International Subcommission on
Jurassic
Stratigraphy

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Newsletter 34 (1)

Edited by Paul Bown, Nicol Morton, Jackie Lees
July, 2007

Contents

Chairman's report

Nicol Morton

Le Chardon, Quartier Brugière, 07200 Vogüé, France; NICOL.MORTON@wanadoo.fr

This issue of the *ISJS Newsletter* is devoted entirely to the Triassic/Jurassic (T/J) boundary and the definition of the base of the Jurassic, and of the Hettangian Stage, at a Global Stratotype Section and Point (GSSP). There will be a further issue of the *Newsletter* later in the year that will deal with the 'normal' range of topics.

The Jurassic Subcommission established a Working Group on the T/J boundary in 1988, led by René Mouterde (until 2000), then by Geoff Warrington. Efforts to find a suitable section have continued since then, but without success in identifying one of the four main sections studied (in SW England, USA, Canada and Peru) to be proposed as meeting the requirements identified by the International Commission on Stratigraphy (ICS). During the period 2001-2005, the activities of International Geological Correlation Program Project 458, '*Triassic/Jurassic Boundary Events*', led by Joszef Palfy, Stephen Hesselbo and Chris McRoberts, resulted in a great amount of new data and information on this poorly understood interval. Although definition of the boundary was not an objective of the project, new research was stimulated that has resulted, during the last two years or so, in the present situation of several options being available to the T/J Boundary Working (or Task) Group and the Subcommission.

Although ammonites have traditionally been regarded as the primary means of correlation, and so for definition of chronostratigraphic boundaries, in the Jurassic, the new research has identified two possible alternatives – radiolarians and a distinctive, negative C-isotope excursion. Even more surprising was the discovery of two new candidate sections, in Austria (in 2005) and in Northern Ireland (2006). During the 7th International Congress on the Jurassic System in Krakow, Poland (September, 2006), new data and proposals were presented and discussed. Only preliminary details of the two new sections could be given, but it was agreed that fully detailed proposals should be submitted by about the end of 2006. During the Working Group discussions, the candidature of the Peru section was withdrawn.

The idea for this newsletter of the Jurassic Subcommission was hatched in Poland on 15th September, 2006, during the post-congress Fieldtrip B1. After a visit to an old quarry with an overhanging face that threatened to create some vacancies in the 'Jurassic research establishment', Axel von Hillebrandt discussed with me how a fully documented proposal for the new candidate section in Austria could be published quickly enough for it to be assessed, together with the other sections, by the members of the T/J Working Group in the Spring of 2007. The best solution we could find was to arrange for the (electronic) publication of an *ISJS Newsletter* as soon as possible in the Spring of 2007. This would contain the up-to-date documentation of the new section in Austria. Inclusion of a proposal, as complete as possible in the limited time available, for the Northern Ireland section was arranged later, though it was clear that the research was at a much earlier stage. Finally, it was suggested that authors of the three remaining 'old' candidate sections should have the opportunity to present updated proposals. The updated proposal for St. Audries' Bay is not yet available, but will be distributed as soon as possible.

In the meantime, it was no longer clear who were the members of the T/J Boundary Working Group who would have the responsibility of selection, presumably by voting, of the preferred candidate section to be proposed to the Subcommission. The published list was some years old and in the meantime many new individuals had become involved in relevant research. Clearly, they also should have the right to be involved. Finally, there was no obviously favoured candidate section that demonstrably fulfilled all the requirements of the ICS Guidelines, so that the selection would have to be of the 'least bad' alternative (by no means an unusual situation for GSSP proposals to the ICS!). Inevitably, the result would be somewhat controversial. Therefore, the membership list of voting members of the Working Group has been expanded to make it as widely representative as possible of a broad spectrum of interests and ensure that the result will be more generally acceptable.

This issue of the *ISJS Newsletter* is being distributed in the usual way by e-mail to all Voting, Corresponding and Honorary Members of the Jurassic Subcommission, who are requested, as usual, to forward it to other colleagues. It will also be distributed to all the members of the T/J Boundary Working Group.

Please study very carefully the proposals contained in this *Newsletter* and, if you are a member of the Working Group or, at a later stage, a Voting Member of the Subcommission, exercise your objective professional judgement. The result will be with us for many years!

A candidate GSSP for the base of the Jurassic in the Northern Calcareous Alps (Kuhjoch section, Karwendel Mountains, Tyrol, Austria)

A. von Hillebrandt, L. Krystyn, W.M. Kuerschner

with contributions from
P.R. Bown, C. McRoberts, M. Ruhl, M. Simms, A. Tomasovych, M. Urlichs

Abstract The Kuhjoch section near Hinterriss (Tyrol, Austria) is proposed as Global Stratigraphic Section and Point (GSSP) candidate for the base of the Hettangian Stage and, as such, the base of the Jurassic System. The exact level is 5.80m above the top of the Koessen Formation and corresponds to the first stratigraphical occurrence (FO) of the ammonite *Psiloceras* cf. *spelae* Guex. This taxon relates to the group of *Psiloceras tilmanni* that is considerably older than the earliest NW 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* 60cm below the proposed stratotype point, and the disappearance of the ostracod *Eucytherura sagitta* immediately above the point. The $\delta^{13}C_{org}$ 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 $\delta^{13}C_{org}$. 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 GSSP selection.

1. Introduction

Sedimentary successions across the Triassic/Jurassic (T/J) 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 200km from the Salzkammergut (Kendlbachgraben, Upper Austria) in the east to the Lahnewiesgraben Valley (NW of Garmisch-Partenkirchen, Bavaria) in the west (Figure 1). Flanked by carbonate platforms to the north and south, this continuously subsiding basin reached 150-200m 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 Formation (Eiberg Member) to marls and clayey sediments of the lower Kendlbach Formation (Tiefengraben Member, corresponding to the British Pre-Planorbis Beds), is interpreted as a result of this sea-level fall. This drastic change in lithology was interpreted during the last decade as the T/J boundary (Golebiowsky, 1990; Hallam & Goodfellow, 1990) because it coincides with the disappearance of typical Triassic fossils, such as ammonoids and conodonts. New studies demonstrate, however, that the lower metres of the Tiefengraben Member (= 'Rhaetische Grenzmergel' *sensu* Fabricius, 1960, including also the reddish Schattwald Beds) still

yield Triassic micro- and nannofossils, and that the earlier cessation of the 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 (Figure 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 recognise, 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 20m, the Karwendel Syncline exposes the most expanded T/J boundary succession of all the proposed Global Stratigraphic Section and Point (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.* cf. *spelae* Guex) within the lower Tiefengraben Member correlates with, and is comparable to, 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.

Figure 1: Triassic/Jurassic boundary sections in the Northern Calcareous Alps

Figure 2: Triassic/Jurassic boundary sections of the western Karwendel Syncline

T/J boundary sections east of the Karwendel Syncline are indicated on Figure 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; Figure 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* cf. *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 18m above the GSSP level, has been studied in a neighbouring locality (Ochsentaljoch), about 750m to the west of the Kuhjoch (Figure 3), where this interval is better exposed.

2. Geographical and geological setting

The Karwendel Syncline is a local, E-W-trending synclinal structure, approximately 30km 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 (Figure 1) and narrows towards the west with increasingly steep to overturned flanks at its western end, close to Mittenwald (Figure 2). All the sections belong to the western half and to the southern flank of the syncline. The GSSP candidate Kuhjoch is located about 25km NNE of Innsbruck and 5km ENE of the village of Hinterriss on the 1:50 000 scale topographic map of Austria (Sheet 118 – Innsbruck); the coordinates are 47°29'02"N/11°31'50"E. It is accessible through the Baumgartenbach Valley by a 16km-long forest road (driving permit from the Österreichische Bundesforste - OEBF), starting south of the village of Fall in Bavaria (Germany), with a 1- to 2-hour walk from the end of the road (Ochsental alp) or a 1.5- to 2-hour walk from the Hochstall alp Niederleger (Figure 3). Kuhjoch peak and Ochsentaljoch, located 750m 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 1700-1800m, *i.e*. beyond the main tree and bush growth zone (Figures 5, 6). This guarantees long-term exposure stability and conservation, with respect to protection status.

3. Stratigraphy
3.1 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).
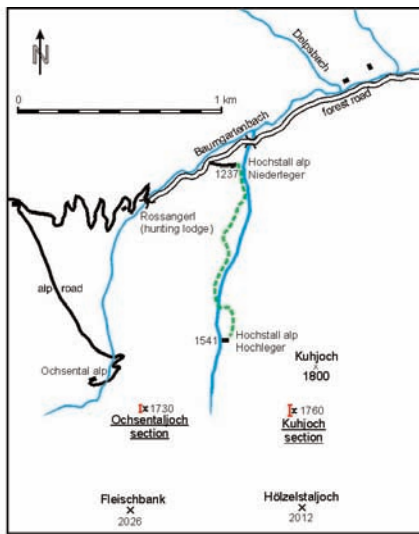
Figure 3: Kuhjoch and Ochsentaljoch sections

Figure 4: Proposed Triassic/Jurassic section south of Kuhjoch

An end-Triassic (late Rhaetian) sea-level fall caused a widespread platform emergence in the southern Northern Calcareous Alps. 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 by relatively late in the late Sinemurian (Krystyn *et al.*, 2005).

3.2 Position of main boundary-relevant ammonite levels 1 to 5 (Figures 7, 8)

Between the widely distributed and long-known *Choristoceras marshi* (1) and *Psiloceras calliphyllum* (5) layers, three new ammonite levels (Figures 7, 8) have been found within the 22m-thick continuous succession of marls and marlstones (Tiefengraben Member): ammonite level (2) with *Psiloceras* cf. *spelae* from 5.80-6.20m, ammonite level (3a) with *Psiloceras* ex gr. *tilmanni* at 8m, and ammonite level (4) with *Psiloceras* cf. *pacificum* at 12.5m above the base of the member. All levels are represented in the proposed GSSP site at Kuhjoch. Levels (2) and (4) are additionally known from Hochalplgraben and levels (3b) to (5) also from Ochsentaljoch (Figures 7, 8). The marlstones have

formerly been called 'Rhaetische Grenzmergel' (type locality Marmorgraben, western Karwendel Syncline; Figure 2) and correspond, in present nomenclature, to the Tiefengraben Member of the Kendlbach area, where the member differs slightly in having additional marly limestone intercalations. The overlying Breitenberg Member (named as 'Liasbasiskalk' by Ulrich, 1960, in the Karwendel Syncline) is rather uniformly developed and consists of a 2-3m 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 NW Europe (Figure 21; Bloos, 2004).

3.3 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 Formation) to Upper Jurassic sediments (Ruhpolding Radiolarite Formation). A narrow topographic depression, visible both on the map and in the field (Figure 4), corresponds to the documented section, which starts 2m below the top of the Koessen Formation/Eiberg Member, with a band of well-bedded and variably thick (up to 50cm), grey, bioturbated limestones (bioclastic wackestones) overlying 5m of black marls with pyrite nodules and rare, thin (5-10cm), limey mudstone intercalations. The 20cm-thick topmost bed (= T in Figure 20a, b) of the Eiberg Member

Figure 5: Proposed stratotype section at Kuhjoch

Figure 6: Boundary between overturned Eiberg Member (E.M.) and Tiefengraben Member (T.M.)
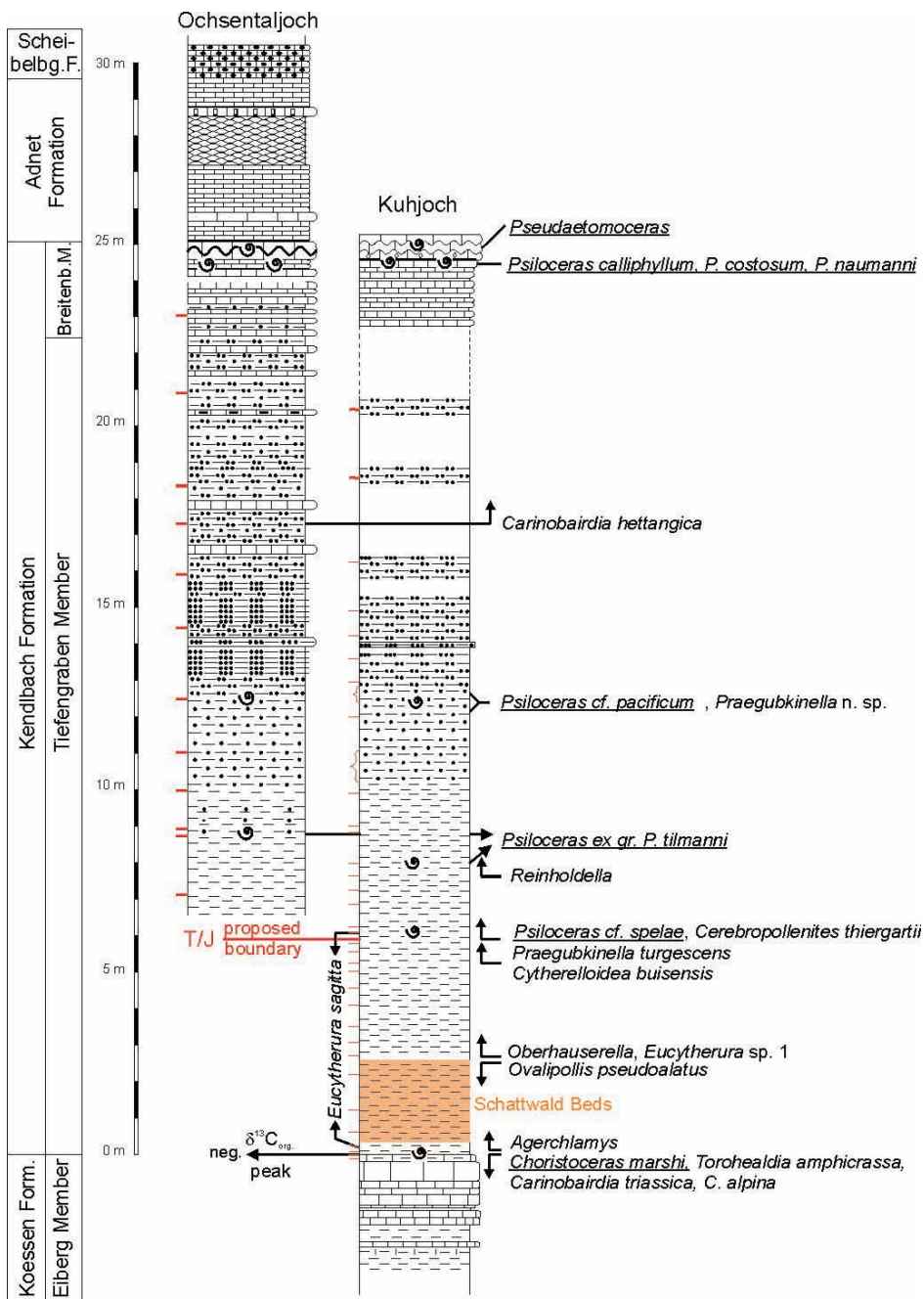
Figure 7: First and last occurrences of biostratigraphically important fossils

the Tiefengraben Member and are overlain by yellowish-weathering marls (30cm thick), passing into reddish, partly laminated, clayey marls, approximately 2m thick. The reddish marls are known as the Schattwald Beds (Figures 6, 20a, b, 22) in the Allgäu Nappe in the north and west of the Northern Calcareous Alps (*e.g.* Lorüns, Vorarlberg - McRoberts *et al.*, 1997; Aschau, Chiemsee, Bavaria; Restental, Upper Austria - Golebiowsky, 1990). Greyish intercalations characterise the transition to the overlying main part of the Tiefengraben Member, 19m thick. Ammonite level (2) with *P.* cf. *spelae* is located 3.5m above the Schattwald Beds, ammonite level (3a) with *P.* ex gr. *P. tilmanni* is 2m higher, and ammonite level (4) with *P.* cf. *pacificum* 4m higher up in the section.

Approximately 8m above the Schattwald Beds, the marls become more silty and, from 10m upwards, also finely sandy. A first sandstone bed (15 to 20cm thick) occurs at around 11m 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 cropping out part of the latter consists of 1.5m of grey, thinly-bedded limestones with thin, hard, black marl layers and a top bed (10 to 15cm) that contains, in the middle and upper parts, a condensed fauna of the *Calliphyllum* Zone, including a hardground layer enriched in ammonites partly preserved as limonitic molds. A 20cm-thick, yellowish bioclastic limestone follows, rich in fine echinoderm debris, with burrows filled by reddish lime-mud and with a ferromanganese oxidic crust on the surface. This layer contains locally (*e.g.* Hochalplgraben) ammonite

differs in having a darker colour and platy weathering. Due to an increased clay content, it is softer than the pure limestones below, and is thinly laminated in the upper half. The top of this bed (~1cm thick and also thinly-bedded) is black and bituminous, rich in bivalves and fish remains (scales) and indicative of an anoxic event and the peak of the regression. Above this follows the Kendlbach Formation, with a sharp and discontinuous contact, which is divided into the lower 22m-thick terrigenous Tiefengraben Member and the overlying 3m-thick calcareous Breitenberg Member.

Brownish marls (up to 10cm thick), with concretions of pyrite and worm-shaped traces, constitute the base of
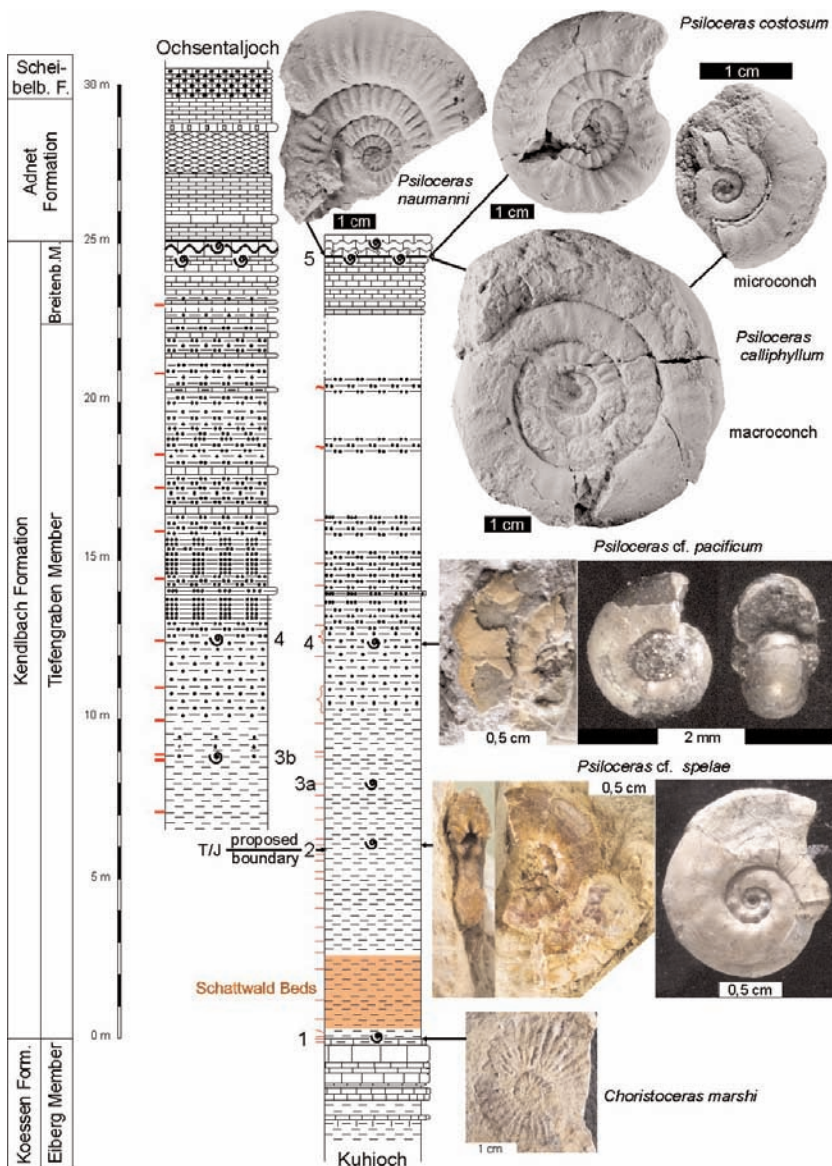
Figure 8: Distribution of ammonites

concentrations of the *Megastoma* Zone, an Alpine middle Hettangian equivalent of the NW European *Liasicus* Zone. Two further red limestone beds (together 30cm) with Fe-Mn oxide nodules and crusts, and yielding rare ammonites of late Hettangian age (*Marmorea* Zone, equivalent to the *Angulata* Zone) make up the end of the studied section.

Better exposures of the upper half of the Tiefengraben Member have been found in the Ochsentaljoch. A mountain trail crosses the steeply dipping sequence, which starts with the same grey marls as in Kuhjoch. An exact correlation with the latter is possible through the presence of ammonite level (4), 4m above the base of the measured section. Higher up in the section follow sandy marls (1.5m) with rare, thin arenitic layers (on Kuhjoch too weathered and therefore not detected), and at the top a thicker sandstone bed (20cm) that matches the single exposed sandstone bed of the Kuhjoch section. The

following 2m are composed of marls, with some silty sandstone beds up to 15cm thick, overlain by a fine-grained limestone bed (20cm) with bivalves and brachiopods at the base. Grey, partly silty, marls continue for another 4.3m, with two marly limestone beds (each 15-20cm) at 0.9m and 3.3m, respectively. The Breitenberg Member starts with a pure limestone bed (15cm) overlain by dark grey marls (0.3m) that are followed by thin, hard intercalations between wavy-bedded, grey bio-clastic limestones (2m). No fossils have been collected from 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 (4.5m) make up the top of the section, up to the cherty limestones of the Upper Sinemurian Scheibelberg Formation.

4. 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 proportion of the calcareous biomass, except for in 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 are unfortunately very rare and extremely small. A first sample set from the Kuhjoch section (collected by AvH 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 pristinely-preserved palynomorphs that have a palynomorph colour of 1-2 on the thermal alteration scale (TAS) of Batten (2002). The microfloral record across the T/J boundary is characterised by significant quantitative changes in the terrestrial and marine components of the assemblages, with a few notable palynostratigraphic events, which are very similar to those described recently from the Tiefengraben section in the eastern part of the Eiberg
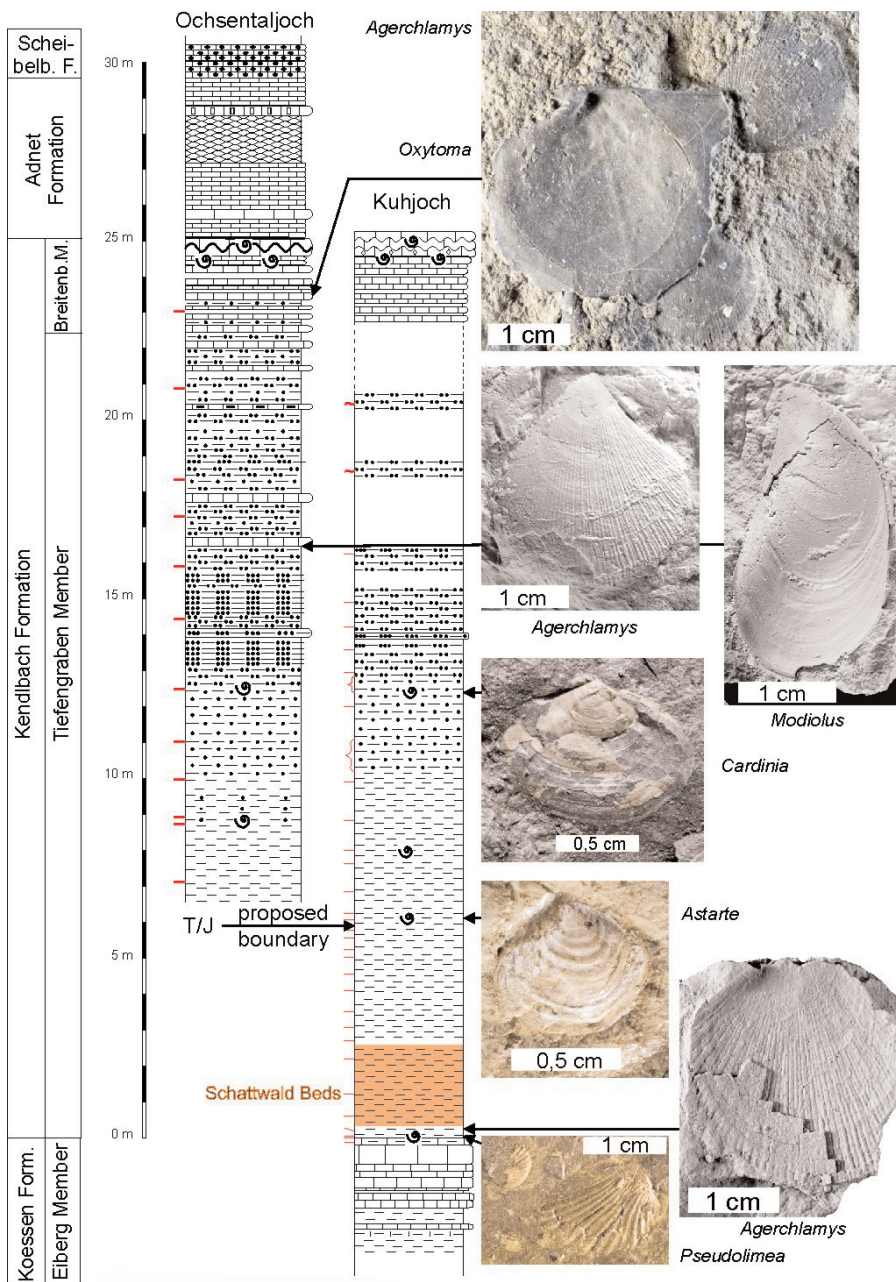
Figure 9: Distribution of bivalves

representing ammonite level (1) and forming the highest (last) occurrence, not only of this genus, but of Triassic ammonoids and conodonts 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 5.8-6.2m above Bed T in the Kuhjoch section, contains mostly flattened and small (rarely >2cm) specimens, but easily visible due to their white aragonitic shells. Rare, pyritised, undeformed phragmocone specimens allow an exact illustration of the cross-section and the suture line (title page and Figure 8). 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 showing also some features of Triassic phylloceratids (high ovale whorl section with well developed umbilical wall). Despite the exceptional preservation, only an approximate determination as *P.* cf. *spelae* Guex was possible because of the badly preserved nature of the holotype of that species.

basin (Kuerschner *et al.*, 2007).

4.1 Macrofossils
4.1.1 Ammonitina (AvH, LK; Figures 7, 8)

Low ammonite diversity, patchy occurrences of determinable specimens and restriction to certain levels are characteristic of the sections, though shell fragments were frequently found in samples for micropalaeontological study (Figure 12). 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* (Figures 7, 8) are to be found in Bed T,

Ammonite level (3a) (Kuhjoch section) was found in the residue of a washed sample containing 20 limonitic casts of inner whorls (<1.7mm), a compressed specimen (3mm), and a whorl fragment (whorl height 2.5mm) with suture lines that can be placed in the *P. tilmanni* group. A similar level (3b) was found in the Ochsentaljoch section, 3.5m below ammonite level (4) (Figures 7, 8).

Ammonite level (4), located 4m above level (3a) and 6m above ammonite level (2), has yielded several shell fragments and one badly preserved specimen in the Kuhjoch section; two specimens from the Hochalplgraben section are illustrated (Figure 8). The tiny juvenile, and a larger form (15mm diameter) with a relatively wide
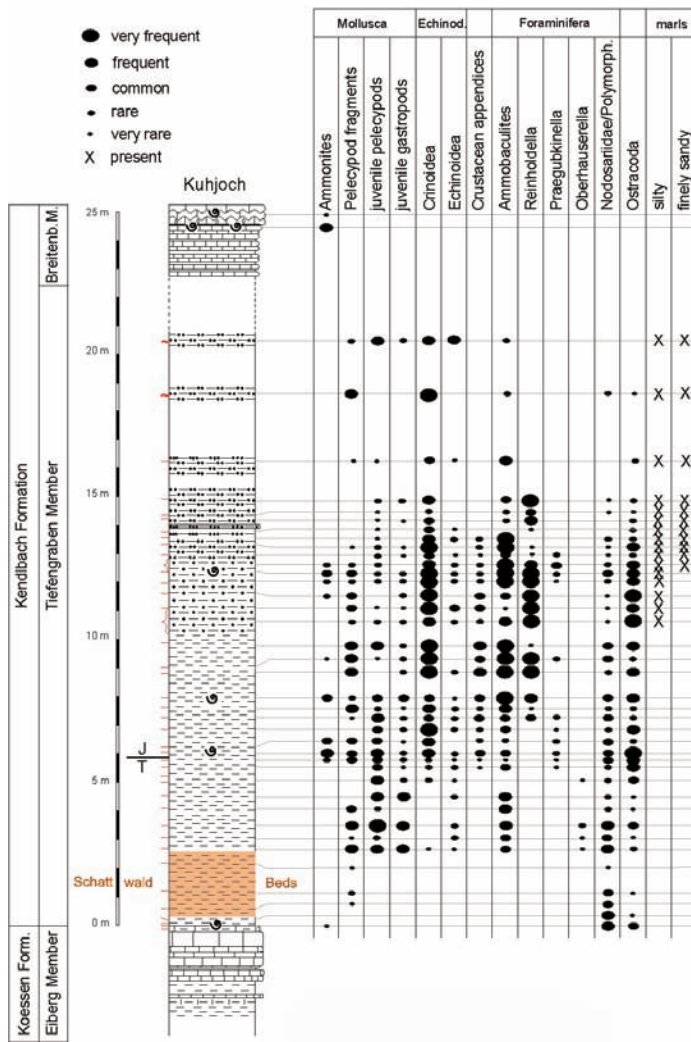
Figure 10: Microfossils, Kuhjoch section

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 (5), rich in ammonites in the Kuhjoch section, follows 12m 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* (Figure 8). The level is condensed, containing the species of two ammonite horizons.

4.1.2 Bivalves (CMcR; Figure 9)

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* 7.45m above the base. The residues of washed

microfossil samples often contain juvenile specimens (mostly molds) or fragments of pelecypods, mostly pectinids and nuculids (Figures 10, 11). The first limestone bed, 4m above ammonite level (4) in the Ochsentaljoch section, yielded *Liostrea* and *Agerchlamys*.

4.1.3 Gastropods and scaphopods (AvH)

Tiny and juvenile gastropods (mainly molds) were often found in the residue of samples washed for microfossils (Figures 10, 11), but determinable specimens are very rare. Fragments of scaphopods appear in the residue of some samples.

4.1.4 Brachiopods (AT; Figure 23)

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*) rhynchonellid-form 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 4m 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; Figure 23). This species is also abundant at the boundary between the Tiefengraben and Breitenberg Members of the Hochleitengraben section (type locality; Siblík, 1999; Tomasovych & Siblík, 2007). It probably preferred low-energy habitats, below storm wave-base, and was able to tolerate some input of terrigenous supply. *T. inopinata* is thus the first rhynchonelliformean brachiopod that colonised the sea-floor 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 & Siblík, 2007). *T. 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 *T. inopinata* thus probably migrated into the western Tethys from adjacent biogeographic regions. The specimens sampled in the Ochsentaljoch section attain 10-16mm in length, 10-18mm in width, and 6-14mm in thickness. Dorsobiconvex shells possess incipient planareas, suberect/erect beaks, relatively sharp beak ridges, hypothyrid/submesothyrid foramen, relatively thick
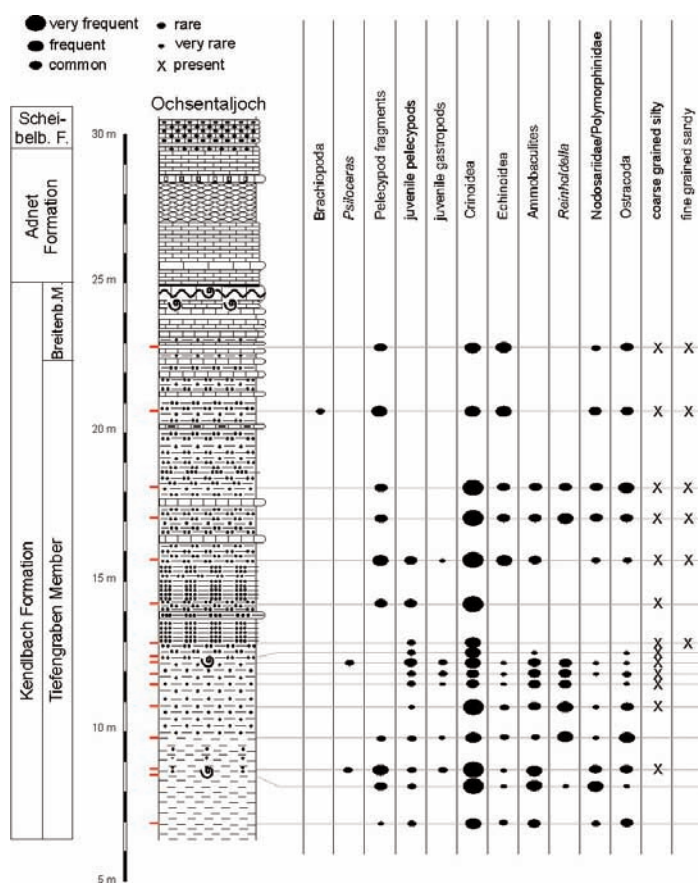
Figure 11: Microfossils, Ochsentaljoch section

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 a few brachids of isocrinids. Different types of columnals (nodals, internodals and infranodals) are found. The number of noditaxes seems to be no more than six or seven at most. The longest pluricolumnal has five columnals. A similar isocrinoid is found in the Larne section in Northern Ireland, 2.5m below the first *Psiloceras erugatum* (first *Psiloceras* in Great Britain). Spines of echinids can be frequent in the uppermost part of the Tiefengraben Member.

4.2 Microfossils

Fifty 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 (Figures 10, 11), foraminifera usually outnumber ostracods. Small appendices of crustaceans can be common in some samples (Figures 10, 11). Radiolaria are extremely rare. Scolecodonta were found in one limestone sample.

4.2.1 Foraminifera (AvH; Figures 10, 11, 13)
(i) Kuhjoch section (Figure 7)

Black and grey marls, 2.5 and 1m 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 thinly-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* (Figure 10) 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

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 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, the presence of a massive median septum connected with the 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 & Siblík, 2007).

