

A CANDIDATE GSSP FOR THE BASE OF THE JURASSIC IN THE NORTHERN CALCAREOUS ALPS (KUHJOCH SECTION; KARWENDEL MOUNTAINS, TYROL, AUSTRIA).

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Abstract

The Kuhjoch section near Hinterriss (Tyrol, Austria) is proposed as GSSP candidate for the base of the Hettangian Stage and, as such, the base of the Jurassic System. The exact level is 5,80 m above the top of the Koessen Formation and corresponds to the FO of the ammonite *Psiloceras spelae* GUÉX n. ssp. This taxon relates to the group of *Psiloceras tilmanni* that is considerably older than the earliest Northwest European psiloceratids (i.e. *Psiloceras erugatum*, *Psiloceras planorbis*) and enables intercontinental Tethys-Panthalassa correlation of the boundary. The ammonite event correlates to the FO of *Cerebropollenites thiergartii*, a widely distributed palynomorph and Early Jurassic marker in continental successions. Additional boundary events are the FO of the aragonitic foraminifer *Praegubkinella turgescens* and of the ostracod *Cytherelloidea buisensis* 60 cm below the proposed stratotype point and the disappearance of the ostracod *Eucytherura sagitta* immediately above the point. The $\delta^{13}\text{C}_{\text{org}}$ record shows an initial negative excursion near the boundary between the Koessen and Kendlbach formations. The Triassic/Jurassic bioevent lies above this peak. The proposed stratotype point coincides with a shift to more positive $\delta^{13}\text{C}_{\text{org}}$. The well-exposed section

displays a high and continuous sedimentation rate - the highest of all proposed GSSP candidates - with a constant facies trend across the boundary level. It contains well preserved and frequent fossils and meets all requirements necessary for a Global Stratotype Section and Point selection.

INTRODUCTION

Sedimentary successions across the Triassic/Jurassic boundary which are expanded and highly fossiliferous in the Northern Calcareous Alps are restricted to the so-called Eiberg Basin, a Rhaetian intraplatform depression, that can be traced over 200 km from the Salzkammergut (Kendlbachgraben, Upper Austria) in the east to the Lahnewiesgraben valley (northwest of Garmisch-Partenkirchen, Bavaria) in the west (Fig. 1). Flanked by carbonate platforms to the north and south, this continuously subsiding 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. Instead, marine conditions prevailed in the basin across the system boundary, though a distinct and abrupt lithological change from basinal carbonates of the Koessen Fm. (Eiberg Mb.) to marls and clayey sediments of the lower Kendlbach Fm. (Tiefengraben Mb., corresponding to the British Preplanorbis Beds) is interpreted as a result of this sea level fall. This drastic change in lithology was interpreted during the last decade as the T-J boundary (Golebiowski, 1990; Hallam & Goodfellow, 1990) because it coincides with the disappearance of typical Triassic fossils such as ammonoids and conodonts. New studies demonstrate, however, that the lower metres of the Tiefengraben Mb. (= "Rhaetische Grenzmergel" sensu Fabricius, 1960, 1966 – including also the reddish Schattwald Beds) still yield a Triassic micro- and nanoflora and that the earlier cessation of Triassic macrofauna may be an effect of deteriorating environmental conditions (Kuerschner et al., 2007).

Within the Eiberg basin, between Lake St. Wolfgang (Kendlbach) 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. The boundary between the Koessen and Kendlbach formations is lithologically similar all over the basin; it is distinct and easy to recognize and therefore interpreted as isochronous in all sections. 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 the most expanded Triassic-Jurassic boundary succession of all the proposed GSSP candidates; it contains the richest marine fauna in the world and an abundant microflora allowing a cross-correlation with the continental realm. A well preserved species of *Psiloceras* (*P. spelae* Guex n.ssp.) within the lower Tiefengraben Member correlates with and is comparable with the oldest *Psiloceras* in North America (Muller Canyon, Nevada, USA) but is much better preserved (aragontic shell, whorl section and complete suture line) than the crushed North American specimens which lack both an exact cross section and the suture line.

T/J boundary sections east of the Karwendel Syncline are indicated on Fig. 1 with a cross; some are classical localities and have been studied by various authors (references in Kuerschner et al., 2007). The boundary sections of the Karwendel Syncline, belonging to the western part of the Eiberg basin, are much less known and currently lack detailed biostratigraphic information. Most of the recently-studied outcrops belong to the southern flank of the Karwendel Syncline, and three of them (Hochalplgraben, Schlossgraben and Kuhjoch; Fig. 2) have become important as a result of the finds of new psiloceratids distinctly older than the well-known earliest *Psiloceras* of England (*P. erugatum*, *P. planorbis*) and the Alps (*P. calliphyllum*). The Kuhjoch section (a peak between the Hochstall and Hölzelstal valleys) is selected as candidate for a GSSP because it is the best continuously exposed and

most complete T/J boundary section of the area, and the bed with the first appearance of *Psiloceras spelae* is proposed as the type level and stratotype point. Only the topmost part of the boundary sequence, with the transition to the *P. calliphyllum* horizon from 10 to 18 m above the GSSP level, has been studied in a neighbouring locality (Ochsentaljoch) about 750 m to the west of the Kuhjoch (Fig. 3), where this interval is better exposed.

GEOGRAPHICAL AND GEOLOGICAL SETTING

The Karwendel Syncline is a local, east-west trending synclinal structure, approximately 30 km long, within the Lechtal nappe of the western Northern Calcareous Alps, extended E-W. 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). All the sections belong to the western half and to the southern flank of the syncline. The GSSP candidate Kuhjoch is located about 25 km north-north-east of Innsbruck and 5 km east-north-east of the village of Hinterriss on the 1:50.000 scale topographic map of Austria (sheet 118 – Innsbruck); the coordinates are 47°29'02"N/11°31'50"E. Geological map 1:75 000, sheet 29, Innsbruck und Achen-See by O. Ampferer & Th. Ohnesorge (1912) (out-of-print). Geological map 1:10 000 by S. Schütz (1974) (unpublished) (Figs. 5, 6). It is accessible through the Baumgartenbach valley on a 16 km long forest road (driving permit from the OEBF = Österreichische Bundesforste) starting south of the village of Fall in Bavaria (Germany), with a 1-2 hours walk from the end of the road (Ochsental alp) or a 1.5 to 2 hours walk from the Hochstall alp Niederleger (Fig. 3). Kuhjoch (Fig. 4) [mountain pass located between Kuhjoch peak (not named on topogr. 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) (airfotographs and topographic maps: <http://tiris.tirol.gv.at/web/index.cfm>; search for place name: Hochstall-Hochleger). This guarantees long-term exposure stability and conservation with respect to protection status.

STRATIGRAPHY

Palaeogeography and sea level history of the Eiberg Basin near the T/J boundary

The Eiberg Basin was an intraplatform trough bordered to the south by a broad Rhaetian carbonate platform (Dachstein Lagoon) with, locally, fringing reefs and an outer shelf (Hallstatt Basin) transitional to the Tethys Ocean. North of the Eiberg Basin there existed another partly terrigenous-influenced carbonate ramp (Oberrhaet limestone lagoon) which was bordered landward by the Keuper area of Southern Germany (or was separated from the latter by the Vindelician high).

An end-Triassic (late Rhaetian) sea level fall caused a wide-spread platform emergence in the southern NCA. The regression was fast; it culminated 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).

Position of main boundary-relevant ammonite levels 1 to 7 (Figs. 9, 10)

Between the widely distributed and long-known *Choristoceras marshi* (1) and *Psiloceras calliphyllum* (5) layers, three new ammonite levels (Figs. 9, 10) have been found within the 22 m thick continuous succession of marls and marlstones (Tiefengraben Member): ammonite level (2) with *Psiloceras spelae* n. ssp. from 5.80-6.20 m, ammonite level (3a) with *Psiloceras* ex gr. *tilmanni* at 7.6-8.0 m and ammonite level (4) with *Psiloceras* cf. *pacificum* at 12.0-12.4 m above the base of the Member. All levels are represented in the proposed GSSP site on

Kuhjoch; levels (2); (4) and (4a) (*Psiloceras* sp.) are additionally known from Hochalplgraben (Figs. 14, 20) and levels (3b) to (5) also from Ochsentäljoch (Figs. 9, 10). The marlstones have formerly been called “Rhaetische Grenzmergel” [type locality Marmorgraben, western Karwendel Syncline (Fig. 2)] (Fabricius, 1960, 1966) and correspond in present nomenclature to the Tiefengraben Member of the Kendlbach area where the member differs slightly 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 horizons (*P. calliphyllum/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. 24; Bloos, 2004), levels 6 and 7 (Kuhjoch) (Fig. 9, 10) are also condensed and can be correlated with the middle Hettangian Alpine Megastoma and the late Hettangian Alpine Marmorea Zones (det. K. Kment).

Lithostratigraphic description of the proposed type section

The south to north crest of Kuhjoch peak exposes, perpendicular to the crest and strike, a steeply dipping continuous sequence of Rhaetian (Koessen Fm.) to Upper Jurassic sediments (Ruhpolding Radiolarite Fm.). A narrow topographic depression, visible both on the maps and in the field (Figs. 4, 5), corresponds to the documented section, which starts 2 m below the top of the Koessen Formation/Eiberg Member with a band of well-bedded and variably thick (up to 50 cm) gray bioturbated limestones (bioclastic wackestones) overlying 5 m of black marls with pyrite nodules and rare thin (5-10 cm) limy mudstone intercalations. The 20 cm thick topmost bed (= T in Fig. 23a, 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 in the upper half it is thinly laminated. The top of this bed (~ 1 cm thick and also thin-bedded) is black and bituminous, rich in bivalves and fish remains (scales) and indicating an anoxic event and the peak of the regression. Above follows the Kendlbach Formation which is divided in the lower 22 m thick terrigenous Tiefengraben Member and the following 3 m thick calcareous Breitenberg Member.

Grey to brownish marls (up to 13 cm thick) with concretions of pyrite and worm-shaped traces constitute the base of the Tiefengraben member and are overlain by yellowish weathering, partly laminated marls (30 cm thick) passing into reddish, partly laminated, clayey marls approximately 2 m thick. The reddish marls are known as Schattwald Beds (Figs. 8, 23a, b, 25) in the Allgäu nappe in the north and west of the NCA (e.g. Lorüns, Vorarlberg – McRoberts et al., 1997; Aschau, Chiemsee, Bavaria; Restental, Upper Austria – Golebiowski, 1990). Greyish intercalations characterize the transition to the overlying main part of the Tiefengraben Member, 19 m thick. Ammonite level (2) with *P. spelae* n.ssp. is located 3,5 m above the Schattwald beds, ammonite level (3a) with *P. ex gr. P. tilmanni* 2 m higher and ammonite level (4) with *P. cf. pacificum* 4 m higher up in the section.

Approx. 8 m above the Schattwald Beds the marls become more silty and from 10 m upwards also finely sandy. A first sandstone 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. The remaining outcropping part of the latter consists of 1,5 m 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 enriched in ammonites partly preserved as limonitic moulds. At Kuhjoch and several other sections of the southern and northern flank of the Karwendel Syncline the next two or three limestone beds contain condensed ammonites of middle and late Hettangian age (Kment 2000). A 18 to 20 cm thick yellowish bioclastic limestone follows, rich in fine echinodermal debris, with burrows filled by reddish lime mud and with a ferromanganese oxidic crust on

the surface. This layer yielded at Kuhjoch an *Alsatites* cf. *lasicus* (det. K. Kment) of the Megastoma Zone, a middle Hettangian Alpine equivalent of the Northwest European Liasicus Zone. Locally ammonite concentrations are found (Kment 2000). One or two more red limestone beds (together up to 30 cm thick) with Fe-Mn oxide nodules and crusts and yielding ammonites of Upper Hettangian age (Marmorea Zone, equivalent to the Angulata Zone) make up the end of the studied sections. At Kuhjoch in this red limestone (20 cm thick) an *Alpinoceras haueri* (det. K. Kment) was found.

Better exposures of the upper half of the Tiefengraben Member have been found at Ochsenaljoch. 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 through 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 sandstone bed (20 cm) that matches the single exposed sandstone bed of the Kuhjoch section. The following 2 m are composed of marls, with some silty sandstone 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. 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 between wavy bedded, grey bioclastic limestones (2 m). No fossils have been collected in the overlying Calliphyllum bed and the middle to upper 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) make up the top of the section up to the cherty limestones of the Upper Sinemurian Scheibelberg Formation.

PALAEONTOLOGY OF THE KUHJOCH AND OCHSENTALJOCH SECTIONS

A broad spectrum of marine invertebrate groups is recorded, although brachiopods are rare. Macrofossils are represented by biostratigraphically (ammonites) as well as palaeoecologically important groups (bivalves, echinoderms). Microfossils constitute a major portion of the calcareous biomass except for the Schattwald beds where only a depauperate foraminifer record is present. Ostracods are usually less frequent than foraminifera and also less diverse. Nannofossils are present in many samples, though coccoliths unfortunately are very rare and extremely small. A first sample set from the Kuhjoch section (collected by A. v. Hillebrandt in 2005) was processed for palynological analysis and a detailed high-resolution study is still in progress. All samples (from the first sampling campaign) were rich in pristine preserved palynomorphs that 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 recently from the Tiefengraben section in the eastern part of the Eiberg basin (Kuerschner et al., 2007).

1. MACROFOSSILS

a) Ammonitina (A. v. Hillebrandt, L. Krystyn) (Hillebrandt & Krystyn, 2007) (Figs. 9, 10)
Low ammonite diversity, patchy occurrence of determinable specimens and restriction to certain levels are characteristic of the sections, though shell fragments were frequently found in samples for micropaleontological studies (Figs. 12, 14). 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* (Figs. 9, 10) are found in bed T, representing the highest (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 (*Arcestes*) in bed T of the Moeserer Alm near Steinplatte (Bökenschmidt & 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 section, contains mostly flattened and small (rarely > 2 cm) specimens, but easily visible due to their white aragonitic shell. Rare pyritized undeformed phragmocone specimens allow an exact illustration of the cross-section and the suture line (p. 2 and pl. 3). The specimens belong to an involute species of *Psiloceras* with predominating psiloceratid characters (inner whorls with well developed “Knoetchenstadium”, psiloceratid suture line without a Suturallobus) but show also some features of Triassic phylloceratids (high ovale whorl section with well developed umbilical wall).

The Alpine specimens first were determined as *P. cf. spelae* because only one specimen was figured from Nevada which does not show all characters to be seen in *P. spelae* from the Alps. Moreover, the variability of the Alpine species was not yet known. A second 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) 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* n. ssp. The two subspecies are closely related phylogenetically and in time. They characterize the ammonite biohorizon of *P. spelae* which is the first ammonite biohorizon of Jurassic aspect.

July 2007 many specimens could be found in the Kuhjoch and Hochalplgraben sections. Three supplementary plates with ammonites were prepared (supplementary plates 1 to 3).

Anaptychi of *P. spelae* n. ssp. and a fragment of ?*Juraphyllites* were also found (supplementary plate 3).

Ammonite level (3a) (Kuhjoch section) was found in the residue of a washed sample containing 20 limonitic casts of inner whorls (< 1.7 mm), a compressed specimen (3 mm) and a whorl fragment (Wh 2.5 mm) with suture lines that can be placed in the *P. tilmanni* group. 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 badly preserved specimen in the Kuhjoch section; four specimens from the Hochalplgraben section are illustrated (Fig. 10; supplementary plate 3). Two tiny juveniles and two larger forms (up to 15 mm diameter) with relatively wide umbilicus are determined as *Psiloceras cf. pacificum* Guex, a species described from Nevada (North America) 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.

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

Ammonite level (6): limestone bed (18 to 20 cm thick), ammonites are rare at the Kuhjoch [Ochsentaljoch?] section [*Alsatites cf. liasicus* (D'ORB.)] (det. K. Kment).

Ammonite level (7): limestone bed (20 cm thick), ammonites are rare at the Kuhjoch [Ochsentaljoch?] section [*Alpinoceras haueri* (GÜMBEL)] (det. K. Kment).

b) Bivalves (Ch. McRoberts) (Fig. 11)

Bed T of the Eiberg member yielded *Cassianella* sp., and at the top *Chlamys valoniensis*. The very base of the Tiefengraben Member contains *Cardinia* sp. and *Agerchlamys* sp. *Pseudolimea* cf. *hettangiensis* is found some centimetres higher, in a brownish layer. The grey marls of the Tiefengraben Member provide at different levels small nuculids and different species of *Cardinia*: *C. cf. listeri* was found in ammonite level (2) and *C. cf. ingens* 7.45 m above the base. The residues of washed microfossil samples often contain juvenile specimens (mostly moulds) or fragments of pelecypods, mostly pectinids and nuculids (Figs. 12, 13). The first limestone bed, 4 m above ammonite level (4) in the Ochsentaljoch section, yielded *Liostrea* and *Agerchlamys*.

c) Gastropods and scaphopods (A. v. Hillebrandt)

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

d) Brachiopods (A. Tomasovych) (Fig. 26)

Brachiopods are rare in the lower part of the Tiefengraben Member and occur only in 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 Alps, their taxonomic affinity is uncertain owing to poorly preserved shape characters.

The biomicritic limestone bed with *Agerchlamys* and *Liostrea* in the Ochsentaljoch section, lying 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 *Tettrarhynchia inopinata* (Siblík, 1999) (Fig. 26). This species is also abundant at the boundary between the Tiefengraben and Breitenberg members of the Hochleitengraben section (type locality, Siblík, 1999; Tomasovych and Siblík, 2007). It probably preferred low-energy habitats below storm wave base, and was able to tolerate some input of terrigenous supply. *Tettrarhynchia 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 Alps coincides with the onset of the Breitenberg Member (Tomasovych and Siblík, 2007). *Tettrarhynchia inopinata* represents the earliest and endemic species of the genus *Tettrarhynchia*, which was a common member of benthic communities in the Early and Middle Jurassic. Rhaetian tettrarhynchiids do not occur in the western Tethys, and ancestors of *Tettrarhynchia 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, hypothyril/submesothyril foramen, relatively thick deltidial plates, and 8-12 relatively rounded costae that reach to umbo in both valves and do not show any bifurcation. The anterior margin is rounded, but rarely flattened. Smaller and larger specimens highly differ 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 enclosing 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. In general, *Lobothyris* became a dominant brachiopod in carbonate-rich environments of the Eastern Alps during the deposition of the Breitenberg Member (Siblík, 1993; Tomasovych and Siblík, 2007).

Echinodermata (in part M. Simms, A. v. Hillebrandt)

Crinoid ossicles can be found in the washed residue of many samples (Figs. 12, 13); fragments of echinids 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 thin layer in the Hochalplgraben (Figs. 14, 20) directly above ammonite level (2) contains nearly exclusively crinoids. Most ossicles are from the cirri with a few hooked terminal cirral ossicles determined so far as isocrinid. The larger material comprises mainly columnals and few brachiids of isocrinids. Different types of columnals (nodals, internodals and infranodals are found). The number of noditaxes seems to be no more than 6 or 7 at most. The longest pluricolumnal has 5 columnals. A similar isocrinoid is found in the Larne section in Northern Ireland, 2,5 m below the first *Psiloceras erugatum* (first *Psiloceras* in Great Britain). 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 section and 10 from the Ochsentaljoch section, with various fossil groups represented. Ossicles of Echinodermata are often more frequent than other microfossils (Figs. 12, 13), foraminifera usually outnumber ostracodes. Small appendices of crustaceans can be common in some samples (Figs. 12, 13). Radiolaria are extremely rare.

a. Foraminifera (A. v. Hillebrandt) (Figs. 12-15)

(i) Kuhjoch section (Fig. 9)

Black and grey marls 2.5 and 1 m below the last series of Koessen limestones yielded only small sized *Trochammina*, *Ammodiscus* and polymorphinids (limonitic casts). A weathered sample from bed T contains *Nodosariidae* typical of the Rhaetian. A similar fauna was found in marls directly above the thin-bedded, black, bituminous top-layer of bed T.

