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The proposal of a GSSP for the Berriasian Stage (Cretaceous System): Part 1.

William A.P. WIMBLEDON¹, Daniela REHÁKOVÁ², Andrea SVOBODOVÁ³, Tiiu ELBRA³, Petr SCHNABL³, Petr PRUNER³, Krýstina ŠIFNEROVÁ³, Šimon KDÝR³, Oksana DZYUBA⁴, Johann SCHNYDER⁵, Bruno GALBRUN⁵, Martin KOŠŤÁK⁶, Lucie VAŇKOVÁ⁶, Philip COPESTAKE⁷, Christopher O. HUNT⁸, Alberto RICCARDI⁹, Terry P. POULTON¹⁰, Luc G. BULOT¹¹, Camille FRAU¹² and Luis DE LENA¹³.

¹ School of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol BS8 1RJ, United Kingdom; ² Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University, Ilkovičova 6, 84215 Bratislava, Slovakia; ³ The Czech Academy of Sciences, Institute of Geology, Rozvojová 269, 165 00 Prague, Czech Republic; ⁴ Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of RAS, Acad. Koptug av. 3, Novosibirsk 630090, Russia; ⁵ Sorbonne Université, UPMC Université Paris 06, CNRS, Institut des Sciences de la Terre Paris (ISTeP), 75005 Paris, France; ⁶ Institute of Geology and Palaeontology, Faculty of Science, Charles University, Albertov 6, Prague 2, 128 43, Czech Republic; ⁷ Merlin Energy Resources Ltd., New Street, Ledbury, Herefordshire, HR8 2EJ, United Kingdom; ⁸ School of Biological & Environmental Sciences, Liverpool John Moores University, Byrom St., Liverpool L3 3AH, United Kingdom; ⁹ CONICET - Museo de La Plata, Universidad Nacional de La Plata, Paseo del Bosque s/n, 1900 La Plata, Argentina; ¹⁰ Geological Survey of Canada, Calgary, Alberta, T2L 2A1, Canada; ¹¹ Aix-Marseille Université, CNRS, IRD, INRAE, Collège de France, Cerege, Site Saint-Charles, Case 67, 3, Place Victor Hugo, 13331 Marseille Cedex 3, France; ¹² NARG, School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Williamson Building, Oxford Road, Manchester M13 9PL, United Kingdom; ¹³ Groupement d'Intérêt Paléontologique, Science et Exposition, 60 bd Georges Richard, 83000 Toulon, France; ¹³ Department of Earth Sciences, University of Geneva, Geneva, 1205, Switzerland.

Key words: Berriasian, GSSP definition, J/K boundary, global correlation, *Calpionella alpina* Subzone, markers and proxies.

Abstract: Here in the first part of this publication we discuss the possibilities for the selection of a GSSP for the Berriasian Stage of the Cretaceous System, based on the established methods for correlation in the Tithonian/Berriasian interval. This will be followed, in the second part, by an account of the stratigraphic evidence that justifies the locality of Tré Maroua (Hautes-Alpes, SE France) as the proposed GSSP. Here we discuss the possibilities for correlation in the historical J/K boundary interval, and the evolution of thinking on the positioning of the boundary over recent generations, and in relation to research in the last ten years. The Tithonian/Berriasian boundary level is accepted as occurring within magnetosubzone M19n.2n. The detailed distribution of calpionellids has been recorded at numerous sites, tied to magnetostratigraphy, and the base of the calpionellid Alpina Zone is taken to define the base of the Berriasian Stage. This is at a level just below the distinctive reversed magnetic subzone M19n.1r (the so-called Brodno reversal). We discuss a wide range of magnetostratigraphic and biostratigraphic data from key localities globally, in the type Berriasian areas of France and wider regions (Le Chouet, Saint Bertrand, Puerto Escaño, Rio Argos, Bosso, Brodno, Kurovice, Theodosia etc.). The characteristic datums that typify the J/K boundary interval in Tethys and its extensions are