4.1.5 Echinodermata (in part, MS, AvH)

Crinoid ossicles can be found in the washed residue of many samples (Figures 10, 11), whilst fragments of echinids are less frequent (Figures 10, 11). Holothurian ossicles are found in some samples, as well as crinoid ossicles which can be very frequent (Figures 10, 11). A 1cm-thick layer in the Hochalplgraben (Figures 12, 18), directly above ammonite level (2), contains nearly
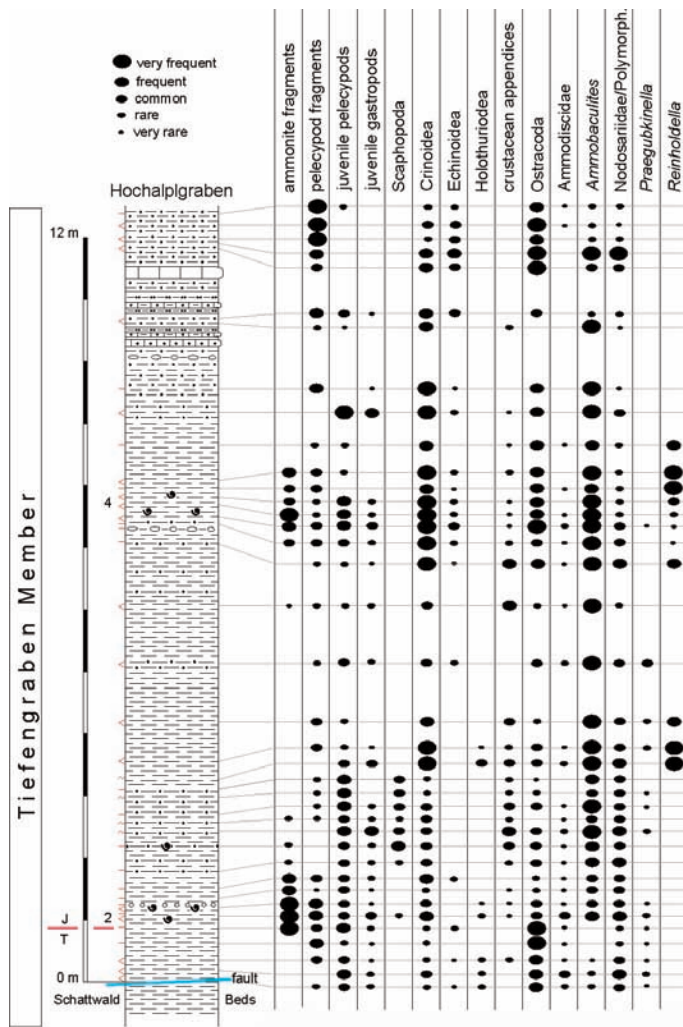
Figure 12: Microfossils, Hochalplgraben section. 2 = level with *P*. cf. *spelae*, 4 = level with *P*. cf. *pacificum*

(2) upwards. *Lenticulina* can be the dominating nodosariid genus in the upper part of the Tiefengraben Member. Robertinina are represented by 3 genera (Figure 13): *Oberhauserella* mostly is very rare; *Praegubkinella* can be common in the intervals around the ammonite horizons; and *Reinholdella* can be very frequent in the middle part of Tiefengraben Member. Both genera are usually preserved with aragonitic shell.

(ii) Ochsentaljoch section (Figure 11)

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 parts 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.

4.2.2 Ostracoda (MU; Figures 14-16)

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 fortenodosa* in the same bed in the Schlossgraben and Hochalplgraben near Hinterriss, and 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 2m break in records during the Schattwald interval. *Cytherelloidea buisensis* appears below ammonite level (2) (Figures 14, 15). 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 (Figure 15) above ammonite level (2). A single record of *Carinobairdia hettangica* from the Hochalplgraben comes from above the first limestone bed of the Tiefengraben Member.

4.2.3 Calcareous nannofossils
(PRB; Figure 17)

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 (0-3.6m) are dominated by *Prinsiosphaera triassica*, but the section probably lies above the last occurrence (LO) of *Eoconusphaera zlambachensis* (the few specimens seen are most likely reworked). At the boundary interval (~6m), there is a switch in dominance from *P. triassica* to calcispheres and *Schizosphaerella punctulata*. The first occurrence (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 LO of *P. triassica* and FO of *S. punctulata* may be extremely useful boundary indicators, as they are common, robust and globally distributed species.

4.2.4 Palynomorphs (WMK)

Pollen and spore assemblages from the Koessen Formation are dominated by *Classopollis meyeriana* and *C. torosus*, accompanied by *Ovalipollis pseudoalatus*, *Rhaetipollis germanicus* and *Ricciisporites tuberculatus*. Marine palynomorphs, such as the dinoflagellate cysts *Rhaetogonyaulax rhaetica* and *Dapcodinium priscum*,
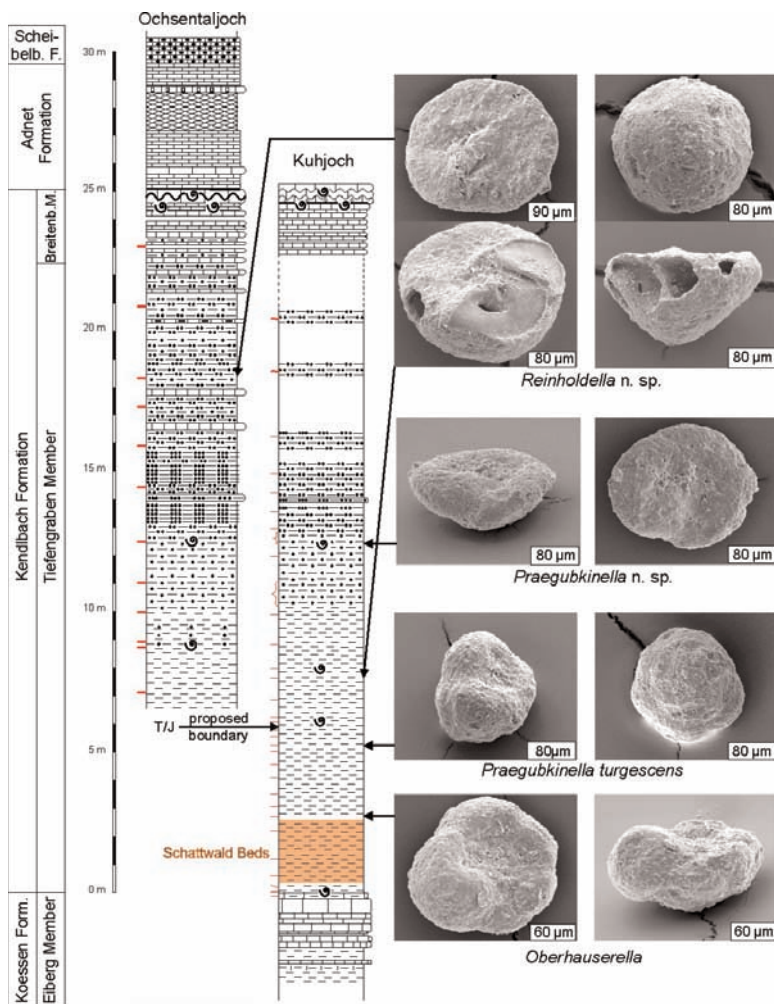
Figure 13: Distribution of aragonitic foraminifera

and some acritarchs (*e.g. Micrhystridium*) are present. The palynomorph assemblages from the topmost bed of the Koessen Formation (black shale) are characterised 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 characterised 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*.

5. Geochemistry (MR, WMK)

Up to now, only carbon-isotope investigations on bulk sedimentary organic matter have been made, while compound-specific measurements are underway. Stable isotopes (C and 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.

5.1 Carbon isotopes and organic carbon content
(Figures 19, 20a, b)

Two sample sets were studied for bulk C-isotopes. The first series of samples (Figure 19, red curve) was taken in 2005 (by AvH) and a closer series of samples in June, 2006 (WMK, MR and Bonis; Figure 19, black curve). Basically, both curves show the same trends, with some additional features in the latter C-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 (Figure 20b). This interval is characterised by a distinct negative C-isotope excursion, which is, in fact, composed of two maxima of about -31‰ and interrupted by slightly more positive C-isotope values. The lower $\delta^{13}C_{org}$ peak coincides with a bituminous, black siltstone layer (1cm) at the top of the thinly-bedded, marly limestone at the top of the Eiberg Member. The second negative $\delta^{13}C_{org}$ 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 20cm 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 Members. 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 cyle in the C-isotope record, 2m above the second peak, followed by a positive tendency and a slightly negative tendency in the upper part of the red curve.

5.2 C_{org} (Figures 19, 20b)

The C_{org} curve shows a sharp maximum of about 10% at the black, bituminous layer, which coincides with the first negative C-isotope maximum, while the rest of the section shows only minor variations between about 1-2%.

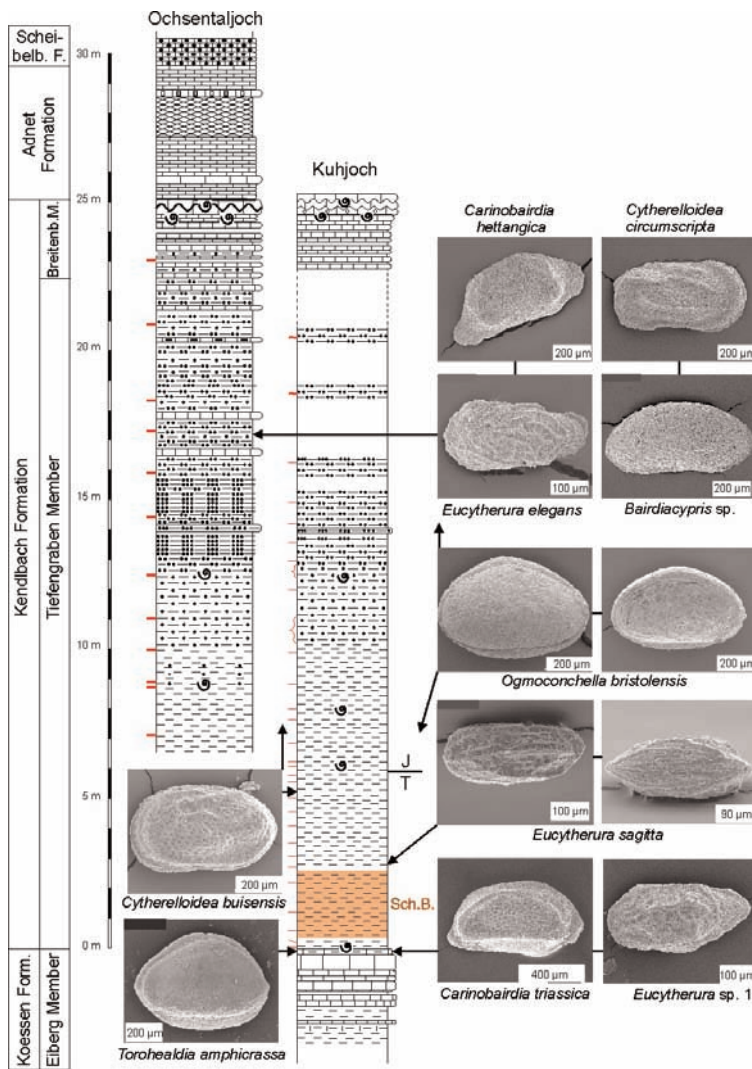### 6. Palaeomagnetism (M. Deenen, M. Szurlies, W. Krijgsman)

Figure 14: Ostracodes, Kuhjoch and Ochsentaljoch sections

three localities (Pletzboden, Tölzer Hütte and Sattelgraben; Figure 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 25cm-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 30cm thick, containing common bivalves and, in the top black bituminous centimetre, *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 palyno-logical and geochemical, datasets for the Northern Calcareous Alps, thanks to the detailed studies of Golebiowsky & 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 (13m), with common limestone intercalations, and in replacement of the Schattwald Beds by olive-grey clays.

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

7. Correlation with other sections of the Eiberg Basin (Figures 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 GSSP candidate. 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 Formations, which have been studied also for magnetostratigraphy; the *Hochalplgraben* (47°28'20", 11°24'42"; Figures 12, 13), 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,

8. Biostratigraphy (Figure 7)

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. A high evolutionary potential provides the basis for a detailed biozonation (Figure 21) and the wide geographic distribution in marine realms facilitates global correlations. Relatively high correlation potential may also be possible with nannofossils and marine palynomorphs. Of minor or local biostratigraphic or ecostratigraphic relevance are bivalves, ostracodes and some foraminifera. Available terrestrial palynomorphs have shown potential for marine-continental correlations.

8.1 Ammonites (AvH, LK; Figures 7, 8, 21)

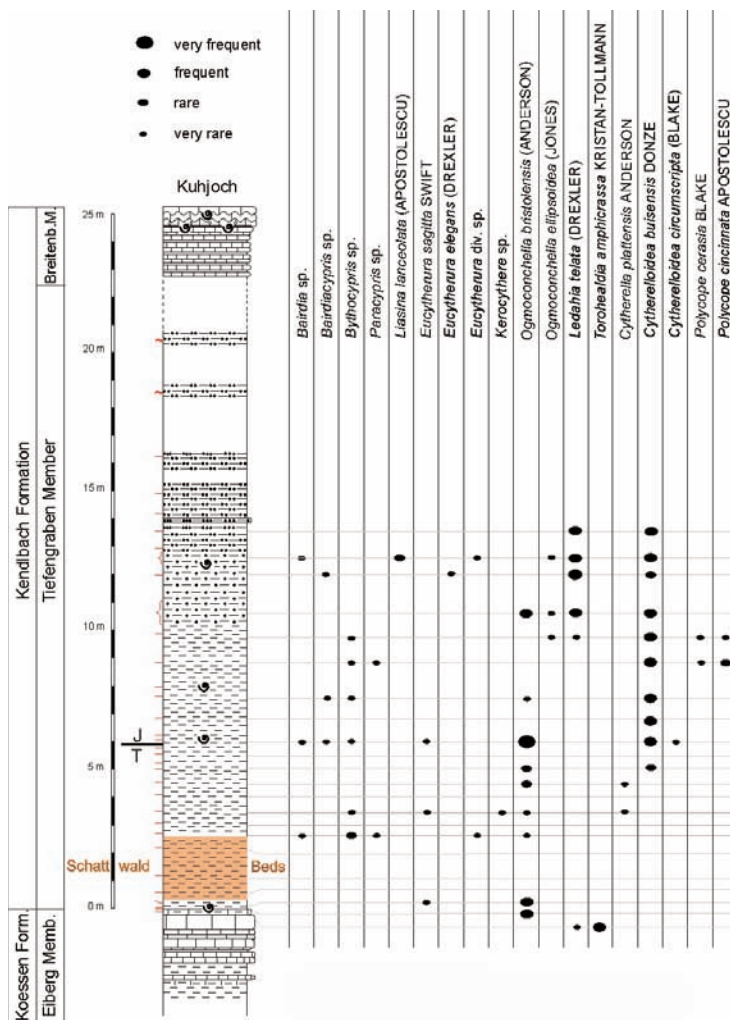The Kuhjochjoch and Ochsentaljoch sections record five

Figure 15: Distribution of ostracodes, Kuhjoch section

ammonite beds or levels of Late Rhaetian (1) to early Hettangian (5) age:
- 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* cf. *spelae*
- ammonite level (1) with *Choristoceras marshi*.

8.2 Bivalves (CMcR; Figure 9)
Cassianella and *Chlamys valoniensis* characterise 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.

8.3 Ostracodes (MU; Figures 14-16)
The beds immediately below and above the

Eiberg/Tiefengraben boundary are characterised 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 *Psilonotum* 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 sharp. However, some species (*Ogmoconchella bristolensis*, *Ledahia telata* and *Cyterella plattensis*) occur from the Rhaetian up to the Hettangian. They indicate that the ecological conditions were unchanged euhaline.

8.4 Foraminifera (AvH; Figures 7, 10-13)
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 Tiefengraben Member 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 aragontic Robertinina are of biostratigraphic importance (Figures 7, 13). *Oberhauserella* was described from the Upper Triassic and is found in gray marls below the *Psiloceras* cf. *spelae* horizon. *Praegubkinella turgescens* appears immediately below this horizon and *Reinholdella* n. sp. is 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* cf. *spelae* and *Psiloceras* cf. *pacificum*. *Reinholdella* n. sp. is found up to the upper part of the Tiefengraben member (Ochsentaljoch section).
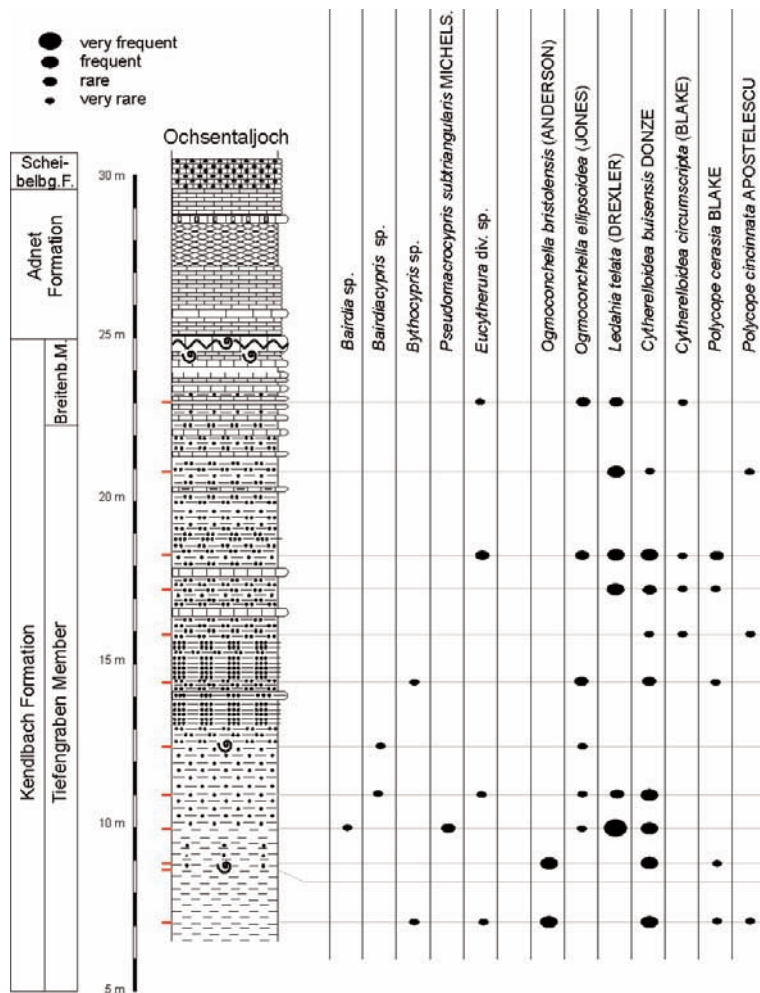
Figure 16: Distribution of ostracodes, Ochsentaljoch section

8.5 Calcareous nannofossils (PRB; Figures 17, 18)

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 are not yet present typically '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.

8.6 Palynomorphs (Figures 7, 22)

Similarly 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 characterise 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* cf. *spelae*. 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* cf. *spelae* horizon.

9. Correlations
9.1 Regional

Ammonite levels (2) and (4) are presently known from three sections in the western Karwendel Syncline. The bivalve fauna and negative isotope excursion of the Kuhjoch within the Eiberg to Tiefengraben Member boundary bed(s) can be observed in many other sections and provide a first-order correlation event within the Eiberg Basin; the same applies for ammonite levels (1) and (5). Vertical changes within the microfaunas further allow fine-tuned correlations within the Tiefengraben Member throughout the basin.

9.2 North-western Europe

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 first occurrence of the genus *Psiloceras* - at that time *P. planorbis*) defined as stratotype point. Later results (Bloos & Page, 2000) demonstrated, however, that the oldest psiloceratid of NW Europe (Great Britain) is *Psiloceras erugatum*, with the first occurrence 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 never been found there and cannot therefore be fitted into the Alpine *Psiloceras* sequence. Considering the more or less pronounced ribbing on the inner whorls, and the occurrence closely below *Neophyllites* in NW Europe, *P. erugatum* should be younger than any of the Karwendel ammonites found below the *Calliphyllum* Zone, in which *Neophyllites* occurs in the Northern Calcareous Alps (Bloos, 2004).

The Kuhjoch and Karwendel ammonites of the Tiefengraben Member (*P.* cf. *spelae* to *P.* cf. *pacificum*) are not known from the barren lower 'Pre-Planorbis Beds' of England and, using the isotopic signal as an additional correlation tool (Kuerschner *et al.*, 2007), should be expected to occur in the lowest few metres of the Blue Lias Formation.
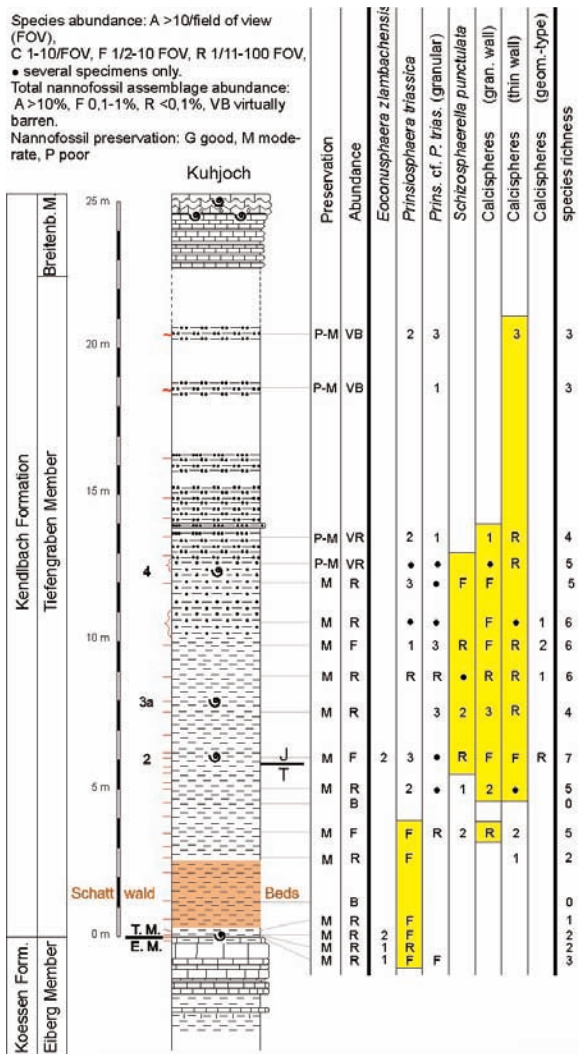
Figure 17: Stratigraphic range-chart for calcareous nannofossils, Kuhjoch section

The NCA microfauna (mostly ostracodes and, in part, foraminifera, mainly nodosariids-polymorphinids) is very similar to that of NW 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 terrestrial realms, a boundary definition should be chosen that enables correlation between the two. 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 & 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.* cf. *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.

9.3 Eastern Pacific (Figure 21)
9.3.1 North America

T/J boundary sections with a most complete ammonite record have been described from the New York Canyon (Nevada, USA: Guex, 1995; Guex *et al.*, 1998, 2002, 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 press).

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. The beds with *Choristoceras minutum, Odoghertyceras deweveri, Psiloceras marcouxi*, *P. tilmanni* and cf. *Neophyllites* (Guex *et al.*, 2002; Lucas *et al.*, 2007), 7.2m higher in the section, may be correlated with ammonite level (3), but choristoceratids and psiloceratids similar to *Psiloceras marcouxi* do not occur in the Hettangian of Europe, and the determination of the *Neophyllites* (without suture and whorl section preserved) is doubtful. The lower part of the beds with *Psiloceras pacificum* (excluding specimens with ribbed inner whorls) may correlate with ammonite horizon (4). 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 GSSP candidate 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. Any exact correlation with other fossil groups (*e.g.* ammonites) is excluded for an interval from 15m below to about 6m above the proposed boundary level, but a concomitant and pronounced negative $\delta^{13}C_{org}$ anomaly is used as a correlation tool to other sections (Ward *et al.*, 2001).

9.3.2 South America

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 in 2006). The first Hettangian ammonite bed is characterised by a species of *Psiloceras* that is distinguished from *Psiloceras tilmanni* by a steeper umbilical wall. In this bed was also found *Odoghertyceras*. Above follow several beds with *Psiloceras tilmanni s.s.* Below this bed, a limestone sample contains radiolarians transitional to basal Hettangian radiolarians, with just a few Rhaetian holdovers. Probably the radiolarian turnover is older than the ammonite turnover (Lucas *et al.*, 2005).

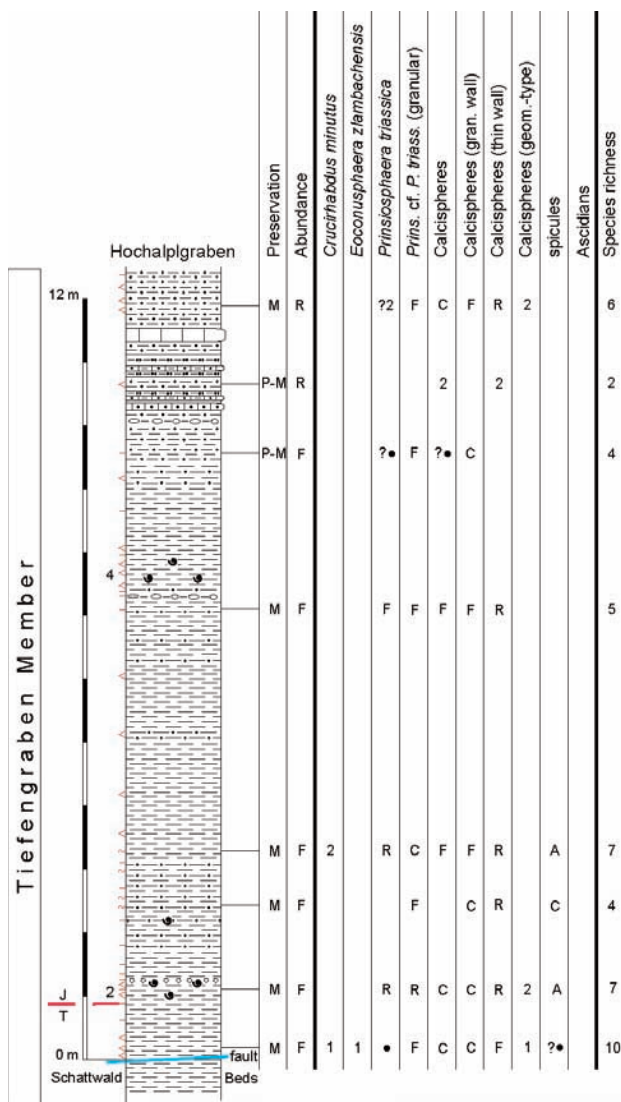There are other complete T/J boundary sections in the

Figure 18: Distribution of nannofossils, Hochalplgraben section

10. 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 NW Europe. The NCA (including the Eiberg Basin) were then situated between the Euroboreal Realm of NW 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 NW 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 Realms. Calcareous nannoplankton are not suitable for biogeographic comparisons, as they are unknown from the *Preplanorbis* Beds of NW Europe, as well as from time-equivalent sediments of the eastern Tethyan Realm and the East Pacific Province.

11. 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 discontinuous nature of a level paralleled by a strong facies change, the continuation of typical Rhaetian microfaunas and microfloras (!) to several metres above, and the long interval (6m) before the first appearance of the earliest Jurassic ammonites. Additionally, last occurrences are not recommended as boundary levels by ICS.

2. First occurrence of *Psiloceras* cf. *spelae* (ammonite level (2)) *P.* cf. *spelae* is the first known *Psiloceras* in Europe and, as *Psiloceras spelae*, in the East Pacific Province (North and South America). *Psiloceras* cf. *spelae* is very well preserved (aragonitic shell) and shows all the 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, enabling

Utcubamba Valley (Hillebrandt, 2000a), but ammonites are mostly compressed and not yet studied in detail. Recently (2007), Guex (written communication) discovered *Psiloceras* cf. *spelae* close to a section described by Hillebrandt (1994, figs 2b, 3; 2000a, fig.5a). *P.* cf. *spelae* (unfortunately compressed) was found just above *Choristoceras crickmayi* and 10m below *Psiloceras tilmanni*. The Utcubamba Valley could eventually provide the possibility of a correlation of ammonite and radiolarian biostratigraphy. Other T/J boundary sections are found in northern Chile (Hillebrandt, 2000a), but the lowest Hettangian ammonite horizons are missing. The oldest ammonite level (*Primocostatum* Zone in Hillebrandt, 2000c) can be correlated with part of the beds with *Psiloceras polymorphum* in Nevada and the *Planorbis* and *Calliphyllum* Zones in Europe (Figure 21). Thickness of the latest Triassic and the lowest Hettangian is still higher than that of the Tiefengraben Member.
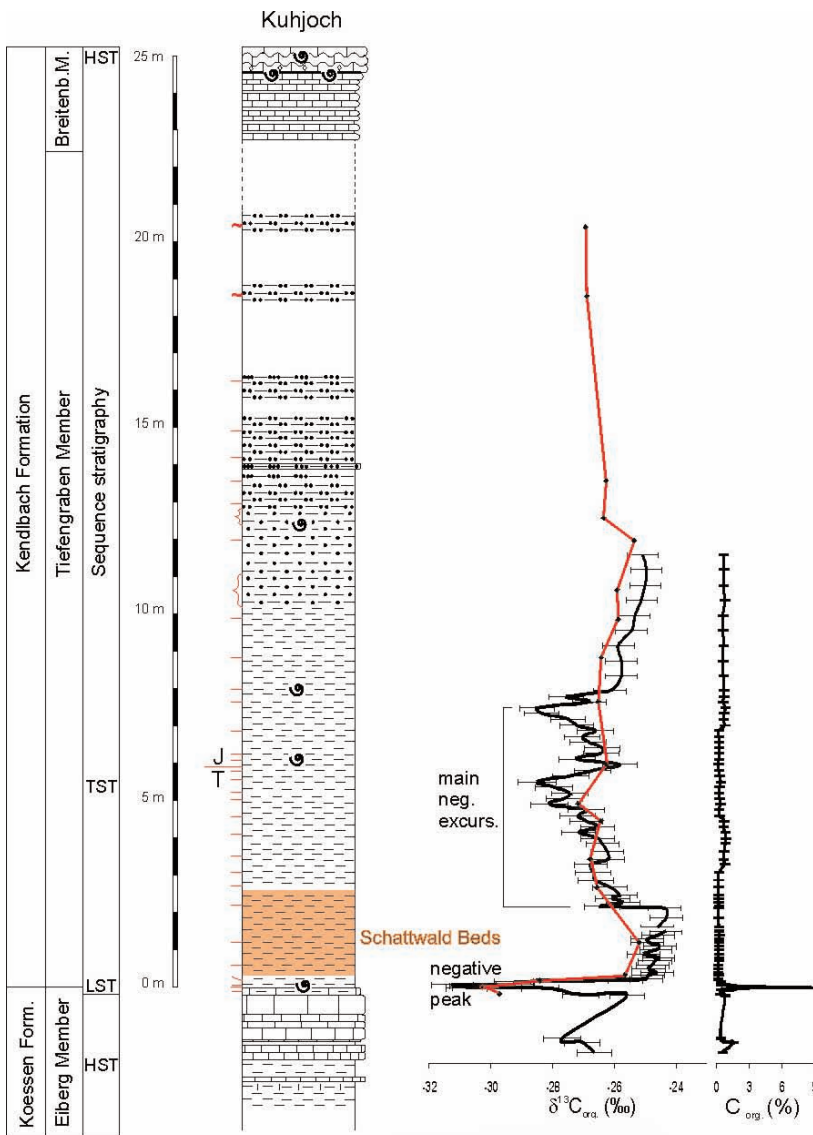
Figure 19: Kuhjoch profile with $\delta^{13}C_{org}$ and C_{org} curves (RHUL *et al*., in prep.). Red curve = samples from 2005

undisputedly have been called Jurassic for 150 years in NW Europe. It is also younger, at least in part, than the proposed boundary level in the English GSSP candidate St. Audrie's Bay.

5. $\delta^{13}C_{org}$ peak at the Eiberg/Tiefengraben Member boundary (Figures 19-21) 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, 7cm higher. A slight increase (significant?) to heavier values occurs between both maxima (Figure 21). It appears difficult to find arguments for the definiton of the T/J boundary based on one of these peaks. Further arguments against this level(s) are given in the discussion of geochemistry and in paragraph 1. The peak(s) is (are) not found at all in biostratigraphically complete T/J boundary sections (*e.g.* Peru), and especially not in the incomplete T/J boundary sections where there are missing beds at the level of this isotope excursion, and where the boundary can only be determined with fossils. An exact identification of the peaks is difficult without additional biostratigraphic control.

local and long-distance correlation of the level in both the marine and 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 50m), 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, correlates with rocks which

12. Conclusions

The proposed stratotype section and boundary point matches all requirements for a GSSP in the sense of the ICS. 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 metres thick. The proposed T/J boundary section (~25m 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 GSSP candidates 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, pointing to a well-oxygenated and open marine environment. No vertical facies changes
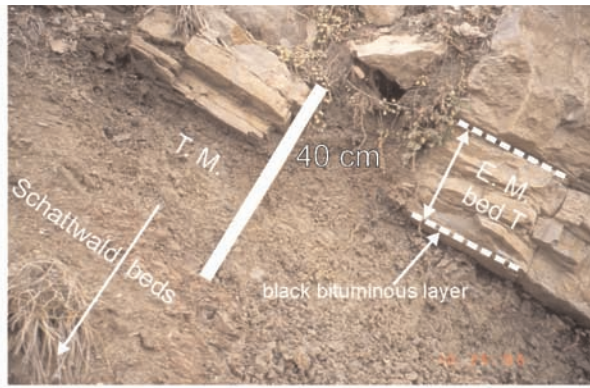
Figure 20a: Boundary between Eiberg and Tiefengraben Members, Kuhjoch section
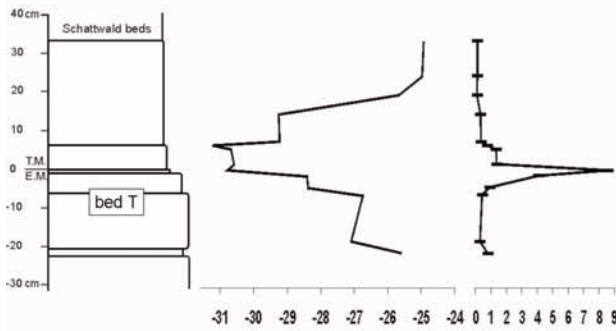

Figure 20b: $\delta^{13}C_{org}$ and C_{org} curves, Eiberg-Tiefengraben Members, Kuhjoch section (RHUL *et al.*, in prep.)

affect the boundary level that can be traced over a considerable area along strike (6km). The decisive boundary marker (*P.* cf. *spelae* Guex) has a low-palaeolatitude global distribution and a short vertical range. Other fossil groups (bivalves, foraminifers, ostracods, dinoflagellates) allow additional means of 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 $^{13}C_{org}$ curve, with two pronounced excursions, provides additional constraints for correlation with other T/J boundary sections, and a magnetostratigraphic investigation is underway.