Samples from the base of the Tiefengraben Member and below the Schattwald Beds yielded mostly compressed *Trochammina* and *Nodosariidae* with a large *Marginulinopsis*, the assemblages are less rich in genera and species than those found below. *Hippocrepina* dominates the Schattwald Beds, accompanied by compressed *Trochammina* and relatively large *Nodosariidae* (especially *Marginulinopsis*), but become more rare towards the top of the Schattwald Beds.

Large *Ammobaculites* (Fig. 12) are common to very frequent in many samples of the grey marlstones of the lower and middle Tiefengraben Member. Compressed and tiny (not compressed) *Trochammina* are mainly found in the lower part of the grey marls. *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 the more frequent from ammonite level (2) upwards. *Lenticulina* can be the dominating nodosariid genus in the upper part of the Tiefengraben Member. Robertinina are represented by 3 genera (Fig. 15): *Oberhauserella* mostly is rare; *Praegubkinella* can be common in the intervals around the ammonite horizons; and *Reinholdella* can be very frequent in the middle part of the Tiefengraben Member. Both genera are usually preserved with aragonitic shell. A characteristic increase of size takes place from *Oberhauserella* (~ 0.06 to 0.12 mm) to *Praegubkinella* (~ 1.5 to 0.2 mm) and *Reinholdella* (~ 0.2 to 0.3 mm) (Hillebrandt, in prep.).

(ii) Ochsentaljoch section (Fig. 13)

Ammobaculites is common to frequent in most samples but disappears in the last two samples. *Glomospira* and attached Ammodiscidae occur in some samples. *Trochammina* was only found in 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 two samples.

b. Ostracoda (M. Urlichs) (Figs. 16-18)

Typical Rhaetian ostracod faunas are represented in bed T and in the Tiefengraben marls directly above. *Torohealdia amphicrassa*, *Ogmoconchella bristolensis* and *Ledahia telata* were found in bed T of the Kuhjoch and additionally *Carinobairdia alpina*, *C. triassica*, *Nodobairdia nodata* and *Monoceratina fortенodosa* in the same bed in the Schlossgraben and Hochalplgraben near Hinterriss, as also at Steinplatte near Lofer. The ostracode fauna (*Eucytherura sagitta*, *Ogmoconchella bristolensis*, *Cytherella plattensis* and *Kerocythere* sp.) becomes poor in specimens in the basal Tiefengraben Member between bed T and ammonite level (2) with a 2 m break in records during the Schattwald interval. *Cytherelloidea buisensis* appears below ammonite level (2) (Figs. 16, 17). Specimens found up to this level are transitional between the Late Triassic *C. praepulchella* and *C. buisensis*. Higher up in the sequence, this species is frequent in many samples. The liassic ostracodes *Liasina lanceolata*, *Eucytherura elegans*, *Ogmoconchella ellipsoidea* and *Polycope cerasia* appear (Fig. 17) above ammonite level (2). A single record of *Carinobairdia hettangica* from the Hochalplgraben comes from above the first limestone bed of the Tiefengraben Member.

c. Conodonts (L. Krystyn)

Since the pioneering study of Mostler et al. (1978) conodonts are known to occur widespread in the Koessen Formation of the NCA. They are more common in the calcareous basal 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 Koessen Formation has produced a relatively numerous and diverse fauna dominated by specimens of the genus *Misikella* (individual numbers in brackets): *M. posthernsteini* Kozur & Mock (26), *M. ultima* Kozur & Mock (2), *Zieglericonus rhaeticus* Kozur & Mock (2), *Neohindeodella* sp. (4). Of these forms, *M. ultima* is the name bearer of the topmost Triassic conodont zone as found in Hungary (Kozur & Mock, 1991; Palfy et al., 2001), Turkey (Gallet et al., 2007) and Austria. Kozur & Mock (1991) distinguished above the *ultima* Z. another short conodont interval (*Neohindeodella detrei* Z.) which eventually could correspond to the topmost bed T of the Koessen Formation in Kuhjoch. This bed seems due to its high marl to silt content unsuitable for conodonts and has not been investigated. A large sample (8 kg) from a counterpart of bed T on the Steinplatte slope (Tyrol) has produced tremendous amount of insoluble residue but no conodonts.

3. Calcareous Nannofossils (P. Bown) (Fig. 19, 20)

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

4. Palynomorphs (W. M. Kürschner, N.R. Bonis) (Figs. 25, 27)

Pollen and spore assemblages from the Koessen Formation are dominated by *Classopollis meyeriana* and *C. torosus* accompanied by *Ovalipollis pseudoalatus*, *Rhaetipollis germanicus*, *Ricciisporites tuberculatus*. Marine palynomorphs such as dinoflagellate cysts *Rhaetogonyaulax rhaetica* and *Dapcodinium priscum* and some acritarchs (e.g. *Michrhystridium*) are present. The palynomorph assemblages from the topmost bed of the Koessen Formation (black shale) 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 *Convolutispora microrugulata*, *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. Of biostratigraphic value is the lowest occurrence of *Cerebropollenites thiergartii* at the entry level of the ammonite *Psiloceras* cf. *spelae*. The palynology of the Kuhjoch section is currently studied in more detail as part of a PhD study by Nina R. Bonis at Utrecht University (Bonis *et al.*).

DIAGENESIS OF SEDIMENTS (A. v. Hillebrandt, L. Krystyn, W. M. Kuerschner)

At the Kuhjoch section no metamorphism is observable. Ammonites, bivalves and aragonitic forams (in part hollow) are preserved with an aragonitic shell. There are absolutely no signs for regional or local metamorphism of the rocks we studied in Austria (Kuhjoch, Hochalplgraben, Schlossgraben and also Tiefengraben and Kendlbach to the East). From the preservation of palynomorphs, notably the colour, it is evident that this material was never heated above about 50°C (see also Kuerschner *et al* 2007). Additionally, the presence of organic-geochemical biomarkers (such as pristine, phytane, hopane, n-alkanes) indicates that the organic matter is extremely well preserved. The organic geochemistry is studied in more detail as part of a PhD study by M. Ruhl at Utrecht University (see below).

GEOCHEMISTRY (M. Ruhl, W. M. Kuerschner)

Thus far only Carbon-Isotope investigations on bulk sedimentary organic matter have been made, while compound-specific measurements are underway. Stable isotopes (C&O) of the carbonate fraction and the clay mineralogy/XRD will be studied in the near future. Investigations of the Strontium Isotopes, Rare Earth Elements, Ca/Mg and Biomarkers/Organic Geochemistry are planned.

1. Carbon isotopes and organic Carbon content (Figs. 21, 22, 23b)

Two sample sets were studied for bulk C isotopes. The first series of samples (Fig. 22, red curve) was taken in 2005 (A. v. Hillebrandt) and a closer series of samples in June 2006 (Kuerschner, Ruhl and Bonis) (black curve). Basically both curves show the same trends with some additional features in the latter Carbon isotope record because of the much higher sample density. The transition from the Eiberg Member to the Tiefengraben Member was sampled at a cm scale (Fig. 23b). This interval is characterized by a distinct negative C isotope excursion, which is in fact composed of 2 maxima of about -31 ‰ and interrupted by slightly more positive C isotope values. The lower $\delta^{13}\text{C}_{\text{org}}$ peak coincides with a bituminous, black siltstone layer (1 cm) at the top of the thin-bedded marly limestone at the top of the Eiberg Member. The second negative $\delta^{13}\text{C}_{\text{org}}$ maximum lies at 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. In the upper part of the Schattwald Beds a second negative shift (-28‰) occurs but is much smaller than the one at the boundary between the Eiberg and Tiefengraben Member. A continuous trend to more negative values persists throughout the lower part of the Tiefengraben Member superimposed on smaller fluctuations. This long term trend is interrupted by a significant positive shift (to -26‰) at the level of the first ammonite horizon. This cycle is followed by a second smaller cycle in the C-isotope record 2 m above the second peak followed by a positive tendency and a slightly negative tendency in the upper part of the red curve.

Additional $\delta^{13}\text{C}_{\text{org}}$ data (Fig. 21) exist from other sections of the Northern Calcareous Alps (Restentalgraben, Hochalplgraben, Kuhjoch/Ochsentaljoch, Kendlbach, Schlossgraben, Steinplatte and some data next to the Tiefengraben; from Kuerschner et al. 2007). All these records show very regularly the distinct initial isotope excursion at the transition from the Koessen Mb to the Grenzmergel.

2. C_{org} (Figs. 22, 23b)

The C_{org} curve shows a sharp maximum of about 10% at the black, bituminous layer which coincides with the initial $\delta^{13}\text{C}_{\text{org}}$ minimum while the rest of the section shows only minor variations between about 1-2%.

PALAEOMAGNETISM (M. Deenen, M. Szurlies, W. Krijgsman)

Palaeomagnetic investigations have been started but all samples studied till now are remagnetized. Investigations of Koessen Beds from the Steinplatte area (Fig. 1) have shown that the beds there are also remagnetized.

The primary paleomagnetic signal was lost by the “overprinting” during the alpine phase as a result of fluid penetration. The organic rich sediments often contain also a lot of pyrite which bias a primary signal.

CORRELATION WITH OTHER SECTIONS OF THE EIBERG BASIN (Figs. 1, 2) **STRATIGRAPHICAL COMPARISONS**

Many sections of the Eiberg basin show a lithological and faunal record of the T/J boundary interval comparable with that of the proposed candidate 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 Koessen and basal Kendlbach Formation which has been studied also for magnetostratigraphy; the *Hochalplgraben* (47°28'20"/11°24'42") (Figs. 14, 20) with the presently best-preserved psiloceratids of the ammonite levels (2) and (4) and the most promising nannofossil record.

On 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. Ammonites have not yet been found in the Tiefengraben Member.

In the eastern Eiberg Basin the *Eiberg quarry* (47°33'/12°10') is 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 bed T 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. The *Moeserer Alm/Steinplatte* section (47°38'20"/12°35'0") has a more calcareous bed T up to 30 cm thick, containing common bivalves and, in the top black bituminous centimeter, *Choristoceras marshi* and *Arcestes* cf. *gigantogaleatus*.

The *Kendlbach* (47°41'15"/13°21'30") section provides, 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 & Braunstein (1988), Krystyn et al. (2005) and Kuerschner et al. (2007). This easternmost section differs in the absence of the top-Koessen bed T due to non-deposition, in a comparatively reduced Tiefengraben Member (13 m) with common limestone intercalations, and in replacement of the Schattwald Beds by olive-grey clays.

BIOSTRATIGRAPHY (Fig. 9)

Only a few fossil groups are suitable for high-resolution long distance correlations of early 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. 24) and their wide geographic distribution in marine realms facilitates global correlations. Nannofossils and marine palynomorphs may also be of relatively high correlation potential. Of minor, more local biostratigraphic or ecostratigraphic relevance are bivalves, ostracodes and some foraminifera. Available terrestrial palynomorphs offer potential for marine – continental correlations.

1. Ammonites (Figs. 9, 10, 24) (A. v. Hillebrandt, L. Krystyn)

The Kuhjochjoch and Ochsentäljoch sections record 7 ammonite beds or levels of Late Rhaetian (1) to Late Hettangian (7) age:

- ammonite level (7) with ammonites of the Marmorea Zone
- ammonite level (6) with ammonites of the Megastoma Zone
- ammonite level (5) with ammonites of the Calliphyllum Zone (condensed, including horizon with *Psiloceras calliphyllum – costosum* and horizon with *Psiloceras naumanni*).
- ammonite level (4) *Psiloceras* cf. *pacificum*
- ammonite level (3a and b) with *Psiloceras* ex gr. *P. tilmanni*
- ammonite level (2) with *Psiloceras spelae* n.ssp.
- ammonite level (1) with *Choristoceras marshi*

2. Bivalves (Fig. 11) (Ch. McRoberts)

Cassianella and *Chlamys valoniensis* characterize the top-bed T of the Eiberg Member. Directly above is the FO of *Agerchlamys* together with *Pseudolimea* cf. *hettangensis*. 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.

3. Ostracodes (Figs. 16-18) (M. Urlichs)

The beds immediately below and above the Eiberg - Tiefengraben boundary are characterized by a Rhaetian ostracode fauna with *Ogmoconchella bristolensis*, *Torohealdia amphicrassa*, *Eucytherura sagitta* and a species transitional from *Cytherelloidea praepulchella* to *C. buisensis* till now only known from the Hettangian. Ostracodes are almost missing from the Schattwald interval and become impoverished in specimen numbers up to ammonite level (2). *Pseudomacrocypris subtriangularis* first appears (Schlossgraben section) in ammonite level (2). This species is found in NW Europe from the Late Hettangian up to the Early Pliensbachian. *Carinobairdia hettangica*, *Eucytherura elegans*, *Ogmoconchella ellipsoidea* and *Polycope cerasia* appear above ammonite level (2) and below ammonite level (5). These species are found in NW Europe first in the Pilonotum and Liasicus Zones respectively. *Liasina lanceolata* [ammonite level (2)] was found in NW Europe first in the lower part of the Late Sinemurian. The faunal change between the Rhaetian and Hettangian is very distinct. However, some species (*Ogmoconchella bristolensis*, *Ledahia telata* and *Cyterella plattensis*) occur from the Rhaetian up to the Hettangian. They indicate that the ecologic conditions have been unchanged euhaline.

4. Foraminifera (Figs. 9, 12-15) (A. v. Hillebrandt)

The nodosariid fauna below the bituminous layer is typical of the Rhaetian as is also the large *Marginulinopsis* fauna above the Tiefengraben Member boundary. The mostly small-sized nodosariids and polymorphinids of the grey marls of the T. M. are poor in species. Characteristic genera like *Ichthyolaria* do not appear 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. 9, 15). *Oberhauserella* was described from the Upper Triassic and is found with different species in the gray marls below the *Psiloceras spelae* horizon. *Praegubkinella turgescens* appears immediately below this horizon. Transitional forms to *Reinholdella* n. sp. are first found above this level. The horizon with *Psiloceras* cf. *pacificum* yielded another new species of *Praegubkinella*. In the Hochalplgraben section a third species of *Praegubkinella* was found between the horizons with *Psiloceras spelae* n.ssp. and *Psiloceras* cf. *pacificum*. *Reinholdella* n. sp. is found up to the upper part of the Tiefengraben member (Ochsentaljoch section). The evolutionary lineage from *Oberhauserella* to *Praegubkinella* and a genus related to *Reinholdella* (probably a new genus) is not only found in the Eiberg Basin but also in the Allgäu and Hallstatt Basins. In the Hallstatt Basin a section was found which also contains this evolution and the characteristic increase of size from *Oberhauserella* to *Praegubkinella*. The uppermost sample yielded an ammonite nucleus (phylloceratid or psiloceratid). Further investigations hopefully will yield determinable ammonites and the continuation of this important section. The mentioned aragonitic forams are very important as proxies. The most rapid and very important evolutionary development took place close to the Spelae horizon.

5. Calcareous nannofossils (Figs. 19, 20) (P. Bown)

Coccoliths s.s. are very small and very rare in the Tiefengraben Member contrary to the Rhaetian Koessen beds and more samples have to be studied. The changes in the "calcisphere" assemblages perhaps are of biostratigraphic importance. There have not yet been found typical "Liassic" nannofossils (e. g. *Schizosphaerella* – the dominant Liassic nannolith), nor any typical coccoliths. The position of the turnover from the Triassic to the Jurassic is not yet well known.

6. Palynomorphs (Fig. 9, 25, 27)

Similar to the palynomorph record from the Tiefengraben section (Kuerschner et al., 2007), four different palynomorph assemblage zones can be distinguished. The *Rhaetipollis* – *Limbosporites* Zone and the *Rhaetipollis* – *Porcellispora* Zone characterize the uppermost part of the Koessen Formation and the marls above the bituminous layer and the Schattwald Beds, respectively. A *Trachysporites* – *Porcellispora* Zone is found between the Schattwald Beds and the beds with *Psiloceras spelae* n.ssp.. Above these is the *Trachysporites* – *Heliosporites* Zone.

The last occurrences of *Rhaetipollis germanicus* and *Rhaetogonyaulax* are situated in the lower part of the Schattwald beds. *Ovalipollis pseudoalatus* is found up to the basal beds of the grey marls of the Tiefengraben Member, *Cerebropollenites thiergartii* first appears at the *Psiloceras spelae* horizon.

CORRELATIONS

1. Regional

Ammonite levels (2) and (4) are presently known from three sections in the western Karwendel syncline. Ammonite levels (5) to (7) are known from many sections of the western Karwendel Syncline. Levels (6) and (7) 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 Members 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). Vertical changes within the microfaunas allow further fine-tuned correlations within the Tiefengraben Member throughout the basin.

2. Northwestern Europe (Fig. 24, 28-30)

St Audrie's Bay, Somerset, England was proposed by Warrington, Cope & Ivimey-Cook (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 & 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 ("Knoetchenstadium") like most of the *Psiloceras* of the NCA, it has not yet been found there and therefore it cannot be inserted into the Alpine *Psiloceras* succession. Considering the more or less pronounced ribbing on the inner whorls and the occurrence closely below *Neophyllites* in northwestern Europe, *P. erugatum* should be younger than any of the Karwendel ammonites found below the Calliphylum Zone where *Neophyllites* occurs in the NCA (Bloos, 2004).

The Kuhjoch and Karwendel ammonites of the Tiefengraben Member (*P. spelae* to *P. cf. pacificum*) are not known from the barren lower "Preplanorbis Beds" of England. Using the isotopic signal as an additional correlation tool (Kuerschner et al., 2007) it should be expected to occur in the lowest few metres of the Blue Lias Formation.

The NCA microfauna (mostly ostracodes and in part foraminifera, mainly nodosariids - polymorphinids) is very similar to that of Northwestern Europe, where the stratigraphically more important aragonitic Robertinina of Hettangian age are unfortunately not yet well known. Because the T-J boundary marks a significant biotic event in the marine and in the terrestrial realm a boundary definition should be chosen that enables correlation between the two realms. However, a palynological approach that is embedded in a marine T-J boundary

definition appears to be difficult because no major microfloral break has been found to be precisely contemporaneous with the T-J definitions proposed so far. In the T-J boundary sections so far studied in the NCA, such as Tiefengraben, Hinteriss, Kuhjoch (Bonis and Kuerschner, ongoing research), the only morphologically distinct post-Triassic pollen morphospecies is *Cerebropollenites thiergartii*. In the Kuhjoch section *C. thiergartii* occurs at the entry level of *P. spelae*. *C. thiergartii* may therefore become useful as a palynological marker species for the base of the Jurassic and make the correlation of the T-J boundary between marine and terrestrial successions possible.

3. North America

Non-marine strata of Late Triassic and Early Jurassic age are found in eastern North America whereas marine Triassic-Jurassic transitional sections are described from western North America.

a. Newark Supergroup (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 northern Atlantic began to open. The Newark Supergroup consists of fluvial sediments with lacustrine intercalations. Basalts of the Central Atlantic magmatic province (CAMP) are inserted in the Jurassic part of the succession beginning most probably in the latest Triassic.