detailed, and the correlative viability of various fossil groups is discussed. The boundary level is correlated to well-known J/K sections globally, and a series of secondary markers and proxies are indicated which assist wider correlation. Particularly significant are the primary basal Berriasian marker, the base of the Alpina Subzone (marked by dominance of small *Calpionella alpina*, *Crassicollaria parvula* and *Tintinopsella carpathica*) and secondary markers bracketing the base of the Calpionella Zone, notably the FOs of the calcareous nannofossil species *Nannoconus wintereri* (just below the boundary) and the FO of *Nannoconus steinmannii minor* (just above). Notable proxies for the boundary are: 1) the base of the Arctoteuthis tehamaensis Zone in boreal and subboreal regions, 2) the dated base of the Alpina Subzone at 140.22 ± 0.14 Ma, which also gives a precise age estimate for the system boundary; and 3) the base of radiolarian “unitary zone” 14, which is situated just above the base of the Alpina Subzone.

1. Preamble

This account is written on behalf of the Berriasian Working Group of the International Subcommission on Cretaceous Stratigraphy. It represents the culmination of ten years of work on J/K boundary interval sections across the globe, and is an introduction to the proposal of a GSSP section for the Berriasian Stage (Cretaceous System). That section, at Tré Maroua, in the Vocontian Basin of SE France, is discussed in Part 2 of this work.

The Berriasian is the first stage/age of the Cretaceous System/Period. Previous work and the decisions of international symposia have consistently confirmed that the Global Stratotype Section and Point (GSSP) for the Berriasian should be located in an outcrop in former areas of the ocean of Tethys. Though it is necessary to recognise the difficulties that are still encountered when trying to correlate between marine late Tithonian - earliest Berriasian levels in Tethys and its extensions [Panthallassa (Japan, Russian Far East, California, Andes), Mexico, Caribbean and the Middle Atlantic] and various isolated boreal marine basins, not to mention the non-marine regions. It is worth noting that such difficulties caused by biotic provincialism that began in the Tithonian continued through the Berriasian and later, affecting correlations in the Valanginian and Hauterivian. However, these difficulties are becoming less insurmountable in the Jurassic/Cretaceous (J/K) interval: obstacles and uncertainties with correlation have been overcome by use of magnetostratigraphy and by recognition of ever-wider recognition of ‘Tethyan’ marker species (*e.g.* nannofossils, calcareous dinoflagellates), as well as proxy species (*e.g.* belemnites) which have FOs that approximate to widespread Tethyan marker species and zonal boundaries.

In 2009, the Berriasian Working Group (BWG) of the International Subcommission on Cretaceous Stratigraphy (ISCS) began a concerted research effort, with the aim of examining and comparing all relevant contender sites that might qualify as a GSSP for the Berriasian Stage, the basal stage of the Cretaceous System. When, by 2009, a core group had coalesced that possesses all the required specialisms, it was agreed that its first aim was to accumulate integrated site data before any consideration was given to a prospective boundary level. Documentation and comparison would, it was hoped, lead to a consensus on the best markers,

which would thus guide the group towards making a decision on the most logical and useful boundary level, before moving on to selecting a specific section for a GSSP. Further, we would examine traditional levels for the boundary, assessing those before moving to new horizons: prospects and possibilities were first assessed (Wimbledon *et al.*, 2011).

Consequent on the initial decision to base any choices of preferred marker levels, or localities, on a systematic appraisal, more than sixty stratigraphic sequences across the globe, some previously studied and some new, were documented and assessed (see Appendix 1). The group's efforts have been directed towards recording ranges of any stratigraphically useful fossil group, and, whenever possible, magnetostratigraphy has been applied. From this growing body of integrated data - in particular, palaeomagnetism, calcareous nannofossils, ammonites, calpionellids and calcareous dinocysts, but also belemnites and palynology - we have been able to assess the usefulness of various biotic markers, and their relative positions.