Acknowledgements

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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. calliphyllum	P. plicatulum		P. rectocostatum
			P. psilonotum	P. polymorphum	P. primocostatum
			P. planorbis		
		Neophyllites	Neophyllites		P. planocostatum
			P. erugatum		
	Tilmanni	P. cf. pacificum		P. pacificum	P. tilmanni
		P. ex gr. P. tilmanni	?	P. marcouxi + Odog.	P. cf. tilm. + Odog.
		Psiloc. cf. spelae		P. spelae	P. cf. spelae
Rhae-tian	Marshi	Choristoceras marshi		Choristoceras crickmayi	+ Ch. marshi Ch. crickmayi

Figure 21: Correlation of Early Hettangian ammonite zones, subzones and horizons (grey). Broken lines = approximated correlations
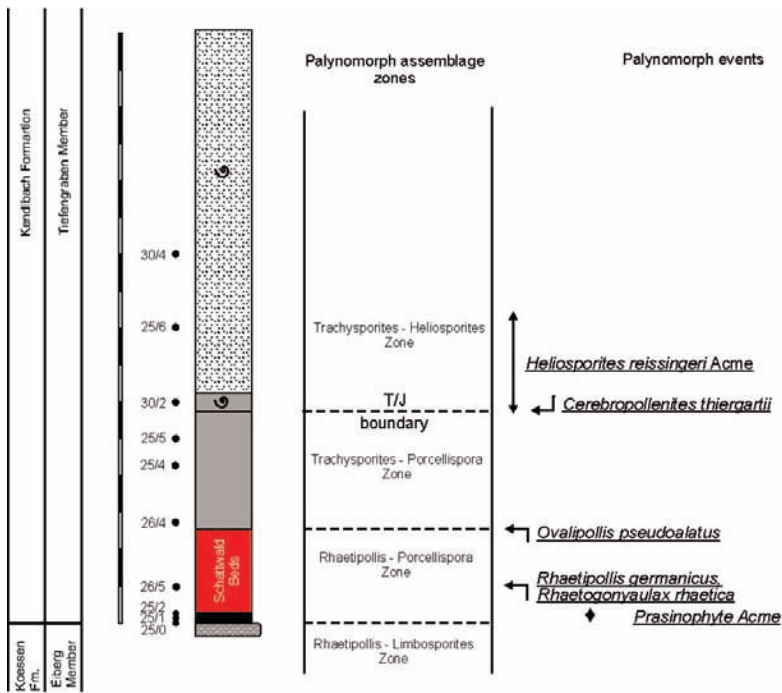
Figure 22: Palynomorph distribution and assemblage zones, Kuhjoch section

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The Triassic-Jurassic transition at Kunga Island, Queen Charlotte Islands, British Columbia, Canada

Louise M. Longridge[1], Elizabeth S. Carter[2], James W. Haggart[3], Paul L. Smith[1]

[1]Department of Earth and Ocean Sciences, University of British Columbia, 6339 Stores Road, Vancouver, British Columbia,V6T 1Z4, Canada; llongridge@eos.ubc.ca, psmith@eos.ubc.ca

[2]Department of Geology, Portland State University, Portland, Oregon, 97207-0751, USA; cartermicro@earthlink.net

[3]Geological Survey of Canada, Vancouver, British Columbia, V6B 5J3; JHaggart@nrcan.gc.ca

1. Introduction

Several stratigraphic sections in the Queen Charlotte Islands of British Columbia, Canada contain exceptionally well-preserved radiolarian faunas that cross the Triassic-Jurassic boundary (TJB). In particular, a section at Kunga Island shows a dramatic turnover of radiolarians that could be used to define and constrain the TJB to within one metre, a precision that is greater than any other fossil group. The Kunga section was originally proposed as a GSSP candidate for the base of the Jurassic by Carter & Tipper (1999) and again by Haggart *et al*. (2002). These proposals are updated here. We propose that, if radiolarian sequences are selected as the primary standard (*sensu* Callomon, 1984) for defining the TJB, then the section at Kunga Island should be selected as GSSP.

If radiolarian sequences are not selected as the primary standard, then we propose that they should be considered as a secondary standard and that the Kunga Island section be designated as a parastratotype in order to better characterize the Triassic-Jurassic transition. In some circles, parastratotypes are also known as auxiliary reference sections. In addition to radiolarians, the Kunga Island sequence permits the calibration of time scales based on ammonites, radiometric ages and, indirectly, with the carbon isotope curve. The aim of designating any stratotype is, of course, to provide the international community with the widest spectrum of stratigraphic information that helps both to define the boundary and to characterize it as thoroughly as possible. This maximizes the potential for regional and global correlation. No single section is perfect in this regard and, consequently, the International Stratigraphic Guide of the IUGS Commission on Stratigraphy (Salvador, 1994) has recognized the benefit of designating a parastratotype. The holostratotype is the GSSP and, of course, always has precedence in defining the boundary. The parastratotype provides critical information not present in the holostratotype. The designation of parastratotypes is a well-established procedure and there are several examples in stratigraphic studies of the Jurassic. These include the definition of the Bajocian, where the Murtinheira section at Cabo Mondego, Portugal, is the GSSP and the Bearreraig Bay section on the Isle of Skye, Scotland, is designated an auxiliary stratotype (Pavia & Enay, 1997) and the establishment of the Lower Jurassic ammonite zonation of North America (Smith *et al*., 1988; Jakobs *et al*., 1994; Taylor *et al*., 2001; Longridge *et al*.,2006a).

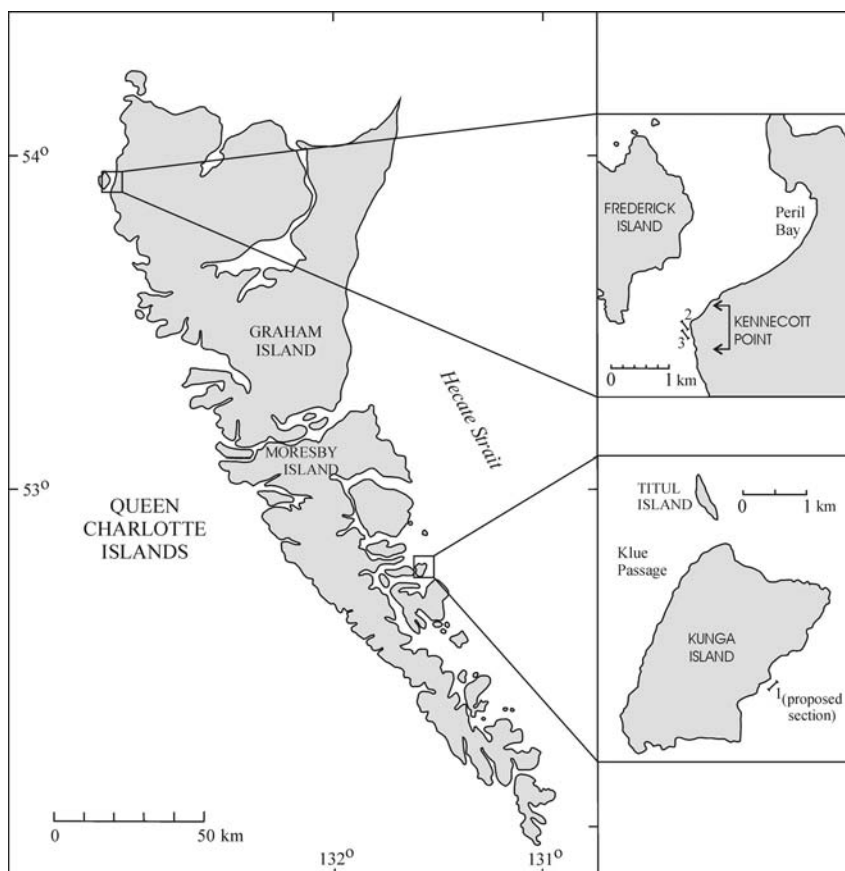Below, we summarize the details of the Kunga Island section as currently understood.

Figure 1: Localities of sections bearing latest Triassic and early Hettangian ammonite and radiolarian faunas in the Queen Charlotte Islands

Figure 2: Proposed stratotype section on Kunga Island. View to NE. Adopted from Smith (1998, p.188, fig.4.32). Photo E. Carter. Inserted arrow indicates the boundary level, but not exactly the stratotype point

2. Location and access

The proposed section is located in the supratidal region on the southeast shore of Kunga Island (NTS 103 B/13, Zone 9; 52°45.573', 131°33.638') (Figure 1, section 1, Figure 2). Kunga Island is a small island on the southeastern edge of the Queen Charlotte Islands (QCI), British Columbia (Figure 1) and is part of Gwaii Haanas National Park Reserve. Although this means a permit is necessary prior to collecting, it also provides protection and conservation of the site (Haggart, in press). Access to Kunga Island involves flying into Sandspit, on Moresby Island, QCI, approximately 55km from the Kunga Island site. The section is then accessed by vehicle over about 60km of logging road and then by boat.

3. Paleogeographical context

Kunga Island is part of the Wrangellia terrane, considered to be allochthonous to North America. During Triassic/Jurassic time, Wrangellia was more southerly and further outboard of its current position, relative to the craton, but it was eventually accreted to North America at some time during the Middle Jurassic (van der Heyden, 1992; Thompson *et al.*, 1991; Haggart *et al.*, 1995), Cretaceous (Monger, 1998) or Paleogene (Ward *et al.*, 1997). The constraints on its location at the end of the Triassic and beginning of the Jurassic are reasonably well documented. Permian coral, brachiopod, and fusulinid

faunas (Monger, 1984; Belasky, 1994; Belasky *et al.*, 2002), Sinemurian and Pliensbachian bivalve faunas (Aberhan, 1999 and references therein), and Pliensbachian ammonite faunas (Smith & Tipper, 1986; Smith *et al.*, 2001; Smith, 2006) tie the terrane to the Northern Hemisphere and the eastern Pacific. The distribution of the ammonites *Sunrisites* and *Badouxia* are additional evidence that Wrangellia was located in the eastern Pacific during the Hettangian (Taylor *et al.*, 1984; Smith, 2006; Longridge *et al.*, in press).

4. Tectonic history and structural setting

The Kunga Island section was deposited in the Mesozoic Hecate Basin (Haggart, 1993). The basin was affected by southwest directed folding and contractional faulting in the Middle Jurassic, block faulting in the Late Jurassic, northeast-directed folding in the Late Cretaceous, and extensional block faulting and reverse faulting in the Paleogene (Thompson *et al.*, 1991). Despite this regional deformation, the section at Kunga Island is, for the most part, structurally intact.

5. Lithostratigraphy and depositional paleoenvironment

The Kunga Island section is part of the Sandilands

Figure 3: Proposed Kunga Island section showing upper Rhaetian and lower Hettangian radiolarian, upper Rhaetian conodont, and lower Hettangian ammonite localities. R = radiolarians, C = conodonts, A = ammonites. Modified after Haggart *et al.* (2002) and Longridge *et al.* (2007)

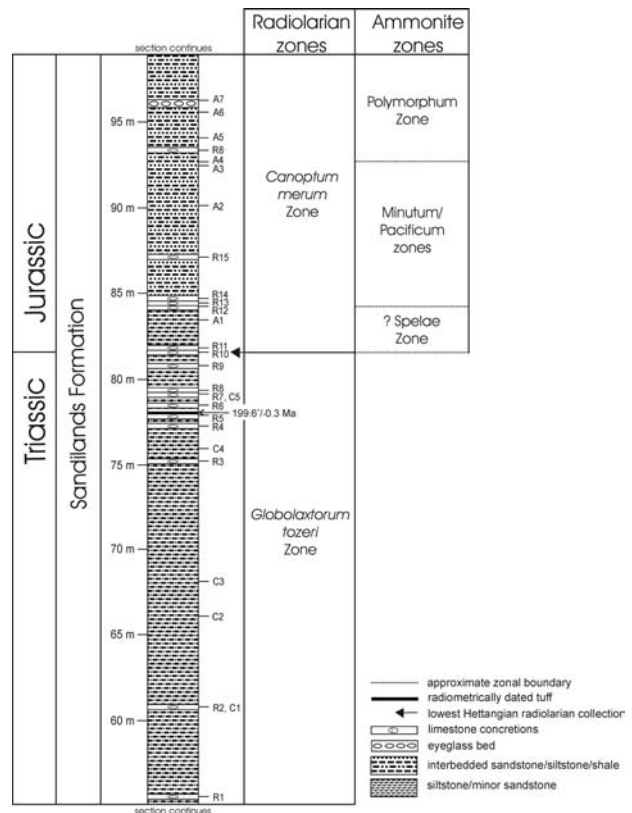| Radiolarian species	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16
Betraccium inornatum Blome	X															
Betraccium sp. C sensu Carter 1993	X															
Canoptum sp. A sensu Carter 1993	X															
Plafkerium fidicularium Carter	X															
Plafkerium sp. A sensu Carter 1993	X															
Praecitriduma apexensis Carter	X															
Nabolella aff. *desrochersi* (Carter)	X															
Entactinosphaera? *amphilapes* Carter	X	X														
Nabolella causia (Carter)	X	X														
Nabolella aff. *causia* (Carter)	X	X														
Nabolella desrochersi (Carter)	X	X														
Betraccium aff. *inornatum* Blome	X	X														
Ferresium sp. C sensu Carter 1993	X	X														
Plafkerium sp. B sensu Carter 1993	<	X														
Citriduma sp. C sensu Carter 1993	X	X	X													
Triassocrucella aff. *triassicum* Kozur & Mostler	<			X												
Globolaxtorum cristatum Carter	X	X				X										
Amuria sp. A sensu (Carter 1993)	<	X					X									
Haeckelicyrtium karcharos Carter	<	X					X									
Citriduma asteroides Carter	X	X	X		X			X								
Plafkerium keloense Carter	X	X					X	X	X							
Spumellaria gen. et sp. indet. C sensu Carter 1993	<								X							
Veghicyclia austriaca Kozur & Mostler	X	X					X		X							
Amuria sp. B sensu (Carter 1993)	X	X					X	X	X							
Betraccium kennecottense Carter	X	X			X	X	X	X	X							
Betraccium nodulum Carter	X	X			X	X	X	X	X							
Betraccium sp. E sensu Carter 1993	X	X	X		X		X	X	X							
Bipedis acrostylus Bragin	<	X					X		X							
Bistarkum cylindratum Carter	X	X	X	X	X	X	X	X	X							
Canoptum aff. *dixoni* Pessagno & Whalen	X	X					X	X	X							
Canoptum triassicum Yao	X	X		X			X	X	X							
Canoptum aff. *unicum* Pessagno & Whalen	<		X	X			X	X	X							
Canoptum sp. B sensu Carter 1993	X	X			X		X	X	X							
Cantalum gratum Carter	X	X	X		X		X	X	X							
Cantalum sp. A sensu Carter 1993	<						X	X	X							
Canutus? *beehivensis* Carter	X	X	X			X	X	X	X							
Crucella? sp. A sensu Carter 1993	X	X	X		X	X	X	X	X							
Deflandrecyrtium nobense Carter	X	X		X	X	X	X	X	X							
Deflandrecyrtium ithacanthum (Sugiyama)	<						X	X	X							
Entactinosphaera? aff. *simoni* Kozur & Mostler	X	X				X	X	X	X							
Entactinosphaera? *spinulata* Carter	<	X	X		X		X	X	X							
Eucyrtid gen. et sp. indet sensu Carter 1993	<	X	X	X	X		X	X	X							
Ferresium teekwoonense Carter	X	X	X			X	X	X	X							
Fontinella clara Carter	X	X			X		X	X	X							
Fontinella louisensis Carter	X	X							X							
Globolaxtorum tozeri Carter	X	X	X	X	X	X	X	X	X							
Haliomma swellensis Carter	X	X				X	X	X	X							
Icrioma? sp. A sensu Carter 1993	X	X	X			X	X	X	X							

Figure 4: Latest Rhaetian and early Hettangian radiolarians from the proposed section at Kunga Island, Queen Charlotte Islands. < indicates range extends lower, > indicates range extends higher

Formation of the Kunga Group. The Sandilands Formation is several hundred metres thick and ranges in age from early Rhaetian to mostly the latest Sinemurian, although its upper contact is diachronous and locally

Radiolarian species	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16
Pseudoheliodiscus aff. *sandspitensis* (Blome)	<				X		X	X	X							
Laxtorum capitaneum Carter	X	X	X			X	X	X	X							
Laxtorum perfectum Carter	X	X		X		X	X	X	X							
Laxtorum porterheadense Carter	X	X	X			X	X	X	X							
Liassosaturnalis aff. *parvis* Kozur & Mostler	X	X					X	X	X							
Livarella densiporata Kozur & Mostler	X	X		X			X		X							
Loupanus thompsoni Carter	X	X	X		X	X	X	X	X							
Orbiculiformella multibrachiata (Carter)	X	X			X	X	X	X	X							
Pantanellium newkluense Carter	X		X		X		X	X	X							
Paronaella beatricia Carter	<		X	X	X	X	X	X	X							
Paratriassoastrum crassum Carter	X	X			X		X	X	X							
Paratriassoastrum omegaense Carter	<	X	X	X	X	X	X	X	X							
Paratriassoastrum sp. A sensu Carter 1993	X	X	X		X	X	X	X	X							
Paratriassoastrum sp. B sensu Carter 1993	<		X	X	X	X	X	X	X							
Pentactinocarpus cf. *sevaticus* Kozur & Mostler	<	X				X	X	X	X							
Octostella dihexacanthus (Carter)	X	X				X	X	X	X							
Plafkerium gadoense Carter	X	X	X			X	X	X	X							
Praecitriduma canthofistula Carter	<							X	X							
Pseudacanthocircus trogeri Kozur & Mostler	X	X	X	X	X	X	X	X	X							
Serilla conclusum (Carter)	X	X				X	X	X	X							
Serilla ellisensis (Carter)	X	X				X	X	X	X							
Serilla stalkungiensis (Carter)	X	X				X		X	X							
Serilla tangilensis (Carter)	X	X				X			X							
Serilla tledoensis (Carter)	X	X				X	X	X	X							
Serilla sp. A sensu (Carter 1993)	X	X				X	X	X	X							
Nabolella sp. C sensu (Carter 1993)	X	X		X					X							
Spumellaria gen. et sp. indet. E sensu Carter 1993	<	X				X	X	X	X							
Spumellaria gen. et sp. indet. D sensu Carter 1993	X	X	X		X	X	X	X	X							
Livarella valida Yoshida	<			X		X	X	X	X	X						
Livarella spp.	X	X	X	X	X	X	X	X	X	X	X					
Eptingium onesimos Carter	<	X	X		X	X	X	X	X		X					
Kungalaria newcombi Dumitrica & Carter	X	X				X	X	X	X		X					
Paratriassoastrum spp.	X	X	X	X	X	X	X	X	X	X	X					
Pseudohagiastrum spp.	X	X	X	X	X	X	X	X	X	X	X					
Deflandrecyrtium sp. B sensu Carter 1993	<						X		X			X				
Fontinella habros Carter	X	X	X		X		X	X	X			X				
Fontinella inflata Carter	X	X				X	X	X	X			X				
Pseudoheliodiscus sp. B sensu (Carter 1993)	<						X		X			X				
Spumellaria gen. et sp. indet. B sensu Carter 1993	X	X		X	X	X	X	X	X			X				
Mesosaturnalis acuminatus Carter				X	X	X	X	X	X			X				
Pseudohagiastrum giganteum Carter & Hori					X		X	X	X							
Serilla sp. B sensu (Carter & Guex 1999)						X	X	X	X							
Globolaxtorum sp. A sensu Carter 1993							X	X	X	X						
Stauracanthocircus transitus Kozur & Mostler							X		X			X				>
Spumellaria indet X (Carter in Longridge et al. 2007)							X	X	X	X		X	X	X		>
Tipperella kennecottensis Carter									X	X	X	X	X	X	X	X
Indet. spherical forms										X	X	X	X	X	X	X
Udalia primaeva Whalen & Carter										?	X	X	X	X	X	X

Figure 4 cont'd

ranges in age from earliest Pliensbachian (Tipper & Carter, 1990; Tipper *et al*., 1991, 1994; Smith & Tipper, 1996) to Toarcian (Haggart, 2004). The Rhaetian and very basal Hettangian part of the Formation at Kunga Island are remarkably consistent, well-indurated silicified silt-stone with minor, fine- to medium-grained sandstone, and thin tuff interbeds (Figure 3). Common micrite concretions frequently yield abundant radiolarians and con-

Radiolarian species	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16
Udalia spp.										X	X	X	X	X	X	X
Tozerium nascens Whalen & Carter										?		X	X	X	X	X
Gen. et sp. indet. A sensu Whalen & Carter 1998										?		X	X	X	X	X
Charlottea spp.											?	X	X	X	X	>
Droltus hecatensis Pessagno & Whalen										X	X	?	X			X
Thurstonia spp.											?	X	X	X	X	X
Atalanta epaphrodita Cordey & Carter												X				>
Archaeocenosphaera laseekensis Pessagno & Yang												X	X	X	X	>
Bipedis elizabethae Whalen & Carter												X		X		>
Laxtorum sp. B sensu Whalen & Carter 1998												X		X		>
Pantanellium tanuense Pessagno & Blome												X	X	X		X
Parahsuum spp.												X	X			X
Paronaella ravenensis Whalen & Carter												X	X			X
Praehexsaturnalis tetraradiatus Kozur & Mostler												X		X		>
Relanus reefensis Pessagno & Whalen												X	X	X	X	>
Spumellaria indet B sensu Carter 1994												X	X	X	X	X
Canoptum merum Pessagno & Whalen												?		X		>
Amuria impensa Whalen & Carter														X	X	>

Figure 4 cont'd

Conodont species	C1	C2	C3	C4	C5	C6
Undifferentiated *Epigondolella*	X					
Epigondolella sp.		X				
Ramiform elements		X		X		X
Epigondolella ex. gr. *bidentata*			X			
Parvigondolella sp.			X			
Neogondolella sp.						X

Figure 5: Latest Rhaetian conodonts from the proposed section at Kunga Island, Queen Charlotte Islands

Ammonite species	A1	A2	A3	A4	A5	A6	A7
Choristoceras aff. *minutus*		X	X				
Odoghertyceras cf. *deweveri*							
Neophyllites (?) sp.							
Psiloceratid indet.	X						
Psiloceras ex. gr. *tilmanni*					X		X
Psiloceras cf. *marcouxi*							
Psiloceras cf. *planocostatum*		X					
Psiloceras cf. *polymorphum*						X	X
Nevadaphyllites (?) sp.							
Transipsiloceras cf. *transiens*			X				

Figure 6: Early Hettangian ammonites from the proposed section at Kunga Island, Queen Charlotte Islands

odonts. Despite intensive search, no macrofossils have been found in the Rhaetian part of the Kunga Island sequence, which was probably deposited in deep water. Above this stratigraphic level, the section becomes much more clastic-dominated and limestone disappears (Figure 3). About 15m higher, limestone concretions reappear and yield middle Hettangian radiolarians (Carter *et al.*, 1998). Beds in the section are near vertical, but otherwise the section displays minimal structural disruption (Carter ,1993; Carter *et al.*, 1998). Permanent markers identifying beds in the section were installed by the Geological Survey of Canada. These markers begin at the latest Triassic radiometrically dated tuff bed (0.0m) and range well into the Hettangian (TJB is at 3.6m).

Cameron & Tipper (1985) suggested that much of the Sandilands Formation was deposited in a relatively deep back-arc basin, somewhat distant from a source of fine volcanic detritus which is present in distal turbidites and less common air-fall tuffs (Pálfy *et al.*, 1990; Tipper & Guex, 1994). However, the precise paleogeographic setting of the Late Triassic-Early Jurassic strata of the Wrangellia terrane is poorly constrained at present, and more recent work suggests that the Rhaetian/Hettangian parts of the Sandilands Formation were deposited in an outer shelf to upper slope setting (Haggart *et al.*, 2001, 2002). The lack of significant turbidites within the Kunga Island section supports the interpretation of deposition in a shallower water environment. Importantly, the presence of abundant radiolarians suggests direct access to the open ocean.

6. Paleontology

The QCI contain two localities with uninterrupted succession of Rhaetian to Hettangian strata: Kennecott Point and Kunga Island (Figure 1). The radiolarians are abundant and well preserved at both localities and clearly represent the most important faunal successions of Rhaetian-Hettangian radiolarians known today. The Rhaetian part of the sequence is dated by closely associated conodonts at both localities (Tipper & Carter, 1990; Orchard, 1991; Carter, 1993; Tipper *et al.*, 1994) and rare ammonoids at Kennecott Point (Tipper & Carter, 1990; Tipper *et al.*,

1994; Ward *et al.*, 2004), while lower Hettangian ammonites date the succession at both localities (Tipper & Guex, 1994; Tipper *et al.*, 1994; Carter *et al.*, 1998; Longridge *et al.*, 2007). Radiolarians are the most abundant group throughout the Rhaetian and provide the most complete and continuous record of faunal change across the TJB. Many closely spaced collections at each locality document the dynamics of faunal change and closely constrain the position of the TJB. The dramatic turnover of radiolarian species (Carter, 1994, 1998; Carter *et al.*, 1998) is characterized by a significant extinction of Rhaetian taxa that are replaced by a low diversity Hettangian fauna composed of very simple forms.
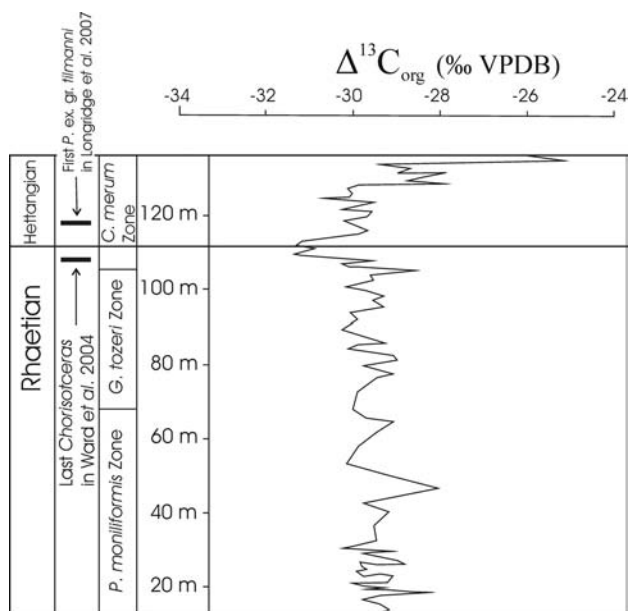

Figure 7: $\delta^{13}C_{org}$ record for Rhaetian to Lower Hettangian strata at Kennecott Point, Queen Charlotte Islands, British Columbia. Modified from Williford *et al.* (2007)

Since the 1970s, Mesozoic radiolarians have been dated by associated ammonoids, conodonts and/or other fossil groups, and vast numbers of radiolarian species have been described. Many were integrated into local and regional zonal schemes that have been increasingly refined over the years. However, subsequent testing over wider areas using the Unitary Associations (UA) method (Guex, 1991) has now reached a level of accuracy that allows radiolarians to stand alone as primary indicators for dating rock. This capability is particularly important in areas where radiolarians are the only fossils available for age dating (*e.g.* chert sequences in oceanic terranes), or where the completeness of the faunal succession is such that the accuracy achieved by radiolarians is superior to that of other fossil groups.

Very few radiolarians of Rhaetian and Hettangian age were known prior to Geological Survey of Canada-sponsored discoveries at Kennecott Point and the southeast side of Kunga Island (1986-1990). Preliminary results clearly indicated that a well-preserved succession of

Rhaetian and Hettangian radiolarians was present at both localities (Carter *et al.*, 1989; Carter, 1990; Tipper & Carter, 1990). Further collecting at Kunga Island in 1997-98 and 2000 increased the sampling density across this critical interval and provided more precise data on the range of key taxa. In 1993, Carter described the Rhaetian faunas and established two radiolarian zones: the *Proparvicingula moniliformis* Zone and the overlying *Globolaxtorum tozeri* Zone using the Unitary Associations method of Guex (1977, 1991). This work was based on the documentation of over 140 short-ranging Rhaetian species, most of which were new (Carter, 1993). A number of species have been described since that time (Yeh & Cheng, 1996; Sugiyama, 1997; Dumitrica & Carter, 1999; Tekin, 1999, 2002a; Carter & Hori, 2005; Longridge *et al.*, 2007); others have been recognized informally, and the ranges of still others, originating in the Carnian and Norian, have been extended to the Rhaetian.

7. Biostratigraphy – radiolarians, conodonts, ammonites

On the southeast side of Kunga Island there is a continuous sequence from the Rhaetian (Carter, 1993, fig.9) to the middle Hettangian (Carter *et al.*, 1998). Over 130m of Rhaetian strata are present in two sections (sections 3 and 5 of Carter, 1993; Figure 1, section 1). These strata overlie up to 100m of partly-disrupted, dark grey, calcite-veined, argillaceous strata with rare *Monotis* in the 30-50m interval. Above the section proposed herein (Figure 3), ~45m of strata contains middle Hettangian ammonites. The two Rhaetian sections have been correlated using radiolarians. Despite intensive search, no macrofossils have been found in Rhaetian beds at Kunga Island, but conodonts are common and radiolarians abundant.

The Triassic-Jurassic transitional interval as discussed herein includes radiolarians from the *Globolaxtorum tozeri* Zone (upper Rhaetian) and the *Canoptum merum* Zone (lower Hettangian) (Figure 4), upper Rhaetian conodonts (Carter, 1993; Figure 5) and ammonites that are possibly from the *Spelae* Zone and definitely from the *Minutum* to *Polymorphum* Zones (lower Hettangian) (Longridge *et al.*, 2007, fig.6) (Figure 3).

In total, radiolarians occur in 16 discrete horizons, collected over a stratigraphic interval of 37.45m, the majority of which are concentrated in about 10m of strata spanning the boundary (Figure 3). Diagnostic TJB radiolarians are shown on Plate 1. Rhaetian radiolarian collections begin 56m above the base of the formation and are present up to 80.75m, an interval of 24.75m. Five conodont horizons occur in the top 20.8m of upper Triassic strata, with the highest conodont occurrence at 79.1m (Figure 3). Prior to collecting in 2000, the first typical Hettangian radiolarians were believed to begin at 84.5m (Carter, 1998; Carter *et al.*, 1998). However, since the finding of transitional faunas (mostly Jurassic) at 81.55m and 81.8m in 2000, this level has been lowered to 81.55m (Carter & Hori, 2005). This level is <1.0m above the final occur-

rence of Rhaetian radiolarians, 2.45m above the last conodonts and 3.6m above a tuff layer within the Triassic-Jurassic transition yielding a U-Pb zircon age of 199.6± 0.3Ma (Pálfy *et al.*, 2000). Seven ammonite horizons occur within 14.8m of early Hettangian strata, with the first ammonite at 83.45m, 1.9m above the first Jurassic radiolarians (Figure 3).

8. Radiolarian biology and extinction

Basal Hettangian radiolarian faunas of the *Canoptum merum* Zone can be recognized by the common occurrence of *Tipperella kennecottensis*, together with other simple spherical forms with rod-like spines, the incoming of *Canoptum merum*, *Droltus hecatensis*, *Tozerium nascens*, *Udalia primaeva* and, a little higher, by the first appearance of the distinctive species *Pantanellium tanuense* (Plate 1). A complete discussion of the lower Hettangian faunas is found in Longridge *et al.* (2007).

Radiolarian faunas from the upper Rhaetian *Globolaxtorum tozeri* zone, up to the extinction event at the end of the Triassic, are rich and diverse, composed largely of genera originating in the late Carnian and Norian, and some in the Rhaetian. They differ from radiolarians of the underlying *Betraccium deweveri* Zone (upper Norian *Monotis* equivalent) by lacking the widely distributed nominal taxon, and many species of *Ferresium* and *Laxtorum* described by Blome (1984). Spumellarians outnumber nassellarians by a ratio of about 2:1. Radiation began early in the Rhaetian at Kunga Island and continued to topmost beds (Carter, 1993), a phenomenon that contrasts sharply with the diminishing diversity of other faunas at this time. The radiolarian fauna includes over 170 short-ranging species: 154 species were described or informally designated by Carter (1993), a few others have been recognized subsequently (Dumitrica & Carter, 1999; Carter & Hori, 2005), and many others are still undescribed. Some are widely distributed, *e.g.* *Globolaxtorum tozeri*, and have proven to be extremely useful for age dating (Yeh & Cheng, 1996; Sugiyama, 1997; Tekin, 1999; Amodeo, 1999; Bertinelli *et al.*, 2004; Yeh & Yang, 2006; Orchard *et al.*, 2007, in press). The most abundant and characteristic genera of the *G. tozeri* Zone are *Betraccium* Pessagno & Blome (but not *B. deweveri*), ?*Canutus* Pessagno & Whalen, *Citriduma* De Wever, *Deflandrecyrtium* Kozur & Mostler, *Fontinella* Carter, *Globolaxtorum* Carter, *Kungalaria* Dumitrica & Carter, *Laxtorum* Blome, *Livarella* Kozur & Mostler, *Loupanus* Carter, *Nabolella* Petrushevskaya, *Plafkerium* Pessagno and *Serilla* (= *Risella*) Carter (Carter, in press).

Twisted spines are characteristic of many Upper Triassic species, to the degree that poorly preserved samples can even be dated approximately by the presence of strongly twisted spines. This distinctive feature is prevalent amongst both spumellarians and nassellarians of Rhaetian age, and is particularly useful when differentiating late Rhaetian (with twisted spines) and early Hettangian faunas (with straight, rod-like spines).

Carter (1990) distinguished several broad taxonomic groups amongst the Rhaetian fauna: (1) conservative forms such as canoptids and pantanellids; (2) architecturally complex forms such as the hat-shaped nassellarians *Deflandrecyrtium*, *Haeckelicyrtium, Nabolella* and *Citriduma*; (3) rapidly-radiating forms of the *Laxtorum-Globolaxtorum* lineage and the *Ferresium-Risella* lineage (Carter & Guex, 1999); and (4) ancestral Jurassic forms such as *Crucella*, *Bistarkum*, *Bipedis*, *Canutus*, *Droltus etc*. Continuing studies indicate these assemblages are still valid, and suggest that each of these groups tends to react in a similar way approaching the TJB, *i.e.* most architecturally complex and rapidly-evolving forms disappear at the end of the Triassic, while the conservative and ancestral Jurassic forms survive.

Radiolarians underwent major faunal change at the end of the Triassic: five families disappeared including the Hexaporobracchiidae, Hindeosphaeridae, Nabolellidae, Pentactinocarpidae (De Wever *et al.*, 2001, p.389) and the Deflandrecyrtiidae. Many Triassic genera became extinct or nearly so (Longridge *et al.*, 2007, p.152), but the most noticeable effect was upon species. Ninety-five species are recorded in the *Globolaxtorum tozeri* Zone alone (Figure 4). A few range upward from the *Betraccium deweveri* Zone or below, over 60 species arose in the *Proparvicingula moniliformis* Zone, and 12 species originated within the *G. tozeri* Zone. With the exception of over 20 species that disappeared in lower beds of the *G. tozeri* Zone, the remainder range into the highest beds of the Triassic, and a very few pass into the basal Hettangian (see discussion of 'short-ranging Rhaetian holdovers' in Longridge *et al.*, 2007, p.153). The abrupt disappearance of over 55 species takes place above the 80.75m level and is followed <1m above by the appearance of a low diversity transitional fauna comprised of a few Rhaetian species, most notably *Livarella*, many peculiar transitional forms, and a few Hettangian genera. Less than three metres above, at 84.25m, an abundant basal Hettangian fauna is present that is characteristic of the *Canoptum merum* Zone.