The Newark Supergroup is extremely thick (up to 6 kilometers). Dinosaur footprints are common, body fossils of terrestrial vertebrates are rare. In lacustrine sediments fossil fish are sometimes frequent. Palynomorphs and conchostracans were used as biostratigraphic tools. A precise biostratigraphy, however, could not yet be achieved and, thus, correlation with marine sections of similar age is difficult. Investigations on radioisotopes from a basal basalt yielded an age of $201,27 \pm 0.06$ Ma (Schoene et al., 2006).

Until a few years ago the T-J boundary was drawn immediately below the first basalt flow with the beginning of the palynofloral *Corollina meyeriana* zone (Cornet 1977). Kozur & Weems (2005) investigated the conchostracans and placed the T-J boundary at the base of the *Bulbilimnadia sheni* zone which lies within the Newark extrusive zone. Lucas & Tanner (2007) interpreted “the sudden dominance of the Newark palynoflora by *Corollina meyeriana* as a result of regional climate change caused by uplift or volcanism, not as a biostratigraphical datum”. They also concluded that the T-J boundary must be drawn within the so-called Newark igneous extrusive zone. Also the vertebrate biostratigraphy suggests that the base of the Jurassic is within that zone. Following Lucas & Tanner (2007) up to now “the carbon isotope record cannot be used to correlate non-marine and marine strata across the TJB with certainty” and “no correlation based on iridium anomalies is possible”. All data indicate that the T-J boundary must be drawn above the lowest basalt of the Newark Supergroup. The CAMP volcanism began during the latest Triassic, most probably at the beginning of the initial negative CIE (Figs. 28, 29). But this is not yet proved.

b. Western North America (Fig. 24, 28-30)

T-J boundary sections with a most complete ammonite record were described from the New York Canyon (Nevada, USA) (Guex, 1995; Guex et al., 1997, 1998; Guex et al., 2002; Guex et al., 2003). Proposed in various ways as T/J boundary GSSP (initial negative isotope excursion – McRoberts et al., 1997; Ward et al., 2007; FO of first *Psiloceras* – Guex et al., 1998) the section seems, however, to be tectonically complicated (Guex et al., in print).

The proposed GSSP horizon of Guex et al., 1998 with the FO of *Psiloceras spelae* as boundary event can be correlated with ammonite level (2) of the Karwendel syncline. Ammonite level (3a and b) (Kuhjoch and Ochsentaljoch) probably have no counterpart in Nevada. The beds with *Choristoceras minutum*, *Odoghertyceras deweveri*, *Psiloceras marcouxii*, *P. tilmanni* and cf. *Neophyllites* (Guex et al., 2002, Lucas et al., 2007) 7.2 m above *P. spelae* may be correlated with ammonite level (4) but choristoceratids and psiloceratids similar to *Psiloceras marcouxii* do not occur in the Hettangian of Europe, and the determination of the *Neophyllites* (without suture and whorl section 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 found in the Nevada sections.

Carter & 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* zone (Carter & Hori, 2005). Any exact correlation with other fossil groups (e.g. ammonites) is not possible over an interval from 15 m below to about 6 m above the proposed boundary level but a concomitant and pronounced negative $\delta^{13}\text{C}_{\text{org}}$ anomaly is used as correlation tool to other sections (Ward et al., 2007).

4. South America (Fig. 24)

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). 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 was also found *Odoghertyceras*. Below this bed a limestone sample yielded radiolarians transitional to basal Hettangian forms 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, Guex, Bartolini, Schoene & Ovtcharova 2008) discovered *Psiloceras spelae* nearby to a section described by Hillebrandt (1994, figs. 2b, 3) and Hillebrandt (2000a, fig. 5a). *P. 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 in the boundary interval.

Other T-J boundary sections are found in northern Chile (Hillebrandt, 2000a). But there the lowest Hettangian ammonite horizons are missing. The oldest ammonite level (Primocostatum Zone in Hillebrandt, 2000c) can be correlated with a part of the *Psiloceras polymorphum* Zone in Nevada and the Planorbis and Calliphyllum Zones in Europe (Fig. 24). The thickness of the Latest Triassic and the Lowest Hettangian in Chile is still higher than that of the Tiefengraben Member in Austria.

PALAEOBIOGEOGRAPHY

Around the T/J boundary the NCA underwent a distinct change in their palaeobiogeographic relations from a uniquely 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 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 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. Ostracodes and foraminifera show relations to the Tethyan and the Euroboreal Realm. Calcareous nannoplankton is not suitable for biogeographic comparisons as it is unknown from the Preplanorbis Beds of northwestern Europe as well as from time-equivalent sediments of the eastern Tethyan Realm and the East Pacific Province.

CHOICE OF THE BEST BOUNDARY LEVEL

The proposed GSSP candidate offers different biostratigraphic and also geochemical events for placement of the T/J boundary:

1. Last occurrence of *Choristoceras marshi* [ammonite level (1)]

The last occurrence of *Choristoceras marshi* (and of conodonts) has often been used as criterion to distinguish Triassic from Jurassic strata in the NCA. Disappearance of choristoceratids (and other Triassic ammonoids) at the top of the Eiberg Member may, however, be biofacially controlled by the strong shallowing of the basin at that time. Other cons are the strong facies change at this level, the persistence of typical Rhaetian microfaunas and microfloras (!) several metres into higher beds and the considerable vertical distance (6 m) to the first appearance of the earliest Jurassic ammonites. Additionally, last occurrences are not recommended as boundary levels by ICS.

2. First occurrence of *Psiloceras spelae* [ammonite level (2)]

P. spelae n.ssp. is the first known *Psiloceras* in Europe and in the East Pacific Province (North and South America). The alpine specimens of *Psiloceras spelae* n.ssp. are very well preserved (aragonitic shell) and show all characters necessary for an exact determination. Within or closely to the proposed boundary level are several FOs of typical Hettangian ostracodes, foraminifera, nannofossils and palynomorphs potentially enabling local and long-distance correlation of the level in both the marine and the continental realms. Important pros for the proposed boundary level are continuous sedimentation, high sedimentation rate and no facies change in close proximity to it. As water depth was below mean wave base (approximately 50 m) favourable open marine conditions may have boosted the presence of fossil groups suited for long distance biostratigraphic correlations.

3. Horizon with *Psiloceras cf. pacificum* [ammonite level (4)]

This horizon is not suitable because a) the presently available specimens of this form are rare and not well preserved and b) no distinct changes in other fossil groups are observed.

4. *Calliphyllum* Bed [ammonite level (5)]

This limestone bed is not recommended because it is condensed and yields *Psiloceras* species of different ages, i.e. at least of two ammonite horizons. It is high above the main faunal change and, moreover, correlates with rocks which undisputedly have been regarded as Jurassic for 150 years in northwestern Europe [dieser Satz ist nicht verständlich]. It is also

younger (at least in part) than the proposed boundary level in the English candidate GSSP St. Audrie's Bay. The correlation with the endemic successions in North and South America is not exactly known.

5. $\delta^{13}\text{C}_{\text{org}}$ peak at the Eiberg - Tiefengraben Members boundary (Figs. 21-23)

The bulk C-isotope record at the Kujoch section shows a major negative C-isotope excursion at the boundary between the Eiberg and Tiefengraben Members, which could be used to define the T-J boundary. Our high resolution study reveals, however, that this excursion consists, in fact, of two peaks, one exactly at the Eiberg-Tiefengraben boundary and a second, 7 cm higher. A slight increase (significant?) to higher values occurs between both minima (Fig. 21). It appears difficult to decide at which of these peaks the boundary should be placed and if these peaks can be exactly correlated with peaks in other sections. Further arguments against this mode of definition are given in the discussion of geochemistry and in paragraph 1. The peak(s) is (are) not yet found everywhere in the world even at sections which biostratigraphically appear to be complete (e.g. in Peru). At incomplete T-J boundary sections where the isotope excursion is lacking the boundary can be found only by fossils. The peaks need biostratigraphic calibration to be identified with certainty.

CONCLUSIONS

The proposed Global Stratotype Section and Point matches all requirements of ICS for a GSSP. The Kujoch 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 the highest found in any of the proposed candidate GSSPs and shows well-separated successive events. Synsedimentary disturbances are missing and no 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 6 km parallel to the elongation of the basin. The primary boundary marker (*P. spelae* GUEx) has a low palaeolatitude global distribution and a short vertical range. Other fossil groups (bivalves, foraminifers, ostracodes, dinoflagellates) admit correlation with marine sections where ammonites are lacking. Finally, terrestrial palynomorphs (FO of *Cerebropollenites thiergartii*) bridge the barrier to the non-marine realm. A well differentiated $^{13}\text{C}_{\text{org}}$ curve with two pronounced excursions provides additional constraints for correlation with other T-J boundary sections. A magnetostratigraphic investigation is under way.

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photographs of microfossils were taken by Mr. J. Nissen (Zentraleinrichtung Elektronenmikroskopie, TU Berlin).

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	About 50 cm for Spelae Horizon and at least 10 m for Tilmanni Zone
Absence of synsedimentary and tectonic disturbances	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	
Radioisotopic dating	No information
Magnetostratigraphy	No result thus far
Chemostratigraphy	Yes ($\delta^{13}\text{C}_{\text{org}}$ and C_{org}) (further geochemical investigations planned)
Sequence stratigraphy	Yes
OTHER REQUIREMENTS	
GSSP indicated by a permanent fixed marker	Yes, if accepted
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)

Tab. 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.

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Fig. 1. Triassic - Jurassic boundary sections in the Northern Calcareous Alps