In 1973, at the time of the J/K colloquium, ammonites ruled where stage definition was concerned; and the Tithonian-Berriasian world consisted essentially of Mediterranean Tethys and limited adjoining Alpine regions, with discussions on wider correlation constrained severely by ammonite provinciality. Earlier iterations of a J/K boundary working group were preoccupied with discussion of that fossil group, and with a rather narrow geographical focus - ammonite correlation between Tethys and boreal Russia being a paramount preoccupation: even though correlative accuracy was poor, sometimes with discrepancies of more than 2 my. Widespread endemism in the ammonites had been repeatedly recognised as an obstacle to correlation, even in the regions of western Tethys, and, thus, though published research on the J/K interval has grown and more profiles have been documented, it has been done relying less on ammonites, and more on calpionellids combined with magnetostratigraphy, and also calcareous nannofossils. Through the identification of these and other fossil groups, we can now regard the Mediterranean/Alpine region as only part of wider Tethyan core area, with, beyond that, magnetostratigraphy and other biotic elements beginning to promise global correlations.

The BWGs aim in the past ten years, with discussions at 15 workshops, has been to broaden horizons, and for work to take place in all regions that have substantial J/K profiles with data to offer, excepting only those where war and risk to life and limb have prevented fieldwork. Latterly, various authors have attempted definition of the boundary level or approximation to a boundary using calpionellids, nannofossils, radiolarians, dinocysts *etc.*, and magnetostratigraphy. This has involved study of parts of the globe far beyond the confines of limited regions that were being considered when earlier ICS J/K discussions ceased (*e.g.* Zakharov *et al.*, 1996a), with the WG focussing its activity in the Andes, Mexico, California, the Russian Far East, China, the Black Sea, North Africa and the Middle East.

In recent decades, calpionellids have consistently been seen as the most useful fossil group for biostratigraphy in the Tithonian-Berriasian boundary interval, and the turnover from *Crassicollaria* species to small, orbicular *Calpionella alpina* has been documented numerous times as a widespread marker falling in the middle part of magnetic zone M19n.2n. The consensus in the Berriasian WG on this was recorded in the account of its Warsaw 2013 workshop discussions. One salient advance has been to expand the known geographical

extent of the *C. alpina* (=Alpina) Subzone (*sensu* Pop, 1974 and Remane *et al.*, 1986) and to gather information on taxa from other fossil groups that bracket this datum. This level lies in the lower part of the interval traditionally labelled as the “*Berriasella jacobii* (=Jacobi) Subzone”, with its geographically limited ‘Mediterranean’ ammonite faunas. The Crassicollaria-Calpionella zonal interval has been shown to be constrained also by the FOs of calcareous nannofossil species (*e.g.* *Rhagodiscus asper*, *Cruciellipsis cuvillieri*, *Nannoconus wintereri*, *N. globulus*, *N. steinmannii*, *Hexalithus strictus*). The BWG activity has also focussed on finding proxies for these various markers in biotically impoverished areas in other marine regions and in areas of non-marine sedimentation; in the latter using magnetostratigraphy to overcome correlation problems (*e.g.* in China, and in the Purbeck facies in Europe). The finding of ‘Tethyan’ calpionellids, nannofossil and calcareous dinocysts outside the regions that they were supposed to typify, notably in the Andes, has been a great advance.

In regions with radiolarian-rich facies (see Radiolaria chapter), other biota can be scarce. The base of radiolarian “unitary zone” 13 coincides with the base of the Crassicollaria Zone, and the base of zone 14 (Baumgartner *et al.* 1995) falls at a level close above the base of the Alpina Subzone, though boreal and austral radiolarian biostratigraphies do not fit with this Tethyan zonal scheme.

The literature and this proposal on the J/K boundary are founded primarily on biostratigraphy and magnetostratigraphy. Internationally there has been no unequivocal stable isotope, or geochemical, event identified that helps determine or fix a boundary: the literature reveals a long-term carbon (C) isotope decline in the later Jurassic-early Cretaceous (Tithonian – Valanginian), that has been widely recorded in Tethys (see Isotopes below). The causes of the J/K declining C isotope trend are not known, although some possibilities have been mooted. A handful of minor anomalies have been suggested close to the J/K boundary (see below): more high-resolution studies are required on these, and on sites in the Vocontian Basin in general. The Berriasian WG earlier sampled one Vocontian Basin profile for stable isotopes, and the results from the Le Chouet locality conformed to the widely-recognised J/K pattern of long-term C isotope decline, with no marked fluctuation. For this reason, local sites, including Tré Maroua, have not been studied in detail, though preliminary results from the locality will be presented in the second part of this paper.

