysis has been used to identify the type and maturity of the sedimentary organic matter (Ruhl et al, 2010a). The initial Carbon Isotope Excursion (CIE) is marked by only minor changes in kerogen, which is distinctly terrestrial in origin. Increased TOC concentrations of 9% at the first half of the initial CIE coincide with HI values of over 600 mg HC/g TOC. The high correlation (with R^2 = 0.93) between HI values and terrestrial Cheirolepidiaceae conifer pollen suggests a terrestrial origin for the hydrogen enriched organic compounds in the sediment. The lack of major changes in the origin of the sedimentary organic matter suggests that the changes in the $\delta^{13}C_{org}$ composition are genuine and represent true disturbances of the global C-cycle. This finding is supported by the compound specific C-isotope record measured in higher plant *n*-alkanes (Ruhl et al., 2011).

4. Carbon isotope in carbonate (written by S. Richoz) (Fig. 21)

Compared to $\delta^{13}C_{org}$ studies, rare $\delta^{13}C_{carb}$ data are reported for the T-J boundary interval in the NCA. Only the Kendlbach section in the Eastern Eiberg Basin has been investigated by Hallam and Goodfellow (1990), challenged by Morante and Hallam (1996) and
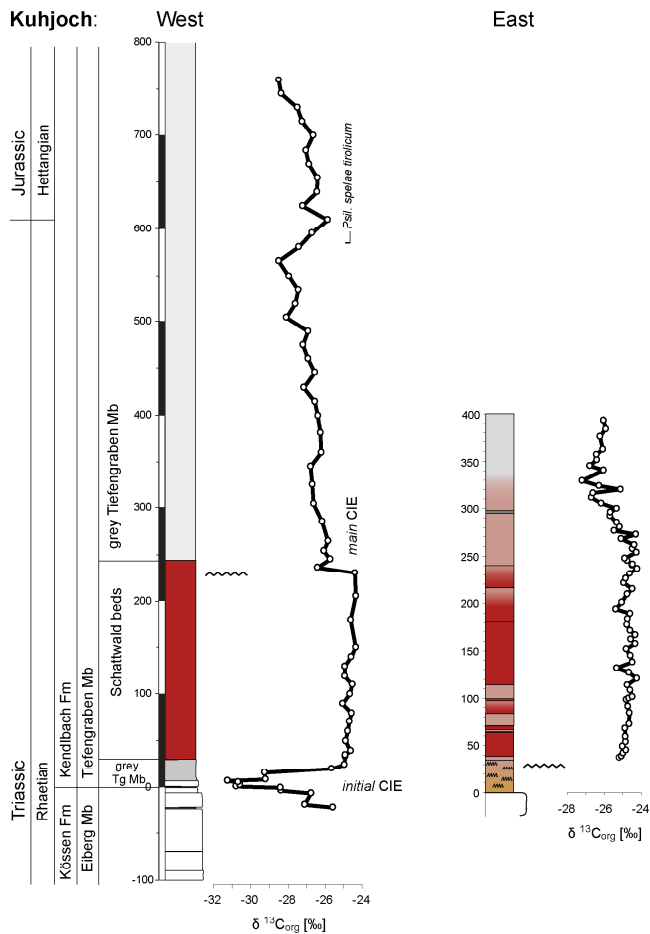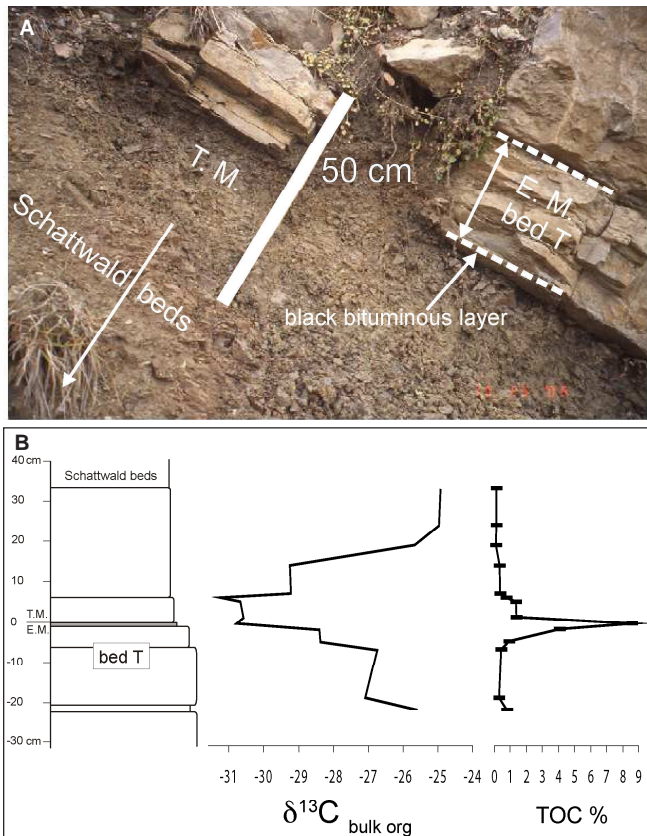
Figure 19. Detailed C-isotope curves from the Kuhjoch West and the Kuhjoch East sections, data for Kuhjoch West are from Ruhl et al. (2009), data for Kuhjoch East are from Schobben et al. (to be submitted).

measured show to some degree recrystallization of the test, which could explain the slightly more negative values. Ammonites from the Tiefengraben Member have been demonstrated to preserve aragonite. The two ammonites here measured display very different values. This difference could be explained by different metabolic effects on the isotopic composition of the shell (Seuss et al., 2012) or by a partial recrystallisation and transformation of the aragonite into calcite. Indeed by applying the ^{13}C-fractionation between aragonite and calcite of 1.8±0.2‰ (Rubinson and Clayton, 1969) to the *Ps.* cf. *pacificum* leads to values around 2‰ being in agreement with the general trend. But using the correction factor for the *Ps. spelae* data would result in too negative values.

The limy sandstone at 14 m, just above the *Ps* cf. *pacificum* level, of Kuhjoch provides a value of 1.4‰, whereas the first limestone bed of the Breitenberg Mb. has a value of 1.9‰. These values increase to 2.4‰ in the middle of this member to stabilize around 1.7‰ at the top and in the successive Adnet Formation. In conclusion, after the initial negative excursion, the values seem to remain constant between 1.5 and 2‰ as already observed by Hallam and Goodfellow (1990) without considering the values of the marls (Morante and Hallam, 1996), and by McRoberts et al. (1997).

Palaeomagnetism (written by M. Deenen, M. Szurlies, and W. Krijgsman)

Palaeomagnetic investigations have been started but all samples studied till now are remagnetized. Earlier investigations of Kössen Formation in the Steinplatte area (Fig. 1) have been shown to be remagnetized, which is in agreement with previous studies in the NCA (Pueyo et al., 2007). The organic rich sediments often contain also a lot of pyrite, which bias a primary signal.

Biostratigraphy (Figs. 10, 11)

Only a few fossil groups are suitable for high-resolution long distance correlations of Lower Jurassic strata, i.e. ammonites and radiolarians, of which the latter are almost missing in the studied sections. Ammonites are, therefore, the most important fossils for detailed biostratigraphic subdivision and correlation of the T-J boundary interval. Their high evolutionary potential provides the basis for a detailed biozonation (Fig. 22) and their wide geographic distribution in marine realms facilitates global correlations. Nannofossils and marine palynomorphs may also be of relatively high correlation potential. Of biostratigraphic or ecostratigraphic relevance are also bivalves, ostracods and foraminifers. Available terrestrial palynomorphs offer potential for marine – non-marine correlations.

1. Ammonites (Figs. 10, 22) (Hillebrandt and Kment, 2011; Hillebrandt and Krystyn, 2009)

The Kuhjoch, Ochsentaljoch, Rissbach and Hochalplgraben sections record 9 ammonite beds or levels of Late Rhaetian to Late Hettangian age:

- ammonite level (7) with ammonites of the Marmorea Zone (Late Hettangian)
- ammonite level (6) with ammonites of the Megastoma Zone (Middle Hettangian)
- ammonite level (5) with ammonites of the Calliphyllum Zone

Figure 20. (A) Boundary between Eiberg (E.M.) and Tiefengraben members (T.M.) (Kuhjoch West section). Beds of photograph overturned. (B) $\delta^{13}C_{org}$ and TOC curves of the Eiberg - Tiefengraben members (Kuhjoch West section) (Ruhl et al., 2010a).

revisited by Korte and Kozur (2011). McRoberts et al. (1997) presented another curve from the Lorüns section in western Austria. Mette et al. (2012) published a $\delta^{13}C_{carb}$ curve for the Late Rhaetian part of the Kössen Formation in Eiberg. A major problem is the very rare occurrence of carbonate beds in the almost pure terrigenous Tiefengraben Member, which do not allow a continuous carbonatic C isotopic curve through the boundary interval. Data presented here are also scattered, taken from different localities and carbonatic sources: we measured the uppermost Kössen limestones and the T-Bed at Scheibelberg, pelycypod fragments from a level 90 cm above the top of the Schattwalds Beds at Hinterissbach, ammonoids (*Ps. spelae* and *Ps.* cf. *pacificum* fragments), the foraminifer *Reinholdella* from the *Ps.* cf. *pacificum* level at Hochalplgraben and the limestones of the Breitenberg Mb. at Kuhjoch.

The Scheibelberg section is located at the southern margin of the Eiberg Basin and contains a particularly well-developed and expanded T-Bed. Its $\delta^{13}C_{org}$ and TOC values have been published in Ruhl et al. (2009). The $\delta^{13}C_{carb}$ data in the Kössen Formation are around 1.8‰, corresponding to the mean values of the Eiberg Member (Mette et al., 2012). The values remain stable or even increase slightly through the lower T-Bed to start decreasing to 1.2‰ only in the upper T-Bed. A very short main negative excursion (to 0.2‰) is restricted to the topmost 10 cm of the T-Bed and thus records a distinct delay in comparison to the $\delta^{13}C_{org}$ negative excursion.

Fossil remains from the Tiefengraben Mb. provide various values with a maximum of 2.1‰ for pelycypods, 2.0‰ for *Ps. spelae*, 4.3‰ for *Ps.* cf. *pacificum* and 1.1‰ for *Reinholdella*. All foraminifers

(condensed; including horizon with *Psiloceras calliphyllum-P. costosum* and horizon with *Psiloceras naumanni*) +(upper part of Early Hettangian).