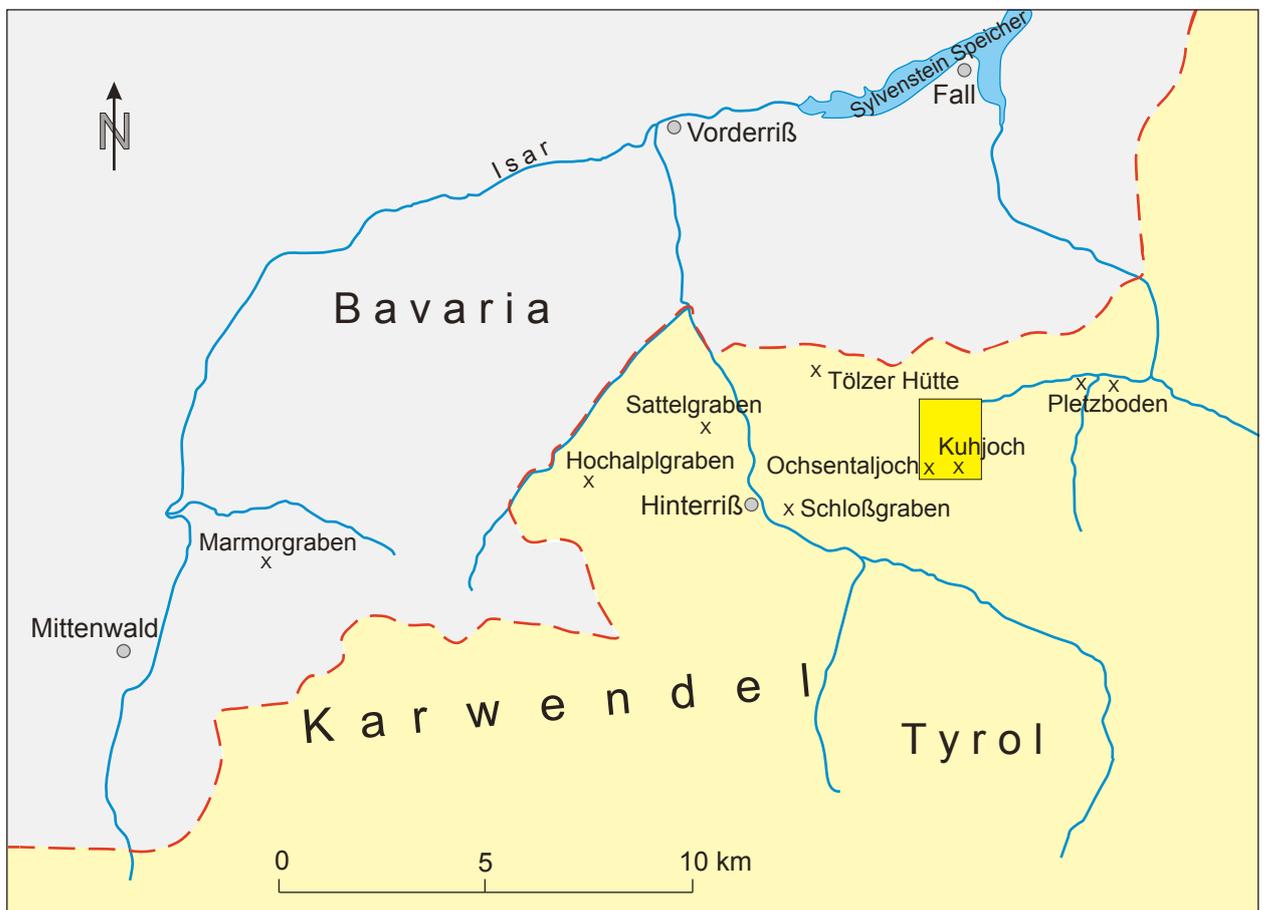


Fig. 2. Triassic - Jurassic boundary sections of the western Karwendel Syncline

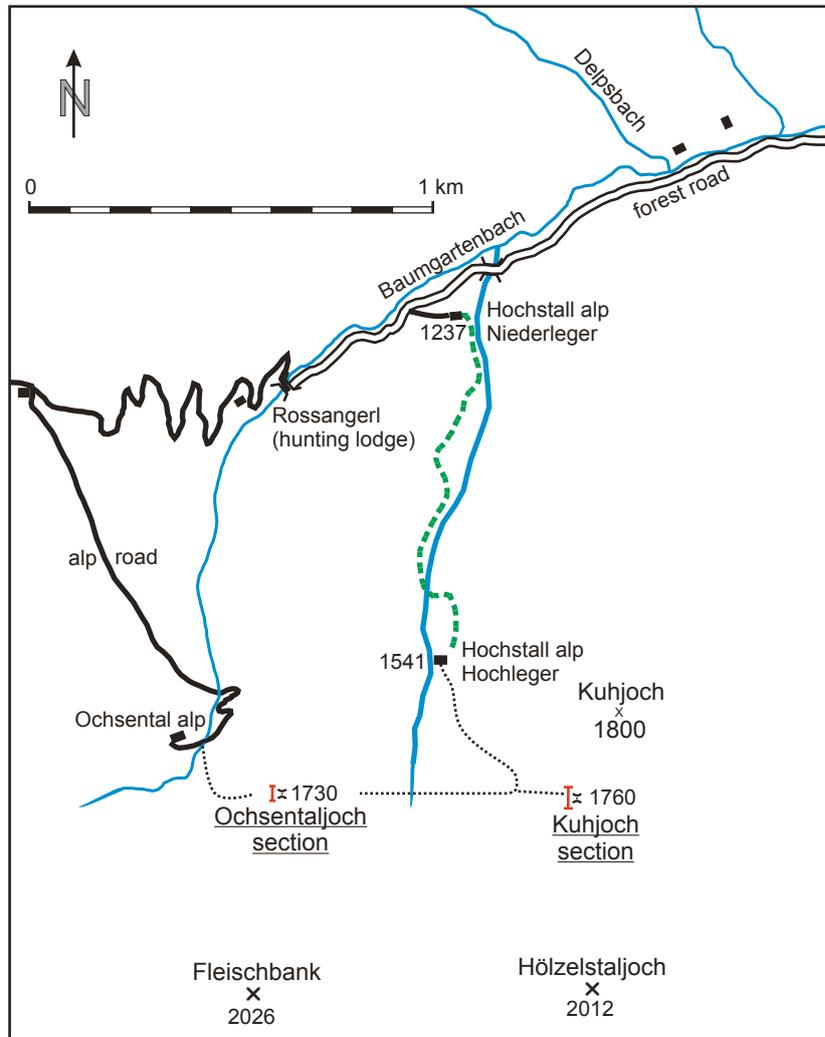


Fig. 3: Kuhjoch and Ochsentaljoch sections

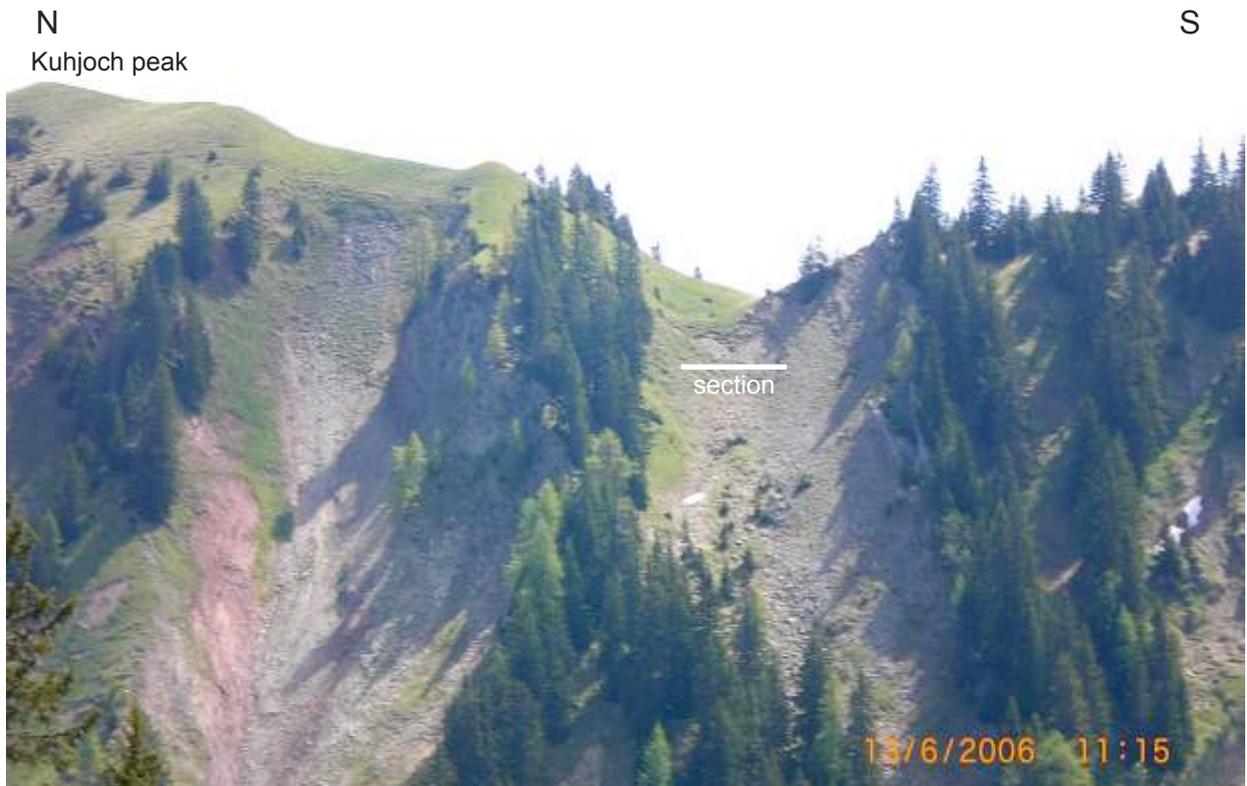


Fig. 4: Proposed Triassic - Jurassic section south of Kuhjoch

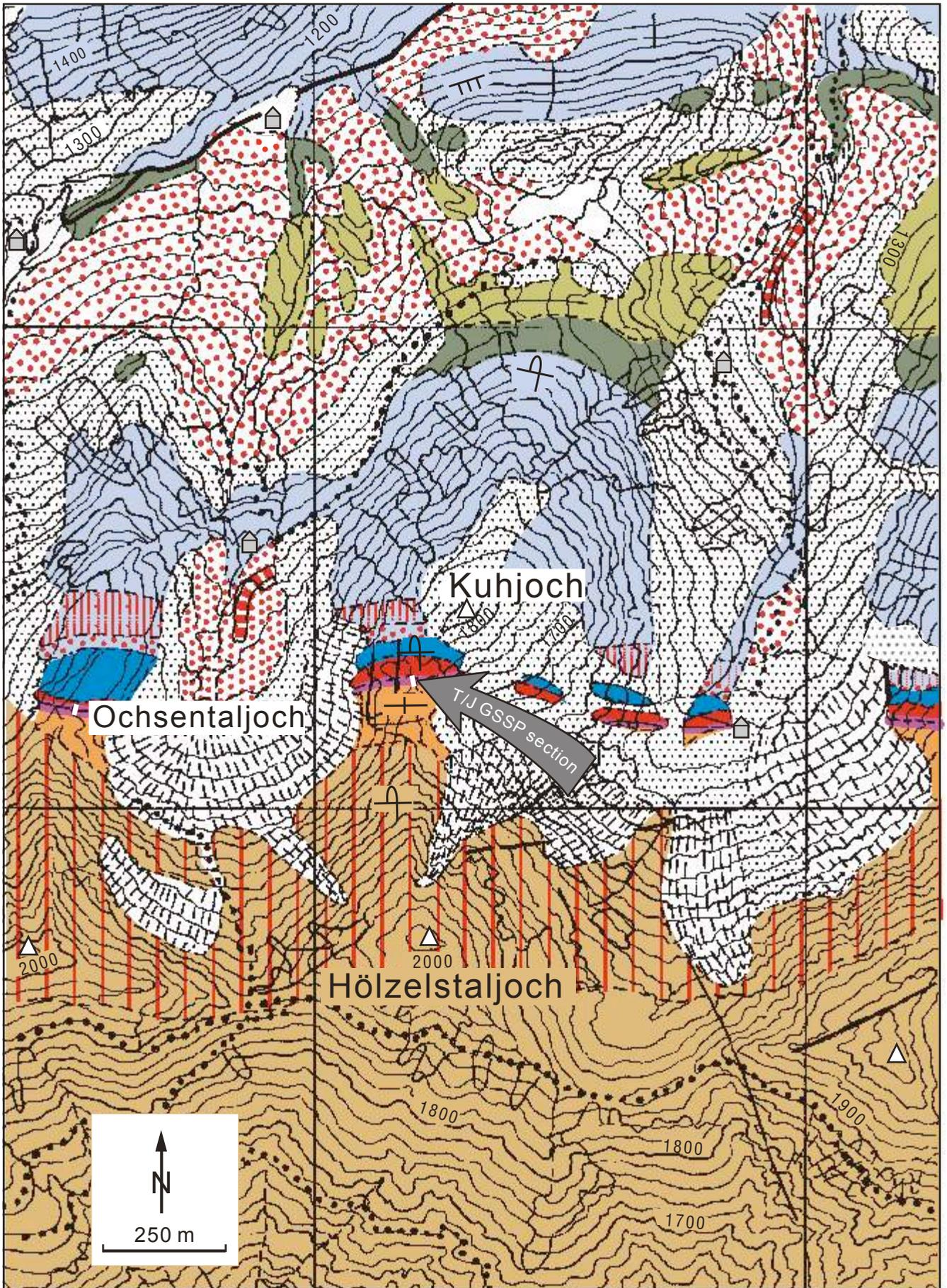
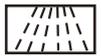
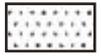


Fig. 5: Geological map Kuhjoch area (S. Schütz 1974)

Holocene

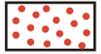


Alluvial cone

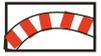


Talus

Pleistocene



Local moraine



Moraine wall

Cretaceous



Marls



Limestones

Schrambach Fm.

Early Cretaceous

Jurassic



Thick-bedded limestones



Limestones



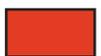
Siliceous limestones & marls



Radiolarite



Red & gray, spotted limestones & siliceous limestones



Red limestones



Marls (upper part with limestones)

Oberalm Fm.

Ruhpolding Fm.

Scheibelberg Fm.

Adnet Fm.

Enzesfeld L.

Kendlbach Fm.

Schattwald Beds

Sinemurian - ?Aalenian

Middle Jurassic

Late Jurassic

Hettangian

Rhaetian

Triassic



Marls and limestones

Koessen Fm.

Rhaetian



Thick-bedded limestones

Plattenkalk



Dolomite

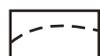
Hauptdolomit

Norian

Fault



Observed



Lithologic boundary



Supposed

Bedding: $\pi\pi$ 60° to 90° \perp vertical ∇ overturned

Fig.6: Caption of geological map Kuhjoch area



Fig. 7: Proposed stratotype section at Kuhjoch



Fig. 8: Boundary between overturned Eiberg Member (E.M.) and Tiefengraben Member (T.M.)