There have been limited consideration of sequence stratigraphy in the J-K interval (Du Chene *et al.*, 1993; Monteil, 1993), cyclostratigraphy is still in its infancy (*e.g.* Ramiel, 2005), and sea-level fluctuations shown in the “Exxon-Haq” composites have not been keyed to well studied and calibrated sequences, such as those described here. Better cyclostratigraphy may come from other sections spanning the Tithonian to Berriasian, such as those in the Neuquen Basin: but for that to happen, there will have to be adjustments to initial magnetostratigraphic determinations and widespread biostratigraphic markers will need to be identified.

In June 2016, the then 70-plus Berriasian Working Group held a formal vote to select the primary marker for the Tithonian/Berriasian boundary. With a 76% majority, the base of the *Calpionella alpina* (Alpina) Subzone was chosen (Wimbledon *et al.*, 2017; Wimbledon,

2017). Thus the proposed boundary level adopted by the BWG was still situated within the Jacobi Zone, between the two ammonite zonal levels (Grandis and Jacobi) put forward during the 1963 and 1973 J/K colloquia, and thus conforming to the usage of recent generations.

After consideration of a shortlist of potential GSSP sites at the WG's workshop at Kroměříž in 2018, two contenders were decided upon: when more documentation was to hand, a choice would be made between stratigraphic profiles in the Vocontian Basin and at Fiume Bosso in the Italian Apennines. In May 2019, the Berriasian Group completed a consultation and a one-month formal vote on the selection of a GSSP locality. The group voted with a 73% majority to select the Tré Maroua section in the Vocontian Basin.

Accordingly, on 1st December, 2019 this proposal of Tré Maroua as the GSSP for the Berriasian Stage (Cretaceous System) was submitted by the Berriasian WG to the ICS/ICS. The GSSP put forward is situated at the base of bed 14 in the lower cliff section at Tré Maroua, a level coinciding with the base of the Alpina Subzone, which is used as the primary marker for the stage base.

2. Historical

The scope of “Neocomian” is a fraught subject; though it is a topic largely beyond the scope of this proposal. It is not a formal unit, but in a loose sense (Hoedemaeker 1990) it comprises the lower stages of the Cretaceous, the Berriasian, Valanginian and Hauterivian. Thurmann (1835), in coining the name Neocomian, depended on de Montmollin's (1835) description of the Cretaceous at Neuchâtel. From that text, it can be interpreted that the *Calcaire Jaune* formation represented the Valanginian, Hauterivian and perhaps part of the Barremian: authors differ on what precisely is represented. Whether Montmollin's *Calcaire Jaune* includes any part of the Berriasian would be speculation, as is the case with his “Portlandian”. Before even 1860, the Neocomian had already been variously defined, with some marked variation: to include the Hauterivian plus the Valanginian (and the Urgonian), or not; and, significantly, plus the Berriasian, and even the Aptian (Renevier, 1874).

To take a step backwards in time, Purbeckian and Portlandian were the stage names with priority, the inventions of Brongniart (1829), and Desor's brief paper introducing the term “Valangien” (=Valanginien/Valanginian) only appeared in 1854. Mid 19th century knowledge could be more or less summarised by Opper's (1865) presumption that his Tithonian facies was the approximate equivalent of the Portland and Purbeck beds of northern Europe: that is the Portlandian (d'Orbigny 1842-1849 definition) and Purbeckian (relegated to the Cretaceous by d'Orbigny), and that somewhere above was the Valanginian. The idea that Tithonian was in part Purbeckian was presumably founded on Edward Forbes' (1851) opinion that marine molluscs and echinoids in the Purbeck Formation were Jurassic. Of course, nowhere had these various units been seen and related one to another in a continuous sequence, in superimposition (with the exception of the Portland/Purbeck junction, described extensively since the time of William Smith).