- ammonite level (5a) (Rissbach) with *Psiloceras* cf. *planorbis* and *P.* n. sp. (upper part of Early Hettangian)

- ammonite level (4a) (Hochalplgraben) with *Psiloceras* sp. A (Fig. 17) (Hillebrandt and Krystyn, 2009, figs. 5, 11.6a,b) (lower part of Early Hettangian)
- ammonite level (4) *Psiloceras* cf. *pacificum* (lower part of Early Hettangian)
  - ammonite level (3a at Kuhjoch and 3b at Ochsentaljoch) with *Psiloceras* ex gr. *P. tilmanni* (lower part of Early Hettangian)
  - ammonite level (2) with *Psiloceras spelae tirolicum* (lowest part of Early Hettangian (Figs.11.1-3)
  - ammonite level (1) with *Choristoceras marshi* (Late Rhaetian) (Fig. 11.6)

2. Bivalves (Figs. 11.4-5) (written by C. McRoberts)

Cassianella and *Chlamys valoniensis* characterize the top Eiberg Member. Directly above is the FO of *Agerchlamys* together with *Pseudolimea* cf. *hettangensis* in the bituminous layer of the T-Bed, both taxa continuing up into the remainder of the Tiefengraben Member. Two species of *Cardinia* and a single one of *Agerchlamys* are found in different beds of the Tiefengraben Member, the latter form ranges up to the lower part of the Breitenberg Member. Of these bivalve taxa known from the GSSP interval, only *Agerchlamys* provides for limited global correlation to other T-J boundary sections where the FO consistently can be found immediately following the onset of extinction and negative C isotope anomaly (see McRoberts et al., 2007; McRoberts et al., 2012). The other bivalve taxa, while ecologically important, posses little biostratigraphic value.

3. Ostracods (written by M. Urlichs) (Fig. 15)

Many ostracod taxa found in the Tiefengraben Member are long ranging, for example from the Hettangian to the Late Pliensbachian or even to the Toarcian. Merely the *Eucytherura* and *Nanacythere* species have a stratigraphic range of only about one stage or somewhat more. The Tilmanni Zone is characterized by the co-occurrence of the Rhaetian *Eucytherura sagitta, Eu. schulzi* and the Hettangian *Nanacythere elongata* and *N. paracostata*. Unfortunately, these species are mostly very rare in the Karwendel sections. *Ogmoconchella bristolensis*, *O. aspinata,* and *O. telata* are against that frequent to abundant in the Tilmanni Zone of these sections and occur also in the Calliphyllum Zone. Both zones are characterized by the co-occurrence of these three *Ogmoconchella* species.

Ogmoconchella martini is the index fossil of the lower part of the "Middle" Rhaetian, of the *martini* Zone in England and of the upper "Middle" Rhaetian, the *virgata* Subzone in NW Germany. It has been furthermore recorded from the lower part of the Upper Rhaetian in England (Ainsworth and Boomer 2009,
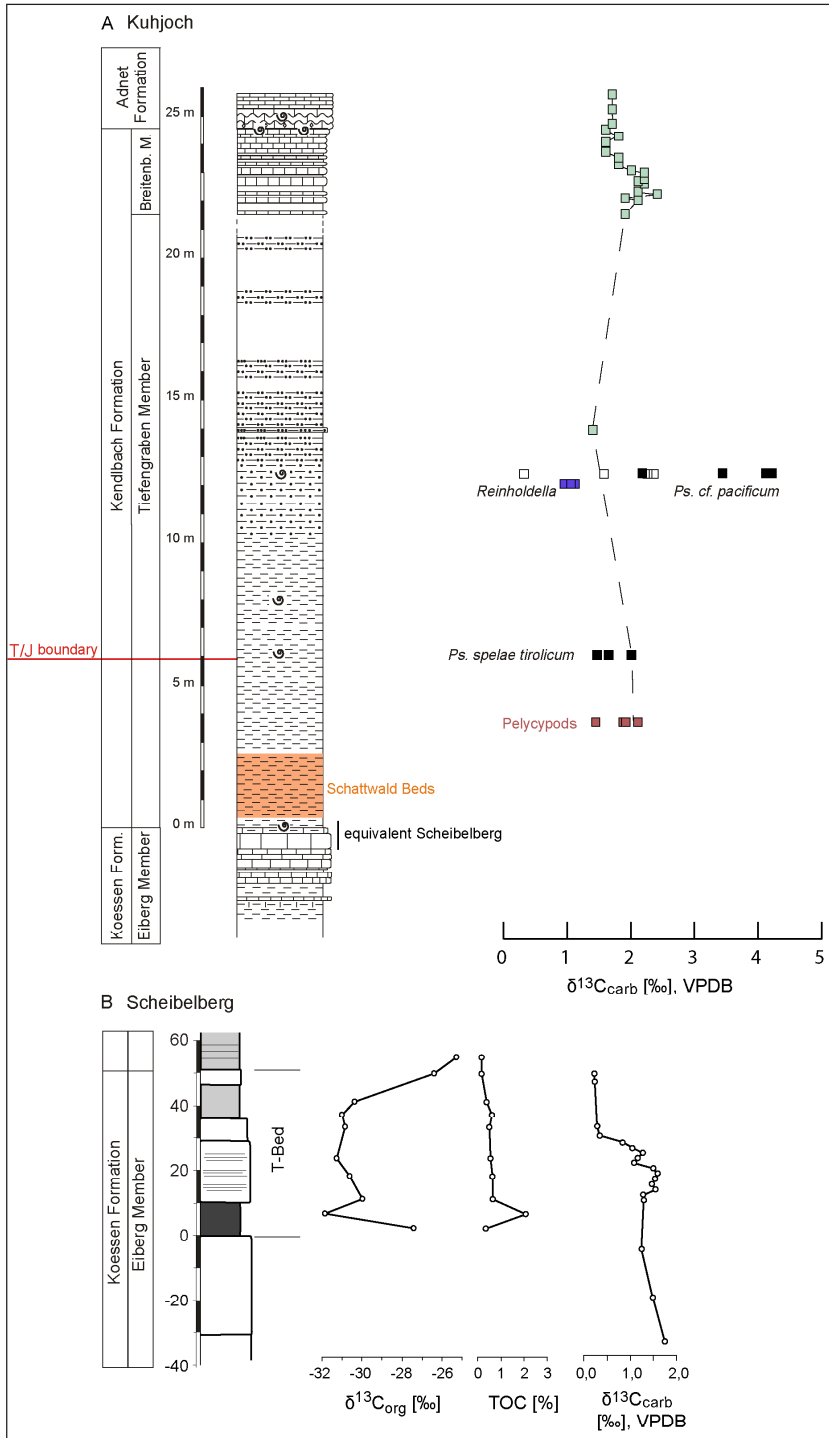

Figure 21. (A) $\delta^{13}C_{carb}$ *values at Kuhjoch West section. The bivalve data (brown squares) are from the Hinterissbach section, some kilometers west of Kuhjoch, calibrated in the section with distance to the Schattwald Beds. Black squares are values for both ammonites, open squares are values for Ps cf. pacificum corrected for the* ^{13}*C-fractionation between aragonite and calcite. The violet squares refer to Reinholdella and turquoise squares are for selected micrite. (B)* $\delta^{13}C_{carb}$*,* $\delta^{13}C_{org}$ *and TOC data from Scheibelberg section;* $\delta^{13}C_{org}$ *and TOC are from Ruhl et al. (2009).*

	Zones	Northern Calcareous Alps HILLEB.& KR. 2009	NW Europe (Great Britain) PAGE 2003 (modif.)	North America (Nevada) GUEX et al. 2004 (modif.)	South America (Peru + Chile) HILLEBRANDT 2000(m.)
Lower Hettangian	Planorbis	P. naumanni	C. johnstoni	C. crassicostatum	P. cf. calliphylloides
Lower Hettangian	Planorbis	P. costosum + P. calliphyllum	P. plicatulum		P. rectocostatum
Lower Hettangian	Planorbis	P. costosum + P. calliphyllum	P. psilonotum	P. polymorphum	P. primocostatum
Lower Hettangian	Planorbis	Neophyllites	P. planorbis	P. polymorphum	P. planocostatum
Lower Hettangian	Planorbis	Neophyllites	Neophyllites	P. polymorphum	P. planocostatum
Lower Hettangian	Tilmanni	P. cf. planorbis	P. erugatum	P. pacificum	P. tilmanni
Lower Hettangian	Tilmanni	P. cf. pacificum	?	P. pacificum	P. tilmanni
Lower Hettangian	Tilmanni	P.ex gr.P.tilmanni	?	P. marcouxi ⎪ Odog.	P. tilmanni
Lower Hettangian	Tilmanni	P.ex gr.P.tilmanni	?	P. marcouxi ⎪ Odog.	P. cf. tilm. + Odog.
Lower Hettangian	Tilmanni	Psiloc. spelae	?	P. spelae	P. cf. spelae
Rhae-tian	Marshi	Choristoceras marshi		Choristoceras crickmayi	Ch. marshi + Ch. crickmayi

Figure 22. Correlation of Early Hettangian ammonite zones, subzones and horizons (grey), broken lines approximated correlation.

fig. 2) and has still a longer range in the Austroalpine Realm than in England and NW Germany, at least from the basal Stuerzenbaumi Zone to the top of the Marshi Zone (Middle to Late Rhaetian). The shorter stratigraphic ranges in the Europe outside of the Alps probably result from low salinity during the Late Rhaetian.

After the disappearance of *Ogmoconchella martini* at Kuhjoch, the first appearance of *Ogmoconchella aspinata* (= *O. ellipsoidea*) at the base of the Tilmanni Zone may be an approximate biostratigraphic marker for the base of the Hettangian. However, the first appearance of *O. aspinata* is not coeval in different regions. In England, this species already occurs from the Lower Rhaetian to the lower part of the Upper Rhaetian (Ainsworth and Boomer 2009, fig. 2) and continues to the earliest Sinemurian (Boomer and Ainsworth 2009, fig. 2). These Rhaetian occurrences should be reconsidered. In continental Europe outside of the Alps, the earliest records of *O. aspinata* come from the Planorbis Zone of Ardèche, Paris Basin, Lower Saxony, and Denmark. In SW Germany, this species appears later, in the early Liasicus Zone (Middle Hettangian), because the condensed carbonatic lithology of the "Psilonotenbank" (Psilonotum Zone) is unsuitable for the extraction of ostracods. Based on ostracods alone, an exact correlation of the Austroalpine Late Rhaetian and Early Hettangian with NW and Central Europe is at present impossible.