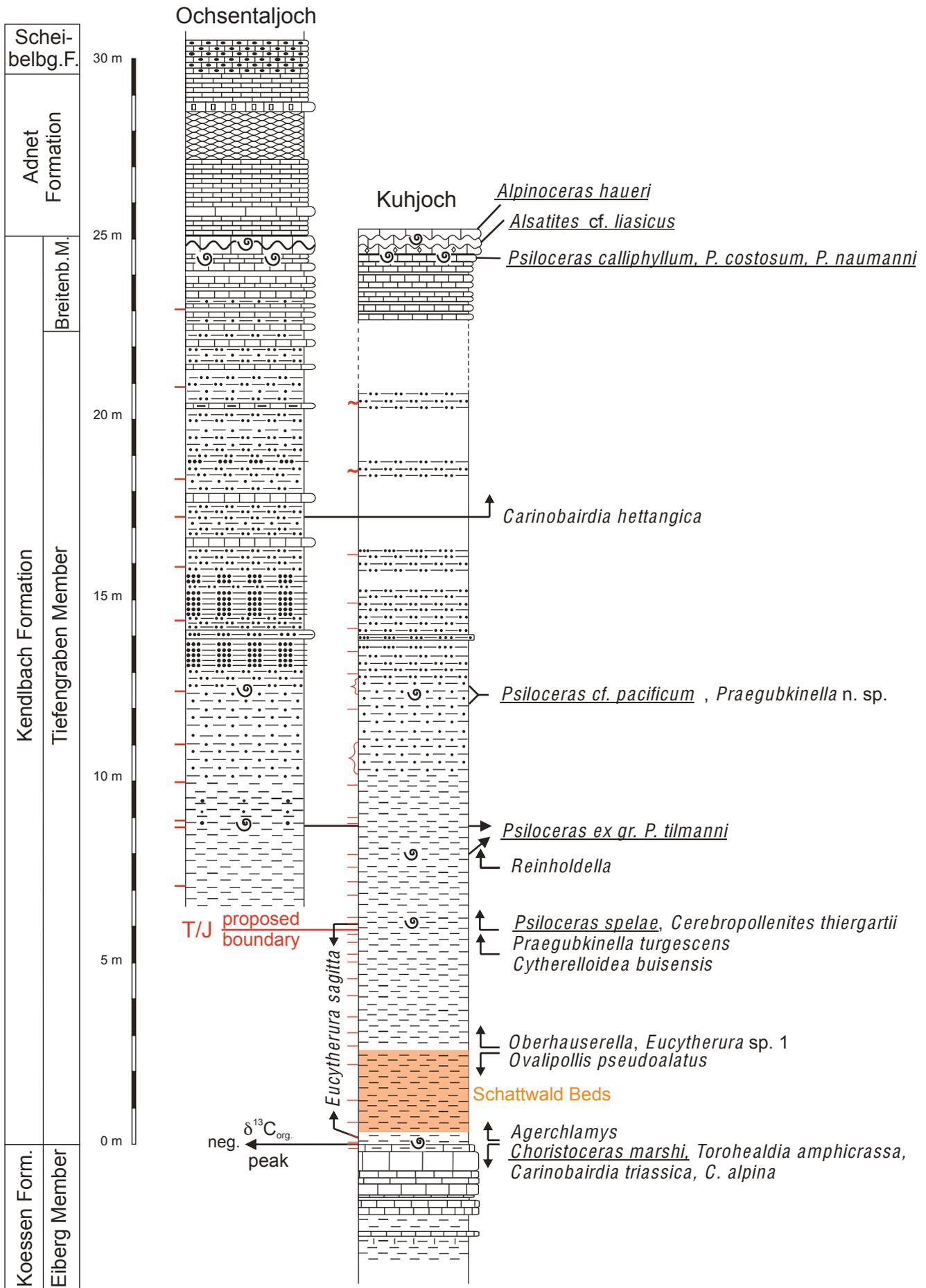


Fig. 9: First and last occurrences of biostratigraphic important fossils

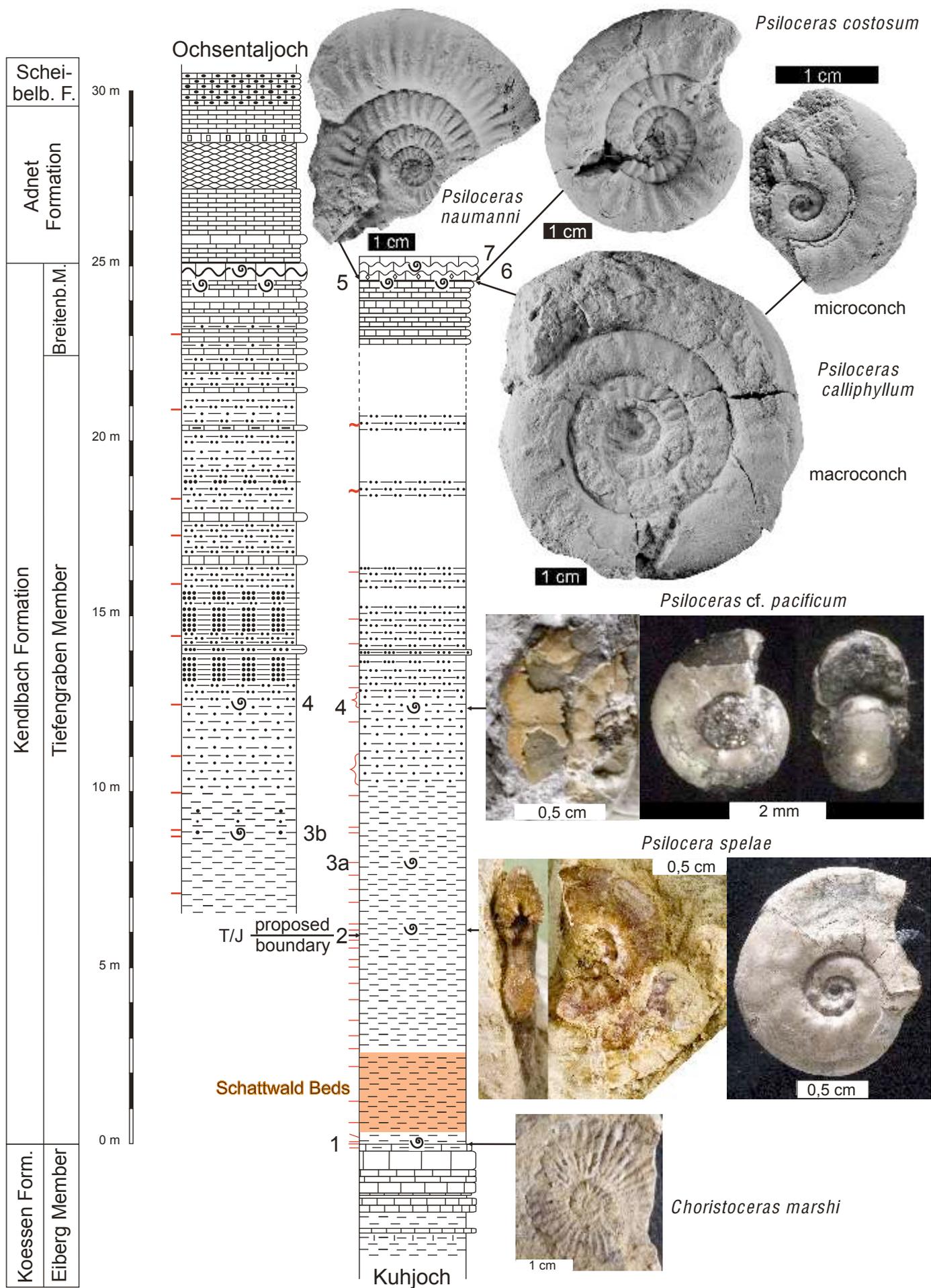


Fig. 10: Distribution of ammonites

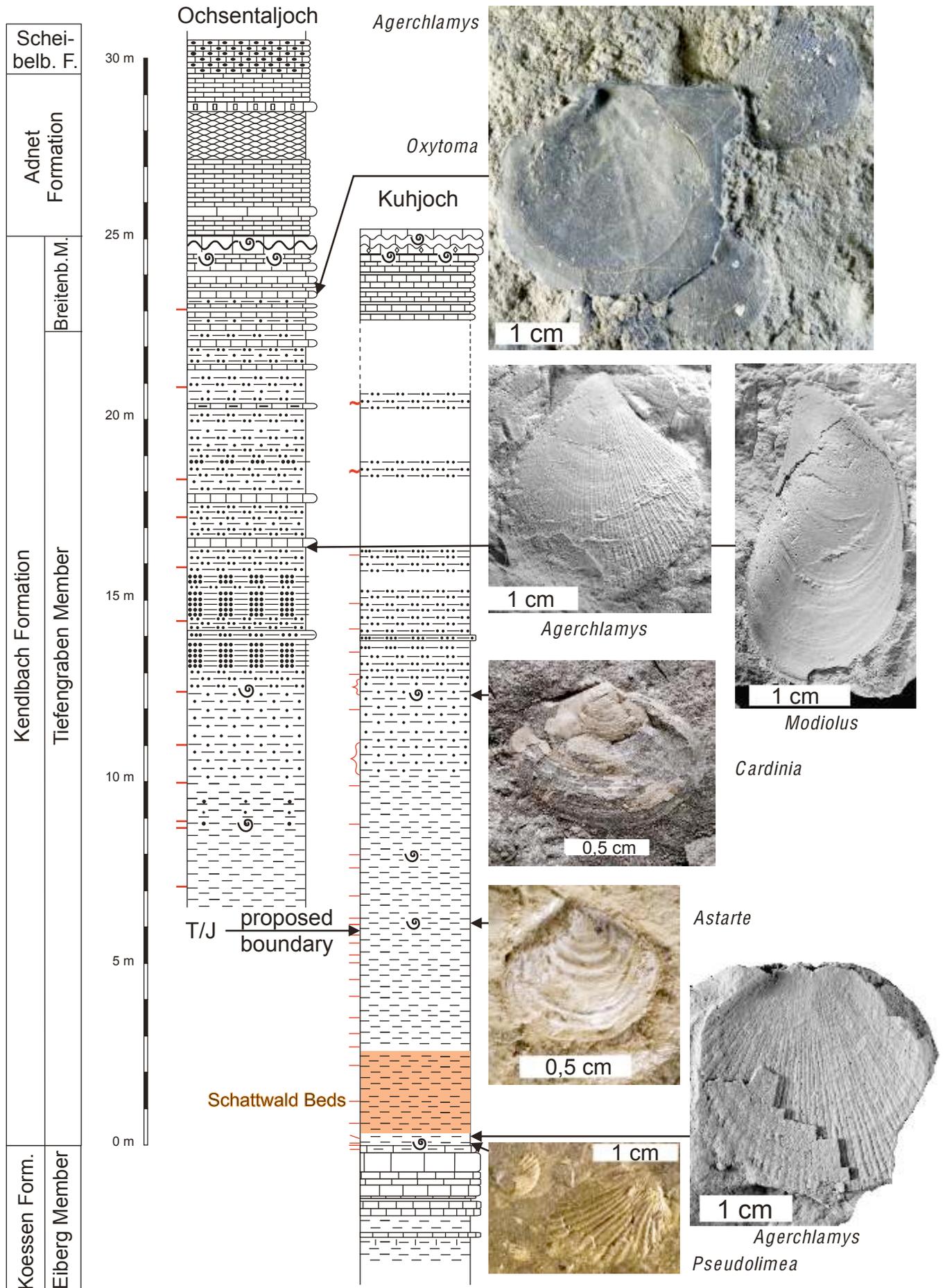


Fig. 11: Distribution of bivalves

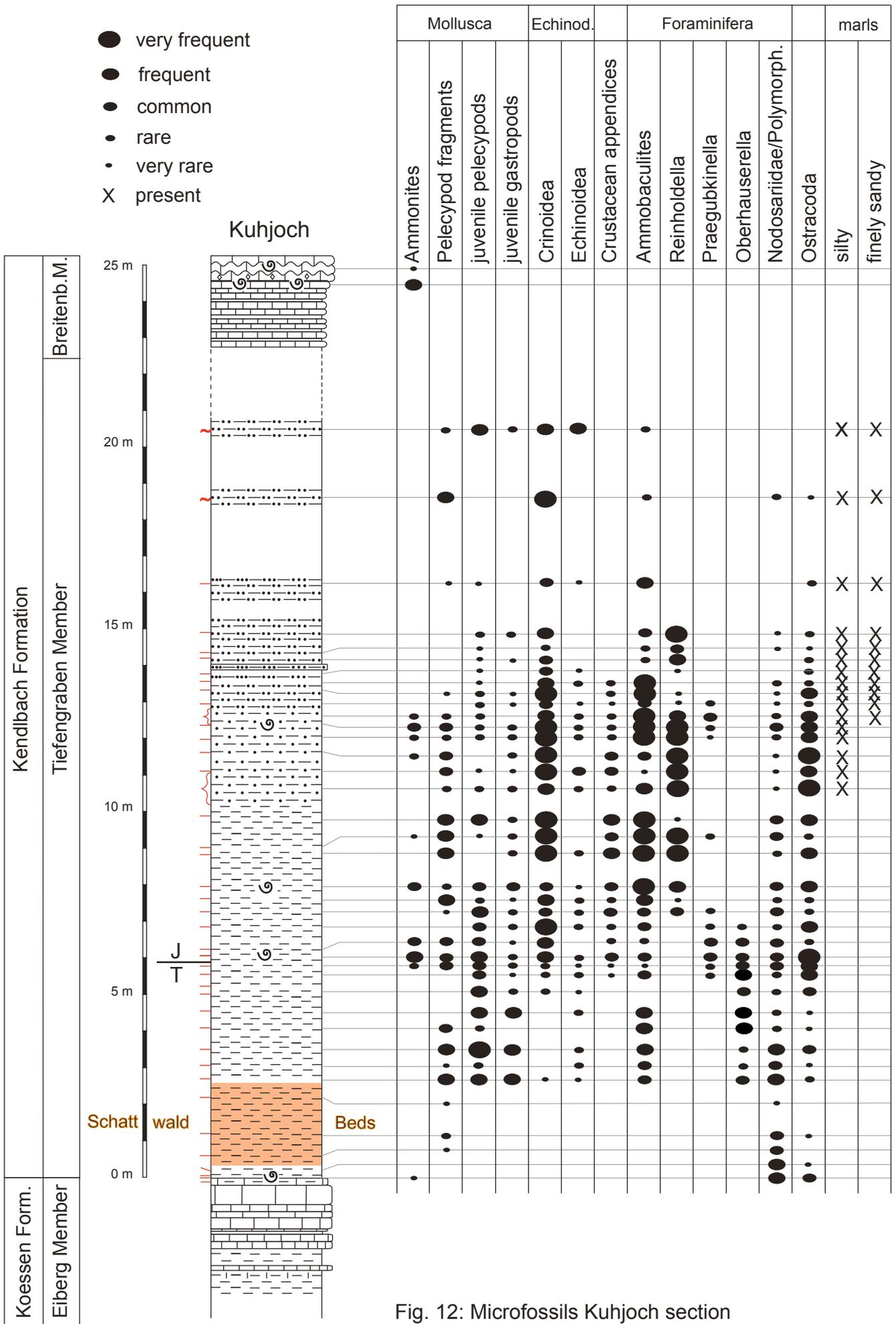


Fig. 12: Microfossils Kuhjoch section

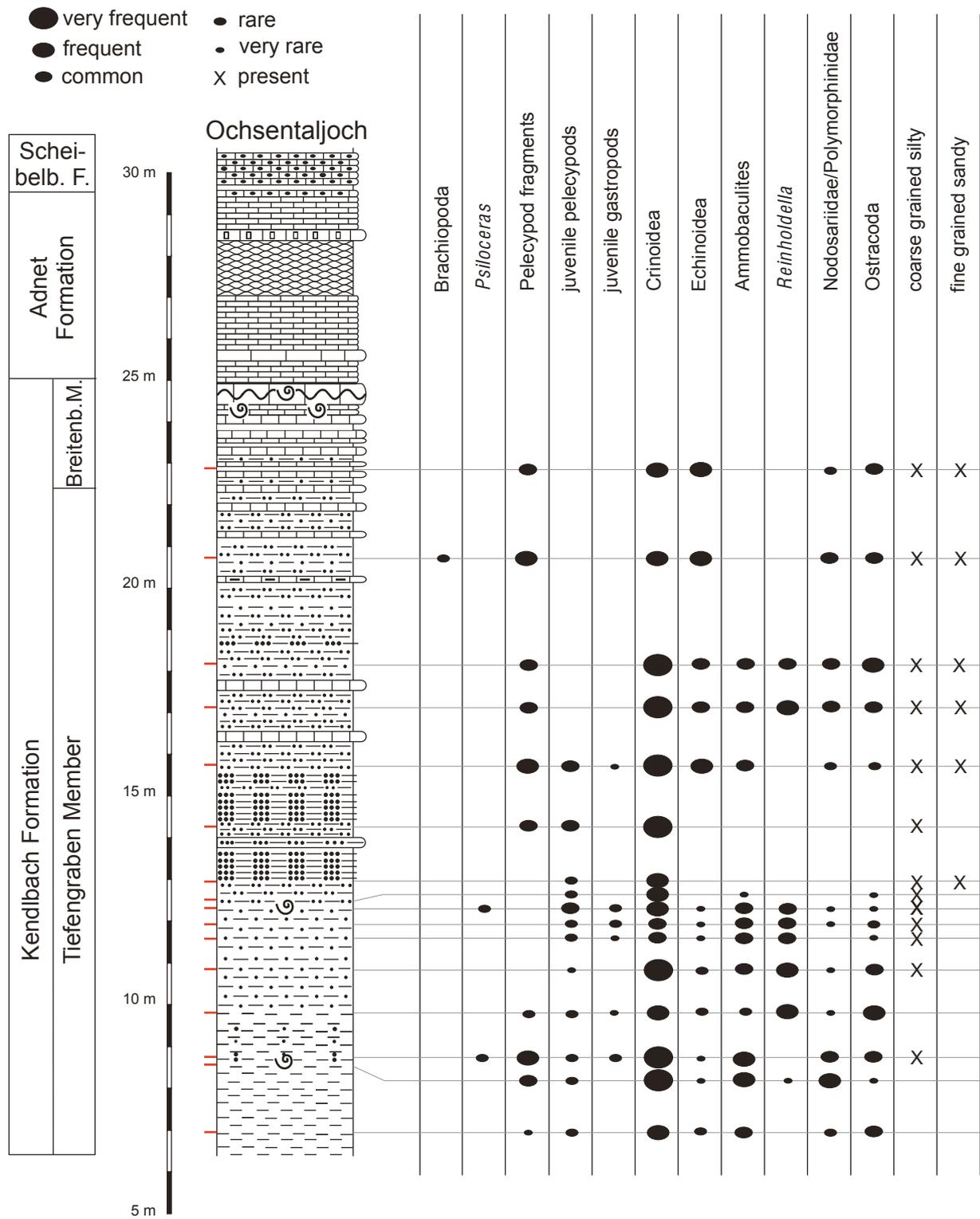


Fig. 13: Microfossils Ochsentäljoch section

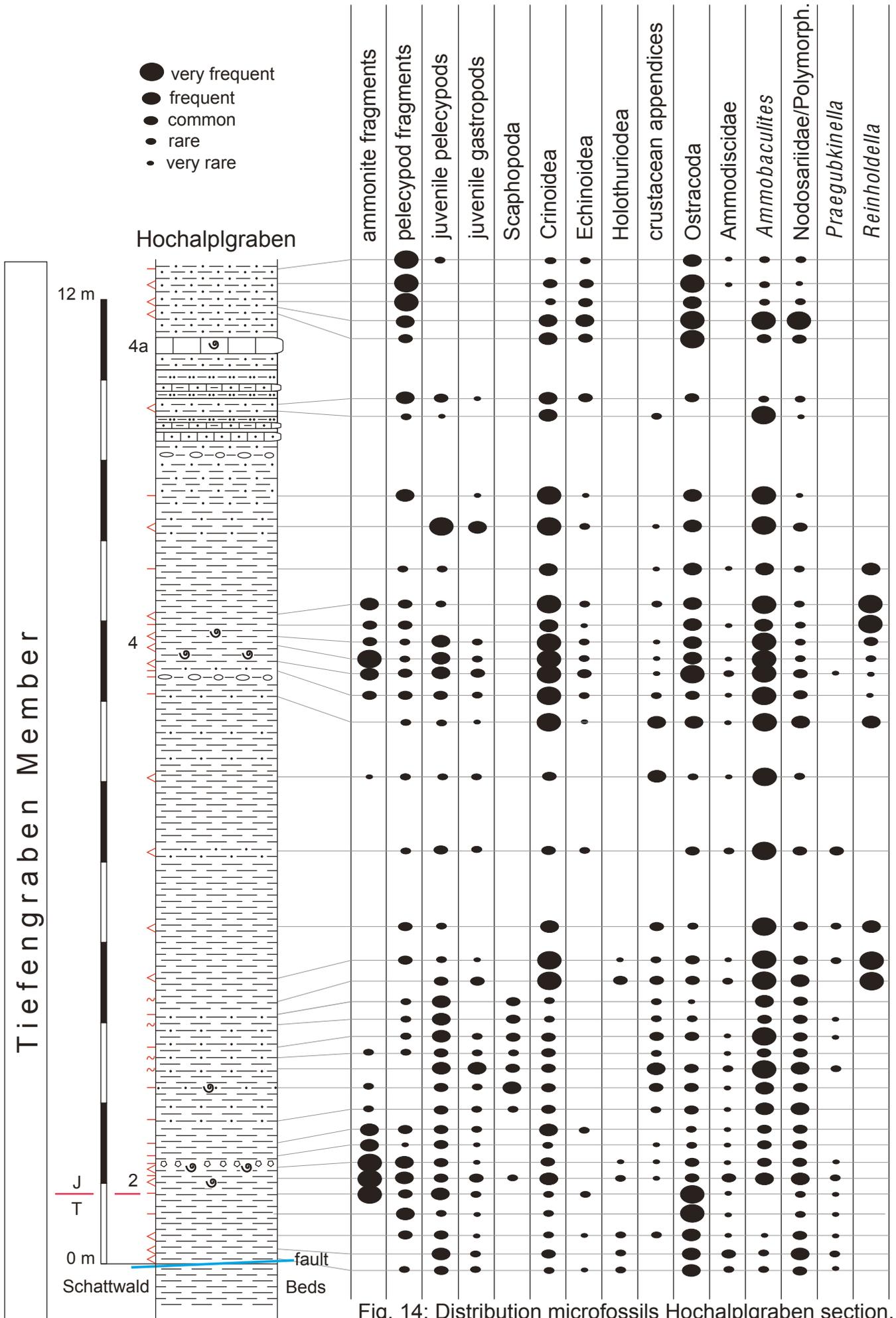


Fig. 14: Distribution microfossils Hochalplgraben section, 2 = level with *P. cf. spelaë*, 4 = level with *P. cf. pacificum*