When modern studies began, the inadequacy of the Valanginian type area was soon recognised: leading to the proposal of alternative type sections in south-east France (see Bulot, 1996). And a multiplicity of publications catalogued the biostratigraphy of the Tithonian and Berriasian, moving beyond the ammonites that had dominated 19th and early 20th century discussions. But the difficulties of correlating non-marine Purbeck and extra-Tethyan Portland beds with marine Tithonian/Berriasian remain.

Returning to the lack of continuity between the sequences of the Upper Jurassic and Lower Cretaceous historical type areas, it was for Coquand (1871) to recognise the ‘missing’, undescribed, Cretaceous interval that sat between the Tithonian and Valanginian, identifying a separate Berriasian, in Ardèche, in southern France. Coquand’s work was founded on Pictet’s collections (Pictet, 1867) of ammonites at Berrias (which, by the way, lacks the basal Berriasian as we currently define it). The ammonite fauna was thought by Pictet to have affinities with the Valanginian, but was correctly seen by Coquand as a distinct assemblage, one that was neither Valanginian nor Tithonian; and Renevier (1874) endorsed that opinion.

Though, by 1870, the two lowest stages of the Lower Cretaceous had been reasonably concretely recognised in France, in superimposition, various workers in Europe continued to invent new stage names and interpretations of existing names around the boundary level. Dubisian (=Purbeckian) (1859 - Desor and Gressly) had already been named, and it was followed by Infraneocomian (1876 - Dumas). De Lapparent (1883) made the Berriasian a substage of the Purbeckian, but still in the Portlandian, and, further, Infravalanginian (1885 - Choffat), Freixilian (=Portlandian: 1887 - Choffat), Aquilonian (=Purbeckian: 1891 - Pavlov) and Allobrogian (=Portlandian-Purbeckian: 1909 - Rollier) were coined. It was a time when the invention of stage-names had gone into overdrive. As an aside, it has to be kept in mind that mid to late 19th century understanding of what constituted a stage or any unit (chrono-, bio- or lithostratigraphic) was flexible; with formations, stages and biozones used more or less interchangeably.

Concentration of study on sites with remanié and mixed (Tithonian/Berriasian) ammonite faunas, collecting *ex situ* in quarries and even from field brash, as at Aizy-sur-Noyarey (Isère) and Chomérac (Ardèche), impeded progress. Fortunately, in time, more complete sequences were studied, such as that at La Faurie (Mazenot, 1939). The disentanglement of autochthonous and remanié elements, and an understanding of the true ranges of the many Tithonian to Berriasian ammonite taxa still proceeds (Bulot *et al.*, 2014; Frau *et al.*, 2015, 2016b)

As the end of the 19th century approached, Kilian (1889) reaffirmed the position of the Berriasian Stage at the base of the Cretaceous. Connected studies of further regions in western Tethys and beyond proliferated (*e.g.* Allemann *et al.*, 1975; Arnould-Saget, 1953; Benzaggagh and Atrops, 1995a, 1995b; Bogdanova and Arkad’ev, 1999, 2005; Donze *et al.*, 1975; Hoedemaeker, 1981, 1982; Kvantaliani, 1989, 1999; Le Hégarat and Remane, 1968; Nikolov and Mandov, 1967; Nikolov and Sapunov, 1977; Nikolov, 1966, 1982; Olóriz and Tavera 1989; Sey and Kalachëva, 1996, 2000; Tavera, 1985; Tavera *et al.*, 1994), and even if many contradictions about macrofaunas were still to be addressed (Mazenot, 1939; Le Hégarat, 1973; Frau *et al.*, 2016a, 2016c), there was stability in stratigraphic nomenclature,

which grew still further with the new emphasis on micropalaeontology and magnetostratigraphy.