4. Foraminifers (Figs. 10, 12-14) (Hillebrandt, 2010, 2012)

The nodosariid fauna of the T-Bed and of the bituminous layer is typical for the Rhaetian just as is the impoverished fauna with large *Marginulinopsis* of the lower part of Tiefengraben Member. The monotonic predominance of *Hippocrepina* in the Schattwald Beds allows no age assignment. The mostly small-sized nodosariids and polymorphinids of the grey marls of the Tiefengraben Member above the Schattwald Beds are poor in species. Characteristic genera like *Ichthyolaria* do not occur and specimens of the *Lingula tenera* group are very rare in the lower and middle part of the Tiefengraben Member.

The aragonitic Robertinina are of biostratigraphic importance (Figs. 11, 14) (Hillebrandt, 2010). *Oberhauserella* was described from the Late Triassic and is still present with various species in the grey marls below the *Psiloceras spelae* horizon. *Praegubkinella turgescens* appears 50 to 60 cm below and disappears about 1.2 m above the *spelae* horizon, which is about 40 cm thick. Transitional forms to

Reinholdella n. sp. are first found above this level. The horizon with *Psiloceras* cf. *pacificum* yields another new species of *Praegubkinella*. In the Hochalplgraben section a third species of *Praegubkinella* occurs between the horizons with *Psiloceras spelae tirolicum* and *Psiloceras* cf. *pacificum*. *Reinholdella* n. sp. continues to the upper part of the Tiefengraben Member (Ochsentaljoch section). *Oberhauserella* and *Praegubkinella* are not only found in the Eiberg Basin but also in the Allgäu and Hallstatt basins. A section in the latter (near Bad Goisern) revealed the same Oberhauserellidae evolution and the characteristic size increase from *Oberhauserella* to *Praegubkinella*. These aragonitic foraminifers are thus very important biostratigraphical proxies for the T-J boundary since their rapid evolutionary development takes place in different Alpine regions close to the *spelae* horizon.

5. Calcareous nannofossils (written by P. Bown) (Figs. 16, 17)

Contrary to the Kössen Formation, coccoliths s.s. are very small and very rare in the Tiefengraben Member where neither typical "Liassic" nannofossils (e. g. *Schizosphaerella* – the dominant Liassic nannolith), nor any true coccoliths have yet been found. More samples have to be studied as changes in the "calcisphere" assemblages could be of biostratigraphic importance for the turnover from the Triassic to the Jurassic, which is not well constrained.

6. Palynomorphs (Figs. 10, 23-26) (written by N.R. Bonis, M.A.N. Schobben, and W.M. Kürschner)

Several studies in the Northern calcareous Alps (NCA) have described the microfloral record across the Triassic-Jurassic (T-J) transition (Morbey, 1975; Karle, 1984; Schuurman, 1979). The discovery of a negative C-isotope excursion (CIE) at the base of the Tiefengraben Member (Kürschner et al, 2007), that correlates with the initial and main negative CIE in many other T-J key sections (e.g. Palfy et al., 2001; Hesselbo et al., 2002; Guex et al., 2004), has renewed the interest in high resolution palynostratigraphic studies in the NCA, which allows calibration of the pollen and spore record with an independent chemo- and marine biostratigraphic framework (Bonis et al., 2009, 2010a; Bonis and Kürschner, 2012). In the western Eiberg Basin, Bonis et al. (2009) presented a detailed high-resolution microfloral record for the Hochalplgraben section together with preliminary data from the Kuhjoch W section. The following paragraph summarizes a new high-resolution palynostratigraphic study from the Kuhjoch GSSP in both outcrops, on the western and eastern flank and represents a revision of earlier work (Bonis et al., 2009). A more detailed account of the palynology of the Kuhjoch sections will be published elsewhere (Schobben et al., to be submitted)

a) Kuhjoch West section (Figs. 10, 23, 25)

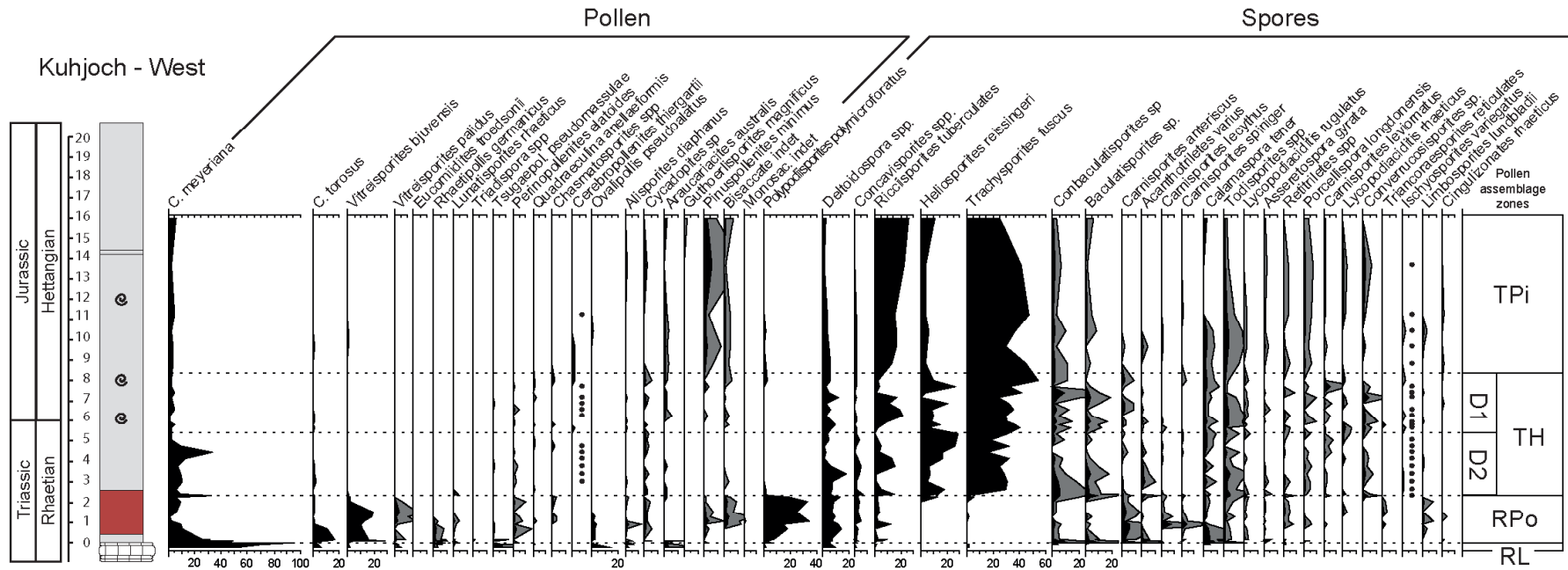In total 44 sub-samples were taken from the same sediment