9. Worldwide correlation using radiolarians

A similar radiolarian fauna has been recognized in Japan (Hori, 1992) and faunal correlation across the TJB on a global scale has been established (Carter & Hori, 2005). Other faunas of Rhaetian and/or Hettangian/Sinemurian age are recognized in Austria (Gawlik *et al.*, 2001), Baja California (Whalen *et al.*, 1998), Italy (Bertinelli *et al.*, 2004), Nevada (Orchard *et al.*, 2007), New Zealand (Spörli & Aita, 1988; Hori *et al.*, 1996), Peru (Suzuki *et al.* 2002), Turkey (Tekin, 1999, 2002a, b), the Philippines (Yeh, 1992; Yeh & Cheng, 1996, 1998) and Far East Asia, including Russia (Bragin, 1991), China (Yang & Mizutani, 1991; Yeh & Yang, 2006) and Japan (*e.g.* Yao *et al.*, 1980; Kishida & Hisada, 1985; Igo & Nishimura, 1984; Sato *et al.*, 1986; Sugiyama, 1997; *etc.*). Studies are

ongoing in several of these localities and although the precise boundary interval is missing in all but Japan thus far, published data fully support observations on faunal extinction and recovery around the TJB.

10. Radioisotopic dating

The Kunga Island section has provided a U-Pb date for the TJB of 199.6±0.3Ma from 3.6m below the boundary (Pálfy *et al*., 2000), and work is underway to refine its accuracy and precision. A slight increase in age is expected (Pálfy & Mundil, 2005). There is also considerable potential to obtain more geochronologic data from the upper Rhaetian and lower to middle Hettangian.

11. Magnetostratigraphy and carbon isotope stratigraphy

Magnetostratigraphy was attempted on the Kunga Island section but the samples were remagnetized (Carter & Galbrun, 1990; Galbrun, pers. comm. to Carter, 1990). The section has been affected by low-grade metamorphism and has a conodont alteration index of 4.5-5.0 (Orchard & Forster, 1991). The diagenetic alteration of the section means that it is not possible to obtain a useful carbon curve (Ward *et al*., 2001). However, a section at Kennecott Point in the northwest QCI (Figure 1, section 2) is much less metamorphosed (Orchard & Forster, 1991; Haggart *et al*., 2001, 2002) and has produced a carbon isotope curve showing a distinct and prolonged negative excursion of ~2 per mil spanning the TJB (Figure 7; Ward *et al*., 2001, 2004; Williford *et al*., 2007). This section is readily correlated with the Kunga Island section using radiolarian and ammonite faunas common to both sections.

12. The base of the Jurassic System at Kunga Island

If the TJB is defined using radiolarians as the primary standard, the Kunga Island section is an excellent candidate GSSP for the base of the Jurassic System. The radiolarian fauna that crosses the TJB in the QCI is the most diverse and well documented of this age in the world. The close correlation of the TJB radiolarian faunas with those in the Inuyama area of Japan demonstrates the global distribution of the radiolarians and their utility as index fossils. Radiolarian preservation is excellent and the rapid stratigraphic turnover, continuous deposition and lack of facies changes make the Kunga Island section an exceptional GSSP candidate. The section has already provided a date to constrain the TJB and has significant potential for further refining the geochronologic time scale for the Late Triassic and Hettangian. The ammonoid fauna from the section permits correlation with early Hettangian ammonite sequences elsewhere (Longridge *et al*., 2007). Although ammonites conclusively restricted to the *Spelae* Zone have not been found, *Psiloceras* cf. *planocostatum* and *Choristoceras* aff. *minutum* can be used to correlate the lower part of the Hettangian portion of the section with the *Minutum* and *Pacificum* Zones. *Transipsiloceras* cf. *transiens* and *Psiloceras* cf. *polymorphum* permit correlation of the upper portion of the section with the *Polymorphum* Zone. Correlations are also possible using Triassic and Jurassic ammonite faunas from sections at Kennecott Point (Figure 1, sections 2 and 3; Longridge *et al*., 2007, sections I and II), where there is a well documented carbon isotope curve showing a negative anomaly that can be used for global correlation (Figure 7; Ward *et al*., 2001, 2004; Williford *et al*., 2007).

The exceptional quality and relatively sharp transition of the radiolarian fauna across the TJB as well as the potential for radiometric dating in the Late Triassic and throughout the early and middle Hettangian make the Kunga Island section unique. Thus, we feel that if radiolarians are not used to define the TJB, the Kunga Island section should be designated as a parastratotype section.
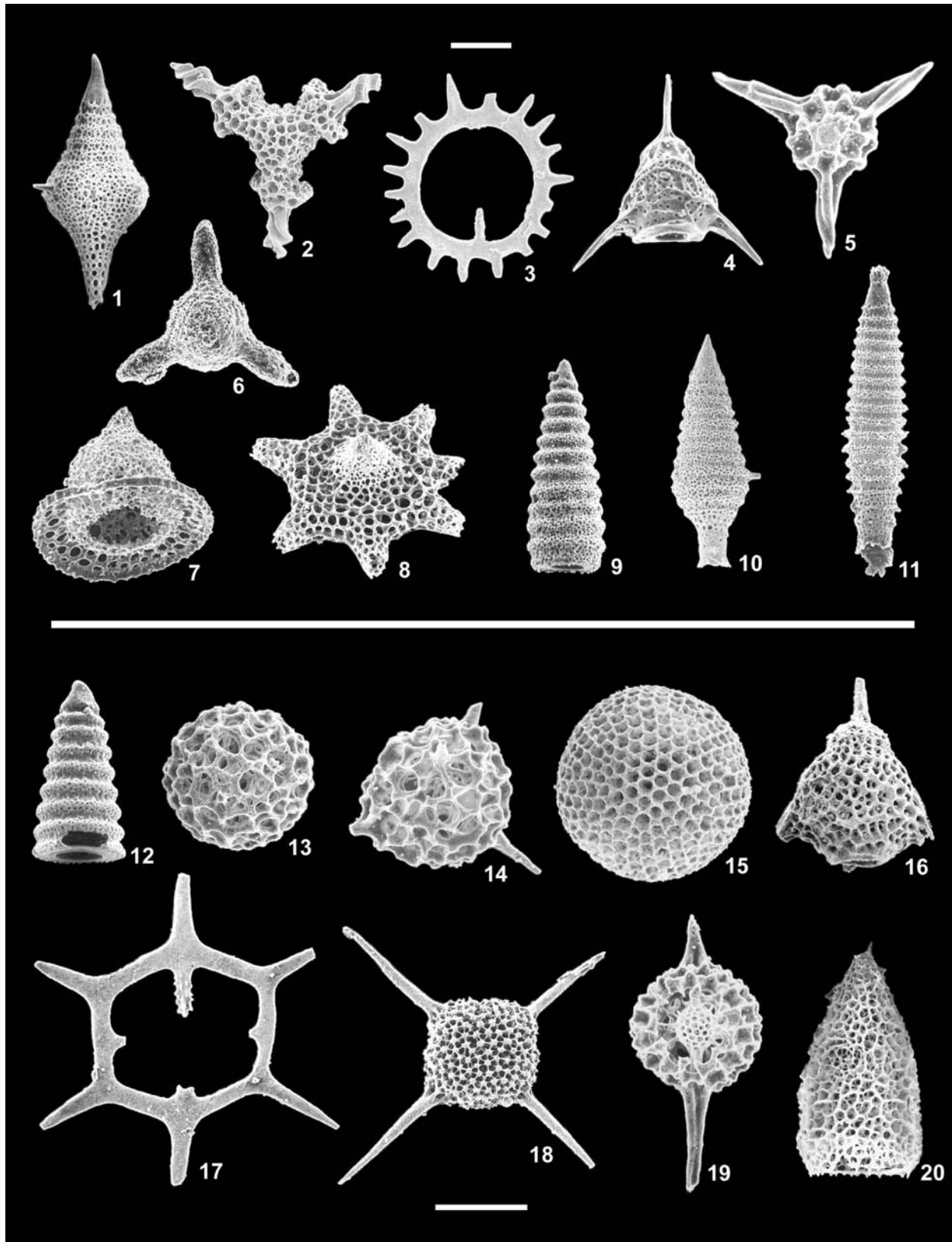
1. *Globolaxtorum tozeri* Carter. GSC 85927 from GSC loc. C-140489, Kennecott Point; scale bar = 100μm.
2. *Risella* sp. D sensu Carter and Guex 1999. GSC 107645 from R-1, GSC loc. C-173287, Kunga Island; scale bar = 100μm.
3. *Mesosaturnalis acuminatus* Carter. GSC 101908 from R-1, GSC loc. C-173287, Kunga Island; scale bar = 158μm.
4. *Bipedis acrostylus* Bragin. GSC 85921 from GSC loc. C-127798, Louise Island; scale bar = 81μm.
5. *Betraccium kennecottense* Carter. GSC 85911 from GSC loc. C-164674, Kennecott Point; scale bar = 80μm.
6. *Livarella densiporata* Kozur and Mostler. GSC 85912 from GSC loc. C-164674, Kennecott Point; scale bar = 100μm.
7. *Nabolella causia* (Carter). GSC 85929 from GSC loc. C-164674, Kunga Island; scale bar = 100μm.
8. *Citriduma asteroides* Carter. GSC 85930 from GSC loc. C-164674, Kunga Island; scale bar = 100μm.
9. *Canoptum triassicum* Yao. GSC 102083 from GSC loc. C-164693/13, Kunga Island; scale bar = 100μm.
10. *Laxtorum capitaneum* Carter. GSC 107648 from R-8, GSC loc. C-173280, Kunga Island; scale bar = 100um.
11. *Canoptum* sp. aff. *C. unicum* Pessagno and Whalen. GSC 85933 from GSC loc. C-140489, Kennecott Point; scale bar = 100μm.
12. *Canoptum merum* Pessagno and Whalen. GSC 99425 from GSC loc. C-140496, Kennecott Point.
13. Spumellaria indet. B sensu Carter 1994. GSC 99423 from R2, GSC loc. C-173357, Kunga Island.
14. *Tozerium nascens* Whalen and Carter. GSC 99424 from GSC loc. C-173332, Kunga Island.
15. *Archaeocenosphaera laseekensis* Pessagno and Yang. GSC 99426 from R2, GSC loc. C-173357, Kunga Island.
16. *Bipedis elizabethae* Whalen and Carter. GSC 99433 from GSC loc. C-173332, Kunga Island.
17. *Praehexasaturnalis tetraradiatus* Kozur and Mostler. GSC 99439 from GSC loc. C-173332, Kunga Island.
18. *Udalia primaeva* Whalen and Carter. GSC 107742 from GSC loc. C-173332, Kunga Island.
19. *Pantanellium tanuense* Pessagno and Blome. GSC 129052 from R4, GSC loc. 173285, Kunga Island.
20. *Droltus hecatensis* Pessagno and Whalen. GSC 99434 from R2, GSC loc. C-173357, Kunga Island.

Plate 1

Scanning electron micrographs of diagnostic Triassic/Jurassic boundary radiolaria from the Sandilands Formation, Queen Charlotte Islands
Figs 1-11 upper Rhaetian: scale-bar at plate top = µm cited for each illustration
Figs 12-20 lower Hettangian: scale-bar at plate base = 100µm for all specimens illustrated

This will further characterize the interval and increase its correlation potential, improving the probability of it being recognized elsewhere. The ammonite faunas from the Kunga Island section, as well as the negative carbon curve excursion at Kennecott Point, permit correlation with several other TJB GSSP candidates. For example, we have previously published information proposing that the North American Jurassic stratotype proposals be combined such that the Ferguson Hill section in Nevada is the GSSP (Taylor *et al.*, 1983; Guex *et al.*, 1997, 2006; Lucas *et al.*, 2007, this *Newsletter*) and the Kunga Island section is a parastratotype (Longridge *et al.*, 2006b, 2007; Lucas *et al.*, 2007; this *Newsletter*). The current level of the TJB in the Kunga Island section, as indicated in Figure 3, is based exclusively on the radiolarian faunas. If the Kunga Island section is designated as a parastratotype, rather than a GSSP, the level of the boundary would have to be adjusted to align it with whatever primary standard is used in the GSSP.

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Appendix

Section 1. Kunga Island, southeast side (= section 5 in Carter, 1993; section SKUD in Carter *et al*., 1998; section III (partial) in Longridge *et al*., 2007). NTS 103 B/13, Zone 9; N 52°45.573', W 131°33.638'.

Radiolarian collections: R1-R9 are Rhaetian faunas from the *Globolaxtorum tozeri* Zone (R1 marks the base of zone); collections R10-R16 are lower Hettangian faunas from the *Canoptum merum* Zone.

R16: GSC loc. C-305413; collected 93.45m above base of section.

R15: GSC loc. C-304141; collected 87.15m above base of section.

R14: GSC loc. C-305412; collected 84.74m above base of section.

R13: GSC loc. C-305411; collected 84.45m above base of section.

R12: GSC loc. C-173357, C-303576, C-304137 and C-305409; collected 84.25m above base of section.

R11: GSC loc. C-305406; collected 81.80m above base of section.

R10: GSC loc. C-305405; collected 81.55m above base of section.

R9: GSC loc. C-164696/11, C-173288, C-303575, C-305404; collected 80.75m above base of section.

R8: GSC loc. C-303574, C-305402; collected 79.3m above base of section.

R7: GSC loc. C-173286, C-173287, C-303573; collected 79.1m above base of section.

R6: GSC loc. C-305401; collected 78.45m above base of section.

R5: GSC loc. C-303572; collected 77.85m above base of section.

R4: GSC loc. C-173285; collected 75.9m above base of section.

R3: GSC loc. C-303571; collected 75.2m above base of section.

R2: GSC loc. C-173280; collected 60.75m above base of section.

R1: GSC loc. C-164696/11; collected 56.0m above base of section.

Additional GSC localities for figured radiolarians on Plate 1 include:

Kunga Island, southeast side. GSC loc. 164696/13 (87-CNA-SKUB-13; section 2, Carter, 1993), C-164674 (87-CNA-SKU-SP-1; section 6, Carter, 1993), and C-173332 (89-CNA-SKUE-6; section 2, Carter *et al*., 1998).

Kennecott Point. GSC loc. C-164674 (87- CNA-KPA-12), C-140489 (87- CNA-KPA-17; section 1, Carter, 1993). GSC loc. C-140496 (87- CNA-KPB-1; section 9, Carter *et al*., 1998).

Louise Island. GSC loc. C-127798 (86-CNA-SP-1/1; section 4, Carter, 1993).

Conodont collections: C1-C5 are Rhaetian faunas from the *Globolaxtorum tozeri* radiolarian Zone.

C5: GSC loc. C-303573, C-173287; collected 79.1m above base of section.

C4: GSC loc. C-173284; collected 75.9m above base of section.

C3: GSC loc. C-173282; collected 68.1m above base of section.

C2: GSC loc. C-173281; collected 66.05m above base of section.

C1: GSC loc. C-173280; collected 60.75m above base of section.

Ammonite collections: A1-A7 are early Hettangian faunas; A1 is possibly from the *Spelae* Zone, A2-A3 are from the *Minutum* and *Pacificum* Zones, and A4-A7 are from the *Polymorphum* Zone.

A7: GSC loc. C-159351; collected 96.35m above base of section.

A6: GSC loc. C-175325; collected 95.75m above base of section.

A5: GSC loc. C-210792; collected 94.2m above base of section.

A4: GSC loc. C-175324; collected 92.85m above base of section.

A3: GSC loc. C-175323; collected 92.55m above base of section.

A2: GSC loc. C-175302; collected 90.2m above base of section.

A1: GSC loc. C-175322; collected 83.45m above base of section.

Updated proposal for Global Stratotype Section and Point for the base of the Jurassic System in the New York Canyon area, Nevada, USA

Spencer G. Lucas[1], David G. Taylor[2], Jean Guex[3], Lawrence H. Tanner[4], Karl Krainer[5]

[1]New Mexico Museum of Natural History, 1801 Mountain Rd. NW, Albuquerque, New Mexico 87104, USA; spencer.lucas@state.nm.us

[2]1272 University of Oregon, Department of Geological Sciences, Eugene, Oregon 97403 USA; blitz124@comcast.net

[3]Department of Geology, BFSH-2, 1015 Lausanne, Switzerland; Jean.Guex@unil.ch

[4]Department of Biological Sciences, Le Moyne College, 1419 Salt Springs Road, Syracuse, New York, 13214 USA; tannerlh@lemoyne.edu

[5]Institute for Geology and Paleontology, University of Innsbruck, Innrain 52, A-6020 Innsbruck, Austria; karl.krainer@uibk.ac.at

Abstract At Ferguson Hill in the New York Canyon area of Mineral County, Nevada, USA, marine strata of the Mount Hyatt and Muller Canyon members of the Gabbs Formation and Ferguson Hill Member of the overlying Sunrise Formation encompass a proposed Global Stratotype Section and Point (GSSP) for the base of the Jurassic System in the Muller Canyon Member. This section has been studied for about a century and is on U.S. Government land with guaranteed conservation and ready access for scientific investigators. At Ferguson Hill, the Muller Canyon Member is ~17m thick and is slope-forming muddy siltstone with intercalated fossiliferous beds of indurated siltstone and bioclastic wackestone. The fossil record of the Muller Canyon Member includes radiolarians, foraminiferans, ostracodes, microbivalves, microgastropods, sponge spicules, ichthyoliths, conodonts, echinoderms, ichthyosaurs, brachiopods, bivalves, gastropods, nautiloids and ammonites. Microfossils from uppermost Triassic strata in the section have been recovered for the first time and include the conodonts *Misikella posthersteini* and *Zieglericonus rhaeticum* and radiolarians of the *Globolaxtorum tozeri* Zone of Rhaetian age. Biostratigraphically significant fossils from the Muller Canyon Member, especially the highest occurrence of conodonts and the distribution of ammonites such as *Choristoceras crickmayi*, *C*. *marshi*, *Arcestes* spp., *Psiloceras spelae*, *P. tilmanni* and *P. pacificum*, provide a strong basis for global correlation to sections in western Canada, Peru, Chile, England and Austria, among others. The base of the Jurassic System should be a marker event of optimal global correlatability, and an ammonite event provides the highest degree of correlatability. Thus, the lowest occurrence of ammonites of the *Psiloceras tilmanni* group (lowest occurrence of *P. spelae*) in the Ferguson Hill section provides the most globally correlatable datum, and thus the best GSSP, both because of the geographically broad distribution of ammonites of the *P. tilmanni* group and because of the close association of the lowest occurrence of *P. spelae* with other criteria (proxies) that can be used to correlate the base of the Jurassic. We also support establishing the Kunga Island section in the Queen Charlotte Islands of western Canada as the parastratotype section of the base Jurassic GSSP. As type and parastratotype sections for the base of the Jurassic, Ferguson Hill and Kunga Island provide a definition of the base of the Jurassic of optimal correlation potential.

1. Introduction

Since the classic work of Muller & Ferguson (1939), palaeontologists have known that fossiliferous marine strata of latest Triassic and earliest Jurassic age are present in the New York Canyon area of west-central Nevada, USA (Figure 1). Taylor *et al*. (1983) and Guex *et al*. (1997, 2006) proposed the Ferguson Hill section, which is just south of New York Canyon, as a candidate for the GSSP for the base of the Jurassic System. Here, we update their proposals and summarize data on lithostratigraphy, microfacies and microfossils, much of it collected during the last few years. We advocate defining the base of the Jurassic System at the lowest occurrence of ammonites of the *Psiloceras tilmanni* group at the Ferguson Hill section, with a parastratotype section for the boundary on Kunga Island in the Queen Charlotte Islands of western Canada.

2. Location and access

New York Canyon is a dry, rocky canyon that drains from northeast to southwest on the western flank of the Gabbs Valley Range in Mineral County, Nevada (Figure 1). The Gabbs Valley Range mostly exposes Cenozoic igneous rocks, but numerous fault blocks of Triassic-Jurassic strata are also present (Ferguson & Muller, 1949). The proposed GSSP for the base of the Jurassic System (Figures 1-2) is located on the north bank of the informally named Muller Canyon, which is the canyon immediately south of New York Canyon; it is on the south-facing slope of Ferguson Hill and is located in the NW/NE sec. 9, T7N, R35E, at and around UTM 405574E, 4260152N (zone 11, NAD 27). The latitude/longitude is latitude 38°29'11.7"N and longitude 118°4'57.5"W.

Access to the Ferguson Hill section is via an all-weather unpaved road that traverses New York Canyon to a point where the section can be reached on foot by a walk of ~0.5km. The Ferguson Hill section and surrounding lands are U.S. Government lands, administered by the Bureau of Land Management (BLM), a branch of the Department of the Interior. At our request, the Bureau of Land Management has guaranteed "that BLM Nevada will maintain access to the GSSP for qualified scientists

Figure 1: Photograph of the Ferguson Hill section, New York Canyon, Nevada, showing (at X) the position of a point 20cm below bed N9; this is the FO of *Psiloceras spelae* and the proposed GSSP. The spot marked 'O' locates the FO of intermediate Phylloceratids, illustrated by Ward *et al.* (2007) and proposed by McRoberts *et al.* (this *Newsletter*) as their GSSP

and will conserve it for future use and study" (letter R. Abbey to SGL, 8 July 2004; see Appendix).

3. Previous Studies

In the late 1800s, reconnaissance geology and fossil collection established the presence of both Triassic and Jurassic rocks in the Gabbs Valley Range. Muller & Ferguson (1936) produced the first substantial publication on the TJB (Triassic-Jurassic boundary) succession in the New York Canyon area, and their subsequent publications (especially Muller & Ferguson, 1939; Ferguson & Muller, 1949) established the basic geological framework of the area. Taylor *et al.* (1983) published a revised and more detailed lithostratigraphy. This was accompanied by palaeoecological studies (Laws, 1982) and a series of articles on the ammonite biostratigraphy of the strata that encompass the TJB (*e.g.* Guex, 1980, 1982, 1987, 1995; Taylor, 1982, 1998; Taylor *et al.*, 1983, 2000, 2001; Guex *et al.*, 1998). Subsequent work in the New York Canyon area has further developed the ammonite biostratigraphy into the most complete succession of ammonite zones known across the TJB, and also has produced a carbon-isotope stratigraphy of the TJB section (Guex, 1995; Taylor *et al.*, 2000; Taylor & Guex, 2002; Guex *et al.*, 2003a, b, 2004; Ward *et al.*, 2007). New data and analyses reported by Lucas *et al.* (2007) and Orchard *et al.* (2007) include information on the microfacies (sedimentary petrography), sedimentology, sequence stratigraphy and micropalaeontology of the Ferguson Hill section that are summarized here.

4. Tectonic history and structural setting

The Triassic-Jurassic rocks of the southern Gabbs Valley Range have been affected by two tectonic events: (1) late Mesozoic compression that resulted in their being transcurrently displaced towards the east (to their present location) as part of what Oldow *et al.* (1993) referred to as the Luning lithotectonic assemblage; and (2) late Cenozoic crustal extension that produced the present-day block-faulted basins and ranges of Nevada, including the Gabbs Valley Range (*e.g.* Stewart, 1980). Volcanism concomitant with the late Cenozoic extension produced the intrusives (mostly diorite, granodiorite and aplite), basalts and rhyolites exposed in the southern Gabbs Valley Range. These intrusives have somewhat metamorphosed the TJB strata in the New York Canyon area (resulting in a conodont alteration index of 3-4: M. Orchard, 2006, pers. comm.).

The rocks in the southern Gabbs Valley Range are broadly folded and cut by two south/southeast-verging
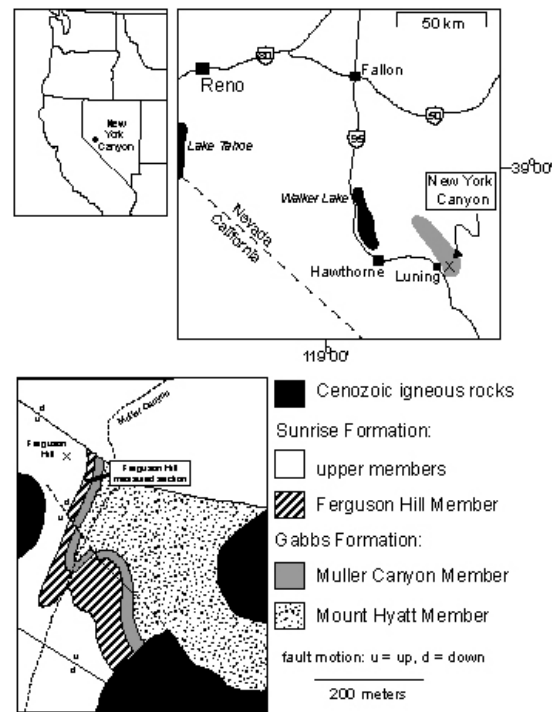

Figure 2: Location map (above) of New York Canyon area in west-central Nevada, USA, and geological map (below) of Ferguson Hill area, showing location of measured section (geology after Ferguson & Muller 1949, pl.5).
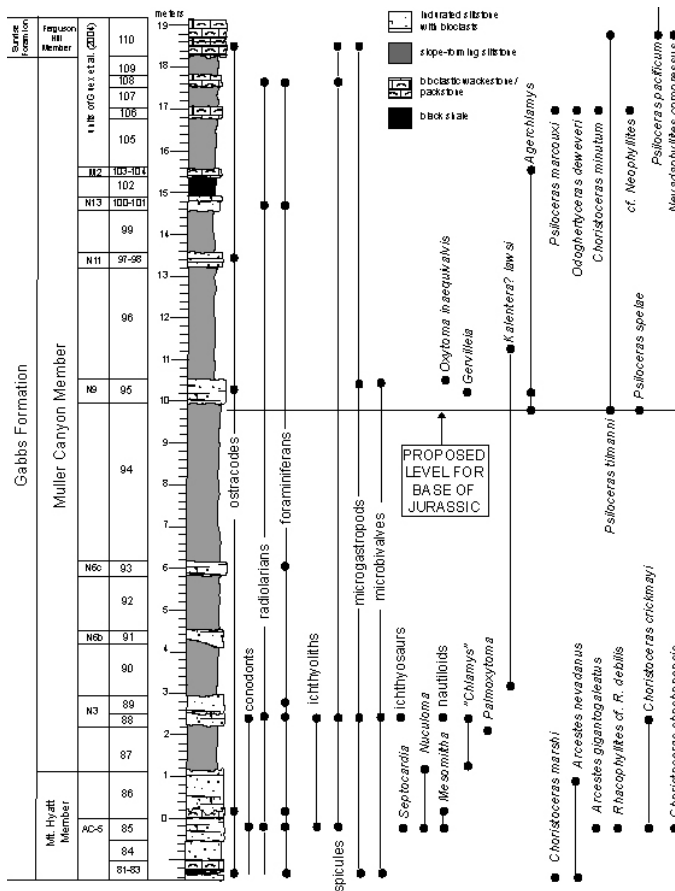
Figure 3: Measured stratigraphic section of the Muller Canyon Member of the Gabbs Formation and adjacent strata at Ferguson Hill. The proposed definition of the base of the Jurassic is at the lowest occurrence of *Psiloceras spelae*, 20cm below bed 95

thrust faults. The New York Canyon thrust (Ferguson & Muller, 1949) is just to the northwest of Ferguson Hill, so that the strata exposed in New York Canyon are in its upper plate, having been thrust over Jurassic strata of the lower plate. This thrust fault, however, has not directly affected the section at Ferguson Hill (Ferguson & Muller, 1949, pl.5). Indeed, despite local metamorphism and structural deformation, the section at Ferguson Hill (Figures 1, 2) is very fossiliferous and structurally intact (homoclinal).

5. Lithostratigraphy

The proposed GSSP section at Ferguson Hill encompasses the upper part of the Mount Hyatt Member and all of the Muller Canyon Member of the Gabbs Formation and the lowermost part of the overlying Ferguson Hill Member of the Sunrise Formation (Figure 2).

5.1. Mount Hyatt Member

At Ferguson Hill, an incomplete section of the upper part of the Mount Hyatt Member is exposed that is ~21m thick and is mostly composed of resistant 'limestone' beds. These 'limestones' are actually different types of calcareous

siltstone (most with abundant bivalves and some ammonites). Most of these beds are medium to dark gray and weather to dark yellowish orange and/or pale yellowish brown. Thin, tabular bedding is characteristic, but a few beds are nodular-weathering. Bed thicknesses range from 10 to 40cm. In many beds, sedimentary structures have been partly or completely destroyed by burrowing and grazing organisms. In some beds, horizontal lamination and small scale ripple cross-lamination is observed. 'Limestone' beds of the Mount Hyatt Member are intercalated with very thin (<10cm thick) beds of dark gray, calcareous shale.

5.2 Muller Canyon Member

At the Ferguson Hill section, the Muller Canyon Member is about 17m thick (Figure 2). Most of the unit (68% of the measured section thickness) is muddy, slope-forming siltstone, which is typically medium light gray, sandy, calcareous and, in some beds, fossiliferous. This siltstone slope is broken by ledge-forming beds of indurated siltstone that are 20 to 60cm thick with bioclasts and bioclastic wackestone/floatstone containing volcanic rock fragments. Primary sedimentary structures are commonly destroyed by bioturbation; in a few beds, horizontal lamination and small scale ripple cross-lamination are preserved. The indurated beds are 26% of the measured section thickness, and they are mostly sandy bioclastic siltstones. The fossil content of the Muller Canyon Member comes mostly from these indurated beds (Figure 2). The Muller Canyon Member also contains a single, 40cm-thick bed of black shale.

The basal contact of the Muller Canyon Member on the Mount Hyatt Member is where nonresistant siltstone rests on two sandy, bioclastic siltstone beds, about 40cm thick (which, in turn, rest on very bioturbated, resistant, calcareous siltstone). The upper contact with the Ferguson Hill Member of the Sunrise Formation is an interval of intercalated siltstone and limestone beds, and we picked the Sunrise Formation base at the top of the highest siltstone bed more than 1m thick (Figure 2).

5.3 Ferguson Hill Member

The section at Ferguson Hill reported here only includes

STAGE		ammonite zones	Ferguson Hill, Nevada	Kunga Island, Canada	Utcubamba Valley, Peru	St. Audrie's Bay, England	Karwendel syncline, Austria
HETTANGIAN		*Psiloceras polymorphum*	●	●	●		●
		Psiloceras pacificum	●	●	●	●	
		Choristoceras minutus	●	●	●		
		Psiloceras spelae	●				●
RHAETIAN		*Choristoceras crickmayi/marshi*	●	●	●		●

Figure 4: Correlation of ammonite zones present at Ferguson Hill, with ammonite records from some other proposed GSSPs for the base of the Jurassic

the base of the Ferguson Hill Member of the Sunrise Formation (Figure 2). These strata comprise very fossiliferous, medium- to thick-bedded sandy limestone that weathers dark yellowish orange to brown.

5.4 Microfacies

Thin sections were cut from selected, resistant beds in the Ferguson Hill section for petrographic analysis. The Mount Hyatt Member is mostly composed of siltstones containing a fairly small proportion of identifiable bioclasts and a substantial siliciclastic component (up to 40%) consisting mainly of quartz. Many beds also have a dark (thermally mature) organic component, including fecal pellets, and stylolites. The proportion of silt increases upward in the section, as does the size of the bioclasts, with large echinoderm and mollusc shell fragments dominant.

The Muller Canyon Member siltstone beds consist of mixed carbonate and siliciclastic grains, commonly bioturbated, containing 10-30%, and rarely up to 60%, siliciclastic material (dominantly quartz, rarely micas). The proportion of bioclastic grains is low. Bioclasts are strongly recrystallized and dominated by shell fragments and echinoderms; rare ostracods and foraminiferans are also present. Locally, the siltstone contains small fecal pellets. In some siltstone beds fossils are completely absent. The rock is slightly silicified and stained brownish-gray, partly black, by Fe hydroxides.

The base of the Sunrise Formation is a nonlaminated, recrystallized, fine-grained arenitic bioclastic packstone. The rock is composed of abundant small, abraded and recrystallized skeletal grains, many displaying thin dark-brown to black rims. Most abundant are echinoderms and shell fragments. Spicules are also common. Other skeletons include small gastropods, ostracods and echinoid spines. Brown lithoclasts, opaque grains and a few quartz grains are present. The bioclasts and lithoclasts are cemented by calcite.

6. Palaeontology overview

The Ferguson Hill section yields a diversity of marine trace fossils and micro- and macrofossils. Most of the microfossils have not been studied; these include foraminiferans, ostracodes, microbivalves, microgastropods, sponge spicules and ichthyoliths from the Mount Hyatt and Muller Canyon Members (Figures 2). Orchard *et al.* (2007) present the first published data on radiolarians and conodonts from the Mount Hyatt and Muller Canyon members. The degree of metamorphism of the Ferguson Hill section has apparently destroyed any palynomorphs from the Muller Canyon Member, as efforts to recover palynomorphs in 2005 (and previously) were unsuccessful (W. Kuerschner, written communication, 2006).

Macrofossils from the section are mostly bivalves and ammonites; the latter have been published on extensively. Other macrofossils from the section include gastropods,

nautiloids (*Pleuronautilus*), brachiopods (terebratulids), ichthyosaurs (isolated teeth and vertebrae) and crinoids (columnals of *Pentacrinus*), but these have not been studied in detail.

6.1 Trace fossils

Hallam & Wignall (2000) reported trace fossils and ichnofabric indices for the Ferguson Hill section. They listed high levels of bioturbation (ichnofabric index of 5) for the upper part of the Mount Hyatt Member and most of the resistant beds of the Muller Canyon Member (Hallam & Wignall, 2000, fig.3). They also noted particularly intensive bioturbation in the middle part of the Muller Canyon Member, with the trace fossil assemblage dominated by *Helminthoida*.

From the Mount Hyatt Member, Twitchett & Barras (2004) described a relatively diverse ichnofauna composed of *Arenicolites, Planolites, Rhizocorallium, Skolithos* and *Thalassinoides*, which are present in the 'limestones'. All ichnotaxa of the Mount Hyatt Member reappear in the Sunrise Formation. Additionally, *Chondrites* and *Diplocraterion* occur in the Sunrise Formation. Twitchett & Barras (2004) concluded, based on the trace fossil assemblages, that the Mount Hyatt Member and Sunrise Formation were deposited in a similar palaeoenvironment. Our outcrop observations of trace fossils in the Ferguson Hill section are consistent with those of Twitchett & Barras (2004), and our petrographic data support the high levels of bioturbation Hallam & Wignall (2000) reported for much of the section.