As a small diversion, the suggestion has been made (Granier, 2019) that d'Orbigny and Opper put forward some evidence for recognition of a base to the Cretaceous; that is, at a time prior to the substantive lowest Cretaceous studies by workers such as Coquand, Pictet, de Lapparent, Kilian *etc.* In fact, what d'Orbigny and Opper wrote highlighted the complete lacuna in knowledge that existed for them where the boundary interval was concerned. Of course, d'Orbigny suggested divisions within the "Neocomian", but Opper was preoccupied with the Jurassic, not the Cretaceous. Opper (1865) recorded three 'Berriasian' ammonites, though without knowing their true age: *Pseudargentinoceras abscissum*, *Pronoceras pronum* (both known also in the uppermost Tithonian), and *Berriasella callisto* (based on an incorrect location given by d'Orbigny).

Much has been written about d'Orbigny's unfamiliarity with the reality of field geology in classical areas - omitting most of the Oxford Clay from the Oxfordian, and placing half the Kimmeridge Clay in the Portlandian. In his *Prodrôme* (1850), there is no "Valanginian", let alone any mention of a substantive base for the Cretaceous: a number of species of *Ammonites* are listed broadly under his "17^{ème} étage", that is, as Neocomian. These comprise the long-ranging *Ptychophylloceras semisulcatum* (known to occur in the Berriasian) and ammonite taxa that we now take to be definitively Valanginian (*Olcostephanus astierianus*, *Platylenticeras gevrilianum*, *Dichotomites bidichotomus*, *Saynoceras verrucosum*, *Neocomites neocomiensis*, *Kilianella asperima*, *Prodichotomites carteroni*, *Kilianella roubaudiana*, *Platylenticeras marcousianum*, *Olcostephanus josephinus*, and *Paquiericeras nicolasianum*). By the time Coquand made his breakthrough in recognising the existence of a substantial pre-Valanginian and post-Tithonian interval, both Opper and d'Orbigny had been dead for some years: the two had no knowledge of these Berriasian rocks or their fossil contents. In fact, d'Orbigny was so little informed about the identity of fossils in this interval that he only mentioned a single typical Berriasian ammonite, *Berriasella callisto*, and this he placed in the Kimmeridgian.

Much of this, and more, was well documented by Breistroffer (1964).

2.1. 1973 Symposium on the Jurassic/Cretaceous boundary

Though numerous meetings have considered the placing of the J/K boundary since, one earlier conference on the topic is much quoted - that at Lyon/Neuchâtel, in 1973. It was the last significant gathering that brought together specialists on the interval prior to the setting up of the current Berriasian WG (2007) and its numerous meetings. An examination of the motions and votes of the 1973 participants reveals the existence of a consensus, a consensus that was carried forward in subsequent years. As all roads lead to and from this conference, it is worth considering the series of motions that came from the floor at the colloquium, and it is useful to record those that touched on J/K boundary definition, as they were proposed by the involved and experienced researchers who were present (Colloque, 1975).

Formal motions (with proposers) in ascending order of popularity:

- The J/K system boundary should be at base of the Upper Berriasian Bossieri zone - 8 votes (Casey: motion 8)(supported by Marek and Dembowska in motion 10 - 8 votes)
- That the J/K boundary should be the Tithonian/Berriasian boundary - 19 votes (Birkenmajer: motion 1)
- J/K should be Tithonian/Berriasian boundary, and be placed at the base of Jacobi/Grandis Zone - 22 votes (Frandrín, Thieuloy, Le Hégarat and Druschits: motion 3)
- J/K should be at the Tithonian/Berriasian boundary, and be defined in Tethys - 22 votes (Remane and Barthel: motion 11)
- More work is required to identify a global stratotype - 23 votes (Hughes, Dilley, Verdier, Middlemiss, Gollisstaneh, Gygi, Haak and Morgenroth: motion 9)
- J/K boundary should be the Tithonian/Berriasian boundary - 24 votes (Hughes, Dilley, Verdier, Middlemiss, Gollisstaneh, Gygi, Haak and Morgenroth: motion 4)
- A French section should be the regional stratotype - 25 votes (Hughes, Dilley, Verdier, Middlemiss, Gollisstaneh, Gygi, Haak and Morgenroth: motion 8).