Figure 23. Relative abundances [%] of pollen and spores through the T-J boundary interval in the Kuhjoch West section and their correlation with pollen assemblage zones after Kürschner et al. (2007), whereby RL = Rhaetipollis -Limbosporites zone, RPo = Rhaetipollis-Porcellispora zone, TH = Trachysporites-Heliosporites zone (with D1 and D2 as local subzones that correlate with local pollen assemblages H3 and H4a in Hochalplgraben (Bonis et al., 2009)), TPi = Trachysporites-Pinuspollenites zone.
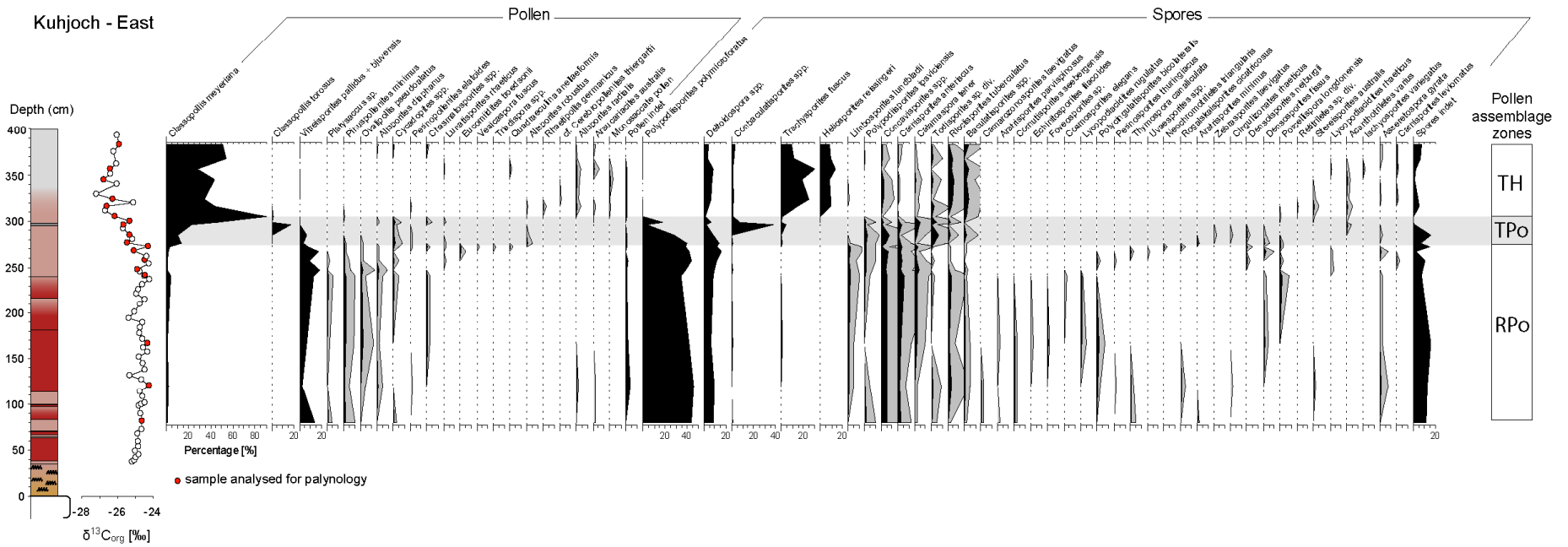
*Figure 24. Relative abundances [%] of pollen and spores through the T-J boundary interval in the Kuhjoch East section and their correlation with pollen assemblage zones after Kürschner et al. (2007), whereby RPo = **Rhaetipollis-Porcellispora** zone, TPo = **Trachysporites-Porcellispora** zone, TH = **Trachysporites-Heliosporites** zone.*
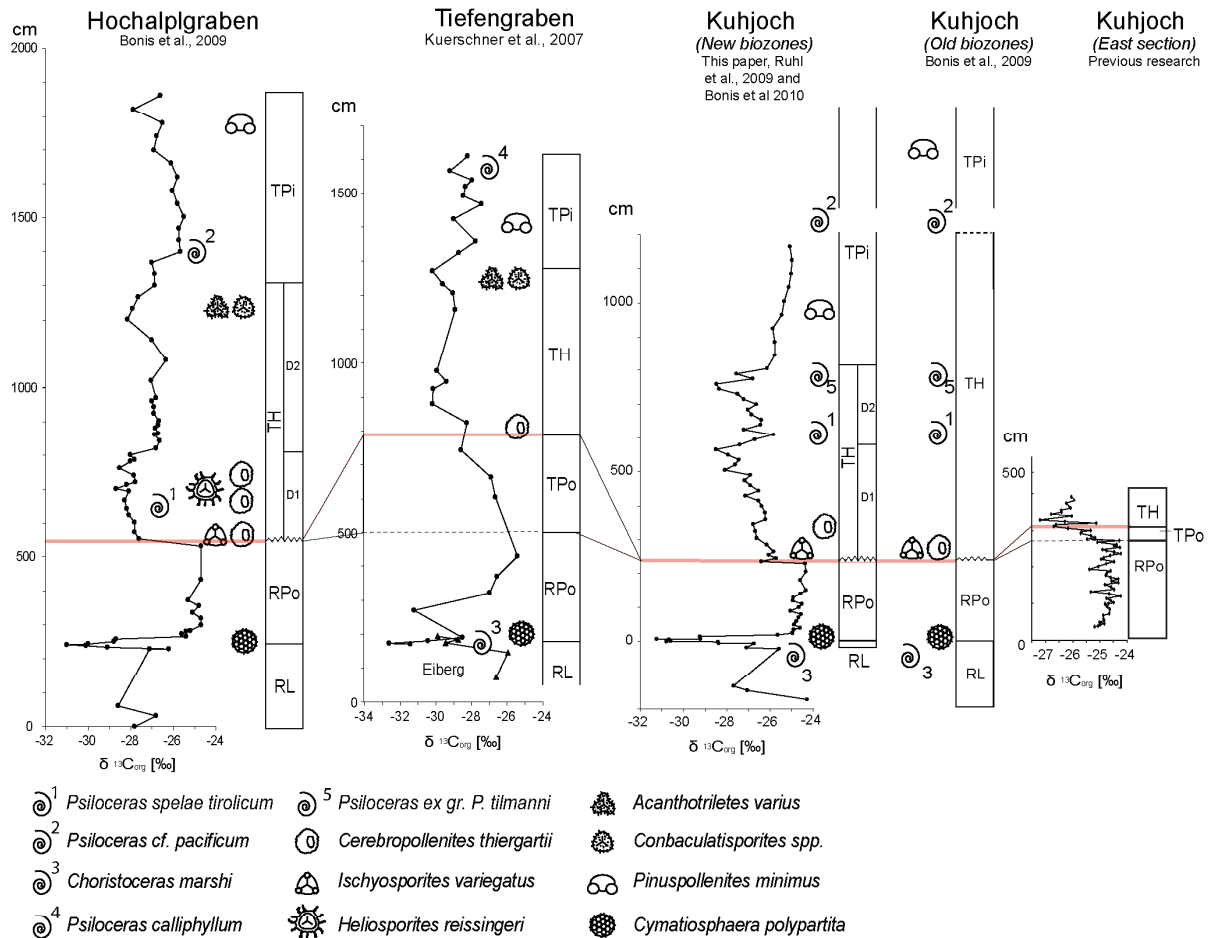
Figure 25. Correlation of Kuhjoch West, Kuhjoch East, Hochalplgraben and Tiefengraben sections based on C-isotope stratigraphy, palynomorph assemblage zones and bio-events, such as FO of ammonites and pollen/spore taxa, position of Cymatiosphaera acme, marked increase in abundance of pollen and spores (e.g. Heliosporites, Pinuspollenites). The pollen assemblage zones are based on Kürschner et al. (2007), Bonis et al. (2009) and Schobben et al. (to be submitted). Dotted lines are correlations based on C-isotope stratigraphy from Ruhl et al. (2009). RL = Rhaetipollis-Limbosporites zone, RPo = Rhaetipollis-Porcellispora zone, TPo = Trachysporites-Porcellispora zone, TH = Trachysporites-Heliosporites zone (with D1 and D2 as local subzones previously local pollen assemblages H3 and H4a in Hochalplgraben (Bonis et al., 2009)), TPi = Trachysporites-Pinuspollenites zone; Red line: base of TH zone.

samples previously studied for the C-isotope composition (Ruhl et al., 2009) and organic geochemistry (Ruhl et al., 2010, 2011). This allows a direct integration of the palynostratigraphy with the C-isotope stratigraphy. The microfloral record across the boundary is characterized by marked changes in the terrestrial palynomorph assemblages that correlate with those of the Tiefengraben section in the eastern part of the Eiberg Basin (Kürschner et al., 2007). Based on cluster analysis 4 pollen assemblage zones can be recognized in the Kuhjoch W section (Fig. 23):

(1) The lowermost interval (base of section = base of Kendlbach Formation to 28 cm height) is dominated by *Classopollis meyeriana* and *Classopollis torosus* accompanied by *Ovalipollis pseudoalatus*. *Rhaetipollis germanicus*, *Limbosporites lundbladii*, and *Cingulizonates rhaeticus* are present. This assemblage corresponds to the *Rhaetipollis - Limbosporites* zone (RL zone).

(2) The next interval (28 cm to 255 cm height) is mainly characterized by an abrupt decline in *C. meyeriana*, while *C. torosus* and *Vitreisporites bjuvensis* increase up to 20%. Furthermore the diversity and abundance within spores increase, typically *Polypodiisporites microforatus* (>20%), *Deltoidospora* spp.,

Concavisporites spp. and *Ricciisporites tuberculatus*. The top of this interval shows again an acme of *C. meyeriana* (>30%), while *Heliosporites* and *Trachysporites* enter the record. This assemblage correlates with the *Rhaetipollis - Porcellispora* zone (RPo zone).

(3) In the following interval (255 cm to 810 cm height), which can be further subdivided in two subzones, *C. meyeriana* remains an important constituent up to 20% but other pollen, such as *Vitreisporites bjuvensis*, *Ovalipollis pseudoalatus,* and *Rhaetipollis germanicus* that were common in previous zones are absent. Furthermore, *Cerebropollenites thiergartii,* and *Ischyosporites variegatus* have their FOD at the base of this zone. Moreover *Polypodiisporites microforatus* disappears, while *Heliosporites* and *Trachysporites* become dominant (30%). In the upper part of this interval *Trachysporites* dominates the sporomorph assemblages with abundances of more than 40% accompanied by *Ricciisporites* (20%). *C. meyeriana abundance* decreases to values around 10% and remains stable. This assemblage correlates with the *Trachysporites - Heliosporites* zone (TH zone).

(4) In the following interval (810 cm to 1600 cm height) the most notable feature is a marked increase in abundance of *Pinuspollenites*
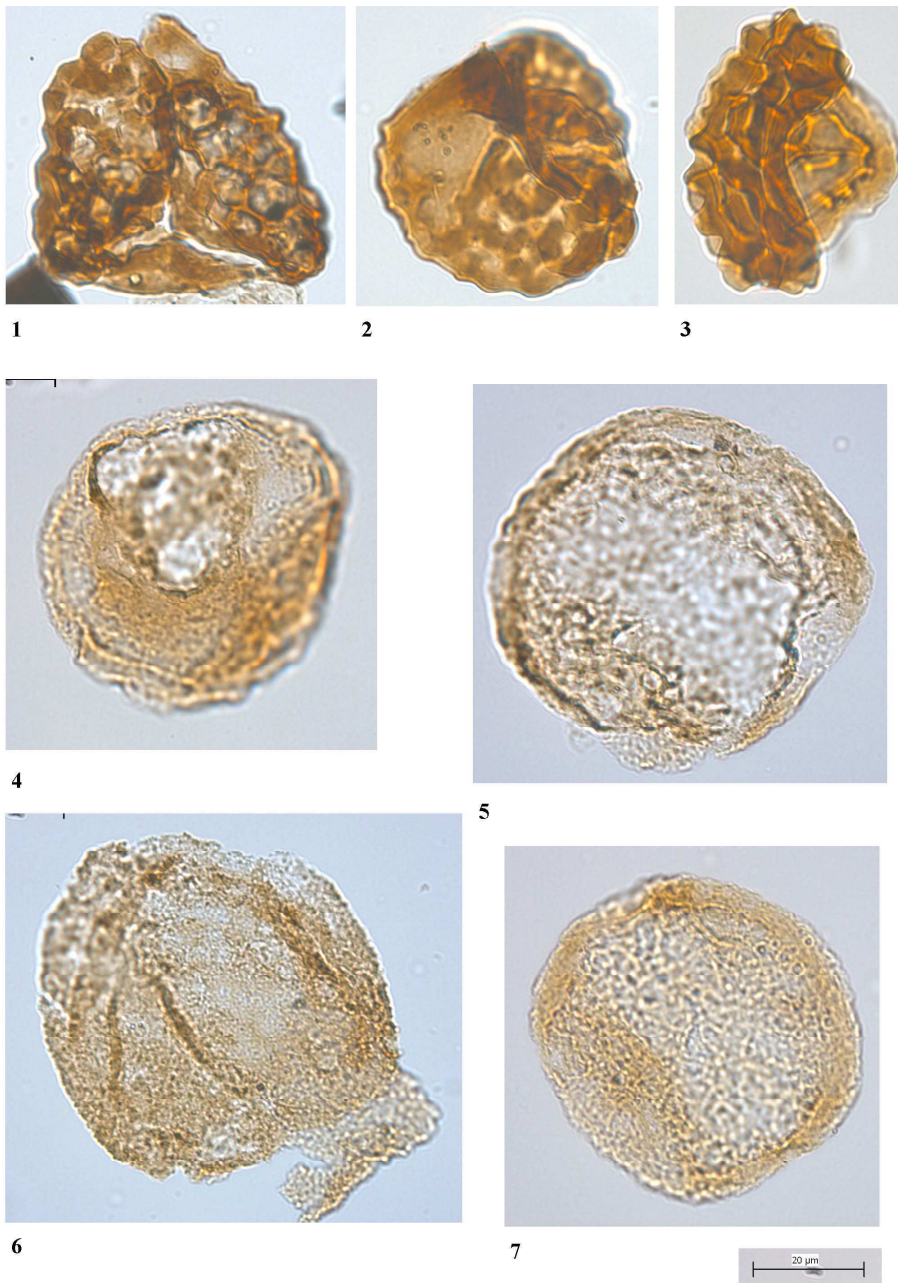
Figure 26. Light microscope illustrations of spores and pollen that mark the Triassic-Jurassic boundary interval (1-3) **Ischyosporites variegatus,** *(4-7)* **Cerebropollenites thiergartii** *.*

minimus and *Ricciisporites tuberculatus,* while *Trachysporites* remains dominant. This assemblage correlates with the *Trachysporites - Pinuspollenites* zone (TPi zone).

b) Kuhjoch East section (Figs. 24, 25)

The Kuhjoch-E palynomorph record consists of 17 samples, which were collected in 2008 from a trench (about 50-100 cm deep) ~20 meters to the east side of the original Kuhjoch-W section (Fig. 8). The sampled ~400 cm interval in the Kuhjoch-E section covered the Schattwald Beds and the transition to the succeeding gray Tiefengraben Mb. The lowermost 30-40 cm from the Tiefengraben Mb / Schattwald Beds in the Kuhjoch-E section, directly succeeding the carbonates from the Kössen Fm., was not sampled because of

tectonic disturbance. This tectonic disturbance most likely reflects the same tectonic fault as at the top of the Schattwald Beds at Kuhjoch-W, which cuts through the stratigraphy.