6.2 Microfossils

Conodonts and radiolarians were recovered from the Ferguson Hill section by bulk sampling in 2003 and in 2005 and are documented by Orchard *et al.* (2007). The conodonts from the upper part of the Mount Hyatt Member through the lower part of the Muller Canyon Member (as high as Bed 88; Figure 2) are the characteristic Rhaetian taxa *Misikella posthersteini* Kozur & Mostler and *Zieglericonus rhaeticus* Kozur & Mock. Sampling of higher beds in the Muller Canyon Member and the basal beds of the Sunrise Formation did not yield conodonts. In general, beds that did yield conodonts in the Ferguson Hill section produced assemblages of low abundance and low diversity.

Identified radiolarians from the Ferguson Hill section are also from the upper Mount Hyatt Member through lower Muller Canyon Member. These include taxa indicative of the *Globolaxtorum tozeri* Zone of latest Rhaetian age (Orchard *et al.*, 2007). Radiolarians are present stratigraphically higher in the Ferguson Hill section than the identified Rhaetian specimens, but have not been studied. Other microfossils have also been identified in the Ferguson Hill section but await study. These are ostracods, foraminiferans, microbivalves, microgastropods and ichthyoliths (Figure 2). Thus, the Ferguson Hill section contains an abundant and diverse microfauna, most

of which remains to be studied.

6.3 Bivalves

Laws (1982) first described bivalve assemblages from the Ferguson Hill section. He assigned the bivalves from the upper part of the Mount Hyatt Member and basal Muller Canyon Member to his *Nuculoma* association, dominated by infaunal deposit feeders and characterized by an abundance (as much as 80% of the assemblage) of *Septocardia*.

Indeed, the upper Mount Hyatt and basal metre of the Muller Canyon Member have a moderately diverse and locally prolific bivalve fauna. *Septocardia*, in particular, is a Triassic indicator that is common in the topmost beds of the Mount Hyatt Member. These beds also yield common *Nuculoma*, undetermined non-siphonate bivalves species, and pteriomorphs. '*Chlamys*' sp. A ranges into the basal metre of the Muller Canyon Member but persists no higher (Figure 2).

Most of the Muller Canyon Member above its base yields a bivalve assemblage that has little in common with the *Septocardia* beds below. This stratigraphically higher bivalve assemblage consists of *Kalentera*, an inoceramid bivalve, undetermined non-siphonate infaunal forms, *Oxytoma inaequivalvis*, and *Agerchlamys boellingi*. The species *Kalentera lawsi*, the inoceramid and *A. boellingi* may be diagnostic of the post-*Septocardia* beds. Thus, there is a substantial turnover in the bivalves in the lower part of the Muller Canyon Member, just above the HO of conodonts and characteristic Late Triassic ammonites.

6.4 Ammonites

Ammonite assemblages from the Ferguson Hill section (Figure 2) are diverse, abundant and well preserved (*e.g.* Guex, 1980, 1982, 1987, 1995; Taylor, 1982, 1998; Taylor *et al.*, 1983, 2000, 2001; Guex *et al.*, 1998). Much of the upper part of the Mount Hyatt Member belongs to the *Choristoceras rhaeticum* Zone, as that zonal species is present and co-occurs with *Arcestes nevadanus* Gabb and occasional *Placites*. The uppermost 5m of the Mount Hyatt Member and lowermost 1m of the Muller Canyon Member yield ammonites of the *Choristoceras crickmayi* zone (Figure 2), including *C. shoshonensis*, *C. marshi*, *Arcestes nevadanus*, *Rhacophyllites* cf. *R. debilis* and *Placites*.

These beds are followed by a stratigraphic interval, about 7m thick, that lacks ammonites. About 20cm below Bed 95 in our section (Figure 2) is the LO of *Psiloceras tilmanni* accompanied by the LO of *P. spelae*. This is the LO of ammonites of the *P. tilmanni* group that we favor as the point for definition of the base of the Jurassic in the Ferguson Hill section. This also defines the base of the lowest Hettangian ammonite zone, the *P. spelae* Zone. The upper beds of the Muller Canyon Member have yielded abundant tiny *Choristoceras* of the *minutum* group, co-occurring with *Psiloceras*, *Odoghertyceras* and *Neophyllites*. This is the *Choristoceras minutum* Zone.

The first abundant, three-dimensional, smooth *Psiloceras* of the *pacificum* group appear about one metre above that zone. This assemblage is characterized by the smooth *Psiloceras* species *P. pacificum*, and is now referred to the *P. pacificum* Zone.

7. Depositional paleoenvironments

Strata in the Ferguson Hill section were deposited in a backarc basin bounded by a volcanic arc to the west and the North American continent to the east (*e.g.* Oldow *et al.*, 1993). The depositional paleoenvironments of the TJB section at Ferguson Hill were all normal marine environments below wave base (Laws, 1982; Taylor *et al.*, 1983). These strata were thus deposited as part of a shelfal terrane (Luning assemblage) along a subsiding continental margin in which there was significant variation in subsidence rates. The TJB strata in the New York Canyon are allochthonous to their current location, though the original site of deposition was not far outboard of the North American continental margin (it must have been east of the volcanic arc). Taylor *et al.* (1983), largely based on the composition of marine invertebrate assemblages, concluded that the Mount Hyatt Member represented transgression, the Muller Canyon Member represented a regression, and the overlying lower part of the Ferguson Hill Member represents a transgression (also see Hallam & Wignall, 2000).

Lucas *et al.* (2007) posit that deposition of the Muller Canyon Member took place on a fairly narrow shelf along the backarc seaway. This shelf was narrow, but sloped steeply enough so that lower Muller Canyon deposition was below fair-weather wave base, but not storm wave base. (Some beds show scour and hummock and swale features indicative of deposition above storm wave base.) This is probably best described as a middle to outer shelf environment, but the shelf was sufficiently narrow to allow a consistently high siliciclastic sediment input. Most of the discrete carbonate grains are nondescript, and may represent material reworked from a shallower setting and redeposited in a deeper setting. The siliciclastics are quartz-rich, so they clearly derived from a continental source, not the arc. The increase in the size and proportion of bioclasts and sand-size quartz in the Muller Canyon Member marks the regressive trend envisioned by previous workers.

Grain size (dominantly silty to muddy sediments with minor amounts of fine sand), sedimentary structures (horizontal lamination and small-scale ripple cross-lamination), fossil content (particularly radiolarians, spicules and abundant ammonites) and the ichnofacies (*Skolithos* and *Cruziana* ichnofacies) indicate deposition of the Muller Canyon Member in a relatively deep, storm-dominated shelf environment. The transition from the Mount Hyatt Member to the Muller Canyon Member is marked by a pronounced decrease in carbonate deposition. This was probably not due to deepening alone, but also a change in conditions that became unfavourable to carbon-

ate producers. A significant increase in siliciclastic influx could do this, particularly muds, but this doesn't seem to be the case. Rather, there was a forced decrease of carbonate production, possibly due to acidification of surface waters by volcanic outgassing. In general, the Muller Canyon sediments appear consistent with the interpretation of continental-derived siliciclastic sediment deposited in a mid-shelf setting, above storm wave base.

8. Sequence stratigraphy

Oldow *et al*. (1993) assigned the Luning, Gabbs and Sunrise Formations into three regionally correlative depositional sequences. The Gabbs Formation, which is divided into the Nun Mine, Mount Hyatt and Muller Canyon Members, belongs to their depositional sequence 2. They interpreted the Nun Mine Member as a transgressive systems tract, and the Mount Hyatt and Muller Canyon Members as a highstand systems tract. The overlying Ferguson Hill Member of the Sunrise Formation was considered as a transgressive systems tract.

From our perception of patterns of ichnofossil abundance and diversity, Hallam & Wignall (2000) interpreted increased oxygenation of bottom waters towards the top of the Mount Hyatt Member, followed by a consequent decrease in the overlying Muller Canyon Member. They regarded this as evidence of a eustatically-driven regressive-transgressive couplet, similar to that interpreted from other sections at the TJB (Hallam & Wignal,l 2000; Hallam, 2001).

From our observations of the sedimentological and palaeontological characteristics of the Ferguson Hill section, such as changes in grain size and lithology and the abundance of benthic fauna, we concur that this interpretation of eustatic sea level change is consistent with the data, although, as noted above, eustatic change alone is insufficient to explain the cessation of carbonate sedimentation on the shelf that occurred during deposition of the Muller Canyon Member. Clearly, the Muller Canyon facies were deposited above storm wave base (*i.e*. not below the CCD). We see no evidence for any disconformities in the section (as did Oldow *et al*., 1993), so we regard the section, at least from lower Mount Hyatt through lower Sunrise, as conformable and thus envision no sequence boundaries in the section.

9. Radioisotopic dating, magnetostratigraphy and carbon isotope stratigraphy

No radioisotopic ages have been published for the Ferguson Hill section, but our discovery of volcanic rock fragments in the Mount Hyatt Member (Lucas *et al*., 2007) opens up the possibility of obtaining a numerical age. Because of metamorphism, the Ferguson Hill section has been remagnetized (J. Geismann, personal communication, 2006), so magnetostratigraphy of the section is not possible.

Guex *et al*. (2003a, b, 2004) presented a carbon iso-

tope stratigraphy of the Ferguson Hill section. This indicates a negative CIE of ~2 per mil that begins near the base of the Muller Canyon Member, slightly below the conodont HO and the HO of *Choristoceras crickmayi*. This negative CIE is readily correlated to similar excursions with the same biostratigraphic constraints (*i.e*. they begin during the latest Triassic) in the Queen Charlotte Islands of western Canada, at St Audrie's Bay in England, and in the Karwendel Syncline in Austria, among others. This negative CIE thus is a powerful proxy for globally correlating a level in the latest Triassic.

Ward *et al*. (2007) published a new carbon isotope dataset for the Ferguson Hill section and obtained a carbon isotope stratigraphy similar to that of Guex and colleagues, except that they found differences in the average $\delta^{13}C$ values and in the positions of the two negative excursions. However, as argued by Guex *et al*. (2007), the apparent offset of the two profiles was produced by Ward *et al*. (2007), inadvertently measuring a fault repeat in their section. When that fault repeat is removed, the isotope profiles of Guex *et al*. and Ward *et al*. are in very close agreement with regard to their shape and biostratigraphic calibration.

10. Correlation

The Ferguson Hill section presents a variety of tools for correlation of the TJB interval. Thus, conodonts and radiolarians identify latest Rhaetian strata of the upper part of the Mount Hyatt Member and lowermost Muller Canyon Member. Characteristic Triassic bivalves disappear in the lower part of the Muller Canyon Member, and are succeeded by characteristic Jurassic bivalves. The beginning of the negative CIE at Ferguson Hill is stratigraphically just below the HO of Conodonta and *Choristoceras crickmayi*, and it can be correlated to a similar negative CIE identified in sections in Canada and Europe.

The most complete succession of ammonites across the TJB boundary is found at Ferguson Hill. Indeed, this succession provides a strong basis for correlation to sections in Canada, South America and Europe (Figure 3), and we believe this is the most precise and widespread biostratigraphic correlation possible across the TJB.

11. Definition of the base of the Jurassic System

Remane *et al*. (1996) listed requirements that a GSSP should meet (Table 1). None of the proposed GSSP candidates for the base of the Jurassic System meets all of these requirements. However, definition of the base of the Jurassic System at the LO of *Psiloceras tilmanni* group ammonites in the Ferguson Hill section produces a GSSP that meets almost all of these requirements.

The Ferguson Hill section exposes the proposed boundary level within a section of ~20m of marine siltstone and wackestone in which there is no substantial facies change and no evident unconformity at or near the proposed boundary level. Sedimentation rates appear to

have been relatively high, as the HO of uppermost Triassic fossils is separated by 7m of unfossiliferous strata beneath the LO of lowermost Jurassic fossils. The section is homoclinal and nearby structures are relatively simple normal faults that do not complicate the proposed GSSP. Thus, geological criteria 1-4 (Table 1) are well met by Ferguson Hill. Criterion 5, however, is the single weakness of Ferguson Hill as a GSSP; the section has been metamorphosed by nearby intrusives so that it will not yield palynomorphs nor can it yield a magnetic polarity stratigraphy.

In terms of biostratigraphic requirements, Ferguson Hill has a diverse and well preserved record of microfossils (Orchard *et al*., 2007; Lucas *et al*., 2007) and macrofossils. These include radiolarians, conodonts, bivalves and ammonites of marine shelfal palaeoenvironments that are of value to long-distance correlation. Indeed, the ammonite record at Ferguson Hill is widely regarded as the most complete such record across the TJB. Non-biostratigraphic studies undertaken at Ferguson Hill include carbon-isotope stratigraphy and sequence stratigraphy. The presence of volcanic rocks in the section may provide potential for radioisotopic dating.

The Ferguson Hill section is very easy to reach. Access and permanent protection are assured. Thus, the section at Ferguson Hill has only two failings, both due to metamorphism of the sediment - the lack of palynostratigraphy and magnetostratigraphy. Its advantages are the continuity of normal marine facies across the Jurassic base, its ammonite record, which is the most complete in the world for the TJB interval, its other fossils (including the microfossils recently documented), and its accessibility and guaranteed access/conservation. We thus advocate choosing the LO of *Psiloceras tilmanni* group ammonites at Ferguson Hill as the GSSP for the base of the Jurassic System. The base of the Jurassic System would thus be defined at the LO of *P. spelae*, which is 20cm below the base of Bed 95 in the Ferguson Hill section (Figure 2).

We also support establishing the Kunga Island section in the Queen Charlotte Islands of western Canada as the parastratotype section of the base Jurassic GSSP, as advocated by Longridge *et al*. (2007). New ammonite data allow a much more precise correlation of the Ferguson Hill and Kunga Island sections than was previously possible. Kunga Island provides the best documentation of a major evolutionary event (extinction) of radiolarians that is very close to the LO of *Psiloceras tilmanni* group ammonites, and is likely to be a microfossil datum that can be correlated globally. Furthermore, Kunga Island has yielded a radioisotopic age in the uppermost Triassic. As type and parastratotype sections for the base of the Jurassic, Ferguson Hill and Kunga Island provide a definition of the base of the Jurassic of optimal correlation potential.

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Geological

Exposure over an adequate thickness of sediments.

Continuous sedimentation; no gaps or condensation close to the proposed boundary level.

Rate of sedimentation sufficient for the separation of successive events.

Absence of synsedimentary and tectonic disturbances.

Absence of metamorphism and strong diagenetic alteration.

Biostratigraphic

Abundance and diversity of well–preserved fossils.

Absence of vertical facies changes at or near the proposed boundary level.

Facies favorable for long-range biostratigraphic correlation (normally corresponding to an open marine environment).

Non-biostratigraphic studies (*e.g.* radioisotopic dating, magnetostratigraphy, chemostratigraphy, sequence stratigraphy, cyclostratigraphy) and knowledge/understanding of regional paleogeographical context and facies relationships should be available.

Other requirements

Physical and logistical accessiblility.

Freedom of access.

Existence of, or provisions for, permanent protection and a permanent fixed marker.

Table 1: Requirements for a GSSP (after Remane *et al*., 1996; Warrington, 2005)

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Appendix

BLM letter (see next page)

United States Department of the Interior

BUREAU OF LAND MANAGEMENT
Nevada State Office
P.O. Box 12000 (1340 Financial Blvd)
Reno, Nevada 89520-0006
http://www.nv.blm.gov

In Reply Refer To:
8100 (NV-930)

JUL 0 8 2004

Spencer G. Lucas, Ph.D.
Curator of Paleontology and Geology
New Mexico Museum of Natural History
1801 Mountain Road, N.W.
Albuquerque, NM 87104

Dear Dr. Lucas:

I am writing in response to your letter dated April 20, 2004, concerning designating the global stratotype section and point (GSSP) for the Triassic-Jurassic boundary. I am pleased that you are nominating a location on Bureau of Land Management (BLM) managed land in Nevada to be a global standard by which all geologists define the Triassic-Jurassic boundary.
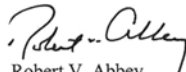
The location you identified in the Gabbs Valley Range near Luning in the NW¼, of the NE¼, Section 9, T7N, R35E of Mineral County is managed by our Carson City Field Office. I have been in contact with the staff there and they fully support the nomination. It is an honor to have BLM managed lands in Nevada designated in this way and there is no conflict with the designation and the BLM's multiple use mandate.

To the extent allowed by the law, I can assure you that BLM Nevada will maintain access to the GSSP for qualified scientists and will conserve it for future use and study.

Thank you for your interest in geological resources on BLM managed land in Nevada. I hope you are successful in having the International Union of Geological Sciences recognize Nevada as the best place for the Triassic-Jurassic boundary GSSP.

If you need any further assistance please contact Pat Barker at (775) 861-6482.

Sincerely,

Robert V. Abbey
State Director, Nevada

1

A proposal for the base Hettangian Stage (= base Jurassic System) GSSP at New York Canyon (Nevada, USA) using carbon isotopes

Christopher A. McRoberts[1], Peter D. Ward[2], Stephen Hesselbo[3]

[1]Department of Geology, State University of New York at Cortland, Cortland 13045, USA; mcroberts@cortland.edu

[2]Department of Biology, The University of Washington, Seattle 98195, USA; argo@u.washington.edu

[3]Department of Earth Sciences, Oxford University, Parks Road, Oxford, OX1 3PR, UK; stephen.hesselbo@earth.ox.ac.uk

Abstract It is here proposed that the Global Stratotype Section and Point (GSSP) for the basal boundary of the Hettangian Stage of the Jurassic System be defined at the peak of the first negative Carbon Isotope Excursion (CIE). The peak CIE occurs within a brownish grey, laminated, muddy siltstone, approximately 8m above the base of the Muller Canyon Member of the Gabbs Formation in the Ferguson Hill section within New York Canyon, Nevada, USA. [N 38°29'10.68", W 118°05'00.72"]. See Figure 1a-c for location and outcrop photographs. This isotopic event is closely associated with secondary biostratigraphic markers, including the FODs of the bivalve *Agerchlamys boellingi* (1.6m above the isotopic event) and ammonoids of the *Psiloceras tilmanni* group (2.6m above the isotopic event).

1. Introduction

The Ferguson Hill section in New York Canyon has been well studied and is the subject of numerous papers describing in detail the stratigraphy, paleontology, and geochemistry (*e.g.* Muller & Ferguson, 1939; Taylor *et al.*, 1983, 2000; Guex *et al.*, 1997, 2003a, b; Ward *et al.*, 2007). This section was first proposed by Guex *et al.* (1997) as a candidate GSSP for the Triassic–Jurassic boundary, and the most recent proposal (Lucas *et al.*, 2005) advocated the first occurrence of smooth ammonoids of the *Psiloceras tilmanni* group at Ferguson Hill as the defining criteria for the base Hettangian GSSP.

As discussed elsewhere (*e.g.* Guex *et al.*, 1997; Lucas *et al.*, 2005; and see also Warrington, 2003), the Ferguson Hill section arguably represents the most complete of known marine Triassic-Jurassic boundary successions with an abundance of shallow-water fossils. This attribute, along with the favourable facies for widespread correlation, fulfill the main requirements of a GSSP of continuous sedimentation in a marine environment (Cowie *et al.*, 1986; Remane *et al.*, 1996). Perhaps most significant is that the defining criterion, the peak initial CIE, offers the most robust datum for correlation in more boundary sequences than other potential biostratigraphic defining criteria and thereby fulfills the "correlation precedes definition" philosophy in GSSP selection as discussed by Remane *et al.* (1996). Furthermore, this section is easily accessible and has already received the guarantee of permanent protected status should it be selected for the GSSP (see Warrington, 2003).

Stratigraphic measurements and biostratigraphic positions mentioned herein are taken from Ward *et al.* (2007) and differ somewhat from those previously published by Taylor & Guex (2002) and Guex *et al.* (2003a, b, 2004). Ward *et al.* (2007) suggested that the differences between their dataset and that of Guex *et al.* (2003a, b, 2004), particularly with regard to the stratigraphic thickness of the strata studied, may be due to the gradational nature of the

lithostratigraphic transitions and different definitions of the lower and upper boundary of the Muller Canyon Member. Both the underlying contact with the Mount Hyatt Member, and the overlying contact with the Sunrise Formation, are gradational in facies, comprising limestone and siltstone interbeds. Additionally, Ward and others measured the section approximately 25m to the northeast of the Guex *et al.* section and may have therefore captured lateral differences in stratal thickness. Guex (pers. comm., 2006) has argued that a small fault, low in the section (below the CIE), may have been overlooked by the Ward *et al.* team. Irrespective of a missed fault of minor consequence, or differences in definition of member contacts, *the relative sequence of events (both isotopic and bioevents) are essentially the same between the two sets of measurements*.

As with all other proposed candidate GSSP sections for the base-Hettangian (St. Audrie's Bay, England; Kunga Island, Canada; Kuhjoch, Austria), the Ferguson Hill section does have a few drawbacks. To date, apart from recently discovered Rhaetian conodont elements belonging to *Misikella* and *Zieglericonus* and as yet unidentified radiolarians in the Mount Hyatt Member (M. Orchard, pers. comm., 2006), no significant microfossils have been reported from the Ferguson Hill Triassic–Jurassic succession. Additionally, the strata in the New York Canyon area, including the section at Ferguson Hill, have been thermally altered, and early attempts to recover a primary remnant magnetic signal have been without success (see Warrington, 2003). In spite of these limitations, we concur with Guex *et al.* (1997) and Lucas *et al.* (2005) that the Ferguson Hill section represents the best available stratigraphic succession to define the boundary.

2. Choice of CIE criterion and precedent

As described in Ward *et al.* (2007), and shown in Figure 1, the $\delta^{13}C_{org}$ profile at Ferguson Hill has a nearly con-

stant value of -28.6‰ VPDB through the upper Mt. Hyatt Member and the first 7.8m of the Muller Canyon Member. Between 7.8m and 9.0m above the base of the Muller Canyon Member, $\delta^{13}C_{org}$ drops steadily to -29.8‰ VPDB marking the initial CIE that peaks at 8.0m. The $\delta^{13}C_{org}$ values then increase steadily to -27.3‰ VPDB at 18.5m, marking the positive excursion, and finally drop to -29.1‰ VPDB at 25m, representing the beginning of the second, broader negative swing. At Ferguson Hill, the initial negative CIE is clearly delineated by a series of seven data points.

Of the three potential data based on geometric inflections of the CIE shown in Figure 2, the choice of the peak initial negative isotope excursion (level B in Figure 2) is primarily based upon the fact that it is an apparently short-lived correlatable event that can be most easily recognized with respect to adjacent segments of the C-isotopic curve that are either strongly positive or, as in the second negative swing, known to have a much longer duration and broader inflection. The alternative datum (level A in Figure 2) also presents a potentially suitable horizon, but is not as easily correlated to other sections, especially those in Alpine Europe, where the strata above the 'event horizon' and below the initial peak negative CIE are either highly condensed or have a demonstrable stratigraphic gap. The highest potential isotopic datum (level C in Figure 2) is deemed unsuitable, in that it is represented by a much broader inflection of $\delta^{13}C_{org}$ values, passing into rather consistently negative values (-29.1‰ VPDB) and therefore more difficult to recognize. Furthermore, and perhaps more importantly, this second excursion occurs above a secondary biostratigraphic marker — the FOD of *Psiloceras tilmanni* group ammonoids.

Lucas *et al.* (2005) have raised two primary objections to choosing a carbon isotope excursion as a GSSP defining criterion for the base Hettangian: (1) geochemical events are not unique, and (2) recognition of CIE geometry is dependent on sedimentation rates and environmental factors, such as the proportion of terrestrial *versus* marine organic carbon input. While this may be true, in the general sense that geochemical anomalies are not unique and that the shape of any geochemical profile is dependant on a host of depositional and paleoenvironmental processes and their rates, when considered along with the adjacent 'background' segments of the isotope profile, such excursions, especially such large ones as observed at the Triassic–Jurassic boundary interval (which average around -3.5‰ VPDB in organic matter) can be easily recognized and correlated, provided geochemical sampling is of sufficient stratigraphic density (*i.e.* not based on a single point; see for example de Wit *et al.*, 2002 for a discussion on the isotopic event with respect to the Permian–Triassic boundary). An independent assessment of the utility of the CIE as the defining criterion can be made by comparison of sections representing different marine facies with different depositional rates (Figure 3, and see discussion below in correlation

section).

There is a precedent in choosing a negative carbon isotope excursion as a GSSP datum. The base Eocene (= base Ypresian) GSSP was selected in 2002 and ratified by the IUGS in 2003 to be the base of the significant negative carbon isotope excursion in the Gabal Dababiya section in Egypt (Aubry & Ouda, 2003). This isotopic event is closely associated with secondary biostratigraphic markers, including the FODs of the nannoplankton *Discoaster anartios* (2.3m above the isotopic event) and the foraminifers *Acarinina sibaiyaensis* and *Acarinina africana* (2.5m above the isotopic event).

In addition to the base Eocene CIE datum described above, other non-biostratigraphic events have been selected as primary defining criteria in the selection of GSSPs. For example, the base Paleocene (= base Danian) is defined by the iridium spike associated with Cretaceous-Paleogene mass extinction (*e.g.* Bensalem, 2002), and the base of the Miocene (= base Aquitanian) is defined as the base of magnetic polarity Chron C6Cn.2 (Steiniger *et al.*, 1997). It can be argued that these defining criteria are, like a CIE, non-unique events that are, however, easily recognized within the context of adjacent segments of their geochemical or magnetic polarity scales.

3. Associated bioevents

The boundary interval at Ferguson Hill contains both ammonoids and bivalves that may serve as secondary biostratigraphic markers closely associated with the proposed CIE GSSP defining datum (Figures 1, 2). Both bivalve and ammonoid associated bioevents occur slightly above (between 1.6 and 2.5m) the CIE and are of a comparable stratigraphic distance from the proposed GSSP as the secondary bioevents for the base Eocene. A brief discussion of both associated bioevents follows below.

3.1 Ammonoids

At the Ferguson Hill section, the initial negative isotope excursion is within the 10.5m-thick interval between typical Triassic ammonoids (*e.g. Choristoceras crickmayi*), within the topmost Mt. Hyatt Member of the Gabbs Formation, and ammonoids considered to be of 'Jurassic' affinity (*e.g.* species of the *Psiloceras tilmanni* group), within the upper part of the Muller Canyon Member of the Gabbs Formation. At the Ferguson Hill section, the FOD of *Psiloceras tilmanni* group ammonoids occur at 10.5m above the base of the Muller Canyon Member and 2.5m above CIE datum. Systematic descriptions of the psiloceratid ammonoids can be found in Guex (2003b).

Ammonoids of the *Psiloceras tilmanni* group are currently known to occur in only three regions: (1) New York Canyon Nevada (*e.g.* Guex *et al.*, 2003a), (2) Utubamba Valley, Peru (*e.g.* Hillebrandt, 1994), and (3) Tirol, Austria (Hillebrandt *et al.*, in prep). However, apart from the Peru material and newly discovered specimens from the Kuhjoch section in Tirol Austria, these ammonoids are
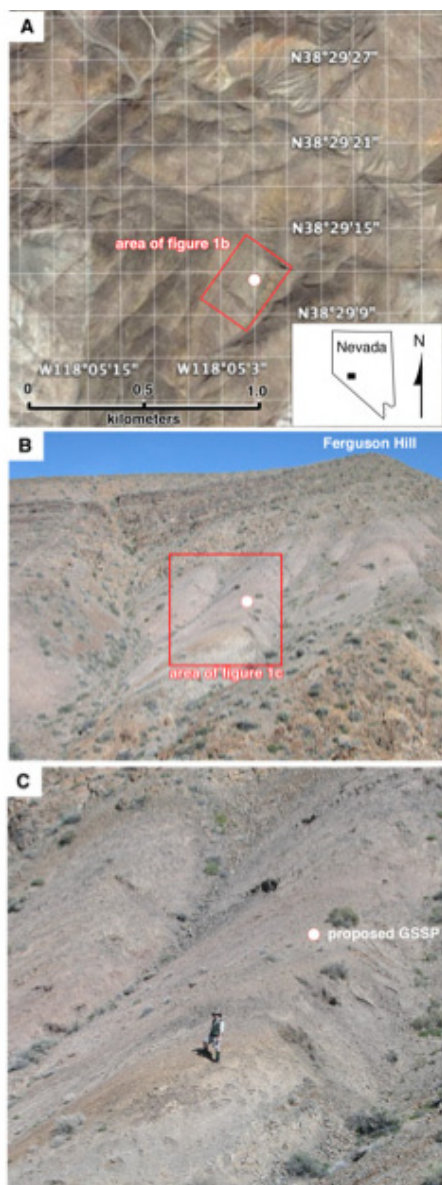
Figure 1: Location and position of proposed GSSP. **A**) Aerial photo of New York Canyon and Muller Canyon region (modified from Google Earth image). **B**) Outcrop photo of SE face of Ferguson Hill. **C**) Detail of Muller Canyon Member of Gabbs Formation showing position of proposed GSSP

represented by crushed specimens in which sutures are not preserved, therefore precluding definitive species identification.

Furthermore, based on the best available data, the first occurrences of *P. tilmanni* group ammonoids can demonstrably be shown to occur at different stratigraphic levels, and, where data are known, they occur at different positions relative to the carbon isotope curve (Krystyn, pers. comm., 2006; Krystyn *et al*., 2005; see also discussion in Bloos, 2006). In fact, Bloos (2006, p.7) notes that "the earliest *Psiloceras* are extremely rare in most parts of the world, proxies are generally needed for correlation". It should be noted that, should ammonoids of the *P. tilmanni* group be selected as a defining criterion, one would have to rely on proxies in more instances than with the

CIE criterion that is now known from more than 10 stratigraphic sections.

A further major detriment to choosing the FOD of ammonoids of the *Psiloceras tilmanni* group at Ferguson Hill is that these ammonoids are not part of an evolutionary series in which any potential ancestor is known. As such, *P. tilmanni* group ammonoids do not represent an ideal choice for defining the base Hettangian GSSP, but they may serve as a close proxy to a CIE defined datum.

3.2 Bivalves

The initial negative isotope excursion is more closely associated with the FOD of pectinacean bivalves. At Ferguson Hill, the FOD of *Agerchlamys boellingi* occurs at 9.6m above the base of the Muller Canyon Member and 1.6m above the CIE datum. The systematic description of *Agerchlamys boellingi* (type locality: Reno Draw section, New York Canyon) is by Taylor & Guex (2002).

The bivalve *Agerchlamys boellingi* is known from several sections in North America at similar, or slightly higher, stratigraphic levels, but never from undisputed Triassic strata. McRoberts (2004) discussed well-preserved representatives of this species from several sections spanning the Triassic–Jurassic boundary interval in northeastern British Columbia. In these localities (*e.g*. Ne Parle Pas Point, Black Bear Ridge and Crying Girl Prairie), *Agerchlamys* first occurs within 1m above the youngest undisputed Triassic strata and approximately 0.2 -3.0m below psiloceratid ammonoids. Recent work in Austria (McRoberts field work, 2006) documented similar bivalves, often identified as '*Chlamys textoria*' (see, for example, Golebiowski & Braunstein, 1988) as first occurring in greater abundance within 0.2–3.0m above the CIE in many alpine sections, including Kendlebachgraben, Tiefengraben, Kuhjoch, Schlossgraben and Steinplatte (Kammerker and Möseralm sections).

As with the ammonoids of the *Psiloceras tilmanni* group discussed above, neither *Agerchlamys boellingi* nor '*Chlamys textoria*' are part of a demonstrable evolutionary series in which potential ancestors are known, and therefore they are not suitable for defining a datum for the base Hettangian GSSP. The original definition of *Agerchlamys* by Damborenea (1993) only lists three included species, of which two (the type *Agerchlamys wunchae* and *Agerchlamys proprius*) are Jurassic. The one Triassic species listed by Damborenea (1993, 2002) as belonging to this genus was originally described as *Chlamys (Camptochlamys) inspecta* Kiparisova (*in* Kiparisova *et al*., 1966) from the Carnian and Norian of Siberia. This species lacks radial ornament on its auricles and is here considered to be distinct from, but closely related to, *Agerchlamys*.

4. Correlation potential

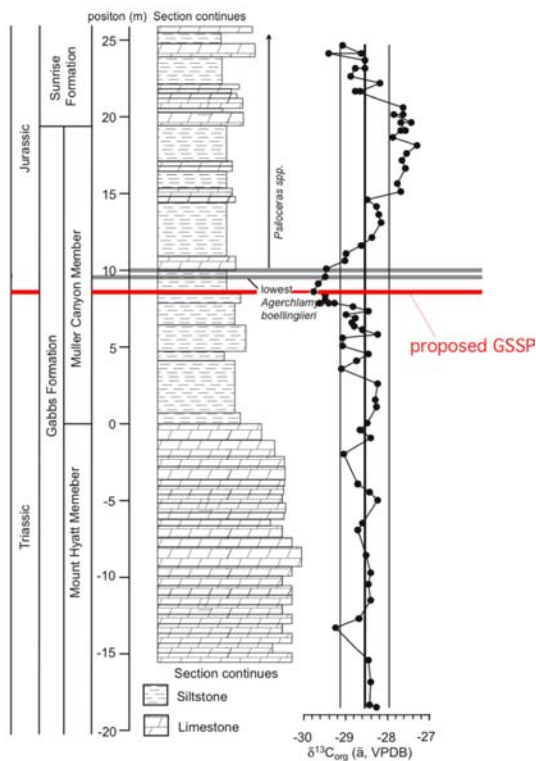As recognized by many authorities (*e.g*. Kump & Arthur, 1999; see also Beerling & Berner, 2002), perturbations in

Figure 2: Lithostratigraphy, biostratigraphy and $\delta^{13}C_{org}$ profile, Ferguson Hill section (New York Canyon, Nevada, USA), showing proposed GSSP (modified from Ward *et al.*, 2007)

the Earth's carbon cycle represent geologically instantaneous events (<5kyr), are of global scale, and can be (or potentially can be) observed in marine and continental settings in a variety of facies (*e.g.* deep-water marine clastic, shallow-water carbonate platform, terrestrial paleosols, lacustrine deposits, *etc.*). Such large CIEs have been repeatedly used as correlation data for many stage boundaries, including the Permian-Triassic boundary (*e.g.* Payne *et al.*, 2004), Cenomanian-Turonian boundary (*e.g.* Sageman *et al.*, 2006), and perhaps most relevant, the base of the Eocene (*e.g.* Aubry & Ouda, 2003).