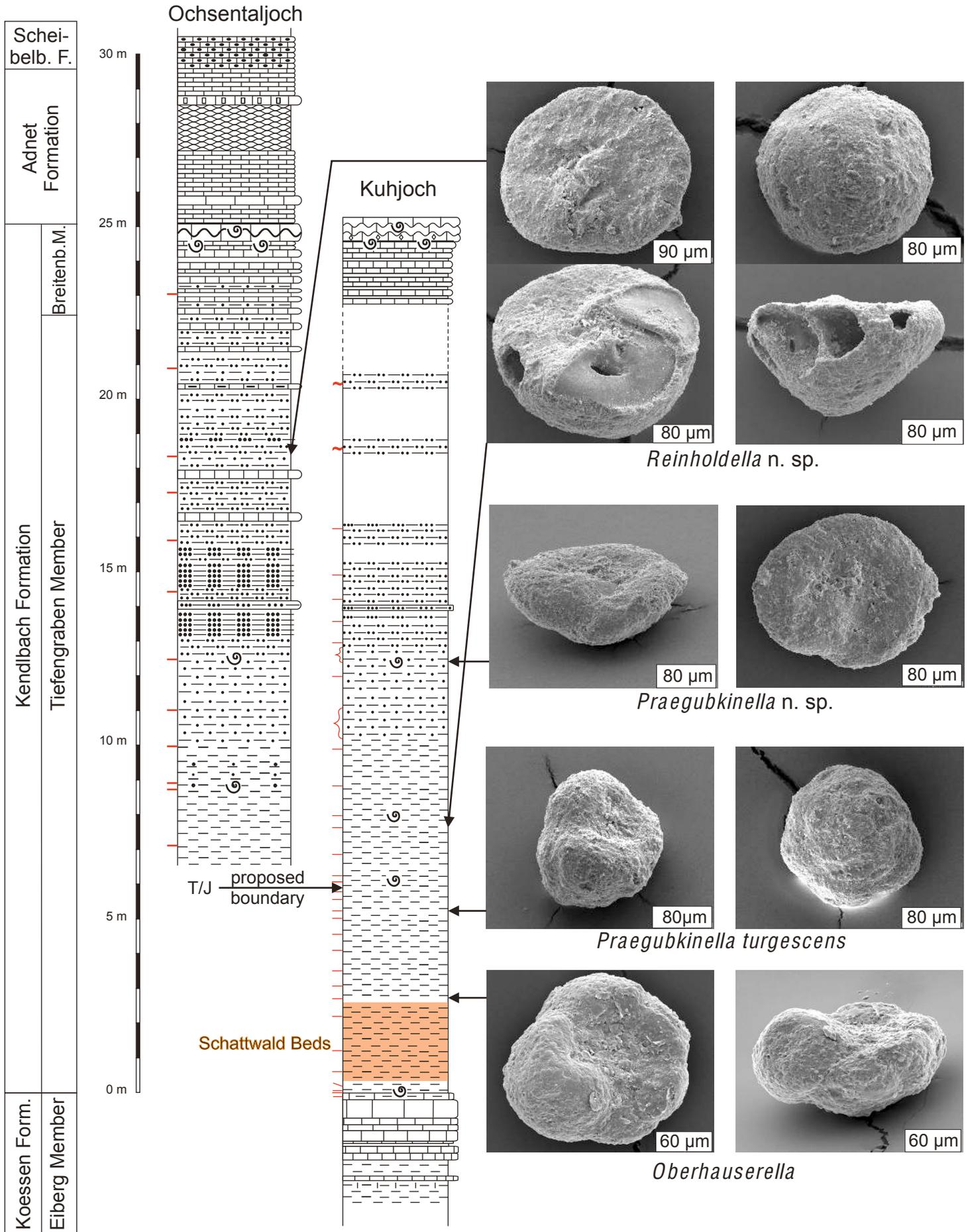


Fig. 15: Distribution of aragonitic Foraminifera

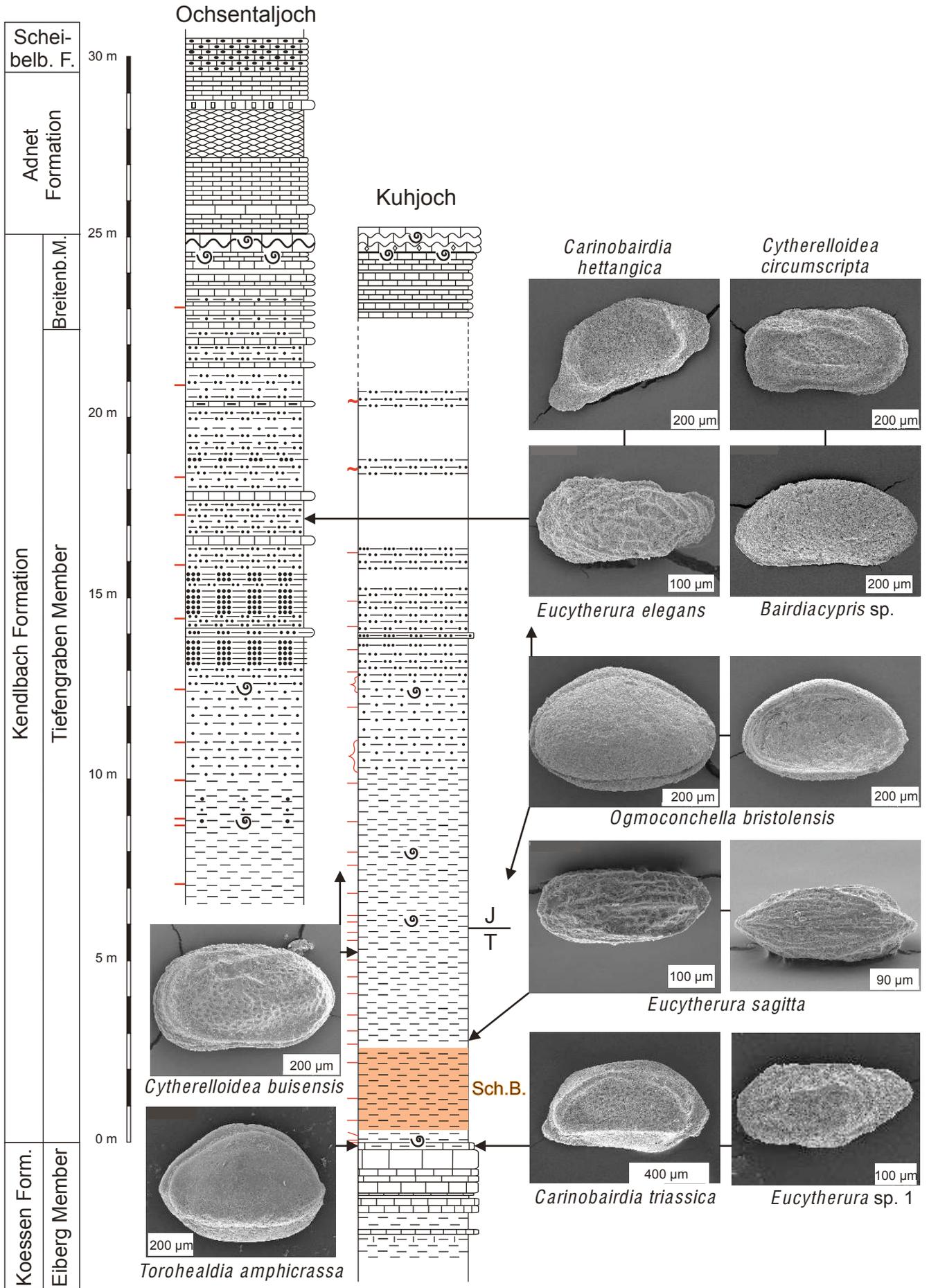


Fig. 16: Ostracodes Kuhjoch and Ochsentaljoch sections

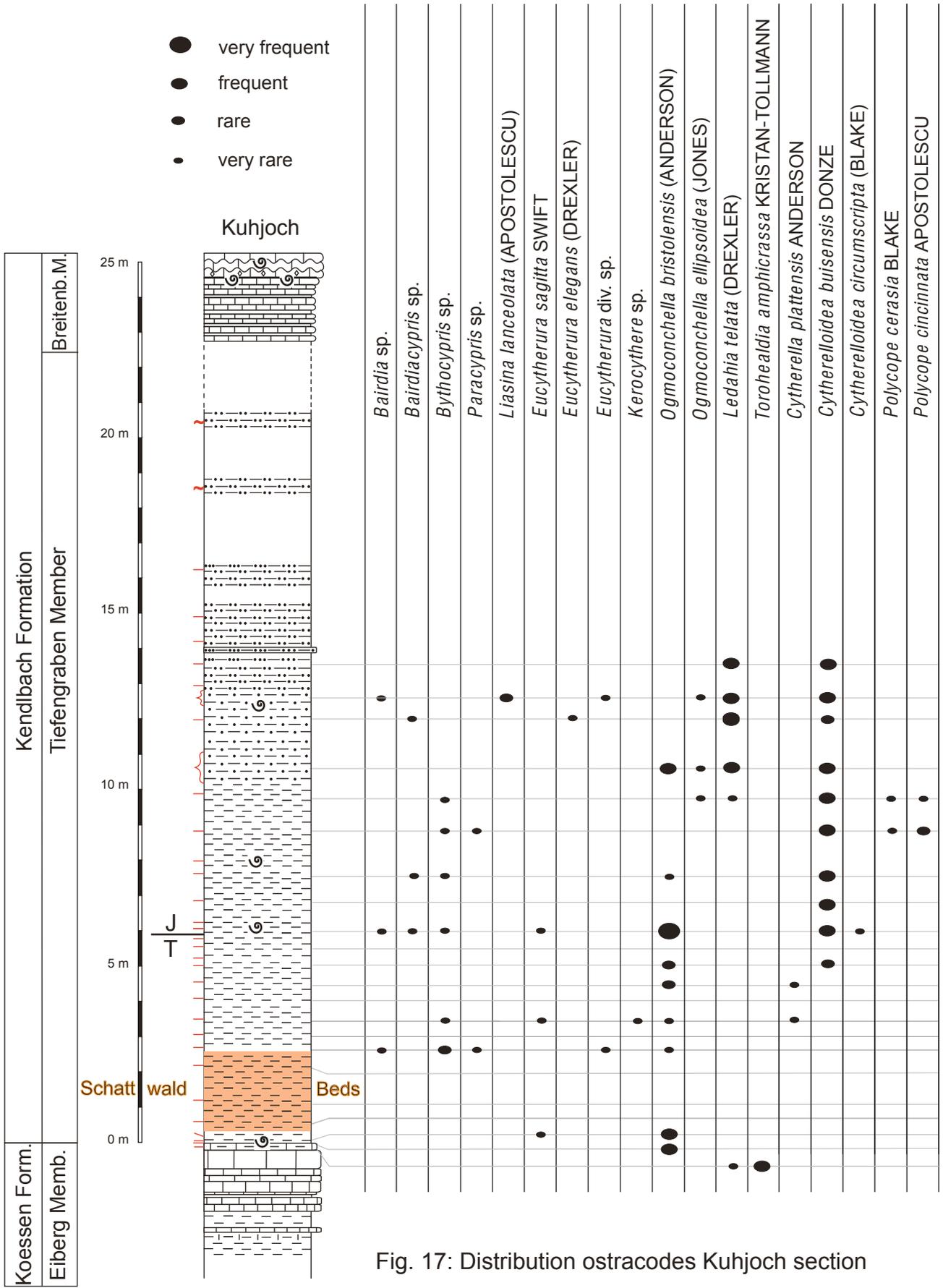


Fig. 17: Distribution ostracodes Kuhjoch section

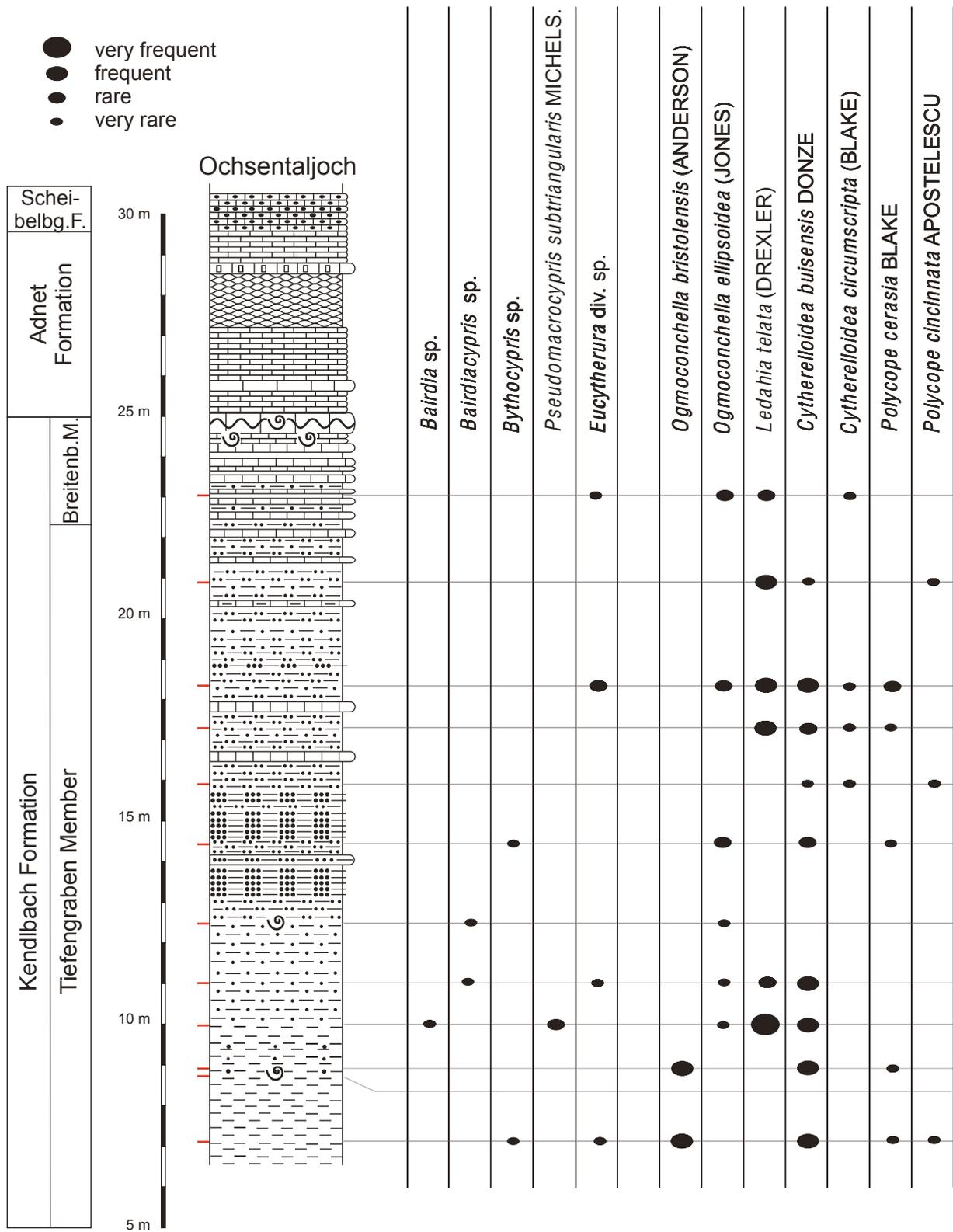


Fig. 18: Distribution ostracodes Ochsentäljoch section

Species abundance: A >10/field of view (FOV),
 C 1-10/FOV, F 1/2-10 FOV, R 1/11-100 FOV,
 ● several specimens only.
 Total nannofossil assemblage abundance:
 A >10%, F 0,1-1%, R <0,1%, VB virtually barren.
 Nannofossil preservation: G good, M moderate, P poor, R very poor

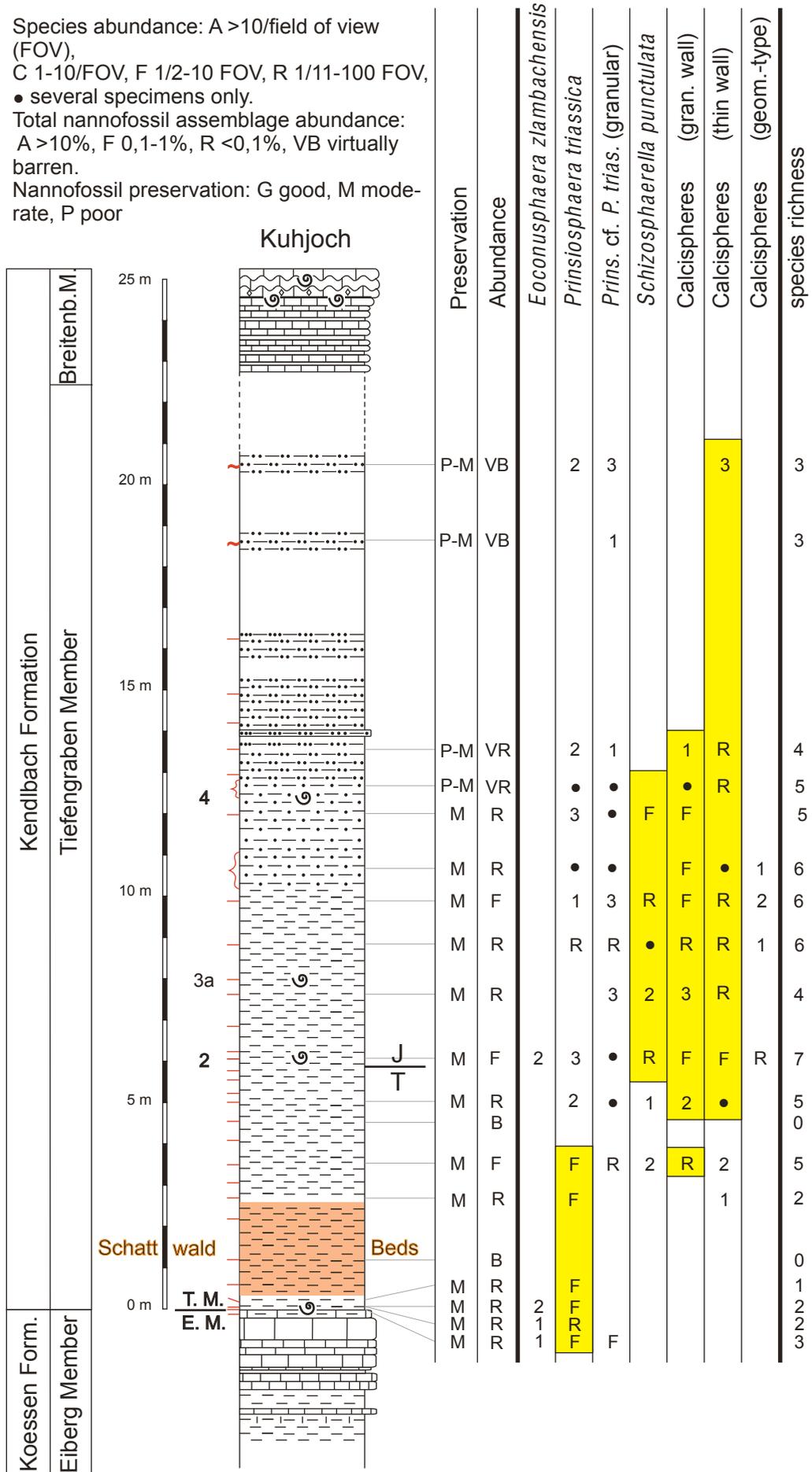


Fig. 19: Stratigraphic range chart for calcareous nannofossils from Kuhjoch.

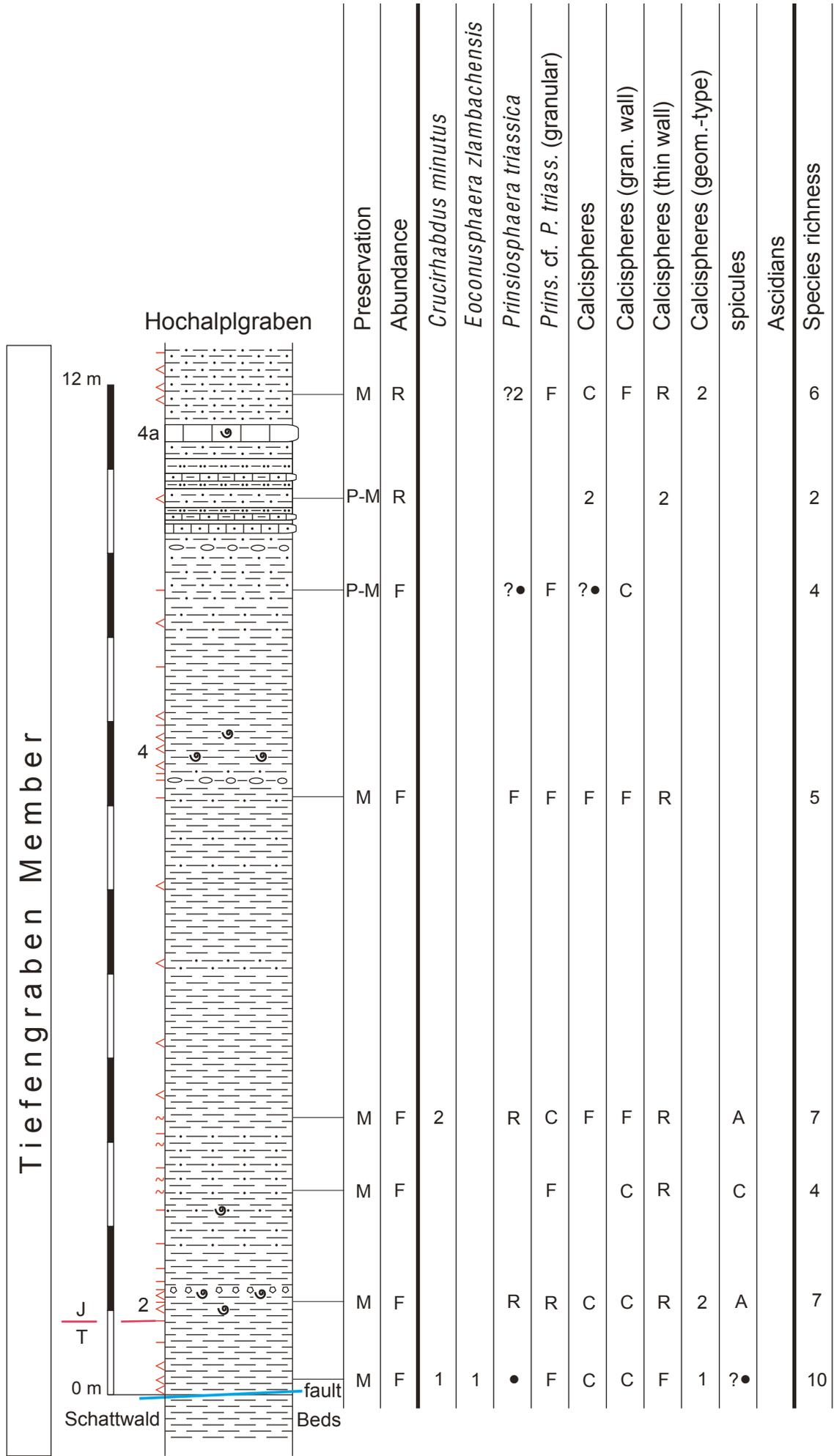


Fig. 20: Distribution nannofossils Hochalplgraben section

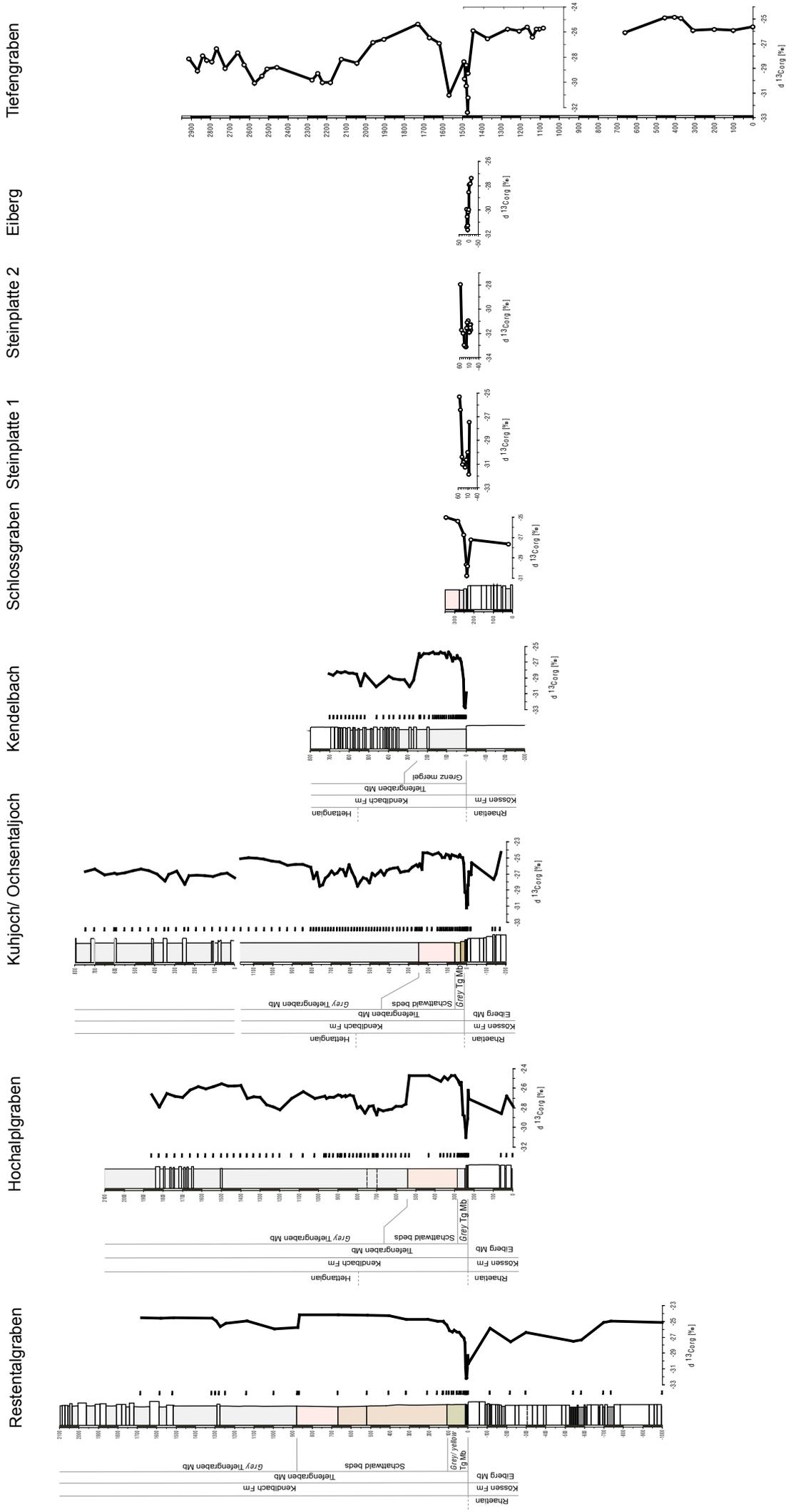


Fig. 21: delta13Corg Curves Eiberg - Tiefengraben Members Northern Calcareous Alps (RUHL et al., in prep.).

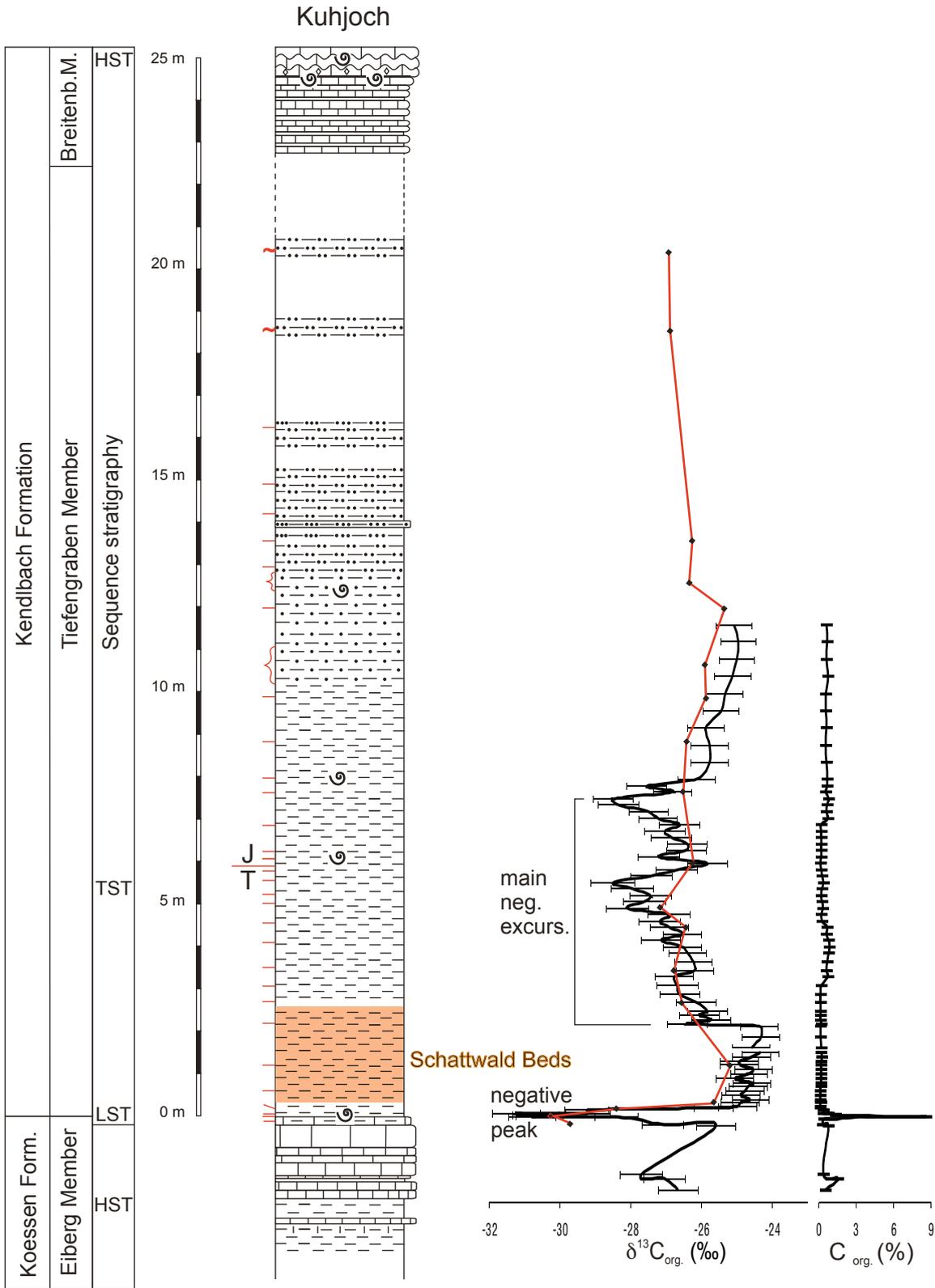


Fig. 22: Kuhjoch profile with $\delta^{13}C_{org.}$ and $C_{org.}$ Curves (RUHL et al., in prep.), red curve samples 2005