Significant changes in the terrestrial palynomorph assemblages occur within the Schattwald Beds. 3 different pollen assemblage zones have been distinguished by cluster analysis:

(1) The lowermost interval (base of section to 275 cm height) is characterized by diverse spore assemblages with high abundances of *Polypodiisporites polymicroforatus* (±40%) accompanied by *Deltoidospora* spp., *Concavisporites* spp., *Carnisporites* spp., *Limbosporites lundbladii* and others. The proportion of pollen is rather low consisting mainly of *Vitreisporites pallidus* and *V. bjuvensis*, accompanied by *Classopollis meyeriana*, *Ovalipollis pseudoalatus*, and *Platysaccus* sp. This assemblage correlates with the *Rhaetipollis - Porcellispora* zone (RPo zone), which is the second pollen assemblage zone in the Kuhjoch-W section.

(2) The following assemblage (275 cm to 310 cm height) is transitional between assemblages the RPo zone and the TH zone. It is characterized by a marked and steadily increasing abundance of pollen, particularly of *C. meyeriana*, while *V. pallidus* and *V. bjuvensis* decline. Also spores, which were dominant in the previous assemblage, such as *P. polymicroforatus* and *Deltoidospora* spp. decline significantly, while *Conbaculatisporites* spp. has a brief acme within this interval. *Trachysporites fuscus* shows a slight increase. Some palynomorphs that are characteristic guide forms of the Rhaetian, such as *O. pseudoalatus, Lunatisporites rhaeticus,* and *L. lundbladii* have their last occurrence. This assemblage correlates with the *Trachysporites – Porcellispora* zone (TPo zone) of the Tiefengraben section (Kürschner et al., 2007), which is absent in the Kuhjoch-W section (see further discussion below).

(3) The following interval (310 cm to 390 cm) is characterized by an acme of *C. meyeriana* (±80%), which is followed by a decline down to ±40-60% for the remaining part of this interval. Spores, particularly *T. fuscus* and *Heliosporites reissingeri* show a marked increase. At the base of this assemblage, *Cerebropollenites thiergartii* has its first occurrence. This assemblage correlates with the *Trachysporites - Heliosporites* zone (TH zone).

The RPo zone of the Tiefenbach could be recognized in the Kuhjoch W and E sections as well as in the Hochalplgraben section (Bonis et al., 2009) because of high diversity of spores with the dominance of *P. polymicroforatus*, the moderate abundance of *V. pallidus / V. bjuvensis* and the low abundance of *C. meyeriana*.

The second pollen assemblage zone at Kuhjoch E shows distinctly gradual changes in the abundance of the pollen and spores, such as

an increase in *C. meyeriana*, a decrease in *V. pallidus*, *V. bjuvensis,* and *P. polymicroforatus* and a brief acme of *Conbaculatisporites*. This assemblage correlates with the TPo assemblage zone in the Tiefengraben section (Kürschner et al., 2007) because of the decrease in *P. polymicroforatus* and *Deltoidospora,* while *Concavisporites* and *Trachysporites* increases. Note that the increase in *Trachysporites* precedes the increase in *Heliosporites*. The latter characterizes the base of the following TH zone in Tiefengraben (Kürschner et al., 2007).

By contrast, in the Kuhjoch W outcrop and the Hochalplgraben the transition from the assemblages from the RPo to the TH zone is characterized by an abrupt increase (acme) in *C. meyeriana* and the disappearance of *V. pallidus*, *V. bjuvensis,* and *P. polymicroforatus*, while the acme of *Conbaculatisporites* is lacking.

This transitional pollen zone is not present at Hochalplgraben and Kuhjoch W because of a minor hiatus caused by a fault. In the Kuhjoch E outcrop this interval is undisturbed and characterized by a gradual decrease in C-isotope values from -25‰ to -27‰, which is similar in magnitude as the abrupt shift at the top of the Schattwald Beds in Hochalplgraben and Kuhjoch West (Fig. 2). Therefore C- isotopes and palynological results independently indicate the presence of a small hiatus at the top of the Schattwald Beds in these two sections and a continuous sedimentary record at Kuhjoch East. The following TH zone can be recognized in all 3 sections (Kuhjoch East, Kuhjoch West and Hochalplgraben) because the dominance of *C. meyeriana* (and the acme at the base of this interval) accompanied by high abundances of spores such as *Heliosporites* and *Trachysporites*.

The fine resolution palynological analysis of the 2 Kuhjoch sections, the nearby Hochalpgraben section and the Tiefengraben section in the eastern part of the Eiberg basin and the Restental section (Mazumder, 2013) show that the pollen assemblage zonation supposed by Kürschner (2007) can be applied for regional correlation throughtout the NCA. However, further studies have to show if similar fine resolution correlations can be established within the Tethys realm. As the succession of the pollen assemblage zones reflects vegetation changes to regional climate changes we expect more complex vegetation patterns on a larger lateral scale (see also Bonis & Kürschner, 2012). This will limit the use for direct one to one correlations on extra-regional long-distances.

c) Correlation within the Eiberg Basin (Fig. 25)

The new high-resolution study of the Kuhjoch sections shows that palynomorph assemblages from this section correlate one to one with those reported from the Hochalplgraben section and the Tiefengraben section. Several bio-events can be recognized in all three sections across the T-J boundary interval (Fig. 24). These include the LO of typical Triassic palynomorphs such as *Lunatisporites rhaeticus*, *Ovalipollis pseudoalatus,* and *Rhaetipollis germanicus*, *Triancoraesporites* spp. in the Schattwald Beds of the Kendlbach Formation clearly above (ca. 2 m) the LO of *Choristoceras marshi*. Bio-events above the Schattwald Beds are the FO of *Cerebropollenites thiergartii* and *Ischyosporites variegatus*, a marked increase in *Heliosporites reissingeri* and *Trachysporites fuscus* (ca. 3 m below the FO of *P. spelae*) and the occurrence of *Pinuspollenites minimus* higher up in the section. The TPo zone, however, is lacking in the Kuhjoch West and Hochalplgraben, due to a minor tectonic fault coinciding with an abrupt shift in the C-isotope records. Our new

palynological and C-isotope data show that the TPo zone is clearly present in the Kuhjoch East section, showing the undisturbed nature of the upper part of the Schattwald Beds.

Radiometric Geochronology

No radiometric data of the T-J boundary are known from the Northern Calcareous Alps or elsewhere in Europe contrary to South and North America from where many radiometric age determinations were published in the last two decades. The CAMP volcanic rocks provided many data and also volcanic ashes intercalated to marine sediments. Palfy et al. (2000) dated in Canada (Queen Charlotte Islands) a tuff layer in marine sediments with an age of 199.6±0.3 Ma. This tuff is found immediately below the change of radiolarian faunas near to the T-J boundary. Schoene et al. (2010) and Guex et al. (2012) dated in Peru tuff layers of the latest Rhaetian with an age of 201.40±0.18 and 201.45±0.14 Ma. Earliest Hettangian (*Psiloceras spelae* horizon) (Guex et al., 2012) samples between two tuff layers were dated with an age of 201.35±0.10 and 201.26±0.13 Ma. The distances between the samples differ between the two publications. Schoene et al. (2010) determined also an earliest Hettangian tuff bed ca. 1.5 m above the *Psiloceras spelae* horizon of the New York Canyon section (Nevada, USA) with an age of 201.33±0.13 Ma. The same author dated the lowest part of the CAMP North Mountain basalt (Nova Scotia, Canada) with an age of 201.38±0.02 Ma. Marzoli et al. (2011, fig. 2) presented a correlation of different North American CAMP basins and the High Atlas (Morocco) based on radiometric ages of superimposed volcanites. The lowest basalts were dated with 200.9±0.8 Ma (Lower Basalt, Morocco) and 201.6±1.2 (North Mt. Basalt of the Fundy Basin, Canada).The averaged age of the T-J boundary can be estimated at around 201.3 Ma.The latest radiometric data of CAMP volcanic rocks were published by Blackburn et al. (2013). The Palisade sill of the Orange Mountain Basalt (oldest volcanite of the Newark Basin, USA) was dated with an age of 201.520±0.034 Ma, the North Mountain Basalt (oldest volcanite of the Fundy Basin, Canada) with an age of 201.566±0.031 Ma and the Amelal sill (Intermediate Unit) of the Argana Basin (Morocco) with an age of 201.564±0.054 Ma.

Correlations

1. Regional

Ammonite level (2) – the boundary level – is presently known from six sections, level (4) from four sections, and levels (3a, b) from two sections in the western Karwendel syncline over a lateral distance of nearly 10 kilometers. Ammonite levels (5) to (7) are known from many sections of the western Karwendel Syncline (Hillebrandt and Kment, 2011). These levels are also found in different sections of its northern flank (Kment, 2000). The bivalve fauna and the negative isotope excursion of the Kuhjoch section in the boundary bed(s) from the Eiberg to the Tiefengraben Member can be observed in many other sections and provide a first order correlation level within the Eiberg Basin; the same applies for ammonite levels (1) and (5).