The CIE in the Triassic-Jurassic boundary interval is now known from many localities from several continents, from low to mid paleolatitudes, and provides a robust and reproducible correlation datum. The CIE is well documented at several other GSSP candidates, including St. Audrie's Bay, England (Hesselbo *et al.*, 2002), Queen Charlotte Islands, British Columbia (Ward *et al.*, 2001, 2004; Williford *et al.*, 2007), and numerous sites in Austria, including the Kendlebachgraben and Tiefengraben sections (Kuerschner *et al.*, 2007) and the newly proposed Kuhjoch/Hinterriss section (Hillebrandt *et al.*, in prep.; Kuerschner, pers. comm.). Other Triassic-Jurassic boundary sections in which a carbon-isotope excursion has been identified (*e.g.* McRoberts *et al.*, 1997; McElwain *et al.*, 1999; Pálfy *et al.*, 2001; Galli *et al.*, 2005) have generally coarser sampling density, or have known stratigraphic gaps precluding the unambiguous identification of the two-fold negative excursion

geometry.

The geometry of the Triassic-Jurassic CIE can be identified irrespective of water depth and depositional rates. For example, the initial CIE at St. Audrie's Bay, Portovenere (Italy) and those from Tirol (Austria) (see Figure 3), arguably the most shallow and condensed sections where the initial CIE is constrained within 1–5m, can be easily correlated to the Kennecott Point section, where the initial CIE is contained within more than 10m of radiolarian-bearing, deep-marine carbonate-bearing siltstone and shale, representing an order of magnitude difference in sedimentation rates. The consistent geometry of the two-fold carbon isotope excursion in both condensed and expanded sedimentary sequences and its position relative to all known biostratigraphic markers is consistent from such widespread regions as the northwestern European seaway and along the western margin of Pangea, provides strong evidence that the isotope event was synchronous and global in scale.

In all of the aforementioned sections, and all others in which the CIE is recognized (*e.g.* both published and unpublished sections in Austria and Italy, elsewhere in North America), the peak of the initial CIE occurs above the primary extinction 'event' horizon, delineated by the loss of marine macrofauna, especially bivalves, radiolarians, gastropods, brachiopods and, in some places, corals. This 'event horizon' also marks the last occurrence of Rhaetian index ammonoid *Choristoceras marshi*. However, some fossil groups, particularly pollen and spores (but also some foraminifers) apparently show a delayed turnover several meters above the CIE (*e.g.* Ergelijk *et al.*, 2004; Kuerschner *et al.*, 2007; Hillebrandt *et al.*, in prep.). Not surprising, however, is that even though the significant taxonomic change in pollen and spores occurs above the main extinction horizon, the strata containing the initial CIE are typified by a dominance/abundance of opportunist palynoflora taxa, such as *Corollina* and fern spores. Additionally, rare con-
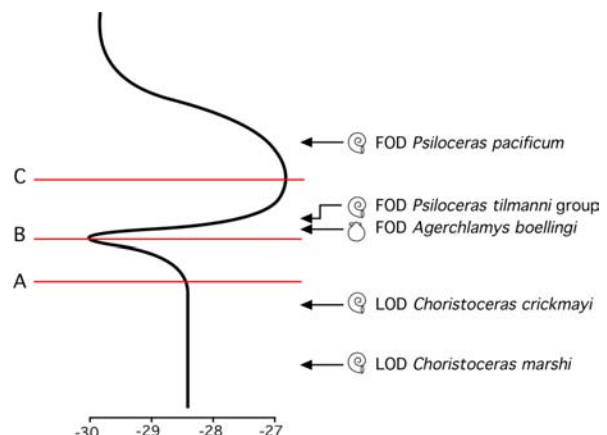

Figure 3: Idealized C-isotope profile and associated important biomarkers from the Ferguson Hill section at New York Canyon. Levels A, B and C indicate potential GSSP-defining criteria, based upon inflections of the C-isotope curve. Level B (peak negative excursion) is the favored GSSP criterion in this proposal. *NB* No vertical scale is implied (see Figure 1 for absolute position)
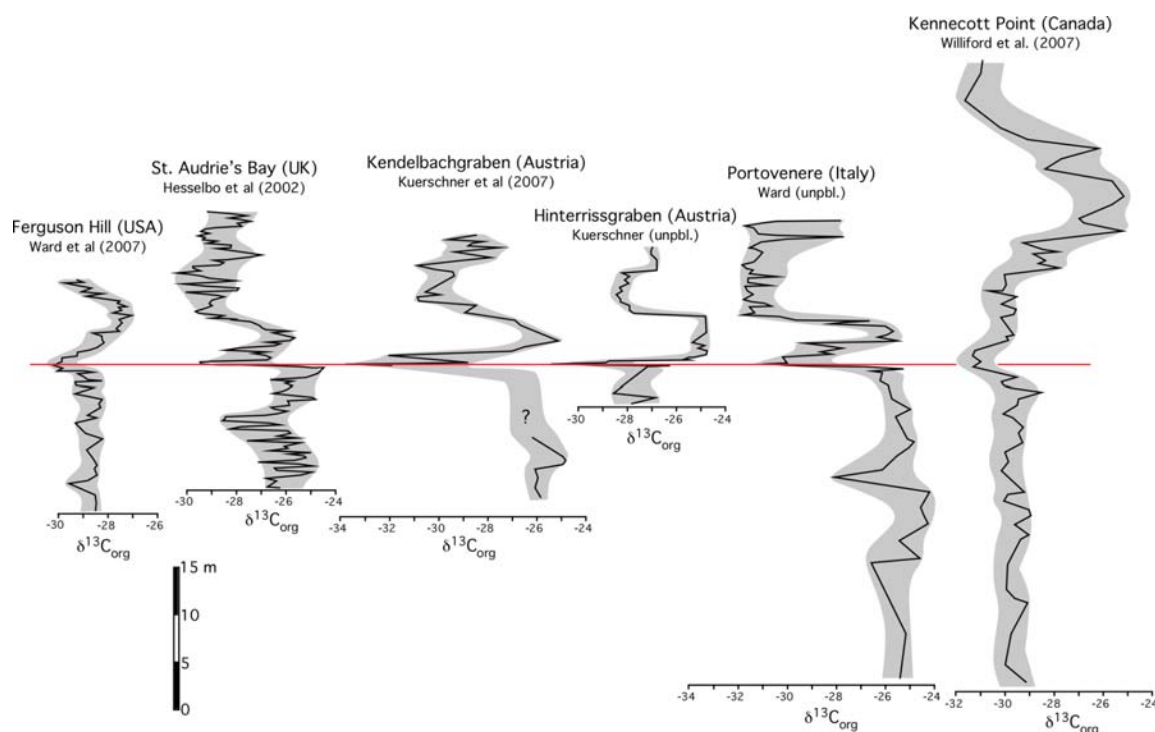
Figure 4: Correlation of C-isotope profiles from North America and Europe. Note that the primary defining criterion for the proposed GSSP is the peak of the initial C-isotope excursion (CIE), indicated by the red line

odonts may range up several meters into the overlying strata above the initial CIE in England and Hungary (Heinz Kozur, pers. comm., 2005; Pálfy *et al*., 2001; see discussion in Hesselbo *et al*., 2004).

To date, the carbon isotope excursion has not yet been reported from South America, where potential boundary sections (*e.g*. Chilingote, Peru) containing *Psiloceras tilmanni* ammonoids are known to occur, nor is it known from other regions, such as New Zealand or Asia. In these regions, and in other areas where post-depositional changes in carbon isotopic composition precludes accurate geochemical analyses, secondary biostratigraphic markers, *e.g*. the FOD of smooth psiloceratid ammonoids, can be used as proxies for recognizing the base Hettangian.

5. Conclusions

A defining criterion for the base Hettangian GSSP at the peak of the first negative Carbon Isotope Excursion represents the best available choice, among alternative biologic or geochemical events. Although somewhat below a traditional definition of the base of the Hettangian, using *Psiloceras planorbis* as defined in the British Isles (see Warrington, 2003; Bloos, 2006), the choice of the CIE would result in putting known psiloceratid ammonoids in the Jurassic and therefore would reduce confusion (or difficulty) in distinguishing amongst poorly preserved psiloceratid species.

As summarized below, the CIE at the Ferguson Hill section is a short-lived event within a continuous sedi-

mentary succession that exhibits attributes permitting widespread correlation:
- A CIE is a global, geologically isochronous event;
- The CIE is easily recognizable both by its magnitude and its profile geometry;
- The CIE in the Ferguson Hill section is within a continuous sedimentary succession;
- The CIE at Ferguson Hill can be correlated to numerous sections from low to mid-paleolatitudes in shallow and deep marine environments;
- The CIE can potentially be correlated to other marine and continental sedimentary strata of different facies;
- The CIE at Ferguson Hill is closely associated with biovents including the FODs of *Psiloceras tilmanni* group ammonoids and the bivalve *Agerchlamys boellingi*, which can serve as proxies for recognizing the base Hettangian;
- The CIE at Ferguson Hill and other localities is positioned above the youngest Triassic ammonoid *Choristoceras crickmayi* and below ammonoids of the *Psiloceras tilmanni* group, thus preserving recent temporal concepts for these taxa and their stage/system assignments.

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Waterloo Bay, Larne, Northern Ireland: a candidate Global Stratotype Section and Point for the base of the Hettangian Stage and Jurassic System

Michael J. Simms[1], Andrew, J. Jeram[2]

[1]Department of Geology, Ulster Museum, Botanic Gardens, Belfast, BT9 5AB, UK; michael.simms@magni.org.uk

[2]Mullagdubh House, 27 Gobbins Path, Islandmagee, Larne, BT40 3SP, UK; Anitajeram@aol.com

Abstract The foreshore at Waterloo Bay, Larne, Northern Ireland (54˚51'26"N, 5˚48'18"W) exposes Rhaetian and Hettangian strata that span the Triassic-Jurassic transition. An abundant, and frequently well preserved, succession of ammonites is present near the base of the Waterloo Mudstone Formation (Lias Group). We argue that the level of first appearance of *Psiloceras planorbis* within this succession is a datum that can be easily correlated, with minimal loss of precision and within well-constrained confidence limits, throughout the NW European faunal province and worldwide via contemporaneous *Psiloceras* species. It therefore offers a useful and stable primary biostratigraphic definition for the base of the Hettangian Stage, and does not rely on chronostratigraphically displaced, or non-ammonite, proxies for wide correlation beyond the GSSP. The Larne section is stratigraphically expanded, and provides a much clearer record of ammonite, and other, events in the vicinity of the proposed boundary level than is available elsewhere. We therefore propose that it be adopted as the GSSP for the base of the Hettangian Stage and the Jurassic System.

1. Introduction

An internationally agreed definition for the base of the Hettangian Stage and the Jurassic System is long overdue. Research into the dramatic global environmental and biotic changes that mark the Triassic-Jurassic transition has intensified over the last decade, but the temporal relationships between events are still poorly understood. We estimate the interval of contentious time at less than 500kyr, so resolving the sequence of events within this interval, and their causes and consequences, requires stratigraphic precision.

Precision can be attained only by employing a standard chronostratigraphic datum. Unregulated use of the term 'Triassic-Jurassic boundary' as a point of reference has undoubtedly hindered progress towards understanding the mass extinction and also, ironically, the debate about a base-Hettangian GSSP. Faunal change, an obvious characteristic of the Triassic-Jurassic transition, should provide a marker of optimum correlation potential that could serve as a common point of reference (Remane *et al*., 1996). Indeed, the idea that the end-Triassic 'mass extinction' would inevitably provide a marker is so ingrained in the literature that the 'mass extinction' and 'boundary' concepts have become inextricably linked, almost to the point of synonymy. Philosophically, however, they are distinct. The task of identifying a GSSP for the base of the Hettangian Stage should rest, therefore, solely on defining a boundary point with optimum correlation potential.

Bloos and Page (Bloos & Page, 1997, 2000; Page & Bloos, 1998; Bloos, 1999, 2004; Page, 2005) provided considerable new information about the basal Hettangian ammonite succession in NW Europe. Their findings encouraged us, in 2006, to reinvestigate the little-known Rhaetian-Hettangian sections in the Larne Basin, Northern Ireland, notably at Waterloo Bay, Larne, where

we found a sequence similar to, but more expanded than, that in SW Britain. Most significantly, the full ammonite succession described by Bloos & Page (2000) is present at outcrop and, in contrast to SW Britain, the material is abundant and commonly well preserved. The purpose of this contribution is to formally propose the Larne section as a candidate GSSP for the base of the Hettangian Stage, and to provide the information required by the TJBWG to assess its potential.

Investigation of the Larne site is at an early stage. We summarise what is known about the succession and, where appropriate, highlight potential for further study. Much of the detailed supporting data for our proposal has been omitted from this paper to make it brief enough for publication in the *ISJS Newsletter*. This, and additional information, can be found on the internet at www.habitas.org.uk/larne/gssp.

2. Geological context

The Larne Basin was initiated in the Permian as one of a series of half-grabens formed by tensional reactivation of pre-existing Caledonian structures (Anderson *et al*., 1995). Located between the NE-SW-trending Southern Uplands Fault Zone and the Highland Boundary Ridge, the Larne Basin, and contiguous Lough Neagh Basin, overlie deeply buried basement of the Midland Valley Terrane (Figure 1).

Onshore, Palaeogene basalts (Antrim Lava Group) largely conceal the Mesozoic basins, with Mesozoic outcrop limited to a narrow belt around the margin of the Antrim Plateau (Figure 2). Exposure is further limited by landslips and Pleistocene deposits. A thick sequence of non-marine 'red bed' mudstones and marls of the mid- to late Triassic Mercia Mudstone Group are overlain by approximately 10m of pale green siltstone and mudstone of the Collin Glen Formation (equivalent to the Blue
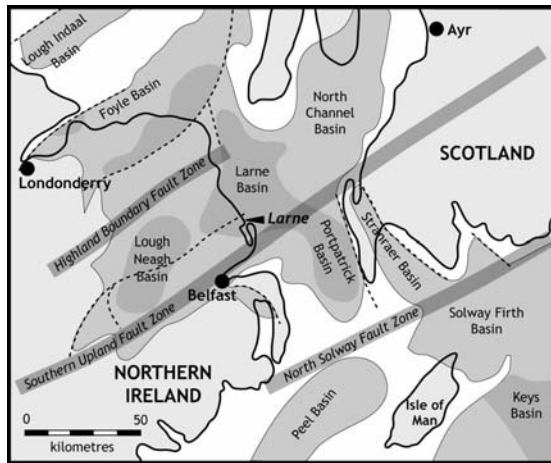
Figure 1: Permian and early Mesozoic basins in Northern Ireland and adjacent areas. The darker shaded areas indicate thicker successions surrounding the depocentres (after Mitchell, 2004)

Anchor Formation elsewhere in the UK). A regional disconformity marks the base of the succeeding Penarth Group and the commencement of Triassic marine deposition, which continued without interruption into the Jurassic.

Late Jurassic to early Cretaceous (Cimmerian) uplift and erosion largely removed the Jurassic sequence that probably extended across much of Ireland. Only in the north-eastern basins did remnants survive, ranging up to the mid-Sinemurian in the Larne-Lough Neagh Basin, and into the Pliensbachian in the adjacent Rathlin Basin. These Lower Jurassic strata are overlain unconformably by Cenomanian-Santonian greensands (Hibernian Greensands Formation), and Santonian-Maastrichtian chalk (Ulster White Limestone Formation). Uplift of the entire region occurred in the Palaeocene prior to emplacement of a thick succession of flood basalts across a large area of north-east Ireland. A vast volume of lava must have passed through the underlying sedimentary basin fill, but thermal metamorphic and metasomatic effects are largely absent, except adjacent to the larger feeder dykes and sills. Such low-grade metamorphism has affected part of the Waterloo Bay site but, in general, Triassic and Jurassic rocks in the basin remain immature for hydrocarbons.

3. Previous research (Rhaetian-Hettangian)

The Rhaetian-Hettangian succession of south-eastern Antrim was investigated early in the history of the science of geology (e.g. Portlock, 1843; Tate, 1867), but has received little attention subsequently. The sinking of the Larne borehole, 2km SE of Waterloo Bay (Manning & Wilson, 1975; Figure 2, inset) prompted Ivimey-Cook (1975) to briefly review Rhaetian and Hettangian exposures in south-eastern Antrim, including the Larne foreshore section. Most of these exposures, and others known to us but not mentioned by Ivimey-Cook (1975), are small and of limited stratigraphic extent, but good prospects

exist for accurate correlation with the key section at Larne (described herein). A useful contribution by Reid & Bancroft (1986) established Larne as the type locality for *Caloceras intermedium* (Portlock), figured type material of *Psiloceras sampsoni* (Portlock) from the Rathlin Basin, and mentioned the occurrence of *Psiloceras erugatum* at Larne and Islandmagee. Simms (2003, 2007) described the Cotham Member seismites at Larne and Whitehead and demonstrated correlation with many other sites across the UK. A general account of the Mesozoic geology of Northern Ireland can be found in Mitchell (2004), in which the Waterloo Bay, Larne, section is named as the stratotype for the Waterloo Mudstone Formation.

4. The Larne section
4.1 Location

Larne is located on the east coast of County Antrim, Northern Ireland, 28km NNE of Belfast (Figure 2). The section is very well exposed, for approximately three hours either side of low tide, on a wave-cut platform on the foreshore at Waterloo Bay (centred on coordinates 54°51'26"N, 5°48'18"W; Irish Grid Ref. D409 037; Figure 3). Access is via the public promenade on the east side of Town Park and Chaine Park. The section was also formerly exposed in a relict sea-cliff, now largely overgrown, on the west side of the promenade. This cliff could easily be cleared to provide a location for a permanent boundary marker, and to provide disabled access to the boundary section. Larne has excellent public transport
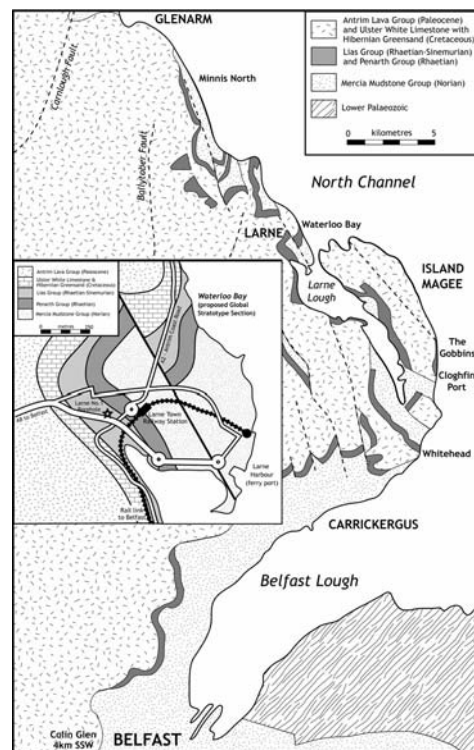

Figure 2: Geology and location of east Antrim showing the outcrop of the Penarth Group and Lias Group, and of localities cited in the text or plate captions. Inset: Map of Larne showing location of the proposed GSSP at Waterloo Bay, and of the Larne No.1 Borehole

links by road, rail, and ferry services (Figure 2). Two airports are located within a one-hour drive of the locality.
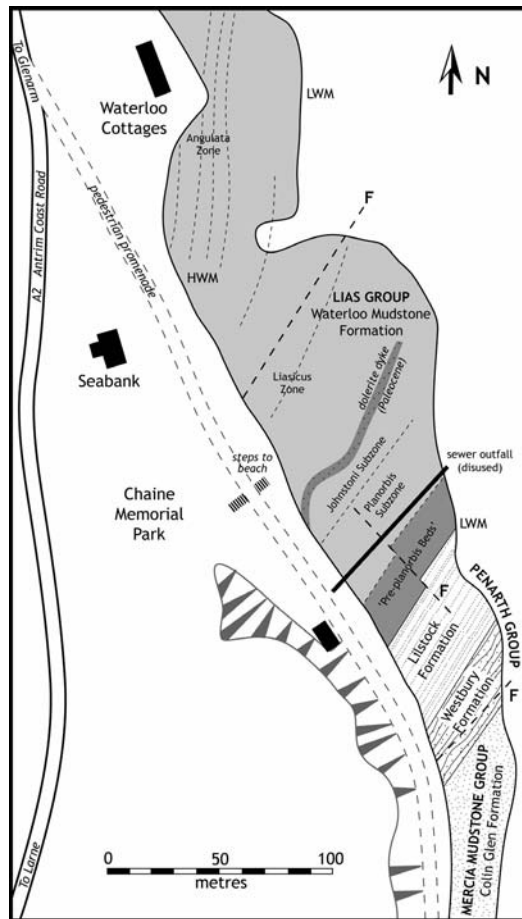

Figure 3: Sketch map of the Triassic and Jurassic strata exposed on the foreshore at Waterloo Bay, Larne (after Ivimey-Cook, 1975). Strata dip to the northwest at 20˚-30˚

4.2 Site ownership and management

The area below the Mean High Water Mark (MHWM) is owned by the Crown Estates and administered on their behalf by Larne Borough Council (LBC). Land above MHWM is owned by LBC. The entire site has unrestricted public access and is bordered by two public parks. The section lies within the Waterloo Geological Area of Special Scientific Interest (ASSI), which was declared on 17th July, 1995 under the provisions of the Nature Conservation and Amenity Lands (Northern Ireland) Order 1985. This provides legal protection for the locality's geological heritage. The Environment and Heritage branch of the Department of the Environment for Northern Ireland is responsible for ASSI protection. Requests for permission to sample or collect from the section should be directed to that body. The Ulster Museum, Belfast, is the official designated repository for material collected from Northern Ireland's ASSIs.

4.3 Lithostratigraphy

Waterloo Bay, Larne, provides an almost complete, con-

tinuously exposed section from the Norian to the Sinemurian (Bucklandi Zone). Strata dip typically at 20˚-30˚ to the NW and are cut by a few minor faults. The combined stratigraphic thickness of the Penarth Group (Rhaetian) and basal Lias Group (latest Rhaetian to top Hettangian) in the Larne area is approximately 115m (Ivimey-Cook, 1975). We have logged, in detail, the section from the top of the Westbury Formation to the base of the Johnstoni Subzone of the Hettangian (Figure 4).

The Penarth Group is a thin, but widely distributed and distinctive, unit. Two formations are recognised in most areas: the Westbury Formation, which is remarkably consistent across its outcrop (and subcrop); and the overlying Lilstock Formation, which is more variable. Previous work on the group is summarised in Swift & Martill (1999), with additional data from St. Audrie's Bay in Hesselbo *et al.* (2004) and Hounslow *et al.* (2004). Predominantly dark grey mudstones and shales of the Westbury Formation contain a low-diversity, bivalve-dominated, marine fauna. Subordinate sandstones commonly contain vertebrate debris and a rich ichnofauna. About 7.5m of strata are faulted out of the Larne section,
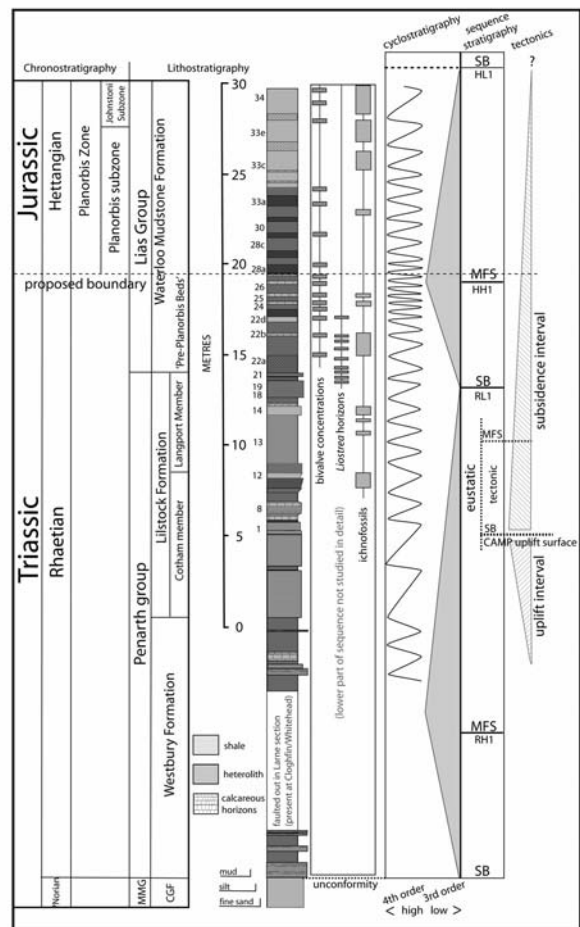

Figure 4: Lithostratigraphic log of the Penarth Group and basal Lias Group exposed at Waterloo Bay, and its relationship to chronostratigraphy, cyclostratigraphy, sequence stratigraphy and tectonic events. For further details and discussion of this diagram see www.habitas.org.uk/larne/gssp

but are present in the Larne borehole and at outcrop at Whitehead and Cloghfin Port. As elsewhere in the UK, the Westbury Formation here comprises a series of coarsening-up and fining-up cycles (Macquaker, 1999). Our preliminary observations in the Larne Basin suggest that they are related to 4th-order cyclicity. An overall deepening trend (initial transgression) is apparent in the lower 9m of the Larne Basin succession, whilst the upper 5m generally coarsens-upward into the Lilstock Formation. Evidence of deposition above storm wave-base is ubiquitous in the Westbury Formation (hummocky cross-stratified sandstones, winnowed shell and vertebrate lags, convex-up shell pavements).

The Cotham Member of the Lilstock Formation succeeds the Westbury Formation abruptly and can be divided into a lower part, dominated by finely interbedded (mm-scale) mudstone and siltstone (= heterolith) and an upper part, with limestones, calcareous marls, mudstone, and more thickly-bedded heterolith. The lower Cotham Member is commonly cross-bedded, with rippled surfaces, and represents a very shallow shoreface facies. It exhibits frequent, and locally intense, soft sediment deformation (Simms, 2003, 2007). A prominent dark shale bed indicates the transgressive phase of a 4th-order cycle, and suggests that the entire lower part of the member was deposited within two 4th-order cycles. A desiccation-cracked emergence surface occurs near the top of the lower Cotham Member, although there is no evidence for erosion at this surface. Macrofossils and bioturbation are largely absent.

The upper Cotham Member generally fines-up, reflecting renewed deepening above the emergence surface. Three distinctive, laminated micritic limestones occur just above this surface and can be correlated to other sites in the basin. Above the limestones, abundant bivalves reappear in marly siltstone and dark shale of similar facies to the underlying Westbury Formation. Bioturbation is present in the thicker-bedded heterolith at the top of the member, along with convex-up shell pavements on discontinuous siltstone laminae.

At Larne, we have placed the Cotham Member-Langport Member boundary at a distinct change from silt-dominant to mud-dominant sediments. The lower half of the Langport Member is of interbedded siltstone and micaceous mudstone, with the frequency and thickness of the siltstones decreasing up-section. The upper half generally coarsens-upward, with siltstone and heterolith facies similar to those in the top of the Cotham Member. At the top of the Langport Member, the heterolith is characterised by a distinctive series of thin micritic limestone ribs and laminae, containing rounded and angular clasts of mudstone.

Above the uppermost limestone bed of the Langport Member, a 1m-thick, dark grey, shaly mudstone is taken to mark the base of the Waterloo Mudstone Formation (Lias Group). This pyrite-rich unit can be correlated with the 'Paper Shale' commonly found at the base of the Lias Group in SW Britain (e.g. Wignall, 2001), which reflects rapid deepening. The base of the Lias Group, below the first appearance of *Psiloceras planorbis*, is generally referred to as the 'Pre-Planorbis Beds' in the UK.

Bivalves are abundant throughout the basal Lias Group at Larne but, in contrast to those in the Penarth Group, convex-up shell pavements do not occur, suggesting deeper water. If salinity was reduced in Penarth Group times (Hallam & El-Sharaawy, 1982), then stenohaline conditions were certainly established very early in the deposition of the Lias Group, as crinoids, an exclusively stenohaline group, appear just over 1m from its base at Larne (Figure 4). The Waterloo Mudstone Formation was deposited primarily as hemipelagic marine mudstone in the extensive, but relatively shallow, north-western European seaway. It consists of rhythmically-bedded mudstone, marl and shale, with variable organic carbon and silt content, and with a diverse, fully marine fauna. Minor limestone horizons are common from the middle of the Johnstoni Subzone upwards. The sedimentology and cyclostratigraphy of the lower part of this formation are more fully described at www.habitas.org.uk/larne/gssp.

4.4 The boundary horizon

The proposed boundary point is at the first appearance of *Psiloceras planorbis,* at the base of bed 28a in the Larne foreshore section (Figures 4 and 5; Plate 1). The highest *Neophyllites antecedens* occurs near the top of bed 27,
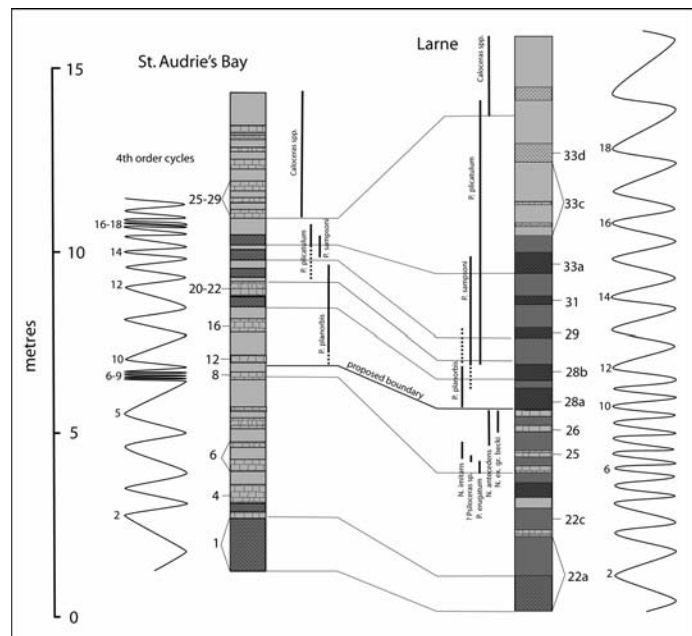

Figure 5: Ammonite ranges and cyclostratigraphy of the basal Lias Group at St. Audrie's Bay and Larne. St. Audrie's Bay ammonites from Warrington *et al*. (1994), with additional data from Doniford Bay (Bloos & Page, 2000). Analysis of the St. Audrie's Bay cyclostratigraphy is ours, with highstands to the left. For further details about the cyclostratigraphic record at this site, see www.habitas.org.uk/larne/gssp
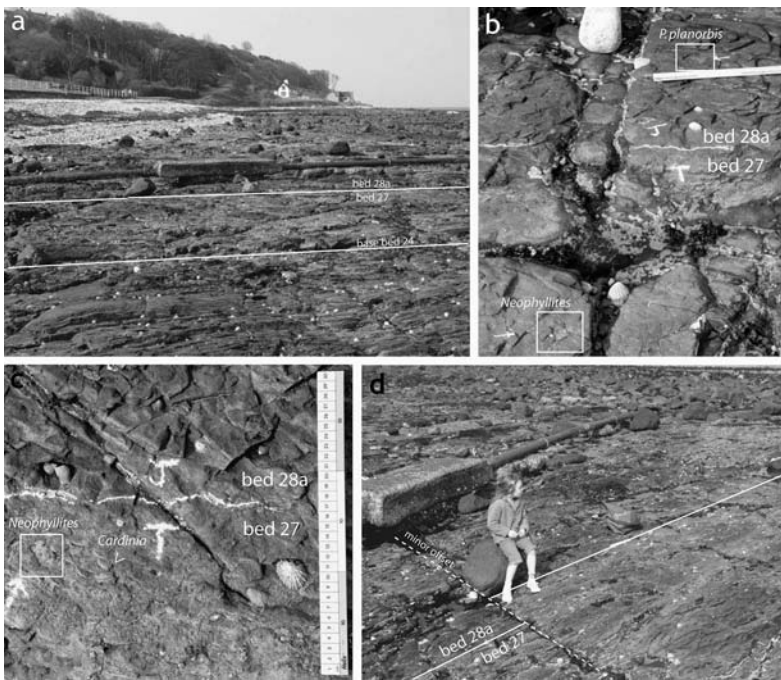
Plate 1

a, General view of the Waterloo Bay foreshore looking north towards Waterloo Cottages. The position of Bed 24, in which ammonites (*Psiloceras erugatum*) first appear, and of the junction of Bed 27 with Bed 28a, the proposed level of the base of the Jurassic, are indicated. The sewer outfall (disused!) is a useful marker, located just to the north of the proposed boundary.

b, c, Detail of the proposed Triassic-Jurassic boundary at the junction of Bed 27 with Bed 28a, showing the proximity of diagnostic ammonite taxa. The condensed, shell-rich, top of Bed 27 is clearly evident in the lower part of figure c.

d, The proposed Triassic-Jurassic boundary on the landward side of the foreshore, just south of the sewer outfall, with a minor fault offset indicated.

4.5 Biostratigraphy
4.5.1 Ammonites

Ammonites have long been the primary biostratigraphic controls for the Triassic and Jurassic successions of NW Europe (Page *in* Simms *et al.*, 2004) and are paramount for regional correlation. They are generally considered to have been stenohaline nektobenthos, although the precise controls on their presence or absence from a particular succession often remain unclear. The preservation of early Hettangian (Planorbis Zone) ammonite faunas in Northern Ireland has long been recognised as generally superior to other sites in the UK (Portlock, 1843) but there is very little detailed stratigraphic data for existing collections.

At Larne, ammonites appear abruptly, in Bed 24 and are abundant at very many levels thereafter. A shell-rich limestone nodule from near the base of Bed 24 yielded several well-preserved, uncrushed, examples of *Psiloceras erugatum* (Plate 2, a; Plate 3, a, d). This, and *ex situ* material from other sites (Plate 3, a, c) demonstrates the variability of the species, with ornamentation varying from inflated node-like ribs only on the innermost whorls through to examples in which low regular ribbing persists throughout the phragmocone and fades only on the body chamber. Crushed examples, with the distinctive nodose inner whorls, are common in the upper part of Bed 24 and lowermost part of Bed 25. *P. erugatum* probably belongs to the *P. tilmanni* group (Guex *et al.*, 2004).

Beds 25 to 27 are dominated by the genus *Neophyllites*. When crushed, they can be difficult to distinguish from generic psiloceratids, but well-preserved examples, particularly in the marl at the top of each of these three units, invariably show the distinctive spiral striations and/or reduced sutures characteristic of *Neophyllites* (Plate 2, b, c, m). Uncrushed specimens from Bed 25 have gently convex whorl sides and a sloping umbilical wall, and are assigned to *Neophyllites imitans* (Plate 2, b; Plate 3, e). Specimens from Beds 26 and 27 have flatter whorl sides and a steeper umbilical wall, with most assignable to *Neophyllites antecedens* (Plate 2, c, m). A few from near the top of Bed 26, and from Bed 27, have weakly developed ribbing on inner whorls and can perhaps be assigned to *Neophyllites* ex grp. *becki* (Plate 3, f). Rare examples of more involute ammonites occur in Beds 25 and 26 (Plate 2, g). They appear distinct from *Neophyllites*, are significantly more involute than *Psiloceras planorbis*, and are tentatively assigned to *Psiloceras* sp.