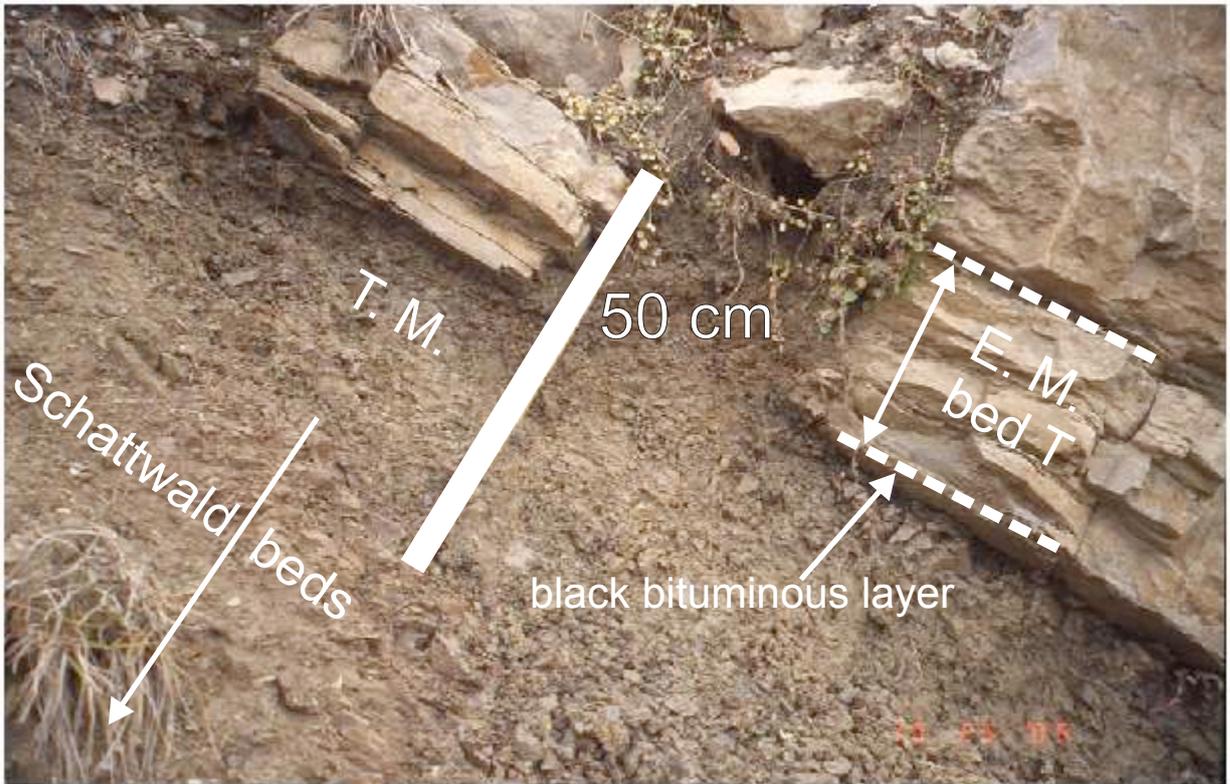


Fig. 23a: Boundary between Eiberg and Tiefengraben Members (Kuhjoch section)

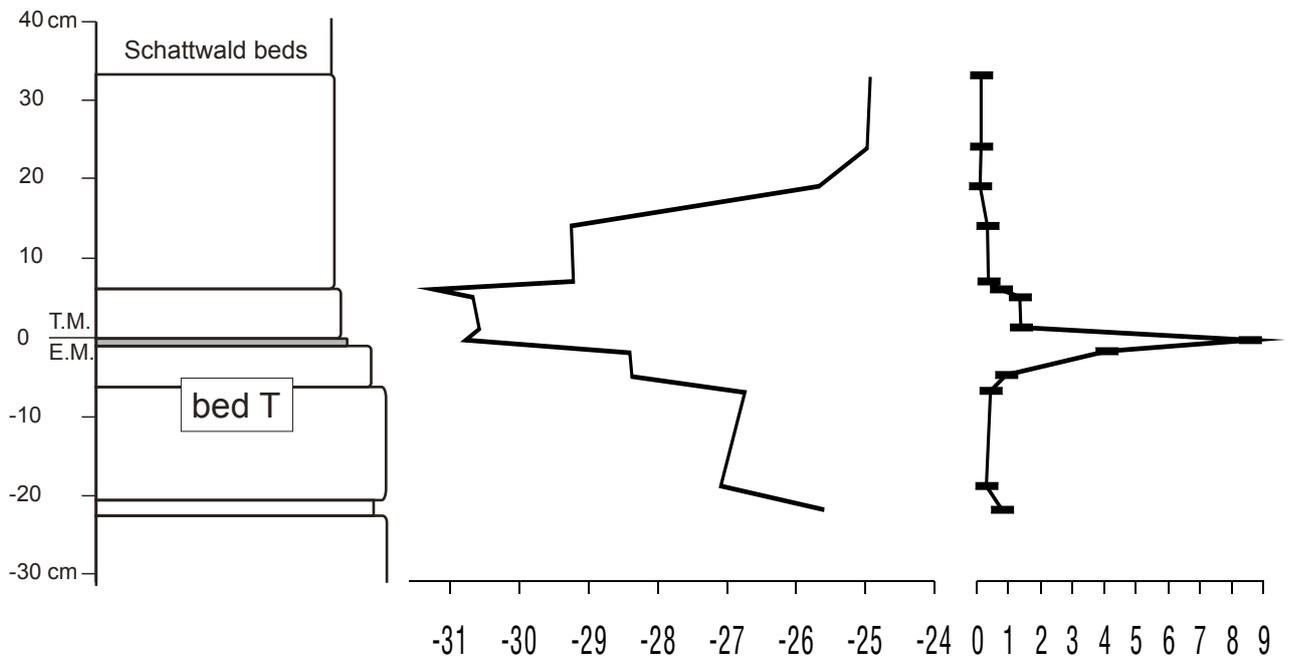


Fig. 23b: $\delta^{13}C_{org.}$ and $C_{org.}$ curves boundary Eiberg - Tiefengraben Members (Kuhjoch section) (RUHL et al., in prep.)

	Zones	Northern Calcareous Alps this paper	NW Europe (Great Britain) PAGE 2003 (modif.)	North America (Nevada) GUEx et al. 2004 (modif.)	South America (Chilingote) HILLEBRANDT 2000b(m.)
Lower Hettangian	Planorbis	P. naumanni	C. johnstoni	C. crassicostatum	P. cf. calliphylloides
		P. costosum + P. calliphylum	P. plicatum P. psilonotum P. planorbis	----- P. polymorphum	P. rectocostatum P. primocostatum P. planocostatum
	Neophyllites	Neophyllites P. erugatum	----- P. pacificum	----- P. tilmanni	
	Tilmanni	P. cf. pacificum P. ex gr. P. tilmanni Psiloc. spelae	?	P. marcouxii + Odog. ----- P. spelae	P. cf. tilm. + Odog. ----- P. cf. spelae
Rhaetian	Marshi	Choristoceras marshi		Choristoceras crickmayi	Ch. marshi + Ch. crickmayi

Fig. 24: Correlation of Early Hettangian ammonite zones, subzones and horizons (grey), broken lines approximated correlation.

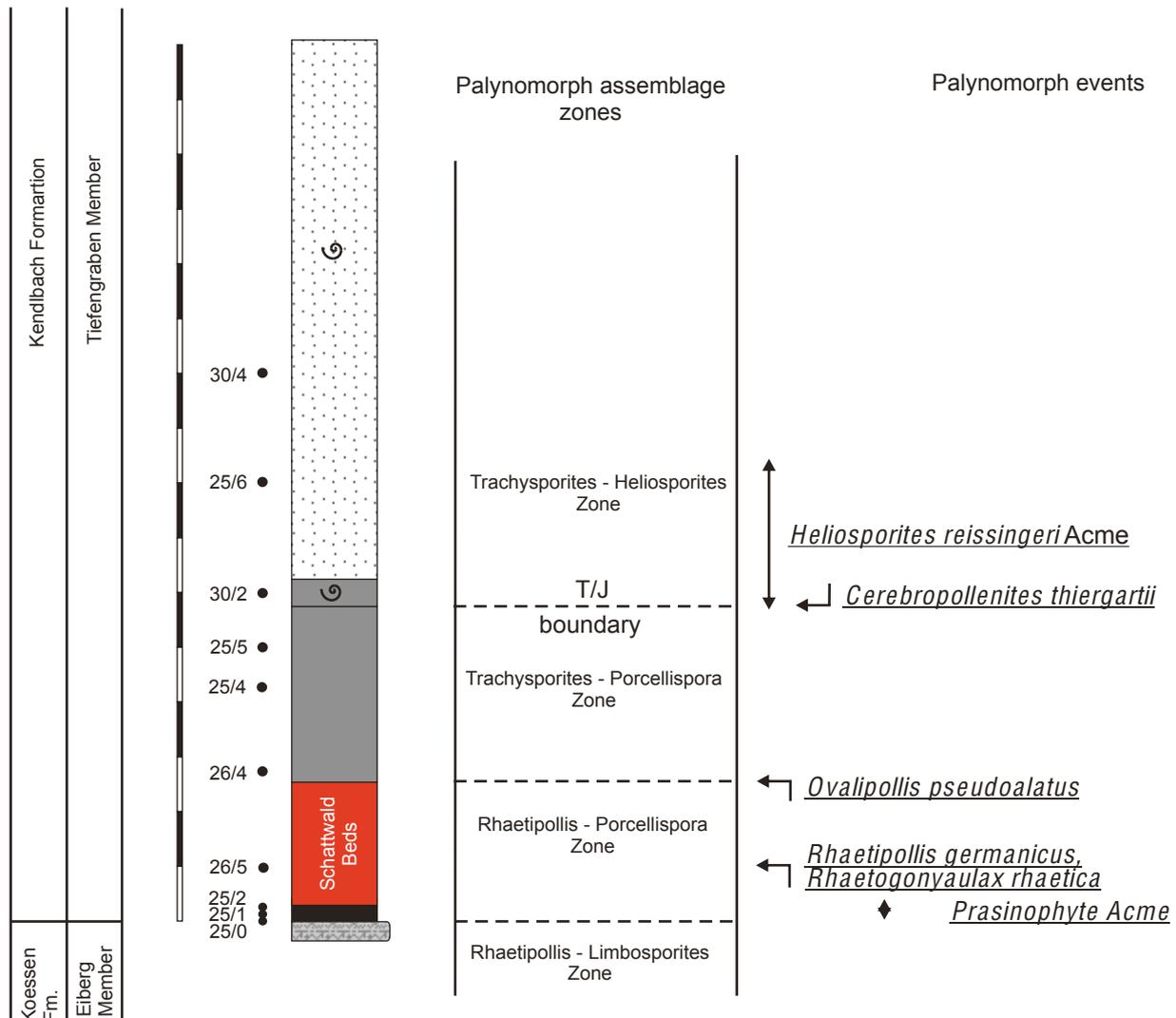


Fig. 25: Palynomorph distribution and assemblage zones Kuhjoch section

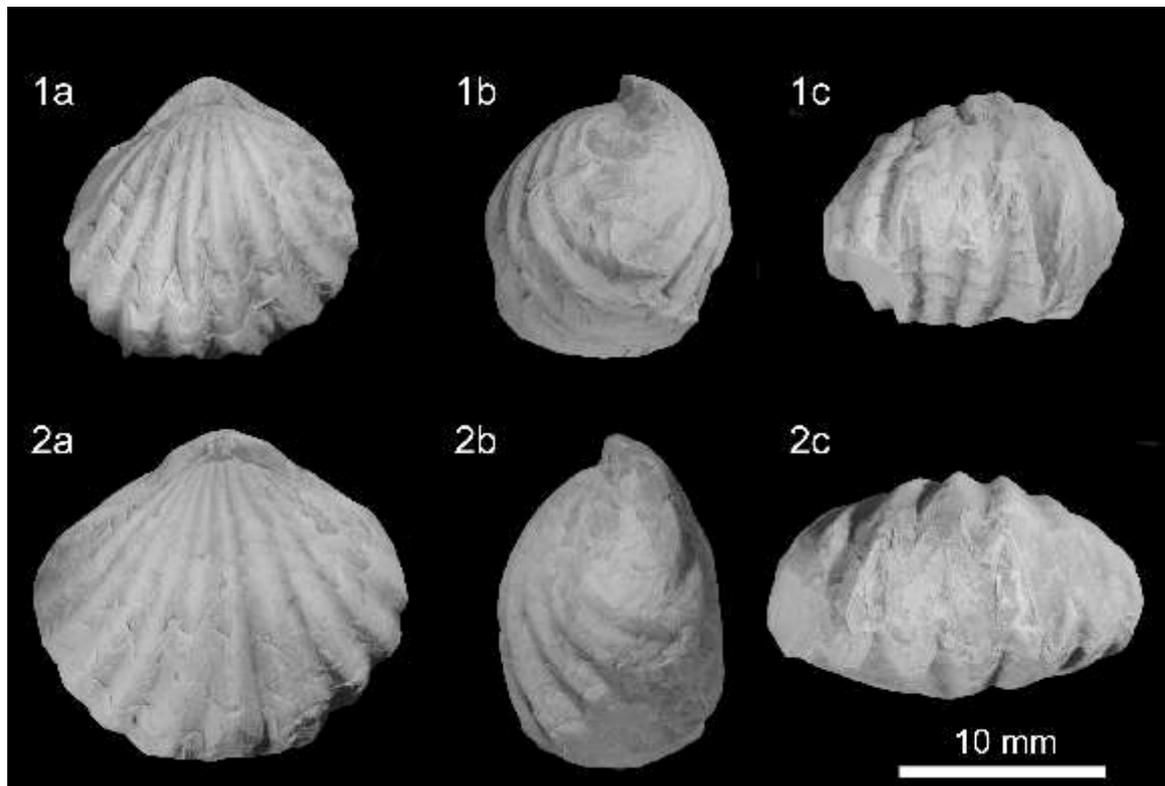


Fig. 26: Two specimens of *Tetrarhynchia inopinata* (Siblik, 1999) from the Ochsentäljoch section (a = dorsal, b = lateral view, c = anterior view).

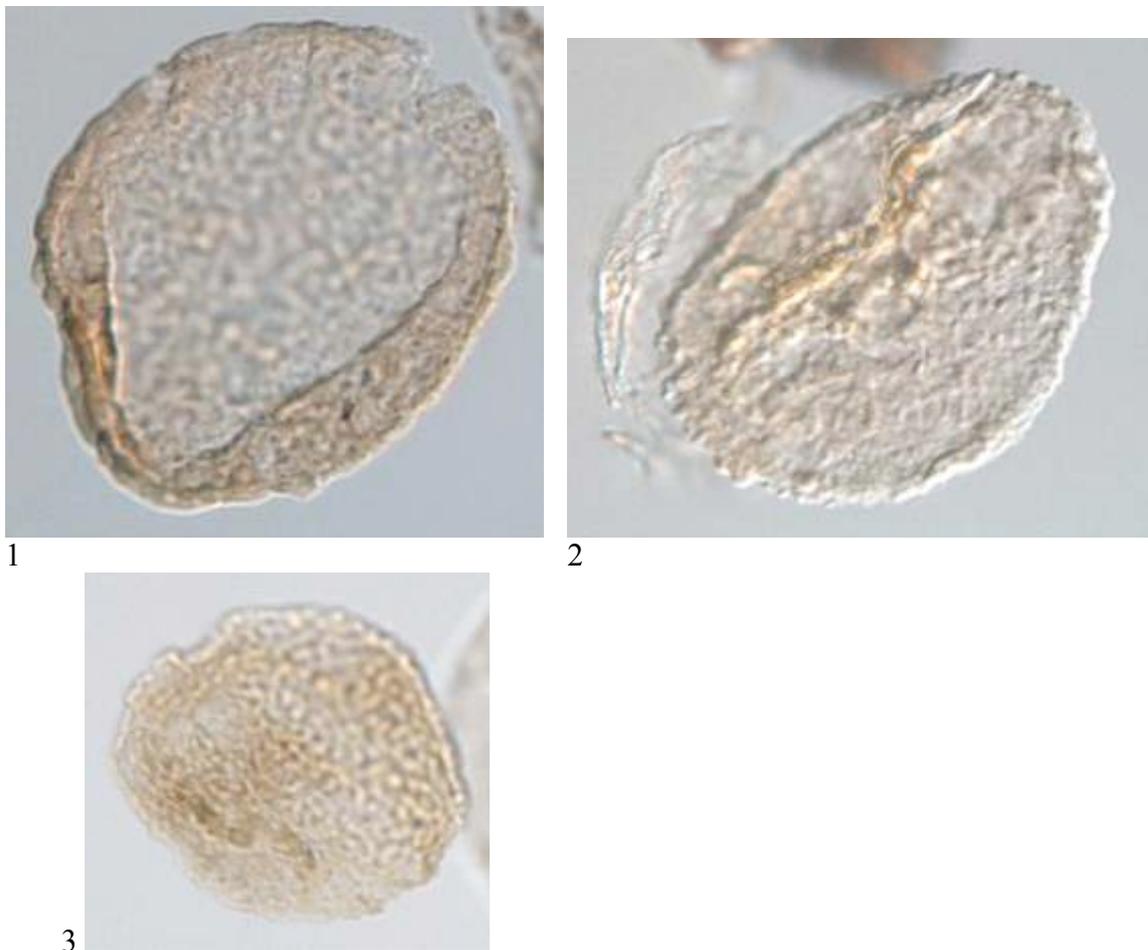


Fig. 27: palynomorphs, 3 specimen of *Cerebropollenites thiergartii* (1 = proximal view, 2= lateral view, 3 proximal view, magn all x750) from the Kuhjoch section Sample 30/2.