Ammonite levels (1) to (3) and (5) to (7) are present also in the Zlambach Basin. In this region small specimens of *Psiloceras spelae tirolicum* (2) were found together with a small *Phylloceras* similar to the specimen found in the *spelae* horizon of Kuhjoch. A second ammonite bed, some meters higher up, yielded large sized

Schistophylloceras and small sized *Psiloceras* cf. *tilmanni* (3). Vertical changes within the microfaunas allow further fine-tuned correlations within the Tiefengraben Member throughout the Eiberg Basin and also the Allgäu and Zlambach basins.

Many sections of the western Eiberg Basin show a lithological and faunal record of the T-J boundary interval comparable to that of the GSSP. Some of the more important sections are the **Schlossgraben** (47°28'30"/11°29'0"), with a flat-lying and exceptionally good exposure of the top Kössen and basal Kendlbach Formation, which has been also – but without success – studied for magnetostratigraphy. The **Hochalplgraben** (47°28'20"/11°24'42") (Fig. 2) shows the presently best-preserved psiloceratids of the ammonite levels (2) and (4) (Hillebrandt and Krystyn, 2009; Hillebrandt and Kment, 2011, fig. 4) and the most promising nannofossil record. The Hochalplgraben section is the type locality of *Psiloceras spelae tirolicum*. Level (2) also was found in the steep trench (**Rohnberggraben***)* between Rohnberg (east of Hochalplgraben) and Hinterriß. The **Rissbach** (47°28'26"/11°28'6") section (Fig. 2) opposite to Hinterriß contains the ammonite levels (2), (4), (5a, with a limestone bed at the boundary of the Tiefengraben und Breitenberg Member containing *P.* cf. *planorbis* and a new species of *Psiloceras,* Fig. 22) and (5).

Within the northern flank of the Karwendel Syncline, three localities (**Pletzboden***,* **Tölzer Hütte** and **Sattelgraben**; Fig. 2) were studied or are under study, with sections of the uppermost Eiberg, Tiefengraben, and Breitenberg members. Macro- and microfaunas are very similar to those of the southern flank. A fragment of *P. spelae* was found at the outcrop south of Tölzer Hütte.

In the eastern Eiberg Basin the **Eiberg quarry** (47°33'/12°10') exhibits an excellent outcrop from the Tiefengraben Member down to a complete Eiberg Member that is topped by a rather shaly, thinly laminated and pyrite-bearing 25 cm thick T-Bed with *Choristoceras marshi* and rich in fish scales and small bivalves. Microfaunas of the Tiefengraben Member are very similar to those of the Karwendel Syncline but part of the Schattwald Beds and the lower part of the Tiefengraben Member are missing by tectonics. The **Möserer Alm/ Steinplatte** section (47°38'20"/12°35'0") has a more calcareous T-Bed up to 30 cm thick, containing common bivalves and, in the top black bituminous centimeter, *Choristoceras marshi* and *Rhaetites* cf. *gigantogaleatus*. There is unfortunately no continuation upwards to the Tiefengraben Member.

The **Kendlbach** (47°41'15"/13°21'30") section provided up to now, together with the nearby *Tiefengraben*, the most complete macro- and micropalaeontological as well as palynological and geochemical data sets for the Northern Calcareous Alps, thanks to the detailed studies of Golebiowski and Braunstein (1988), Hallam (1990), Krystyn et al. (2005), and Kürschner et al. (2007). This easternmost and marginal section of the Eiberg Basin differs in the absence (respectively reduction to the 1 cm bituminous top layer) of the Kössen T-Bed due to non-deposition or erosion, in a comparatively reduced Tiefengraben Member (13 m) with common limestone intercalations but without ammonites, and in replacement of the reddish Schattwald Beds by black clays.

2. Northwestern Europe (Fig. 27)

St. Audrie's Bay, Somerset, England was proposed by Warrington et al. (1994) as GSSP for the base of the Hettangian and bed 13 (thought to represent the FO of the genus *Psiloceras* – at that time *P. planorbis*) defined as stratotype point (Hounslow et al., 2004). Later

results (Bloos and Page, 2000) demonstrated, however, that the oldest psiloceratid of Northwestern Europe (Great Britain) is *Psiloceras erugatum* with the FO in bed 8 at Doniford Bay (near St. Audrie's Bay) followed closely above by *Psiloceras planorbis* in the upper part of bed 9. Though *P. erugatum* has inner whorls with nodes ("Knötchenstadium") like most *Psiloceras* specimens of the NCA, it was not yet found there and therefore it cannot be integrated into the Alpine *Psiloceras* succession. Considering the more or less pronounced ribbing of the inner whorls and the occurrence closely below *Neophyllites* in Northwestern Europe, *P. erugatum* should be younger than *Psiloceras* cf. *pacificum* from the Karwendel and older than the psiloceratids from the Calliphyllum Zone with *Neophyllites* as oldest ammonite (Bloos, 2004).

The Kuhjoch and Karwendel ammonites of the Tiefengraben Member (*P. spelae* to *P.* cf. *pacificum*) are not known from the barren lower "pre-Planorbis Beds" of England. The carbon isotopic signal is an additional correlation tool (Kürschner et al., 2007). The boundary should be expected to occur in the lowest few meters of the Blue Lias Formation (Fig. 27).

The similarity of the Hettangian microfauna (mostly ostracods and in part foraminifers, mainly nodosariids - polymorphinids) between the NCA and Northwestern Europe is not very helpful as long as in the latter the stratigraphically more important aragonitic Robertinina are not well documented. An exact correlation with the help of C-isotopes seems to be difficult.

The boundary definition at Kuhjoch was chosen because it enables a correlation between the marine and the terrestrial realm. The T-J boundary marks a significant biotic event in both realms. Palynological markers for the base of the Jurassic potentially enable correlation between terrestrial and marine sedimentary records and recognition of the T-J boundary in the continental realm. However, definition of terrestrial palynomorph markers for the base of the Jurassic in the studied marine sedimentary records is not straightforward. No major microfloral break has been found to be precisely contemporaneous with the T-J definition. A few notable LO and FO bio-events have, however, been found to characterize the T-J boundary interval, besides quantitative changes in the terrestrial pollen assemblages. These first and latest occurrences can be used for the correlation outside the Alpine realm. Typical Triassic palynomorph assemblages (e.g. *Lunatisporites rhaeticus*, *Ovalipollis pseudoalatus* and *Rhaetipollis germanicus*, *Triancoraesporites* spp.) are still present in the Kössen Formation and the Schattwald Beds. The records of these taxa show that they disappear at the top of the RPo zone. In St. Audrie's Bay (UK), the LO of these taxa is at the top of the Cotham Mb. of the Lilstock Fm. although they do not disappear exactly synchronously at this level (Warrington et al., 1994; Hounslow et al., 2004; Warrington, 2005; Bonis et al., 2010b).

There is no major palynofloral turnover that correlates precisely with the level of the T-J boundary as defined by the first occurrence of the ammonite *Ps. spelae tirolicum*. The only post-Triassic miospores with FO close to the base of the Jurassic, but 2 m below the entry level of *Ps. spelae tirolicum*, are *Cerebropollenites thiergartii* and *Ischyosporites variegatus* (see also discussion in Kürschner and Herngreen, 2010; Cirilli, 2010). *C. thiergartii* occurs within the turn to more negative $\delta^{13}C$ values in the lower part of the main carbon-isotope excursion, well above the extinction level of Triassic biota but significantly below the lowest occurrence of the first Jurassic ammonite. Bonis et al. (2010b) reported *C. thiergartii* and *I. variegatus* about 4 m above the base of the Blue Lias Fm. in St. Audrie's Bay.
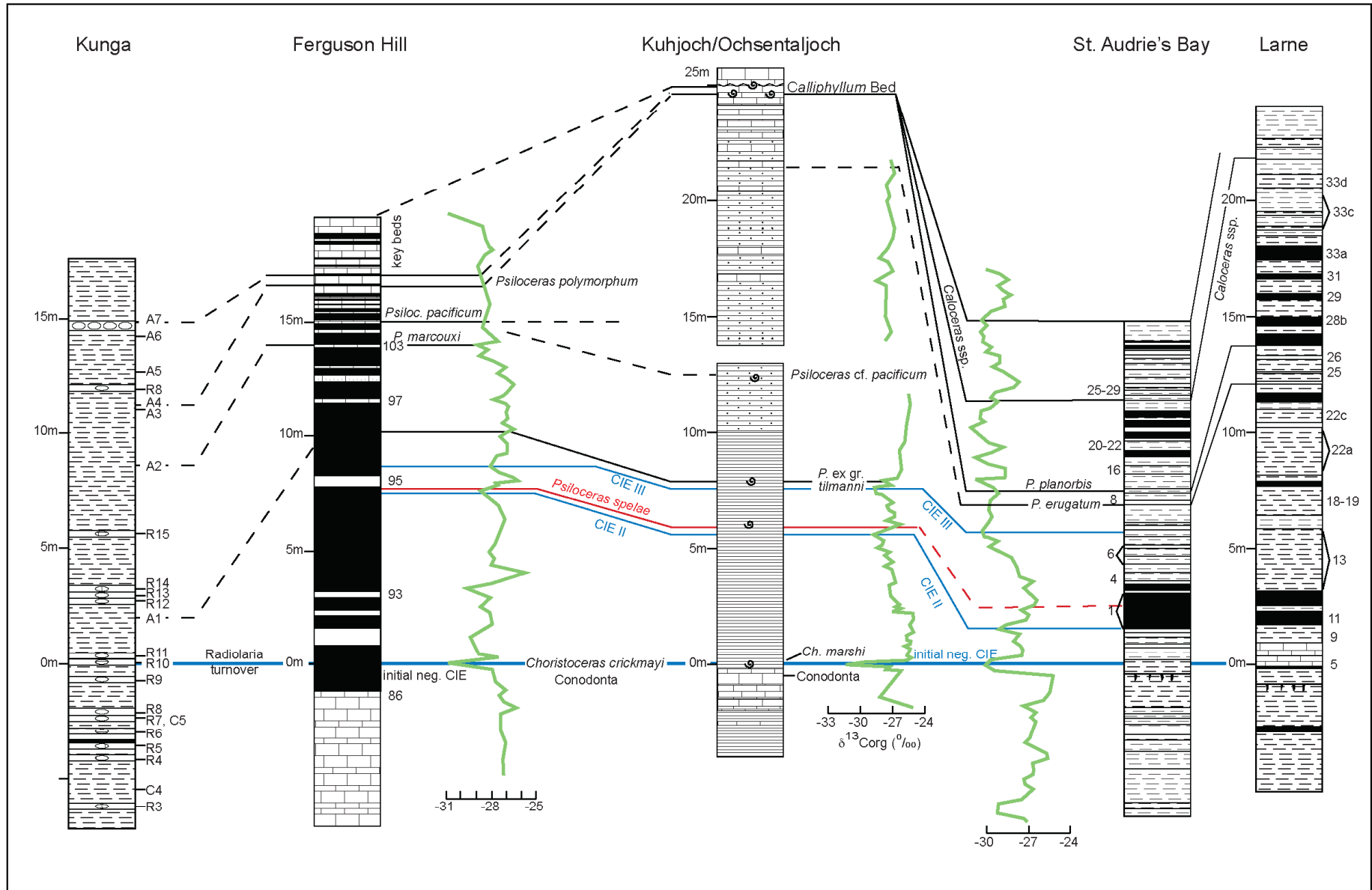
Figure 27. Correlation of GSSP Kuhjoch with the other sections proposed for the T-J boundary and correlation of $\delta^{13}C_{org}$ curve (equal vertical scale).