5cm below the lowest *P. planorbis* (Plate 1b), so this horizon is effectively the *Neophyllites antecedens/Psiloceras planorbis* junction. The boundary level is easily located, its approximate position on the wave-cut platform being marked by a disused outfall pipe (Plate 1a, d). It is offset by a single normal fault, which downthrows strata ~1.5m to the NE (Figure 3). The boundary level can also be traced in the adjacent cliff section.

The proposed boundary point is secondarily defined by its position on the eustatic/cyclostratigraphic curve, one 4th-order cycle above the widely identifiable 3rd-order HH1 highstand surface (Figure 4), and within the 'main' excursion (*sensu* Hesselbo *et al.*, 2002) of the carbon isotope curve. The latter is determined by precise correlation of the horizon with the St. Audrie's Bay record and is supported by preliminary isotope data from Larne (Figure 6). No suitable horizons for radiometric dating of the proposed boundary level are present in the Larne section. Based upon the available biostratigraphic data, and our analysis of 3rd-order cyclicity, the boundary level is approximately 100kyr younger than the radiometric date of 199.6±0.3Ma, obtained by Pálfy *et al.* (2000) from British Columbia.
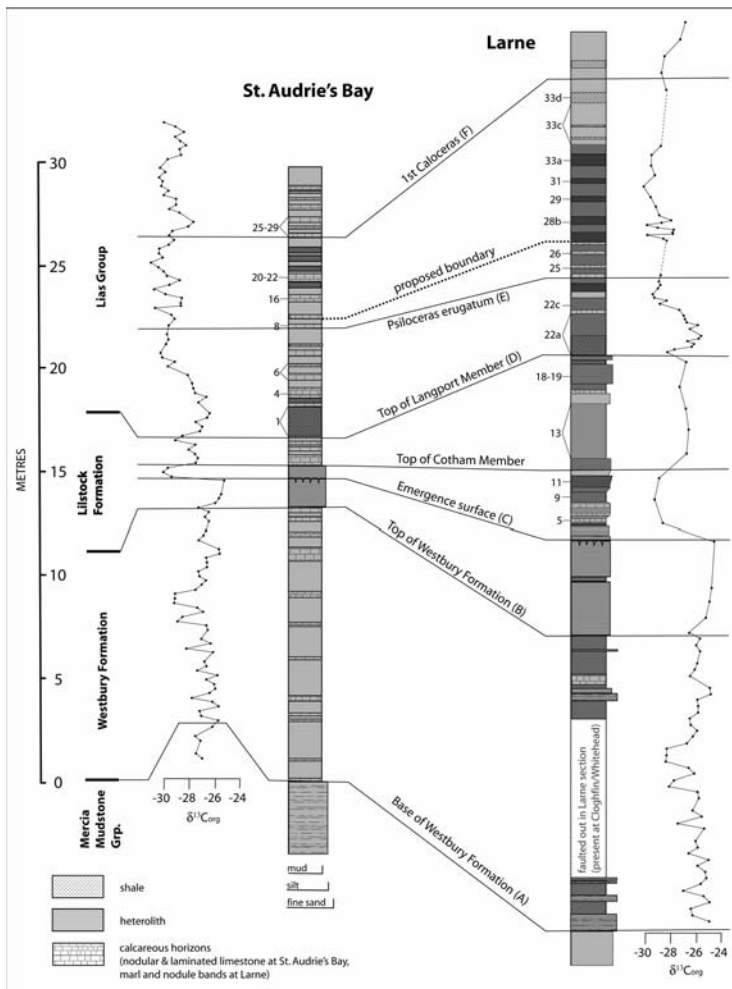
Figure 6: Correlation of the Penarth Group and basal Lias Group between the St. Audrie's Bay and Larne Sections. St Audrie's Bay after Warrington *et al.* (1994) with carbon isotope curve and additions from Hesselbo *et al.* (2002). The St. Audrie's Bay curve has been modified to fit the Larne lithostratigraphy and biostratigraphy by expanding, or compressing, five correlateable segments, which occur between six reliable points of correlation (labelled A-F). The actual sample results for the Waterloo Bay section are indicated by crosses; note that four of these lie virtually on the proxy curve. For further details see www.habitas.org.uk/larne/gssp

Bed 27 is succeeded by dark shales and mudstones (Beds 28 to 33b), in which specimens of *Psiloceras* are abundant and often well preserved, although usually crushed. The earliest examples yet found are from 4cm above the base of Bed 28 (Plate 2, d). Specimens from Bed 28 are moderately evolute, smooth, with well-preserved growth lines, but without the spiral striations of *Neophyllites* (Plate 2, f, k). We assign them to *Psiloceras planorbis* since they are morphologically identical to topotypes, also crushed, from the Somerset coast, and occur at the same stratigraphic level, above the highest *Neophyllites*. *Psiloceras sampsoni*, the holotype of which is from Northern Ireland (Portlock, 1843; Reid & Bancroft, 1986), is more evolute than *P. planorbis* (Plate 3, h) and occurs slightly higher in the Planorbis Subzone (Bloos & Page, 2000; Page *in* Simms *et al.*, 2004). Distinguishing the two can be difficult at diameters of less than 4-5cm, which led Reid & Bancroft (1986) to suggest

that the two species might be conspecific. However, at larger diameters, they are distinct (cf. Plate 2, f; Plate 3, g; see biometric data at www.habitas.org.uk/larne/gssp). A pyritic specimen from Bed 29 (Plate 2, e) is clearly assignable to *P. sampsoni* and establishes, unequivocally, the presence of a highly evolute *Psiloceras* above *P. planorbis*. *P. sampsoni* (Portlock) is a probable senior synonym of *P. psilonotum* (Quenstedt) (Bloos & Page, 2000).

Weakly plicate ammonites appear again near the top of Bed 28b, and we have assigned most to *Psiloceras plicatulum* (Plate 2, j). These occur in moderate abundance through to near the top of Bed 33e. Most examples at Larne are crushed, but occasionally they are found in excellent pyritic preservation here and at other sites (Plate 3, j). The first definite examples of *Caloceras*, albeit crushed, occur in Bed 33e, alongside *Psiloceras plicatulum*. A succession of *Caloceras* faunas can be recognised in the Johnstoni Subzone at Larne, but has yet to be documented in detail. The genus is represented by material in excellent preservation from here and, *ex situ*, from other sites in Northern Ireland (Plate 2, l; Plate 3, i, k).

The ammonite succession recorded at Larne corresponds closely with that documented by Bloos & Page (2000) and Page (*in* Simms *et al.*, 2004). However, compared with other UK surface exposures, the succession at Larne is considerably expanded and contains abundant and well-preserved ammonites at many levels rather than at the discrete narrow horizons typical elsewhere.

4.5.2 Bivalves
The Larne section preserves an abundant and diverse, but largely unstudied, bivalve fauna (Figure 7). Their biostratigraphic potential is probably limited, due to facies dependence, taxonomic difficulties and limited knowledge of their ranges and distribution. However, two faunal events in the Larne borehole and foreshore sequences are potentially useful.
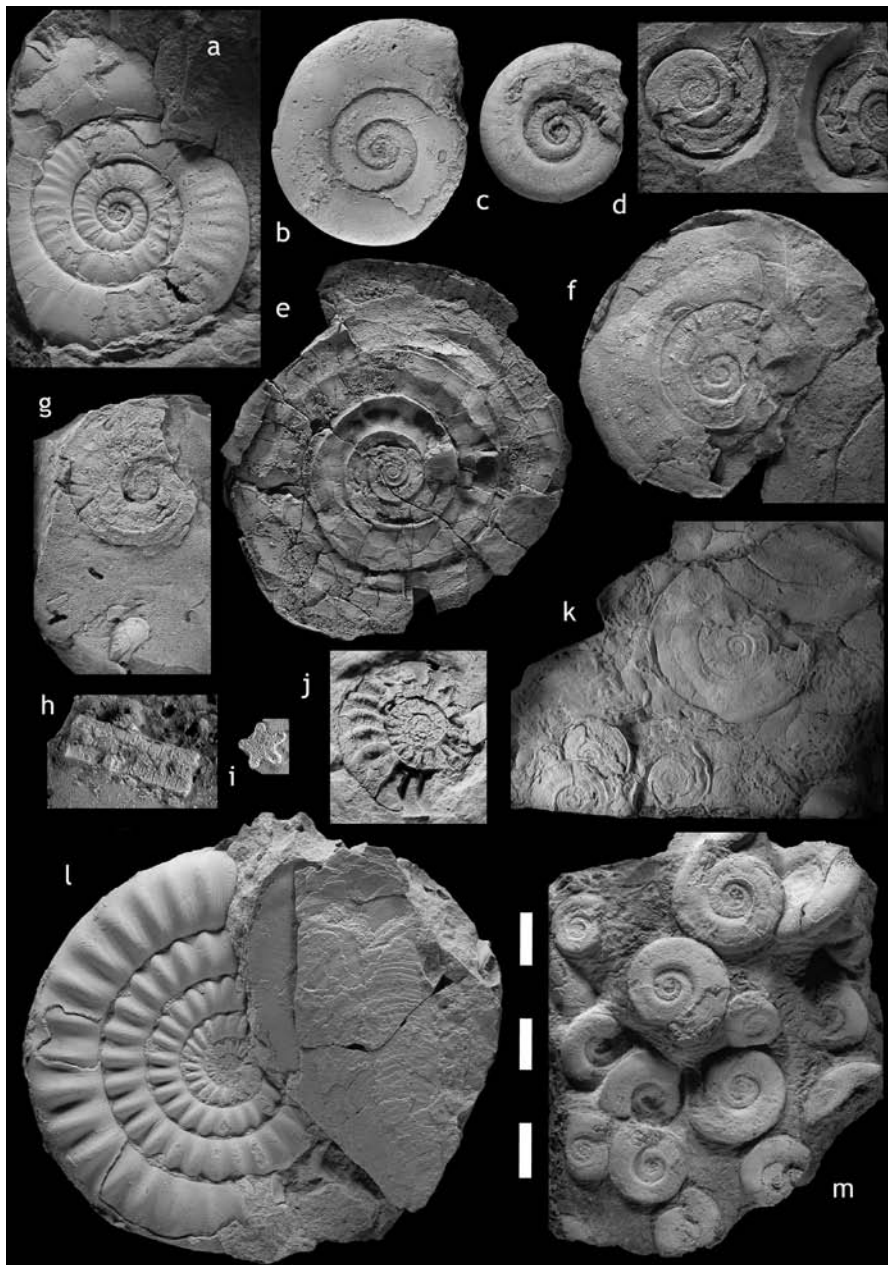
The first, at the top of the Cotham Member (Figure 7), involves the extinction of some typically 'Triassic' forms (*e.g. Eotrapezium*, *Protocardia rhaetica*) and first appearances of 'Jurassic' forms (*e.g. Cosmetodon hettangiensis*, *Lucina* sp.). This faunal event has also been recognised in SW Britain and was suggested as a potential boundary position (Poole, 1979), but, unlike in SW Britain, there is no significant facies change across this level in the Larne Basin.

The second event records the closely synchronous appearance of a cohort of typically 'Hettangian' bivalve

Plate 2
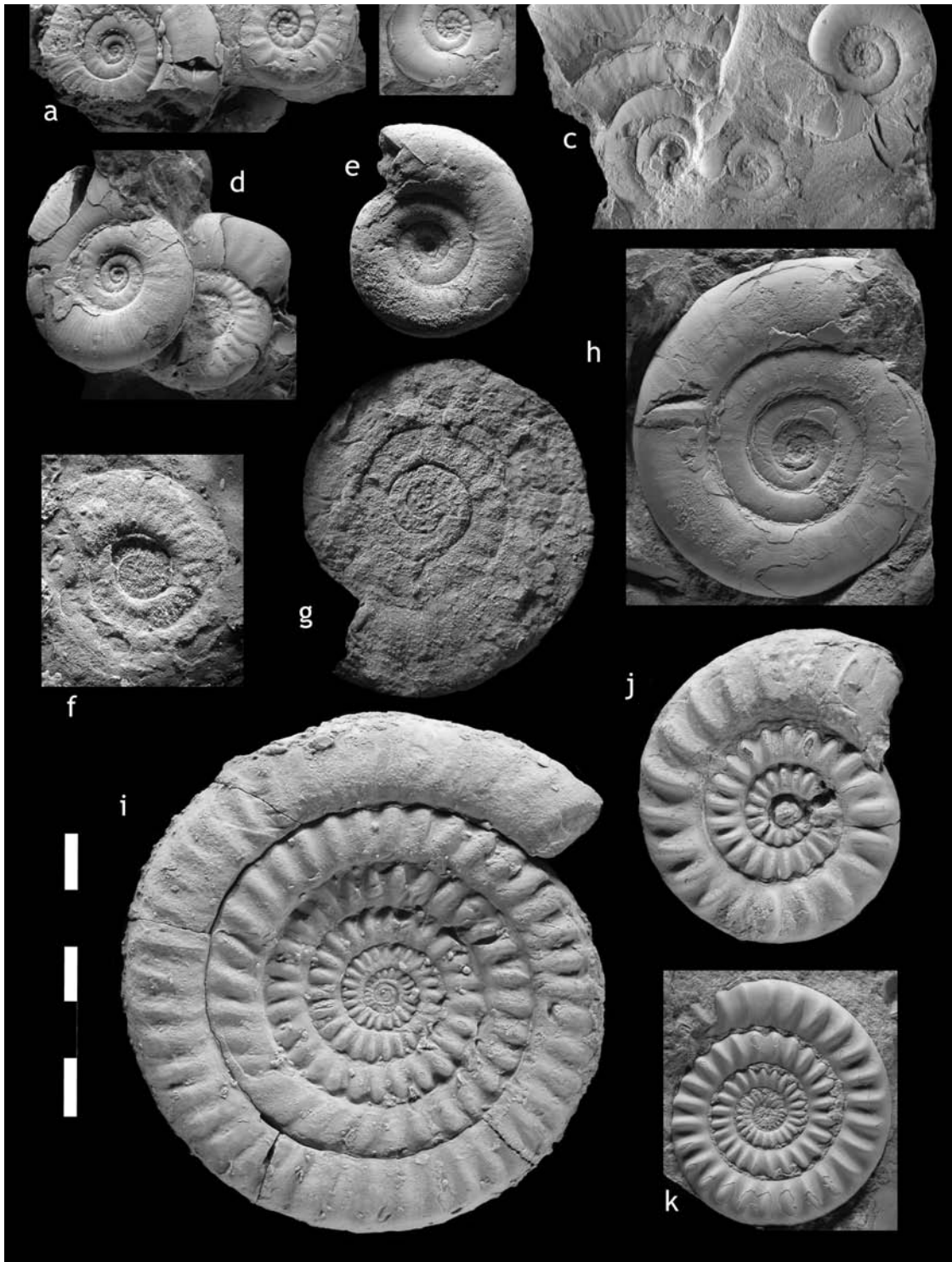All specimens from Waterloo Bay, Larne, Co. Antrim
All specimens to same scale, except figs k and m (x0.5), and figs h and l (x2.5). Scale bar = 5cm

a, *Psiloceras erugatum*. Large uncrushed plicate example, nodule in middle of Bed 24.

b, *Neophyllites imitans*. Uncrushed example, marl in middle of Bed 25.

c, *Neophyllites antecedens*. Pyritic internal cast, 6cm below the top of Bed 26.

d, *Psiloceras planorbis*. Crushed examples, 4cm above base of Bed 28a. These are stratigraphically the earliest examples of this species found at Larne.

e, *Psiloceras sampsoni*. Partly crushed pyritic example, 6cm above the base of Bed 29.

f, *Psiloceras planorbis*. Crushed example, 20cm above base of Bed 28a. This is the large specimen in the centre of Fig k.

g, *Psiloceras* sp.. Crushed involute specimen, 15cm above base of Bed 25 or possibly Bed 26. A specimen of *Modiolus minimus* and part of an ambulacrum of *Diademopsis*, are visible in the lower part of the block.

h, *Isocrinus* sp. nov. Intact noditaxis, 20cm below top of Bed 22a.

i, *Isocrinus* sp. nov. Symplectial articulation, Bed 23.

j, *Psiloceras plicatulum*. Crushed example associated with *Caloceras* sp., 30cm below top of Bed 33e.

k, *Psiloceras planorbis*. Crushed examples from 20cm above base of Bed 28a.

l, *Caloceras johnstoni*. Uncrushed example *ex situ* from limestone, Johnstoni Subzone. A specimen of *Pinna* cf. *similes* obscures the right hand side of this specimen.

m, Shelly limestone block with 15 complete or partial, mostly uncrushed, *Neophyllites antecedens*; several show characteristic spiral striations. Top of Bed 26.

Plate 3
All specimens to same scale. Scale bar = 5cm

a, d, *Psiloceras erugatum*. From single nodule in middle of Bed 24, Waterloo Bay, Larne, Co. Antrim.

b, c, *Psiloceras erugatum*. From single nodule, ex situ, shore below Mullaghdubh House, Islandmagee, Co. Antrim. Specimen b shows the typical nodose inner whorls found in many examples of this species.

e, *Neophyllites imitans*. Faintly ribbed specimen from marl in middle of Bed 25, Waterloo Bay, Larne, Co. Antrim.

f, *Neophyllites* sp. ex grp. *becki*. Strongly ribbed specimen from top of Bed 26, Waterloo Bay, Larne, Co. Antrim.

g, *Psiloceras ? sampsoni*. Crushed, faintly plicate example, top of Bed 28b, Waterloo Bay, Larne, Co. Antrim.

h, *Psiloceras sampsoni*. Typical uncrushed example from *ex situ* nodule, Collin Glen, Belfast, Co. Antrim.

j, *Psiloceras plicatulum*. Uncrushed pyritic internal cast, *ex situ*, Minnis North, near Glenarm, Co. Antrim.

i, *Caloceras intermedium*. Partly crushed example, Johnstoni Subzone, Waterloo Bay, Larne, Co. Antrim.

k, *Caloceras intermedium*. Uncrushed example from limestone, *ex situ*, Minnis North, near Glenarm, Co. Antrim.
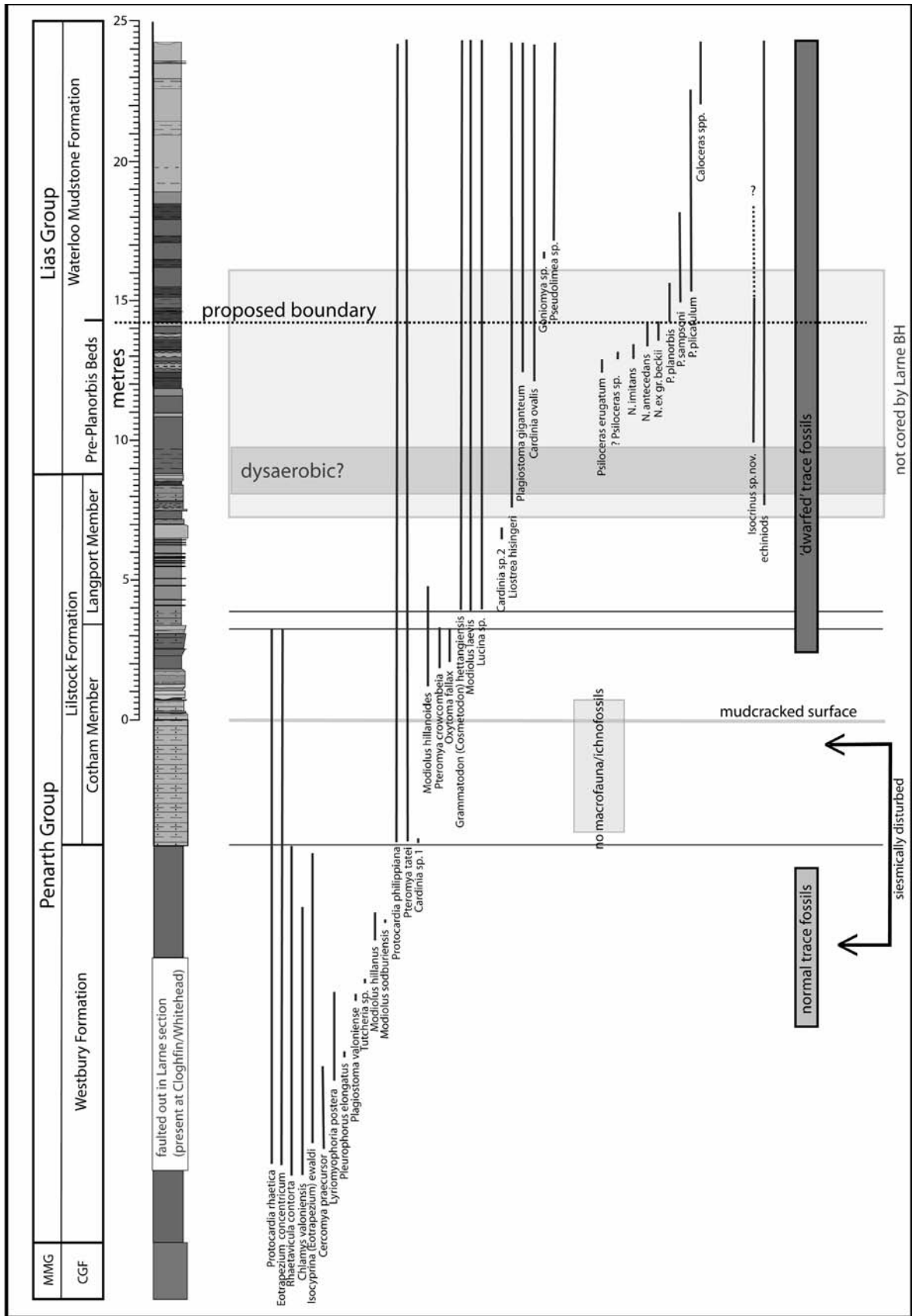
Figure 7: Faunal biostratigraphy for the Penarth Group and basal Lias Group at Larne. Data from Ivimey-Cook (1975) and our own observations

taxa in the upper Pre-Planorbis Beds, just below the first appearance of *P. planorbis*. It was first recognised, again in SW Britain, by Hodges (see Hodges & Simms *in* Simms *et al*., 2004), who noted, with reference to the first appearance of *Plagiostoma giganteum* (op. cit., p. 35) that "In the absence of ammonites, it can be used as a biostratigraphical marker for the approximate base of the Planorbis Zone". *Plagiostoma giganteum* appears at very similar positions in the Tiefengraben section (Kuerschner *et al*., 2007, fig.10), and in the main shell bed of the Germig section (Yin & McRoberts, 2005). At Larne, *P. giganteum* first occurs at the base of Bed 24. *Cardinia ovalis*, another member of this cohort, makes its first appearance in Bed 23. Both occurrences are less than 2m below the FO of *Psiloceras planorbis*, as are Hodge's records from SW Britain. Hodges & Simms (*in* Simms *et al*., 2004, fig.1.14) also identified *Pteromya tatei*, *Chlamys pollux*, *Ctenostreon philocles*, *Pholadomya glabra* and *Camptonectes punctatissimus* as common members of this cohort. The potential for the first appearance of this group of bivalves to provide a reasonably accurate proxy for the base of the Planorbis Zone in sections lacking ammonites has yet to be tested outside the NW European province, but would seem promising.

4.5.3 Echinoderms

Echinoderms, although not a conspicuous element of the fauna at Larne, are more common in the Lias Group than generally thought (Simms *et al*., 2004). Echinoid plates and spines are common at certain horizons and were reported by Ivimey-Cook (1975) from the upper Planorbis Subzone and lower Johnstoni Subzone. We have found them throughout the Lias Group. Most can be assigned to *Diademopsis* (Plate 2, g), with *Miocidaris lobatum* occurring less commonly. Disarticulated spines and plates of *Diademopsis* are especially common in the *Liostrea* shell pavements that occur in the 'Pre-Planorbis Beds' here and elsewhere in the UK. Small, intact ophiuroids have been found in the Westbury Formation (*Aplocoma damesi*) and in the Johnstoni Subzone (? *Sinosura* sp.; Ulster Museum coll.). Neither echinoids nor ophiuroids have significant biostratigraphic value (Simms *et al*., 2004), and ophiuroids at least are moderately euryhaline and poor indicators of fully marine salinity.

Crinoids are the most common echinoderms in the Lias Group. At Larne, columnals and other ossicles of a small isocrinid (Plate 2, h, i) appear in some abundance, about a metre above the base of Bed 22a, continuing in moderate abundance into at least the lower part of the Johnstoni Subzone. Simms (1989) recognised only a single isocrinid species, *Isocrinus psilonoti* in the Hettangian, but preliminary analysis indicates that the material from Larne is a distinct, as yet undescribed, species. In Lias Group isocrinids, the number of columnals per noditaxis (from one nodal columnal to the next) is variable, but characteristic, for each species. *Isocrinus psilonoti* has typically 14-18 columnals in large speci-mens, with rarely fewer than 12 in even the very smallest examples. In contrast, the columnals from Larne, mostly less than 4mm in diameter, have only 7 or 8 columnals per noditaxis (Plate 2, h). Crinoids have some biostratigraphic value within the Lias Group (Simms *et al*., 2004), but the significance of this new isocrinid, which also occurs in the Hinteriss/Kuhjoch section (Hillebrandt, written comm., 2006), remains uncertain until Rhaetian/Hettangian material from elsewhere can be taxonomically reassessed.

4.5.4 Palynomorphs

Samples from the Larne borehole (Harland & Warrington, 1975) established the presence through the boundary interval of a moderately diverse, and generally well-preserved, assemblage of miospores, dinoflagellates and acritarchs. Their distribution is plotted in Figure 8, and correlated with the Larne shore section. Although of low resolution, the data is consistent with that from the much better known record in SW Britain (Hounslow *et al*., 2004).

Six samples from the foreshore exposure were collected, and organic residues recovered by Trinity College Dublin Palynology Laboratory, using standard palynological processing techniques. The locations of these samples are indicated on Figure 8. All the organic residues are dominated by amorphous organic matter (AOM) though, in some cases, the AOM appears to have formed from degraded higher-plant tissues, including cuticle. Palynomorphs constitute <1% total organic matter, except for a sample from the upper part of Bed 19 that contains *ca*.5% palynomorphs. Relatively rare phytoclasts include vitrinite and inertinite particles. Dinoflagellate cysts, acritarchs, spores and bisaccate pollen were recognised though most are indeterminate. Preservation is poor due to a combination of exine pyritisation and high thermal maturity. A vitrinite reflectance survey of the section could help to locate less mature parts of the section for re-sampling. Photomicrographs of typical specimens can be seen at www.habitas.org.uk/larne/gssp.

4.5.5 Calcareous microfossils

No detailed data are yet available for calcareous microfossils through the boundary interval. Benthic foraminifera and ostracods are frequently abundant in the Pre-Planorbis Beds and Planorbis Zone of the Larne section, but the indurated mudstone and marl lithologies are not conducive to processing. However, basal Lias Group sections close to Larne are known to contain well-preserved assemblages. In a *Report of the Belfast Naturalists' Field Club* (*Proc. Belfast Nat. F. C.*, Vol. 1, 1873-1880, p.269), five localities are cited. Faunal lists were provided for Barney's Point, Islandmagee (12 spp.), and Ballygalley Head (10 spp. foraminifera, 6 spp. ostracods). So far, we have only processed a single sample (from beds containing *Neophyllites antecedens* at Whitehead). In addition to abundant echinoderm remains,
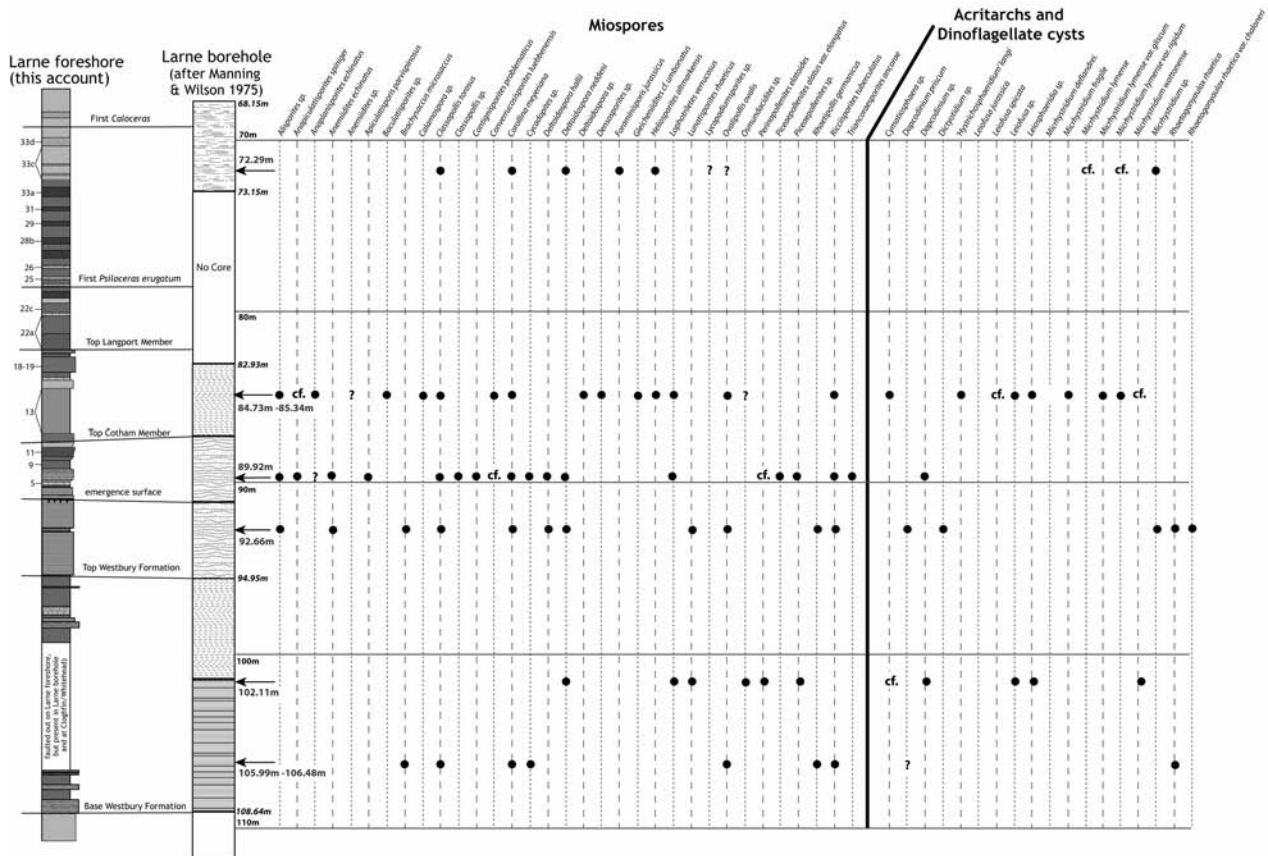
Figure 8: Palynostratigraphy of the Penarth Group and basal Lias Group in the Larne Borehole (data from Warrington & Harland, 1975) correlated with the section at Waterloo Bay. **Larne Borehole**: figures in italics indicate lithostratigraphic markers; figures in grey, and associated arrows, indicate location of samples within borehole. **Larne foreshore**: arrows indicate locations of preliminary samples processed by Geoff Clayton

the sample residue contains common foraminifera, ostracods, sponge spicules, scolecodonts, micro-bivalves, micro-gastropods, fish teeth, scales and otoliths, and phytoclasts, including well preserved cuticle. These records demonstrate clear potential for further work on the calcareous microfossils of the Larne Basin.

4.5.6 Conodonts

Small samples (300g) from the upper Cotham Member (Bed 5a) and the top of the Langport Member (Bed 18) have been processed, but no conodonts have yet been recovered. The presence of abundant fish teeth and scales in the Langport Member sample suggests that conodonts, if present, should be preserved, but those reported from the Langport Member in southern Britain are very small in size and low in abundance (Swift, 1989), and hence might easily be missed in small samples.

4.5.7 Trace fossils

Ichnofossils are known to have potential for correlation, particularly associated with mass extinction events, when macrofauna is rare or absent (Twitchett & Barras, 2004). Trace fossils often occur in facies which do not preserve body fossils and which cannot therefore be easily correlated by other methods. At present, relatively few data are

available for the Triassic-Jurassic boundary interval (Olsen *et al.*, 2002; Barras & Twitchett, 2007).

The Larne succession preserves a good trace fossil record spanning the proposed boundary. In the upper part of the Westbury Formation, a diverse ichnofauna includes *Diplocraterion, Rhizocorallium, Thallassanoides, Planolites, Palaeophycus, Spongeliomorpha, Taenidium, Chondrites, Lockeia, Asteriacites, Rusophycus*, a variety of limulid traces, occasional fish traces, and many small unassigned burrows and trails. They are best preserved in the Cloghfin Port section, but some are also present in the correlative sandstones at Larne.

Trace fossils, and evidence of bioturbation, are absent from the lower Cotham Member, suggesting adverse environmental conditions. They reappear in the Larne section near the top of the Cotham Member (Beds 11-12), but at very low diversity (?*Diplocraterion, Arenicolites, Planolites*) and numbers, and continue through into the Langport Member. Compared with the ichnofauna of the Westbury Formation, trace fossils in the upper part of the Lilstock Formation are 'dwarfed'. Two taxa, *Chondrites* and *Thallasanoides*, reappear at very small size in the Pre-Planorbis Beds at Larne. Through the Waterloo Mudstone Formation, there is a gradual increase in diversity and size, similar to that observed in SW Britain (Barras &

Twitchett, 2007).

4.5.8 Vertebrates

Disarticulated fish remains are common in the Westbury Formation at Larne, Whitehead, Cloghfin Port, and the Larne borehole. The diverse assemblage is closely comparable to that found elsewhere in the UK (*e.g.* Duffin, 1999). They also occur sparsely in the Cotham Member limestones and are common in some of the limestone ribs at the top of the Langport Member, and in the Lias Group. Each of these assemblages is distinctive, suggesting biostratigraphic potential. Isolated marine reptile bones occur in the Westbury Formation, the top of the Langport Member, and the basal Waterloo Mudstone Formation, with an articulated ichthyosaur collected from the middle of the Langport Member at Larne. These reptile remains are unlikely to be of biostratigraphic significance.