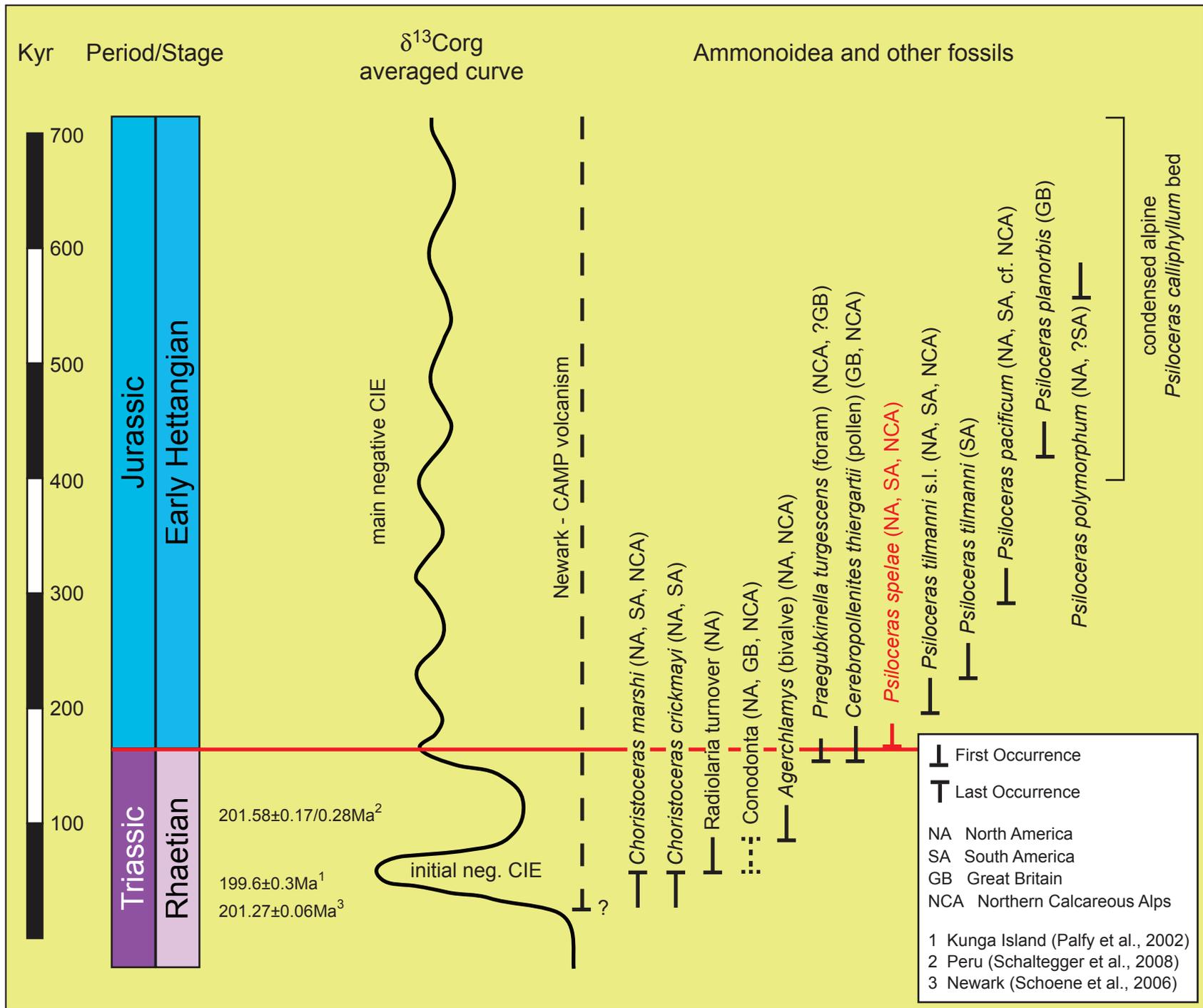


Fig. 28: Important T/J boundary markers, time scale according to A. Jeram (unpublished diagram).

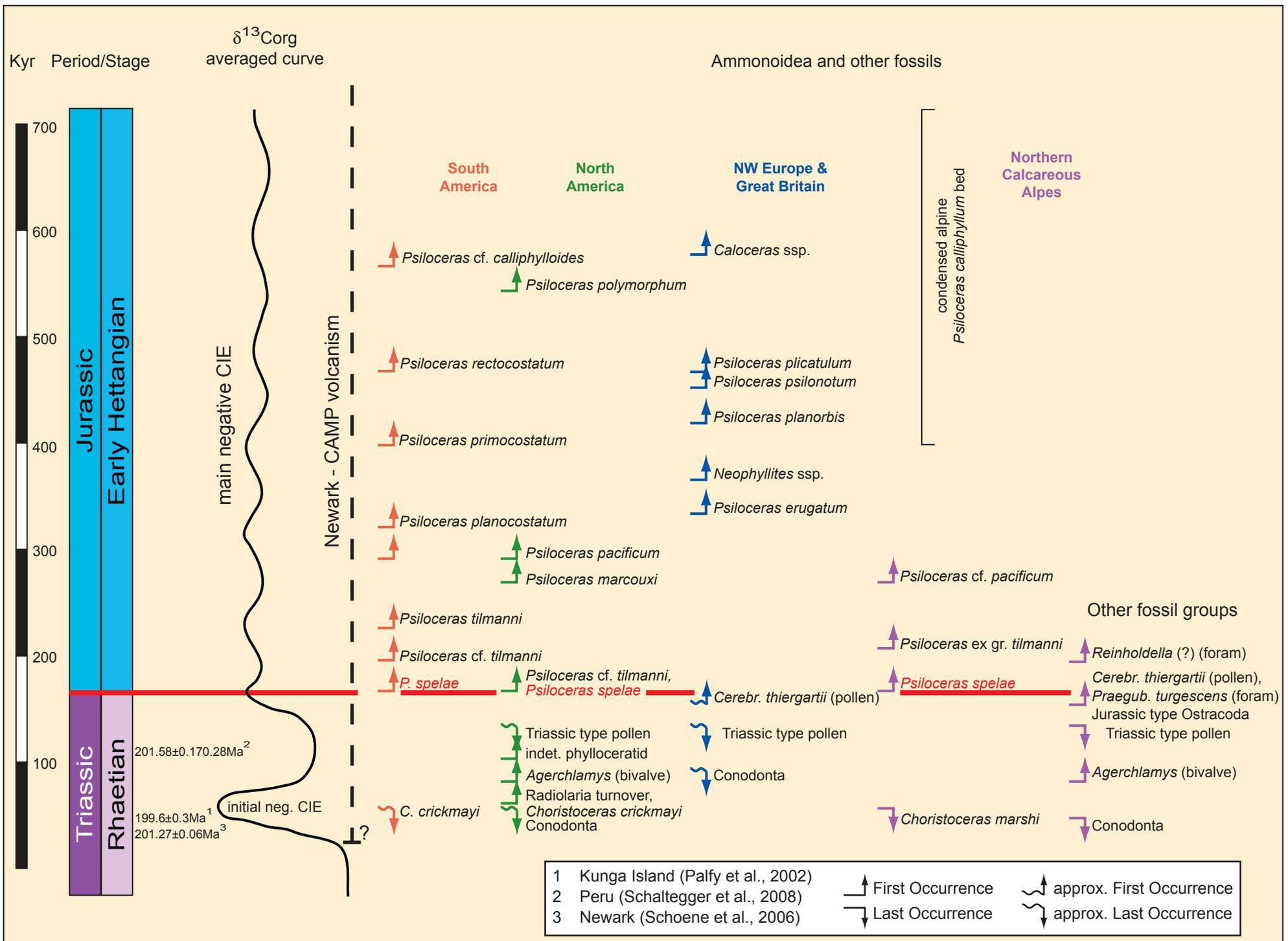


Fig. 29: Correlation of T/J boundary markers from different faunal provinces, time scale according to A. Jeram (unpublished diagram).

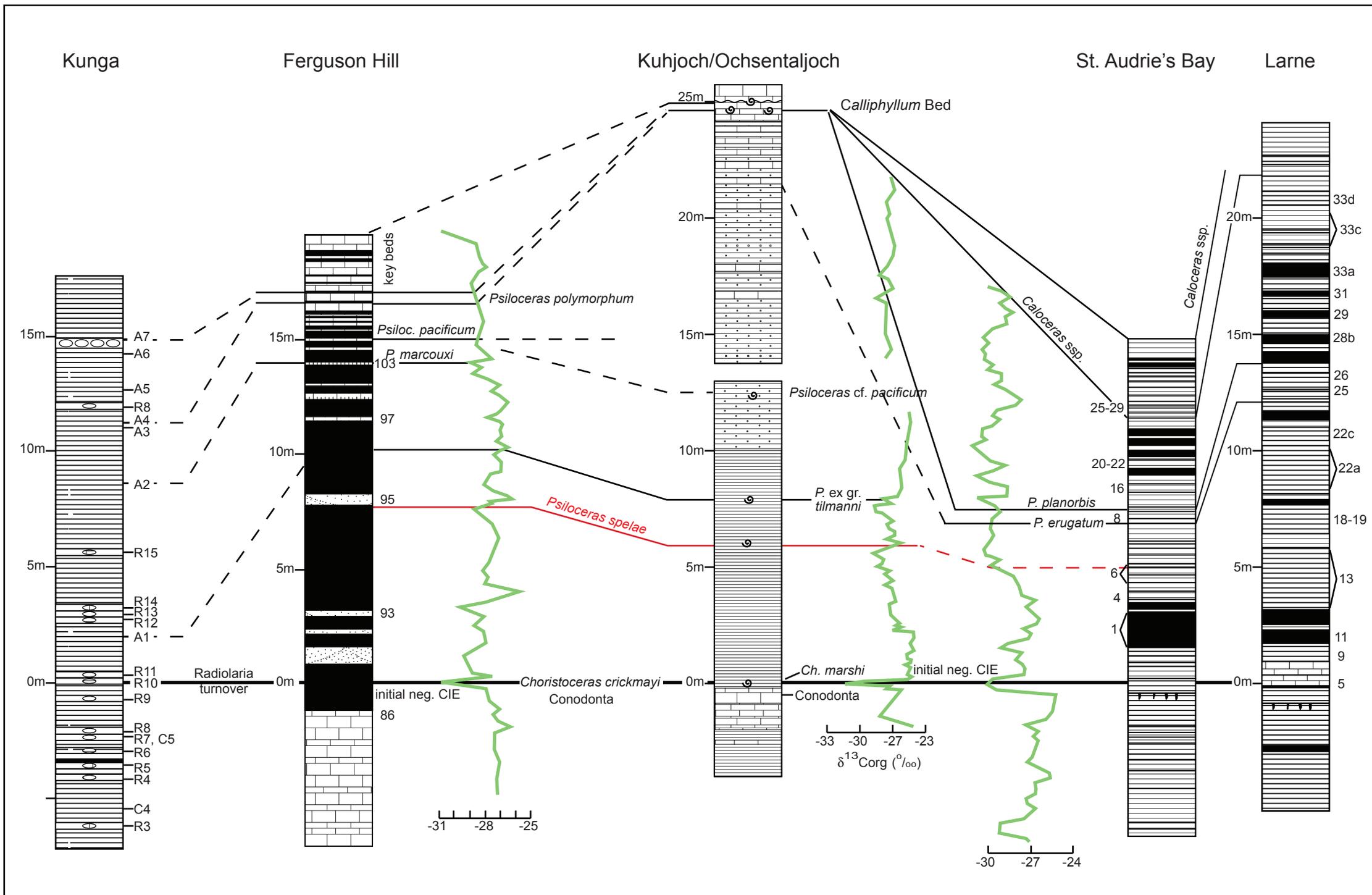


Fig. 30: Correlation of proposed T/J boundary stratigraphic sections and $\delta^{13}\text{C}_{\text{org}}$ curves (all with the same vertical scale).

Supplementary plates with *Psiloceras spelae* GUEX, *Psiloceras cf. pacificum* GUEX and ?*Juraphyllites* from the Karwendel syncline (Northern Calcareous Alps, Tyrol, Austria) and *Psiloceras pacificum* (Nevada) and *Euphyllites struckmanni* (Zlambach beds, NCA).

Axel von Hillebrandt

Plate 1

Figs. 1–10. *Psiloceras spelae* GUEX.

Hochalplgraben near Hinterriss (Karwendel mountains, Tyrol, Austria); ammonite level 2 (Fig. 12); with aragonitic shell, in part with part of body chamber.

Plate 2

Figs. 1–12. *Psiloceras spelae* GUEX.

Hochalplgraben near Hinterriss (Karwendel mountains, Tyrol, Austria); ammonite level 2 (Fig. 12); with aragonitic shell.

1, 2, 4: with end of body chamber; 11, 12: end of body chamber.

Plate 3

Figs. 1–9. *Psiloceras spelae* GUEX.

Figs. 1–3, 7, 8: Hochalplgraben near Hinterriss (Karwendel mountains, Tyrol, Austria); ammonite level 2 (Fig. 12); 1-3 with shell.

Figs. 7, 8: Anaptychus.

Figs. 4, 6: Kuhjoch near Fall (Karwendel mountains, Tyrol, Austria); ammonite level 2 (Fig. 8); inner cast, phragmocone (with suture line) and part of body chamber.

Figs. 5, 9: Schlossgraben near Hinterriss (Karwendel mountains, Tyrol, Austria); 5: inner cast, phragmocone (with suture line) and part of body chamber; 9: Protoconch.

Fig. 10: *Psiloceras pacificum* GUEX.

New York Canyon (Nevada, U.S.A.), Pacificum Zone; with calcified shell.

Figs. 11–14: *Psiloceras cf. pacificum* GUEX.

Hochalplgraben near Hinterriss (Karwendel mountains, Tyrol, Austria); ammonite level 4 (Fig. 12); with aragonitic shell.

Fig. 15: ?*Juraphyllites* sp.

Hochalplgraben near Hinterriss (Karwendel mountains, Tyrol, Austria); ammonite level 2 (Fig. 12); inner mould.

Fig. 16: *Euphyllites struckmanni* (NEUMAYR).

Zlambach Graben near Goisern (Austria), probably Calliphyllym Zone; with aragonitic shell.

Plate 1

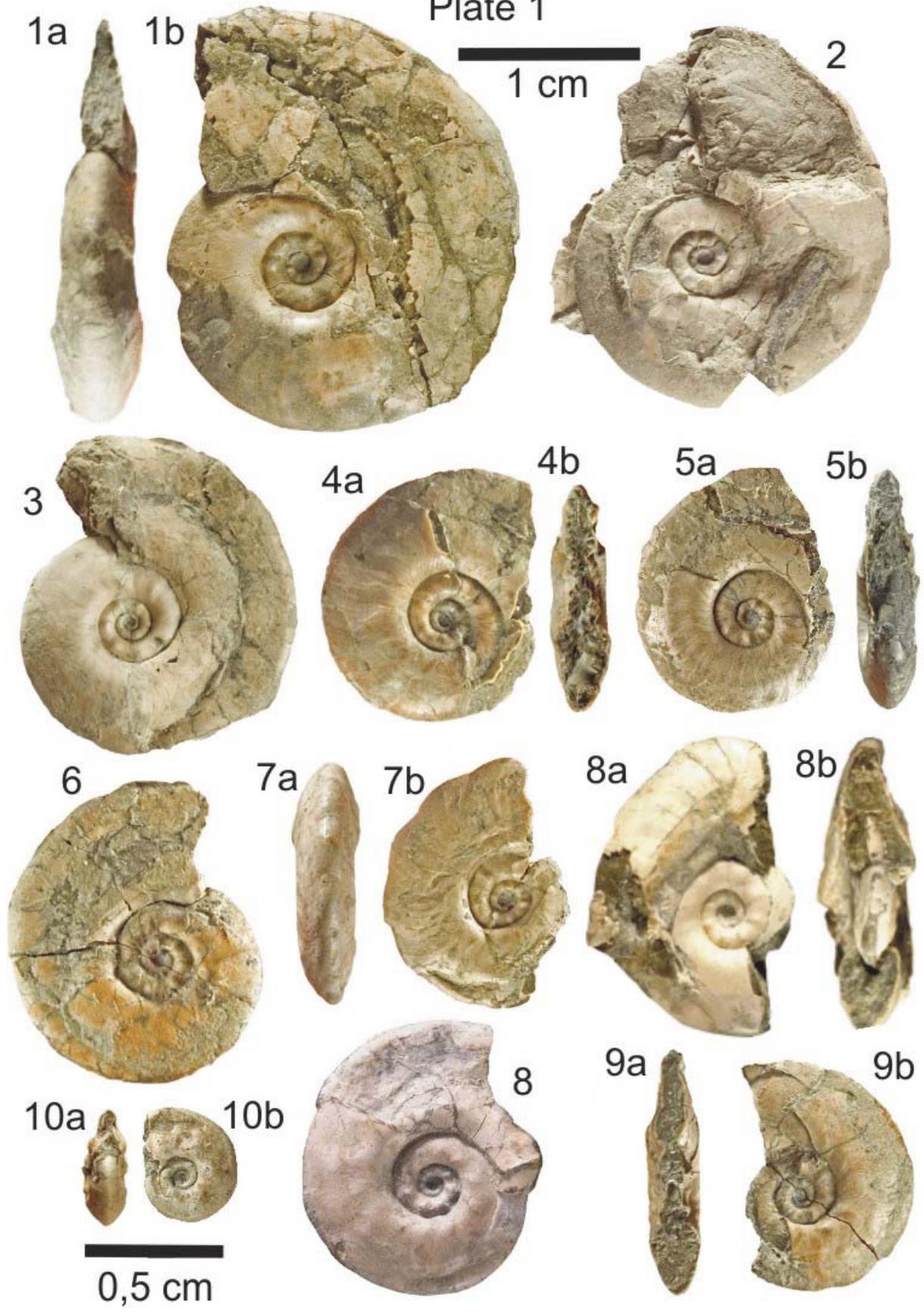
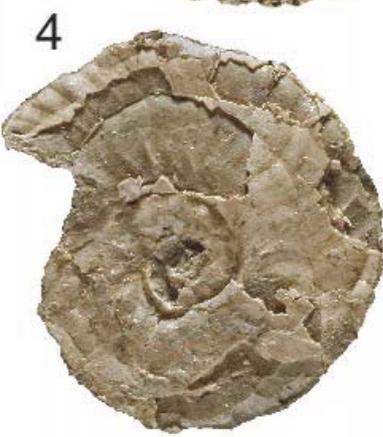
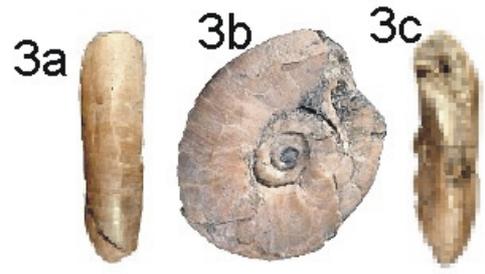


Plate 2

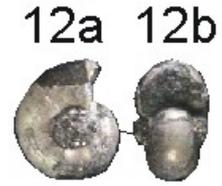
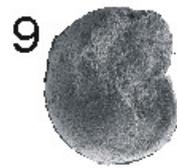
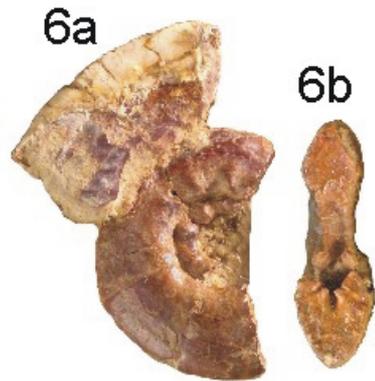
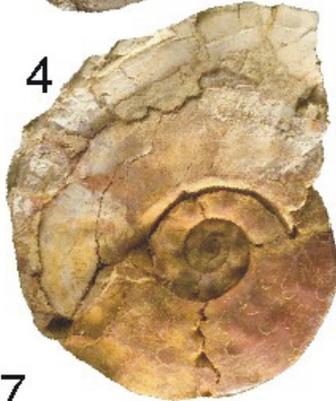


1 cm

Plate 3



1 cm



0,5 mm

0,5 cm



1 cm

1 cm



14