Fisher and Dunay (1981) reported *C. thiergartii* in the Watchet area at the top of Richardson's (1911) Paper Shale in the lower part of the Blue Lias. Moreover, *C. thiergartii* has been reported from lowermost Liassic sediments in the Germanic Triassic Basin in the Mariental core 1 (van de Schootbrugge et al., 2009; Heunisch et al., 2010) and in the Kamien Pomorski core in Poland (Pienkowsky et al., 2012), in high latitudes, Greenland (Pederson and Lund, 1980; Mander et al., 2010, 2013) and Sverdrup Basin (Suneby and Hills, 1988) and in the central Tethys realm, the Alborz Mountains in Iran (Achilles et al., 1984).

However, in the eastern North America basins there is presently no palynological event known that correlates with the T-J boundary. The prominent palynofloral turnover, which marks the base of the *Classopollis* pollen assemblage zone, appears to be of latest Rhaetian age (e.g. Whiteside et al., 2010 and further discussion below). For the southern hemisphere palynostratigraphic subdivisions of the Late Triassic and T-J transition have been documented in a number of palynological studies in Australia (e.g. Dolby and Balme, 1976; Helby et al., 1987; Brenner, 1992; Backhouse and Balme, 2002; Grice et al., 2005). In this region, Hettangian pollen assemblages are dominated by *Classopollis*. But a correlation of the base of this *Classopollis torosus* zone with the T-J boundary level as defined by the FAD of *Ps. spelae* is not well constrained. By contrast, in New Zealand an acme of *Classopollis* is not present but the lowermost Jurassic pollen zone, the Hettangian *Retritriletes austroclavatidites* zone is mainly dominated by spores (De Jersey and Rain, 1990). Also in this region the exact correlation of the base of this pollen zone with the T-J ammonoid biochronology is yet not well constrained (De Jersey and Rain, 1990). However, several palynological studies (e.g, Foster et al., 1994; Buratti and Cirilli, 2007) showed that Late Triassic microfloral assemblages alongside the western Tethys margin show some characteristic similarities with the microfloral assemblages in the NW-Australia described as the Onslow microflora by Dolby and Balme (1976). Therefore it may be possible to establish supra-regional palynostratigraphic correlations across the T-J transition but further detailed fine resolution studies are needed.

3. Central Atlantic Magmatic Province (CAMP) and T-J boundary

During the past years, evidence has been collected supporting the idea that the end-Triassic biotic crisis is linked with the environmental changes associated with a major volcanic event, the Central Atlantic Magmatic Province (e.g. Blackburn et al., 2013, Bonis and Kürschner, 2012; Deenen et al., 2011; Marzoli et al, 2004, 2006, 2008, 2011; Ruhl et al., 2011; Whiteside et al., 2007, 2008, 2010). Radiometric dating of both events resulted in corresponding ages. The CAMP is an extensive and relatively short magmatic event. In particular the Newark Basin and other basins of northeastern North America and basins of Northwestern Morocco provided many data and were studied in detail. Correlations between the different CAMP basins and marine basins were made, which differ in part (Deenen et al., 2011; Marzoli et al., 2008, 2011; Whiteside et al., 2007, 2008, 2010). Deenen et al. (2010, 2011) elaborated a detailed Trans-Atlantic CAMP correlation using cyclostratigraphy, palaeomagnetism, basalt geochemistry, and carbon isotope chemistry. Besides a correlation between the terrestrial and marine (United Kingdom) realm, a chronostratigraphic time frame for the end-Triassic extinction was provided. Deenen et al. (2011) concluded that the onset of CAMP

started earlier (20 ka) in Morocco as found in the North American Newark Basin and the initial $\delta^{13}C_{org}$ shift (extinction level) (= ICIE) can be traced from the marine to the terrestrial realm and is found in the topmost sediments below the base of the oldest Moroccan basalt. The T-J boundary is located by Deenen et al. (2011) 120 ka above the initial isotope shift. The main period of CAMP magmatism is suggested to extend over ~1.5 Ma (Nomade et al., 2007). A longer duration for volcanism is affirmed by Verati et al. (2007) for Morocco as compared for North America. Blackburn et al. (2013) presented new geochronologic data on the age and duration of the T-J volcanism within CAMP. Seven sites in eastern North America and one in Morocco were investigated. The chronology proved the synchroneity between the earliest volcanism and terrestrial extinction. The release of magma occurred in four pulses over about 600 ka. The astrochronologic time scale is said to be proved. The oldest CAMP volcanites are said to be found in Morocco. The terrestrial end-Triassic extinction is dated with 201.564 ka. An exact radiometric date seems to be realistic to within 100 ka. An exact biostratigraphic correlation between terrestrial and marine realms up to now is not possible (Blackburn et al, 2013).

a) Eastern North America

The Newark Supergroup is developed in several rift basins along the eastern coast of the United States, which were formed in Late Triassic and Early Jurassic times when the Atlantic began to open. The Newark Supergroup consists of fluvial sediments with lacustrine and volcanic intercalations. Basalts of the Central Atlantic Magmatic Province (CAMP) start in the topmost Triassic or lowermost Jurassic, depending on presumed correlations (Schoene et al., 2010).

The Newark Supergroup is extremely thick (up to 6 kilometers). Although dinosaur footprints are common, body fossils of terrestrial vertebrates are rare. In lacustrine sediments, fossil fishes are sometimes frequent. Palynomorphs and conchostracans were used as biostratigraphic tools. Until a few years ago, the T-J boundary was drawn immediately below the first basalt flow with the beginning of the palynofloral *C. meyeriana* zone (Cornet, 1977). Recently, the integration of new cyclostratigraphic, palaeomagnetic, geochemical and palynological evidence has been used to constrain the position of the T-J boundary in the Newark Basin (Lucas et al., 2007; Deenen et al., 2010; Ruhl et al., 2010b). The new data indicate that the T-J boundary is positioned between the Orange Mt./Talcott and the Preakness/Holyoke basalts in the continental Newark and Hartford basins. These findings are in agreement with biostratigraphic data based on conchostracans, which are said to fix the T-J boundary at the base of the *Bulbilimnadia sheni* zone, which lies within the Newark extrusive zone (Kozur and Weems 2005, 2010) and palynological data from the Fundy Basin (Cirilli et al., 2009). Investigations on radioisotopes from a basal basalt yielded an age of 201.27±0.06 Ma (Schoene et al., 2006) and more recently of 200.1±0.9 Ma (Jourdan et al., 2009). New radiometric data of the Newark and Culpeper basins were presented by Marzoli et al. (2011, fig. 2). The Orange Mt. basalt (lowest volcanite of the Newark Basin) was dated with a radioisotopic age of 201.6±1.4.Ma and an intruded sill of this basalt was dated by Blackburn et al. (2013) with an age of 201.52 ±0,034 Ma. Cirilli et al. (2009, fig. 2) correlated the different basins of eastern North America. A correlation of the Newark Basin and marine T-J sections was also provided by Whiteside et al. (2010).

b) Morocco

The CAMP volcanics of the Argana Valley and the Central High Atlas of Morocco are underlain by a thick continental clastic succession of cyclical playa sediments where red beds predominate. In the upper part (described in detail by Hofmann et al., 2000) the cycles commonly comprise ephemeral lakes or dry playa mudflat deposits, saline mudflat mudstones, overlain by sheet flows and aeolian sandstones. Four basaltic units are distinguished: The end Triassic extinction and and the first basaltic lava flow are said to be isochronic according to Blackburn et al. (2013). The third lava flow was dated with 201.564 ±0.054 Ma.

Palynomorphs immediately below the lower basalt were dated by Cirilli et al. (2009) as probably Jurassic and the T-J boundary was drawn with question mark at this level. Deenen et al. (2010) also studied the palynomorphs of the Argana Basin and came to the result that due to the very low number and poor preservation of the palynomorphs they are of limited use for correlation purposes. Hofmann et al. (2000, fig. 7) indicate conchostracans, which perhaps may be of use for a correlation with North America (Kozur and Weems, 2005, 2010).

4. Western Americas (Figs. 22, 27)

a) North America

T-J boundary sections with the most complete ammonite record were described from the New York Canyon (Nevada, USA) (Guex, 1995; Guex et al., 1997, 1998, 2002, 2003; Lucas and Tanner, 2007). The sections were proposed in various ways as T-J boundary GSSP (initial negative isotope excursion: McRoberts et al., 2007 or the FO of *Psiloceras*: Guex et al., 1998, 2009).

The proposed GSSP horizon of Guex et al. (1998) with the FO of *Psiloceras spelae spelae* as boundary event can be correlated with ammonite level (2) of the Karwendel syncline. Ammonite levels (3a and b) of Kuhjoch and especially Ochsentaljoch probably have no counterpart in Nevada. The beds with *Choristoceras minutum, Odoghertyceras deweveri, Psiloceras marcouxi*, *P. tilmanni* and cf. *Neophyllites* 7.2 m above *P. spelae* may be correlated with ammonite level (4), 6 m above *P. spelae tirolicum* at Kuhjoch but choristoceratids and psiloceratids similar to *Psiloceras marcouxi* do not occur in the Hettangian of Europe, and the determination of the *Neophyllites* (without suture line and whorl section not preserved) is doubtful. Ammonite level (4a) of the Hochalplgraben section probably lies in the range of the beds with *Psiloceras pacificum* in Nevada. The pelecypod *Agerchlamys* occurs slightly earlier than *Psiloceras spelae* mirroring the situation in the NCA. Hettangian microfossils of biostratigraphic value were not yet found in the Nevada sections.