4.6 Other correlation methods
4.6.1 Cyclostratigraphy/sequence stratigraphy

The Larne section preserves an excellent record of 3rd- and 4th-order sedimentary cycles (Figures 4 and 5) that should prove extremely useful for correlation. We provisionally attributed this cyclicity to eustatic change, specifically to variations in rates of sediment supply and deposition that would be anticipated by a sequence stratigraphic model. However, the bundling of approximately twenty 4th-order cycles within each 3rd-order cycle strongly suggests a causal link to orbital climatic forcing. At present, there is a fundamental difference between sequence stratigraphy and cyclostratigraphy in the way that 3rd-order cyclicity is interpreted (see Perlmutter & Azambuja Filho, 2005). Sequence stratigraphic models suggest that 3rd-order cycles (sequences) are due to low-frequency, high-amplitude, eustatic changes. By contrast, cyclostratigraphy views 3rd-order cycles as modulated bundles of higher frequency cycles (4th-order cycles), not as a separate, higher-amplitude phenomenon. Under the cyclostratigraphic interpretation, the 4th-order cyclicity at Larne is most likely related to a precession signal of 21± 2kyr, with the 3rd-order cyclicity representing eccentricity modulation of the precession signal to produce a 413kyr periodicity. In Figure 4, we present both interpretations. It should be noted that, in the sequence stratigraphic interpretation, the identified sequence boundaries (Figure 4) are distal-equivalent (lowstand) surfaces, where a sequence boundary could be expected in an up-dip situation. The only unconformity identified at Larne is at the base of the Westbury Formation. The sequence stratigraphy is further complicated by a tectonic uplift event (see below) that has superimposed a 'tectonic' sequence boundary (emergence surface) in the Cotham Member and a secondary maximum flooding surface in the middle of the Langport Member. Clearly there is much scope for further work on the cyclostratigraphic record at Larne, particularly extension of the analysis up-section to confirm the number of 4th-order cycles per 3rd-order

cycle and, potentially, to test the conflicting cyclostratigraphic/sequence stratigraphic models.

Although the cyclostratigraphic record at Larne is particularly clear, we suggest that the 3rd-order, and sometimes the 4th-order, signal can also be detected in many other sections. This opens up the prospect of very high-resolution correlation across the boundary interval, through the construction of a calibrated time frame, within which boundary events can be analysed. We have taken a first step towards this by identifying 'highstand' and 'lowstand' (3rd-order) surfaces from the published logs and descriptions of sections with a carbon isotope record (Figure 9). These surfaces maintain a high degree of congruency with the available biostratigraphic data, suggesting that they are isochronous. If our cyclostratigraphic analysis is correct, the surfaces are spaced at intervals of ~206kyr, and at Larne they can be further subdivided by intervals of ~21kyr. Cyclostratigraphic studies in the Jurassic are becoming increasingly important for correlation (*e.g.* Smith, 1989) and cyclochronology (*e.g.* Hinnov & Park, 1999). A complete cyclochronology for the Hettangian to Pleinsbachian, rooted in Lias Group GSSPs already established at East Quantoxhead (base Sinemurian) and Wine Haven (base Pliensbachian) (Simms *et al.*, 2004), with the addition of Larne (base Hettangian), constrained by detailed biostratigraphic control down to the level of biohorizons, is an attractive, and achievable, possibility. Radiometric calibration, as recommended by Meyers *et al.* (2001), may also be practical, because the cyclostratigraphic record is preserved in the Queen Charlotte Islands section. At Kennecott Point, it is broadly expressed by the distribution of shales and turbidites in the section and, on Kunga Island, by the distribution of nodular limestones.

A more complete account of the cyclostratigraphic record at Larne, and the derivation of Figure 9, may be found on the internet (www.habitas.org.uk/larne/gssp).

4.6.2 Event stratigraphy

Superimposed on a long-term (2nd-order) rise in RSL in Europe, from the Rhaetian into the Hettangian, are shorter-term changes in RSL (Figure 4). Some of these can be related to tectonic events ranging from regional to intrabasinal in extent and have applications to correlation. Simms (2003, 2007) described a soft-sediment deformation event in the lower Cotham Member that extends right across its UK outcrop and subcrop, and possibly beyond. Comparison of the UK and Austrian Rhaetian successions, particularly with reference to carbon isotope curves (Figure 9), indicates that this corresponds closely to the timing of rapid tectonic uplift in the Northern Calcareous Alps (see Krystyn *et al.*, 2005). Bolide impact has been suggested as the cause of the soft-sediment deformation, but the evidence for this remains inconclusive (Simms, 2007). Here, we consider it more probable that the widespread Cotham Member deformation is due to seismic events associated with region-wide uplift and basin inver-
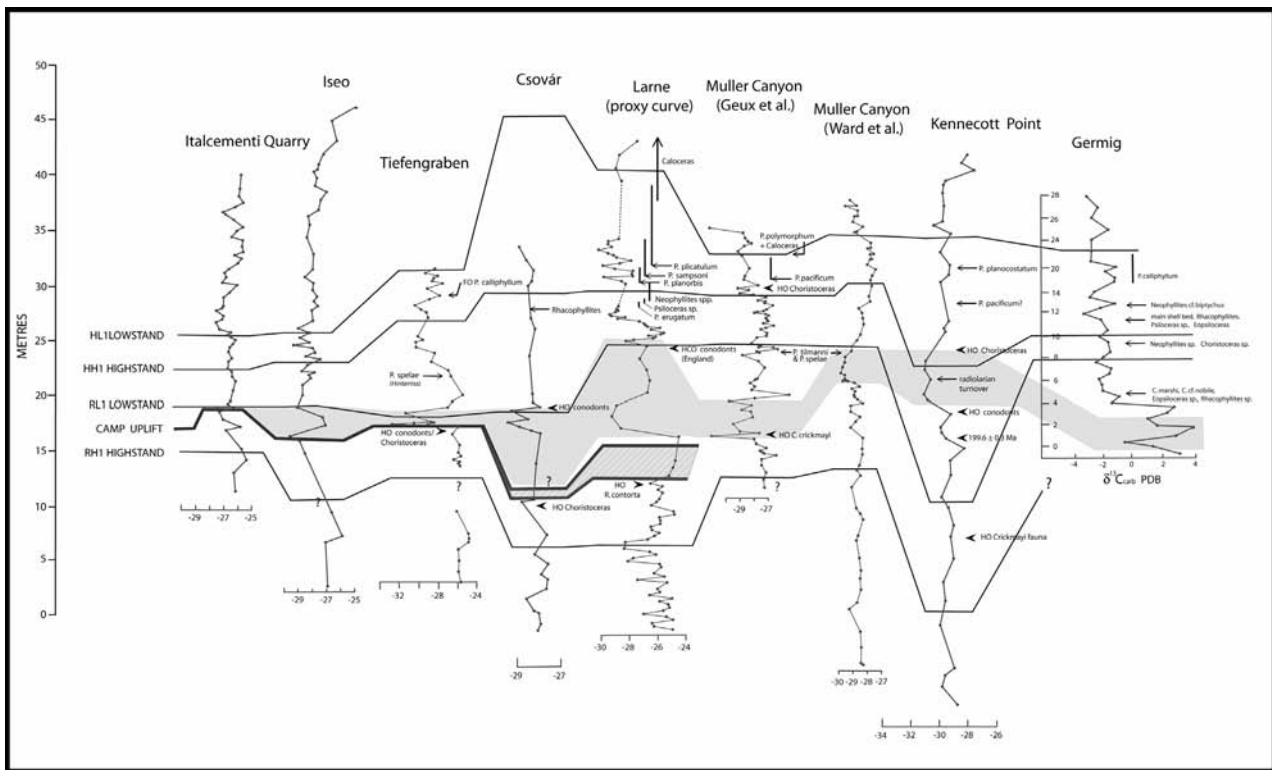
Figure 9: Global correlation of the Triassic-Jurassic boundary interval. Carbon isotope curves are all reproduced at the same vertical and horizontal scales, except for the Germig curve, which has scales exactly as in Yin *et al*. (2006), and Tiefengraben, which has a slightly reduced horizontal scale. The lowstand/highstand surfaces are based upon our interpretation of a 3rd-order cyclostratigraphic/eustatic signal that can be detected in the original authors' logs and descriptions of these sections, and are spaced at intervals of ~206kyr. Grey shading indicates the 'initial' negative carbon isotope excursion, as identified by authors, except for the Csovar curve, where we suggest a possible earlier start to the excursion. Note that the positions and durations of the excursions identified in the curves to the right of the Larne proxy curve are inconsistent with each other and with the European curves. The cross-hatched area indicates the interval of CAMP-related uplift where there is continuous sedimentation. For a full explanation of this chart, and details of how we have derived the data from individual sections, see www.habitas.org.uk/larne/gssp

sion, and is coupled to the event recorded in the Northern Calcareous Alps. A minor emergence surface above the deformed strata also appears to be correlateable across the UK. A minor transgression above this emergence surface correlates closely with the 'initial' carbon isotope excursion of Hesselbo *et al*. (2002; cf. Figures 4 and 6). If, as these authors suggest, the isotope excursion is linked to the initiation of CAMP volcanism, then this short rise in RSL may reflect regional subsidence as the magma that had pooled beneath and within the crust was extruded. Clearly, this implies that tectonic activity associated with the emplacement and extrusion of CAMP lavas extended beyond the limits of the magmatic province.

In the Larne area, seismically disturbed strata are also present in the upper few metres of the Westbury Formation. Deformation in the Cotham Member appears to represent a single event (Simms, 2007), but preliminary observations at Cloghfin Port, and comparison with sites in southern England, suggest these lower deformation horizons are due to an earlier series of shocks which are less widely recorded.

4.6.3 Magnetostratigraphy
Very little has been published on the magnetostratigraphy of the Penarth Group and Lias Group in the UK other than

for the Somerset coast (Hounslow *et al*., 2004). Six samples collected from the Larne foreshore (from Beds 5b, 7, 18, 19 and 28) are currently being processed by Oxford University to assess the magnetostratigraphic potential of the section.

4.6.4 Isotope stratigraphy
Carbon isotope stratigraphies have been published for many sections through the Triassic-Jurassic boundary, including the proposed base Hettangian GSSP at St Audrie's Bay (Hesselbo *et al*., 2002). A proxy curve for the Larne succession has been produced from the St. Audrie's Bay isotope curve, which has been modified to fit the Larne lithostratigraphy and biostratigraphy by expanding, or compressing, five correlateable segments, defined by six reliable points of correlation (A-F in Figure 6).

Using this proxy curve as a guide, seven samples from the Larne foreshore succession were selected, and processed by Oxford University with a view to establishing the potential for an isotope stratigraphy at this site. These are plotted separately against the Larne proxy curve and show a remarkable correspondence with the predicted values (Figure 6). This is highly significant since it establishes that a clear $\delta^{13}C$ signal is present at

this site, where the significantly expanded section could potentially provide greatly enhanced resolution of the Triassic-Jurassic isotope excursions.

5. Potential for further study

In general, Triassic and Jurassic rocks throughout the Larne Basin have been unaffected by Palaeocene thermal metamorphism. However, the Larne section is locally indurated to a variable degree by low-grade thermal metamorphism, making it more resistant to erosion and slumping than correlative strata elsewhere in the basin. Thermal effects across the outcrop show a pronounced gradient. Alteration is greatest at the southern end of the outcrop, from the Collin Glen Formation into the lower part of the Cotham Member, and progressively decreases up-section. At its most extreme, the mudstones and siltstones have been altered by the growth of low-grade metamorphic minerals, such as diopside, and conspicuous analcime 'spherules' in the siltstones. The Lias Group, within which the proposed boundary lies, is only mildly altered. Moderate hardening of mudrocks, some calcite recrystallisation, and growth of euhedral pyrite, are the principal effects seen in this part of the section.

This thermal alteration may limit the potential for some studies at the Larne section. Micropalaeontological investigations are most likely to be affected, due to thermal degradation of organic-walled microfossils and recrystallisation of calcareous microfossils. It is not yet known if a primary remnant palaeomagnetic record can be retrieved.

Other unaltered exposures in the Larne area (Figure 2) can be correlated accurately with the Larne section and offer viable alternatives for sampling affected parts of the succession. However, only at Larne are the Langport Member and much of the Pre-Planorbis Beds currently exposed, although they could be investigated by trenching a suitable locality nearby, or by sinking a shallow borehole specifically for this purpose.

6. Discussion

6.1 The end-Triassic 'mass extinction' and the T-J boundary

Ten to 15 years ago, when the co-ordinated international effort to investigate the Triassic-Jurassic boundary interval really started to gather momentum, perceptions of the boundary interval were somewhat different from those of today. The T-J boundary was seen as being marked by a significant mass-extinction event (Raup & Sepkoski, 1982) that, in the marine realm, was exemplified by the ammonite record. Put simply, the highest Triassic ammonite zonal indices (*Choristoceras* spp.) were separated by a faunally impoverished boundary interval from the lowest Jurassic zonal indices (*Psiloceras* spp.). Naturally, the end-Triassic 'mass extinction' was presumed to lie close to the base of this interval. However, traditionally, the base of the Jurassic has been taken as the first appearance of the genus *Psiloceras*. Although no cos-

mopolitan species was known, the first appearance of *Psiloceras* was thought to be globally synchronous "within practical limits of stratigraphical resolution" (Warrington *et al*., 1994, p.198).

Since then, careful documentation of the most continuous marine sections available has provided important new data. Ammonite faunas that clearly lie within the boundary interval have been discovered in North and South America, northern Europe, the Alpine region, and Tibet, creating considerable overlap between the ranges of 'Triassic-type' ammonites (*e.g.* *Choristoceras, Odoghertyceras, Eopsiloceras, Rhacophyllites*) and that of *Psiloceras*. The *prima facie* case for the globally synchronous appearance of *Psiloceras* to serve as a marker for the T-J boundary has been refuted by the discovery of *Psiloceras* species, mainly of the *P. tilmanni* group, at various stratigraphic levels below the FA of *P. planorbis*, in several faunal provinces.

With these discoveries, the concept of a single correlateable mass-extinction at 'the T-J boundary' has gradually faded. None of the stratigraphically expanded boundary interval sections shows convincing evidence for a single large end-Triassic extinction event (Tanner *et al*., 2004). Current evidence suggests that many extinction events had already occurred by the Norian-Rhaetian boundary, and last appearances of various other taxa are staggered through the Rhaetian. By the base of the T-J boundary interval (*i.e.* the top of the Marshi/Crickmayi Zones), surviving faunas were depauperate and sparse, with a mixed aspect comprising remaining elements of the Triassic fauna and new elements that were to become characteristic of the Jurassic. Adverse environmental conditions continued through the boundary interval, perhaps a consequence of massive volcanism in the Central Atlantic Magmatic Province (*e.g.* Ward *et al*., 2001; Hesselbo *et al*., 2002; Guex *et al*., 2004), and some opportunistic species originating at this time may constitute a discrete 'boundary fauna' that became extinct as environments recovered (Ciarapica, 2007). It is against this background of protracted biotic change, rather than a major abrupt extinction event, that the T-J boundary needs to be defined by a Global Stratotype Section and Point.

6.2 Selecting a boundary index

In selecting a GSSP, it is the potential for unequivocal correlation that is the paramount consideration (Cowie *et al*., 1986; Remane *et al*., 1996; Walsh *et al*., 2004). Despite this, relatively little progress has been made regarding the general problem of correlation within the T-J boundary interval (Bloos, 2004b). Most sections contain bioevents that potentially might be correlateable but, for some reason, correlation has yet to be achieved. We suggest that this is a consequence of the low resolution of the stratigraphic data set, which does not bode well for the correlateability, potential or otherwise, of any GSSP or its proxies (see below), if it is located within the faunally impoverished boundary interval.

There are two reasons why the dataset is poor:

1. There are relatively few complete sections, due to a widespread regression (RL1 in Figures 4 and 9).

2. After a protracted period of extinction, faunas were generally sparse and of low-diversity. Ammonites, in particular, are extremely rare below the top of the boundary interval.

These points are important because the accuracy and confidence limits of correlations are determined by the size and resolution of the available dataset. It might be argued that there is no need for accuracy and confidence when it comes to correlation within the boundary interval; the number of sections is relatively low, and the interval is well-constrained between the HO of Triassic zonal indices and the LO of *P. planorbis* and its presumed sister species. Indeed, if the boundary point is placed near the eustatic lowstand it will lie within a hiatus at most localities, with unequivocally Triassic rocks below, and Jurassic above. To accept this argument is to accept that the entire duration of the faunally impoverished boundary *interval* is a reasonable error bar to attach to specific correlations from the boundary *point*, and that this level of stratigraphic resolution is 'good enough' for a Stage and System boundary. However, its weakness is that it disregards the scientific imperatives for accuracy and confidence.

There is general consensus that:

1. The GSSP for the base of the Hettangian Stage, and thus for the base of the Jurassic System, should be placed above the highest occurrence of established Triassic zonal index species;

2. Ammonites offer the best prospect for a globally correlateable biostratigraphic definition of the boundary (*e.g.* Lucas *et al.*, 2005; Bloos, 2006).

3. The lower limit for placement of the boundary is at the top of the Marshi/Crickmayi Zones, with the upper limit the traditional 'working' base of the Jurassic System at the first appearance of *Psiloceras planorbis* (Warrington *et al.*, 1994). We estimate the duration of this boundary interval, based upon the Larne cyclostratigraphic record (Figure 4), at approximately sixteen 4th-order cycles, or ~340kyr. This is the margin of error that would have to be accepted if the boundary point is placed near the data-poor eustatic lowstand. It is represented by 15-20m of sediment in expanded sections, so it can hardly be regarded as trivial or insignificant.

6.3 Proxy horizons

Chronostratigraphic correlation is the identification of points that lie on the same time plane. It does not equate to the vague correlation of biostratigraphic zones, but demands that we are able to demonstrate the isochrony of specific points in two or more sections. There is always a margin of error attached to correlations but, because chronostratigraphy is a science, not an art, we should strive to minimise, and preferably quantify, that error.

Even approximate correlation by ammonites within the boundary interval is barely possible, so it has been suggested that correlation might be achieved using proxies (Lucas *et al.*, 2005; Bloos, 2006). Most suggested proxies are events occurring at different horizons to the proposed boundary point. However, the use of temporally displaced events to correlate the GSSP knowingly introduces chronostratigraphic error at source, without any means to determine its magnitude. Stratigraphic thickness is not a chronostratigraphic measure, so the 'closeness' of proxy horizons to a proposed boundary point is relatively meaningless.

Whilst proxy horizons certainly have a role to play in helping to locate the boundary in sections that lack the primary defining event, their availability in a potential GSSP section in no way compensates for a lack of correlation potential of the defining event itself. Remane *et al.* (1996, p.79) state clearly that it is the *primary defining event* of a GSSP that should be of optimal correlation potential. This is to ensure that chronostratigraphic error is minimised as far as possible at the start of a correlation chain. Obviously, the greater the number and geographical spread of correlative points linked directly to the defining event of the GSSP, the more accurately the boundary can be correlated.

Relying upon proxy horizons from the outset to correlate the boundary level beyond the GSSP location undermines the basic principle of a GSSP as a chronostratigraphic datum. Proxy horizons should be used as far down a correlation chain as possible, when no accurate alternative is available. Indeed, if proxy horizons in a potential stratotype section really have any significant correlation potential, why they were not selected as the primary defining event from the outset?

6.4 Ammonites and the boundary

No cosmopolitan ammonite species are known, either in the boundary interval or in the basal Hettangian (Bloos, 2006), so whatever ammonite event is employed to define the GSSP, the use of proxy species is unavoidable. However, if ammonites are the most suitable group for defining the boundary itself, then it follows that they must also be the most suitable group for providing proxies and, indeed, the use of ammonite proxies has been all but assumed in previous Jurassic GSSP proposals (*e.g.* Bloos & Page, 2002). From the Planorbis Zone upwards, ammonites are generally widespread and abundant in Jurassic marine strata, *i.e.* the dataset is very good. In our proposal, ammonite proxies are required to correlate the proposed boundary level to sections outside the NW European Province. These are 'time-equivalent' ammonite events, in the sense that, within the present limit of stratigraphic resolution, they can be demonstrated to occur at the same time as the FO of *P. planorbis* (Figure 9). Within the NW European Province, ammonite proxies (*P. sampsoni*/*psilonotum* and *Neophyllites* spp., respectively) above and below the proposed boundary point can be employed where *P. planorbis* is absent, so the bound-

ary is easily recognised at very many localities. Most importantly, the chronostratigraphic separation of these proxies from the boundary level at Larne is known, and is very small.

The base of the Planorbis Zone is effectively the earliest point above the top of the Marshi/Crickmayi Zones that can be correlated worldwide by ammonites (Bloos, 2006). Although cosmopolitan species are unknown, reliably correlateable sequences of ammonites occur in most regions. These sequences provide a biostratigraphic context within which the proposed boundary level, the GSSP, can be located with a good degree of accuracy. The base of the Planorbis Zone in NW Europe can be correlated with the base of the Calliphyllum Zone in the Alps (and Tibet) because both zones are immediately underlain by species of *Neophyllites*. The *Neophyllites*/*Psiloceras* junction may also be recognisable in North America (Guex *et al*., 2003, 2004), although the identification of *Neophyllites* there is unconfirmed (Bloos, 2006). Correlation of the bases of the Planorbis, Calliphyllum, and Pacificum Zones is supported by their positions just above a eustatic highstand surface (HH1 in Figures 4 and 9) and, to some extent, by carbon isotope curves (Guex *et al*., 2004; Figure 9).

The base of the Tilmanni Zone in South America was formerly thought to correlate with the base of these three regional zones (*e.g.* Hillebrandt, 1994), but the discovery of significantly earlier material in Nevada suggests that the range of *P. tilmanni* extends below the base of the Pacificum Zone. Hillebrandt (1994, p.305) noted that some evolute forms of *P. tilmanni* in Peru "are identical to *P. pacificum*", while Guex *et al*. (2004) recorded possible *P. tilmanni* at the base of the base of the Pacificum Zone in Nevada. Hence the ranges of *P. tilmanni* and *P. pacificum* may well overlap. Further research on the well-preserved South American faunas may enable recognition of a level equivalent to the base of the Pacificum Zone, above the HO of *Odoghertyceras*, but probably still within the Tilmanni Zone.

6.5 Non-biostratigraphic correlation methods

A variety of non-biostratigraphic signals are potentially available for correlating the T-J boundary interval. They include magnetostratigraphy, cyclostratigraphy and chemostratigraphy. However, such data are an 'equivocal' tool in stratigraphy (Remane *et al*., 1996; Odin *et al*., 2004), in the sense that potentially correlateable characteristics (excursions, trends, reversals, *etc*.) are not unique to that time interval but are repeated cyclically or randomly through time. By contrast, geochronology and biostratigraphy can be considered 'unequivocal' tools since they provide unique values in time. These equivocal techniques can be very useful in supporting unequivocal data but should not be used to define the boundary.

Carbon isotope stratigraphy has been the non-biostratigraphic method most widely applied to the issue of

the T-J boundary, and has been suggested as a possible means to define the boundary at the level of a distinctive negative excursion (Hesselbo *et al*., 2002). To test the validity of correlations based on the carbon isotope record, we have cross-correlated the cyclostratigraphic record with a number of isotope curves and their associated biostratigraphic data (Figure 9). Four 3rd-order highstand/lowstand surfaces in the boundary interval constrain three independently correlateable segments of the isotope curves, and a tectonic uplift surface provides an additional datum in the CAMP-influenced area. These surfaces maintain a highly congruent relationship to the available biostratigraphic data, and illustrate clearly how sedimentation rates vary in different sections through the progression of a cycle. Significantly, the cyclostratigraphic data suggest that the radiolarian turnover recorded in the Queen Charlotte Islands may occur within the 'main' isotope excursion of Hesselbo *et al*. (2002), not the 'initial' excursion.

6.6 Candidate GSSP sections in the UK: St Audrie's Bay and Larne

Two candidate GSSP sections within the UK, at Larne and at St. Audrie's Bay, propose the FO of *P. planorbis* as the primary defining criterion. These successions are very similar and can be correlated accurately (Figures 5 and 6). St. Audrie's Bay has a long history of study and there is currently a considerable array of data available from that locality. Ammonites traditionally regarded as 'Triassic' (*i.e. Choristoceras* spp.) are absent, as elsewhere in NW Europe. However, this does not detract from the definition or correlation of the proposed boundary point because the top of the Marshi/Crickmayi Zones corresponds to the start of the 'initial' carbon isotope excursion (Figure 9). The position of this excursion was first established in the St. Audrie's Bay section (Hesselbo *et al*., 2002) at a level that can be correlated very reliably with the Larne section (Figure 6).

Ammonite preservation, diversity, and abundance (see Plates 1 and 2) around the proposed boundary level are all considerably better in the Larne section than at St. Audrie's Bay. Moreover, at St Audrie's Bay the proposed boundary occurs within a strongly condensed interval (Figure 5) where species identifications are uncertain due to poor preservation (Bloos & Page, 2000, p.32). Because the boundary horizon, its immediate stratigraphic context, and the sequence of ammonites on either side of the boundary can be established at Larne with much greater clarity and confidence, it should take priority over St. Audrie's Bay as a potential GSSP.

It might be supposed that the greater availability of alternative methods of correlation established for the St. Audrie's Bay section means that it has higher correlation potential than the Larne section. Actually, this is not the case, particularly since none of the other methods can achieve the same degree of stratigraphic resolution as that provided by ammonites. The two sections can be correlat-

ed reliably by lithostratigraphy, biostratigraphy, cyclostratigraphy and event stratigraphy (Figures 5 and 6). Thus, events in the carbon isotope, magnetostratigraphic and palynological records at St. Audrie's Bay can be accurately correlated with the Larne section. In essence, because they can be correlated with such precision, the two sections have equal correlation potential, but the defining criterion is much clearer in one (Larne) than the other (St. Audrie's Bay).

At present, we have only limited data concerning the availability of non-ammonite biostratigraphic proxies (other than those previously mentioned) for the proposed boundary point at Larne, but the large number of sections at which this level can be confidently identified maximises the potential for discovery. For example, the base of the TPi Palynozone in Austria correlates closely with the proposed boundary level, according to our correlation of the carbon isotope curves of Tiefengraben and St. Audrie's Bay (Kuerschner *et al.*, 2007, Figs 8, 9; Figure 9), and therefore is a potential proxy. As noted above, the radiolarian turnover may also be a late boundary interval event, chronostratigraphically closer to the FA of *P. planorbis* than to the FA of P. *tilmanni* group ammonites.

The clear cyclostratigraphic record (Figures 4 and 5) allows events at Larne, and in correlative sections elsewhere, to be located accurately relative to the boundary. The 'initial' carbon isotope excursion, for example, starts 14 to 15 4th-order cycles below our proposed boundary level, while the SA5r Magnetozone lies eight cycles (*ca*.168kyr) below it. This means that there is a high probability that the boundary level can be located in similarly cyclical sequences, either marine or lacustrine, by cycle counting from known proxy levels (cf. Hinnov & Park, 1999). Potential for correlating the proposed marine boundary at Larne with the terrestrial record (cf. Olsen, 1986) would therefore seem to be good.

The Larne section fulfils nearly all of the GSSP requirements listed by Remane *et al.* (1996). All major facies changes in the extended section occur below the Lias Group and therefore do not affect the defining criteria. Synsedimentary deformation is similarly confined to the Penarth Group and adds to, rather than detracts from, correlation potential of this section. The only uncertainty surrounds the extent to which thermal alteration may limit the potential for micropalaeontological, geochemical and palaeomagnetic investigations, specifically at Waterloo Bay. Our preliminary investigations indicate that, for the carbon isotope curve at least, this is not an issue, and the potential of this section to provide a precise, stable, and widely correlateable boundary definition is clear.

7. Concluding remarks

The selection and definition of a GSSP is an exercise in chronostratigraphy that should be undertaken independently of any questions surrounding perceived extinction events. It is the correlation potential of the boundary point that is *the* guiding principle (Walsh *et al.*, 2004). In the specific case of the GSSP for the base of the Hettangian Stage, the debate surrounding which level to select centres on one key question: is it better to define the boundary point at a time when the stratigraphic record is at its highest resolution, or at its lowest? The correlation potential, precision, and confidence limits of a GSSP are maximised by an abundance of data in the former instance. Conversely, where stratigraphic resolution is low through lack of data, correlation is achieved only through compromising on precision and confidence. Whatever the specific attributes of individual sections, potential for correlation of a boundary point *is* related to the quantity and quality of the wider stratigraphic record. When the boundary *point* can be correlated only as a wide boundary '*zone*', compromise has gone too far.

Of the available options, the first appearance of *Psiloceras planorbis* offers a boundary point definition that has proven potential for accurate and reliable correlation, and already has a history of use as the defining point of the base of the Jurassic System (Cope *et al.*, 1980). As such, what is to be gained by adopting an earlier level where the stratigraphic resolution is demonstrably much lower? It is irrelevant whether or not the boundary position renders some psiloceratids Triassic and others Jurassic; or if conodonts survive the boundary; or if the boundary does, or does not, coincide with a mass extinction horizon. It is not the function of a GSSP to give chronostratigraphic meaning to any event traditionally perceived to be of significance unless, coincidentally, that event has optimum correlation potential.

We therefore advocate that the base of the Hettangian Stage be defined by the first appearance of *Psiloceras planorbis* in the section that best documents the ammonite faunas and events in the vicinity of the proposed boundary. That section is at Waterloo Bay, Larne, in Northern Ireland.

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List of persons for Hettangian GSSP vote

Aberhan, Martin	Berlin, Germany	martin.aberhan@rz.hu-berlin.de
Bartolini, Annachiara	Paris, France	Chiara@ccr.jussieu.fr
Bloos, Gert	Stuttgart, Germany	bloos.smns@naturkundemuseum-bw.de
Boomer, Ian	Birmingham, U.K.	i.boomer@bham.ac.uk
Bown, Paul	London, U.K.	p.bown@ucl.ac.uk
Bucher, Hugo	Zurich, Switzerland	hugo.fr.bucher@pim.uzh.ch
Carter, Elisabeth	Portland, Oregon, USA	cartermicro@earthlink.net
Ciarapica, Gloria	Perugia, Italy	ciarapic@unipg.it
Cirilli, Simonetta	Perugia, Italy	simocir@unipg.it
Coe, Angela	Milton Keynes, U.K.	a.l.coe@open.ac.uk
Cohen, Anthony	Milton Keynes, U.K.	a.s.cohen@open.ac.uk
Cope, John	Cardiff, Wales, U.K.	john.cope@museumwales.ac.uk
Copestake, Phil	Ledbury, U.K.	Phil_Copestake@merlinenergy.co.uk
Damborenea, Susana	La Plata, Argentina	sdambore@fcnym.unlp.edu.ar
Enay, Raymond	Lyon, France	raymond.enay@univ-lyon1.fr
Feist-Burkhardt, Susanne	London, U.K.	S.Feist-Burkhardt@nhm.ac.uk
Furrer, Heinz	Zurich, Switzerland	heinz.furrer@pim.uzh.ch
Gazdzicki, Andrzej	Warsaw, Poland	gazdzick@twarda.pan.pl.
Götz, Annette	Halle, Germany	annette.goetz@geo.uni-halle.de
Guex, Jean	Lausanne, Switzerland	jean.guex@unil.ch
Haas, János	Budapest, Hungary	haas@ludens.elte.hu
Haggart, Jim	Vancouver, Canada	Jhaggart@nrcan.gc.ca
Hall, Russell	Perth, Australia	hallrl@westnet.com.au
Hallam, Anthony	Birmingham, U.K.	A.Hallam@bham.ac.uk
Herngreen, Waldemar	Utrecht, Netherlands	g.f.w.herngreen@bio.uu.nl
Hesselbo, Stephen	Oxford, U.K.	stephen.hesselbo@earth.ox.ac.uk
Hirsch, Francis	Kyoto, Japan (1/5-30/9 2007)	abafran@hotmail.com
Hori, Rie	Matsuyama, Japan	shori@sci.ehime-u.ac.jp
Hounslow, Mark	Lancaster, U.K.	m.hounslow@lancaster.ac.uk
Ivimey-Cook, Hugh	Taunton, U.K.	hugh.ivimey-cook@tiscali.co.uk
Jeram, Andrew	Larne, N. Ireland, U.K.	AnitaJeram@aol.com
Korte, Christoph	Berlin, Germany	korte@zedat.fu-berlin.de
Kozur, Heinz	Budapest, Hungary	kozurh@helka.iif.hu
Krystyn, Leopold	Vienna, Austria	leopold.krystyn@univie.ac.at
Kuerschner, Wolfram	Utrecht, Netherlands	w.m.kuerschner@bio.uu.nl
Lathuilière, Bernard	Nancy, France	bernard.lathuiliere@g2r.uhp-nancy.fr
Lindström, Sofie	Lund, Sweden	sofie.lindstrom@geol.lu.se
Longridge, Louise	Vancouver, Canada	llongridge@eos.ubc.ca
Lord, Alan	Frankfurt/M., Germany	Alan.Lord@senckenberg.de
Lucas, Spencer	Albuquerque, New Mexico, USA	spencer.lucas@state.nm.us
Makhlouf, Issa	Jordan	makhlouf11@yahoo.com
Mancenido, Miguel	La Plata, Argentina	mmanceni@ciudad.com.ar
Matsuoka, Atsushi	Niigata, Japan	matsuoka@geo.sc.niigata-u.ac.jp
McRoberts, Christopher	Cortland, New York, USA	mcroberts@cortland.edu
Menning, Manfred	Potsdam, Germany	menne@gfz-potsdam.de
Michalik, Jozef	Bratislava, Slovakia	geolmich@savlba.sk
Mouterde, René	Lyon, France	david.besson@rhone.fr
Ogg, James	West Lafayette, USA	jogg@purdue.edu
Olsen, Paul	Palisades, New York, USA	polsen@ldeo.columbia.edu
Page, Kevin	Plymouth, U.K.	kpage@plymouth.ac.uk
Pálfy, Jozsef	Budapest, Hungary	palfy@nhmus.hu
Pie?kowski, Grzegorz	Warsaw, Poland	grzegorz.pienkowski@pgi.gov.pl
Prinz-Grimm, Peter	Frankfurt/M., Germany	prinz-grimm@em.uni-frankfurt.de
Riccardi, Alberto	La Plata, Argentina	riccardi@fcnym.unlp.edu.ar
Roniewicz, Ewa	Warsaw, Poland	eron@twarda.pan.pl
Ruckwied, Katrin	Halle, Germany	wied@geo.uni-halle.de
Sha Jingeng	Nanjing, P.R. China	jgsha@nigpas.ac.cn
Siblik, Milos	Prague, Czechia	siblik@gli.cas.cz
Simms, Michael	Belfast, N Ireland, U.K.	michael.simms@magni.org.uk
Smith, Paul	Vancouver, Canada	psmith@eos.ubc.ca
Stanley, George	Missoula, Montana, USA	george.stanley@umontana.edu
Stevens, Graeme	Lower Hutt, New Zealand	dianeandgraeme@xtra.co.nz
Tanner, Lawrence	Syracuse, New York, USA	annerlh@lemoyne.edu
Taylor, David	Portland, Oregon, USA	Blitz124@comcast.net
Tomasovych, Adam	Chicago, USA	geoltoma@savba.sk
Urlichs, Max	Stuttgart, Germany	urlichs.smns@naturkundemuseum-bw.de
von Hillebrandt, Axel	Berlin, Germany	hil10632@mailbox.TU-Berlin.de
Vörös, Attila	Budapest, Hungary	voros@nhmus.hu
Ward, Peter	Washington, USA	argo@u.washington.edu
Warrington, Geoffrey	Leicester, U.K.	gw47@le.ac.uk
Yin Jiarun	Beijing, P.R. China	yjr@cugb.edu.cn