The section underwent contact metamorphism and it is not clear how much the $\delta^{13}C_{org}$ curve may have been affected and/or changed.

Carter and Tipper (1999) proposed another candidate GSSP for the T-J boundary in a section at Kunga Island (Queen Charlotte Islands, Canada) where the base of the Jurassic was defined by the first occurrence of Hettangian radiolarians of the *Canoptum merum z*one (Carter and Hori, 2005). Any exact correlation with other fossil groups (e.g. ammonites) is impossible over an interval from 15 m below to about 6 m above the proposed boundary level. A concomitant and pronounced negative $\delta^{13}C_{org}$ anomaly is used as correlation tool to other sections (Ward et al., 2007.

b. South America (Fig. 22)

The Chilingote section in the Utcubamba valley of Northern Peru was proposed as GSSP candidate for the T-J boundary (Hillebrandt, 1997; the proposal was withdrawn 2006). At Chilingote, the first Hettangian ammonite bed is characterized by a species of *Psiloceras,* which is distinguished from *Psiloceras tilmanni* by a steeper umbilical wall. In this bed, *Odoghertyceras* also occurs. Below this bed, radiolarians transitional to basal Hettangian forms occur with just a few Rhaetian holdovers. Probably the radiolarian turnover is older than the ammonite turnover (Lucas et al., 2005). Above follow several beds with *Psiloceras tilmanni* s.str.

There are other complete T-J boundary sections in the Utcubamba valley (Hillebrandt, 2000a) but ammonites are mostly compressed and not yet studied in detail. Recently (Schaltegger et al., 2008) discovered *Psiloceras* cf. *spelae* near a section described by Hillebrandt (1994, 2000a). *Psiloceras* cf. *spelae* (unfortunately compressed) was found above *Choristoceras crickmayi* and 10 m below *Psiloceras tilmanni.* The Utcubamba valley eventually could provide a correlation of ammonite and radiolarian biostratigraphy within the boundary interval. Schaltegger et al. (2008), Schoene et al. (2010), and Guex et al. (2012) dated several ash beds in this section and state an age for the base of the Jurassic between 201.35±0.10 and 201.26±0.13 Ma.

Other T-J boundary sections are found in northern Chile (Hillebrandt, 2000a) but earliest Hettangian ammonites are missing. The oldest ammonite level (Primocostatum Zone in Hillebrandt, 2000b) can be correlated with a part of the *Psiloceras polymorphum* Zone in Nevada and the Planorbis and Calliphyllum zones in Europe (Fig. 22).

5. Tibet

Yin et al. (2007) described from southern Tibet (Germig) two sections rich in megafossils. Ammonite beds allow a detailed biostratigraphic subdivision in Late Triassic (Rhaetian) and Early Jurassic (Hettangian) ammonite zones and subzones. Two nearby sections (A and B) were measured and correlated. The Late Rhaetian Marshi Zone was proved with different species of *Choristoceras* and *Eopsiloceras* (level B1). Above this zone was distinguished a zone named Tibeticum Zone and said to be of earlied Hettangian age. Level B2 (section B) is located some meters above level B1 and contains a new species of *Choristocers* (*C. nyalamense*) and a small specimen determined as *Neophyllites* sp.indet..This specimen has a corroded suture line and also could be a *Psiloceras.* In the authors (A.v.H.) opinion level B2 with *C. nyalamense* belongs to the Late Rhaetian Marshi Zone. Level A1 (section A) of this zone is characterized by the new species *Psiloceras tibeticum, Rhacophyllites* and a specimen determined as *Eopsiloceras.* This specimen is a latex cast without suture line and difficult to determine, even on generic level. *P. tibeticum* belongs to the *P. calliphyllum* group with deeply indentated and retracted suture lines. The Tibetian level A1 is the first ammonite horizon of Jurassic age but *P. tibeticum* does not belong to the oldest *Psiloceras* like *P. spelae* or the *P. tilmanni* group. One meter above level A1 was found level A2 with *Neophyllites* cf. *biptychus*, a genus found in NW Europe below *P. planorbis*. Levels with *P. calliphyllum* occur in Germig at both sections. This species characterizes the *Calliphyllum* bed of the NCA and lies at the GSSP 18 m above the T-J boundary. At Germig is missung the entire Tilmanni Zone.

Isotope and Cyclo-Stratigraphy (written by M. Ruhl and W.M. Kürschner)

The sedimentary sequence of the Rhaetian Kössen Fm. is marked by a distinct change from alternating limestone beds and marls to clays and marls. In the western Eiberg Basin the cyclicity of the Kössen Formation has been described in the Eiberg quarry based on palynological data but no frequency analysis was applied (Holstein, 2004). Cyclostratigraphic analysis of the T-J boundary interval has not been performed because long continuous outcrops suitable for quantitative cyclostratigraphic analysis have not yet been found in the Eiberg Basin. However, physical and chemical proxy records covering the uppermost Triassic and lowermost Jurassic marine successions of St. Audrie's Bay and East Quantoxhead (UK) have been used to establish a floating astronomical time-scale of about 2.5 Ma (Ruhl et al., 2010b). Based on these findings, the extinction interval coinciding with the initial negative C-isotope excursion represents 1-2 precession cycles (about 20-40 ka), while the recovery interval preceeding the first Jurassic ammonite is confined to 6 precession cycles (about 120 ka). These findings are in agreement (within the analytical error) with radiometric age assessments of ash beds in T-J boundary sections in Peru and N-America (Schoene et al., 2010).

Several studies (Kürschner et al., 2007; Bonis et al., 2009; Ruhl et al., 2009) have confirmed the use of C-isotope stratigraphy for high-resolution correlation of T-J boundary sections within the Eiberg Basin. The interval of the end-Triassic mass extinction is characterized by a distinct negative C-isotope excursion, which is also referred to the initial negative carbon isotope excursion. Correlation of the C-isotope record across the extinction interval in marine records of the Eiberg Basin to St. Audrie's Bay (UK) (Kürschner et al., 2007; Ruhl et al., 2009; Ruhl and Kürschner, 2011) and outside Europe (Guex et al., 2004; Ward et al., 2007) is relatively straightforward. The base of the Hettangian, as defined by the FO of *Ps. spelae tirolicum*, coincides with a second, longer lasting 'main' negative C-isotope excursion, which can be used as an independent correlation tool.

Palaeobiogeography

Around the T-J boundary, the NCA underwent a distinct change in their palaeobiogeographic relations from a typical Tethyan to an intermediate position between Tethys and Northwestern Europe. The NCA (including the Eiberg Basin) were then situated between the Euroboreal Realm of Northwestern Europe and the Tethyan Realm of the Mediterranean and were differentiated as an Austroalpine Province before the opening of the Ligurian-Penninic ocean and the separation of the Adriatic microplate (Blau, 1998). *Choristoceras* is a typical low palaeolatitude Tethyan-Panthalassian faunal element and the psiloceratids of the Tiefengraben Member must also have immigrated from the Tethyan Realm since they are not found in northwestern Europe. Only a direct faunal exchange between the western Tethys and the Panthalassa Ocean can explain the presence of the East Pacific ammonites (*Psiloceras spelae, Psiloceras* cf. *pacificum*) in the Alps. The first obvious ammonite links to the Euroboreal are younger and date to the time of the Calliphyllum Zone. The bivalve *Agerchlamys* is found in the Tethyan Realm and the East Pacific Province. Ostracods and foraminifers show relations to the Tethyan and the Euroboreal Realm. Calcareous nannoplankton is not suitable for biogeographic comparisons as it is unknown from the pre-Planorbis Beds of England as well as from coeval sediments of the eastern Tethyan Realm and the East Pacific Province.

Conclusions

The selected Global Stratotype Section and Point matches the requirements of ICS for a GSSP. The Kuhjoch section offers not only a well-exposed boundary section but also an outcrop with a continuous sequence of sediments of Late Triassic and Jurassic age, which is some hundreds of meters thick. The proposed T-J boundary section (~ 25 m thick) shows a high sedimentation rate with continuous sedimentation and no condensation in the proximity of the boundary level. The sedimentation rate is high enough to show well-separated short-lived successive events. Synsedimentary disturbances are missing and only minor tectonic overprint disrupts the sedimentary sequence. The fossils are very well preserved (aragonitic shells) and different groups of macro- and microfossils are found indicating a well-oxygenated, open marine environment. No vertical facies changes affect the boundary level. The boundary can be traced over 10 km parallel to the strike of the basin and some kilometers vertical to its axis. The primary boundary marker (*P. spelae*) has a low palaeolatitude global distribution and a short vertical range. Other fossil groups (bivalves, foraminifers, ostracods, dinoflagellates) allow correlation with marine sections where ammonites are lacking. Finally, terrestrial palynomorphs (FO of *Cerebropollenites thiergartii* and *Ischyosporites variegatus*) bridge the barrier to the non-marine realm. A well-differentiated $^{13}C_{org}$ curve with two pronounced excursions provides additional constraints for correlation with other T-J boundary sections.

Table 1: Summary of the requirements of the International Commission on Stratigraphy for the Kuhjoch Section as base of the Jurassic (T/J boundary) and candidate GSSP.

The requirements for a GSSP (ICS)	Kuhjoch Section (Western Karwendel, Tyrol, Austria)
GEOLOGICAL REQUIREMENTS	
Exposure over an adequate thickness	Yes
Continuous sedimentation. No gaps or condensation close to the boundary	Yes
Rate of sedimentation	At least 50 cm for *spelae* horizon and 10 m for Tilmanni Zone
Absence of synsedimentary and tectonic disturbances near boundary level	Yes
Absence of metamorphism and strong diagenetic alteration	Yes
BIOSTRATGRAPHIC REQUIREMENTS	
Abundance and diversity of well preserved fossils	Yes
Absence of vertical facies changes at or near the boundary	Yes
Favorable facies for long-range biostratigraphic correlations	Yes
OTHER METHODS	
Radio-isotopic dating	No information
Magnetostratigraphy	No result thus far
Chemostratigraphy	Yes ($\delta^{13}C_{org}$ and C_{org}) (further geochemical investigations planned)
Sequence stratigraphy	Yes
OTHER REQUIREMENTS	
GSSP indicated by a permanent fixed marker	Yes (at section Kuhjoch East)
Physical and logistical accessibility	Yes, driving permit from Österreichische Bundesforste
Free access for research	Yes
Permanent protection of the site	Yes, natural reserve (Karwendel Naturpark)

Acknowledgements

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