It can be seen that, apart from Casey's, most motions coincided and/or overlapped, and most votes were for the system boundary to be at the Tithonian/Berriasian boundary. No motion from the floor suggested that the base of the Cretaceous should be anywhere except at or close to the base of the Berriasian, in the Jacobi/Grandis subzonal interval.

The conference organisers did not find these votes, and this consensus, conclusive: so they produced a questionnaire of their own devising, to re-test opinion (results Colloque, 1975, p. 392). A completely new question was posed, one not devised by the involved specialists who had identified their own priority motions. It was: "Should the Berriasian be moved to the Jurassic?" Only 16 (of 84) attendees agreed with this proposition. The conclusion of the organising committee was then that "A large majority want the Berriasian to remain in the Cretaceous". Further, according to the questionnaire responses, a majority agreed that the base of the Cretaceous should be the base of the Berriasian (question 1, p. 392), and 62 of the 82 cast a vote for the Jacobi/Grandis subzones to be the base of Berriasian (question 4, p. 392). In a geological symposium, where it can be hard to reach a consensus amongst specialists, such a sizeable majority was decisive.

Subsequently, though numerous individual works focussed on regional boundary intervals, concerted efforts to explore broader boundary definitions and correlations were few and a period of stasis followed. Hoedemaeker, uniquely, tried to think more widely and surmount some of the larger obstacles to correlation, even in the non-marine (Hoedemaeker, 1987, 2002). Discussions were still ammonite-dominated, more generalised and not directed to correlative potential, and even less to detailed site documentation and comparison: as summarised in Zakharov *et al.* (1996a). As, diplomatically, analysed by Remane (1991), the conclusion in 1996 was more or less the same as it had been in 1973: that the Berriasian was the basal stage of the Cretaceous and that it should have its base defined in Tethys.

2.2. Stage nomenclature

Long before the two international J/K symposia, Berriasian was already well entrenched, and Jocelyn Arkell (1956) could state that the “Berriasian has been adopted for the lowest stage of the Cretaceous, in conformity with almost universal modern usage”. Just below, in the Jurassic, everything was not so clear. Portlandian (d’Orbigny, 1842-51) had been in use (even in France - *Lexique Stratigraphique International* for France, Dreyfus *et al.*, 1956) as the primary contender with priority for the final stage of the Jurassic System. However, fruitless, generations-long arguments and stalemate between English and French geologists over how to define Portlandian (*sensu anglico* or *sensu gallico*) had blocked decisions. The impasse was finally broken when the International Jurassic Subcommittee made an arbitrary, but understandable, decision to promote Oppels’s facies term Tithonian/*Tithonique* over d’Orbigny’s original stage name, Portlandian (the senior synonym) - adopting this as the global stage label (though with no stratotype), with Portlandian being suppressed (Sarjeant and Wimbledon, 2000).

This decision also had an impact on the global application of the stage name Berriasian. An immediate increase in stability and some momentum was given to the use of a single set of names in the Late Jurassic to Early Cretaceous interval, turning away from the use of reputedly synonymous rival regional stages. Notwithstanding the fact that in most regions outside Tethys (California, Mexico, Argentina, Chile, Middle East, Middle Atlantic, Japan, Russian Far East, New Zealand, and Australia) the standard stage names of Tithonian and Berriasian had generally been in use.

Though neither the Portlandian nor the Tithonian was ever extended by their promoters to include part of the Cretaceous, this was not the case with the junior synonym “Volgian”, used in Russian basins. Nikitin’s original conception was rather limited: a formation (*Volgaformation*, Nikitin, 1881) of Early Tithonian age (=old Late Kimmeridgian - see Arkell, 1933). In an attempt to make “Volgian” equate with Tithonian, it was extended (Gerasimov and Mikhailov, 1966) to cover the Klimovi to Nodiger zonal interval. However, as became clear (see Casey, 1973), this made it correspond not only to both Lower and the Upper Tithonian, but even some part of the Berriasian. It was fortunate that the Russian Stratigraphic Commission made a decision (Zhamoïda and Prozorovskaya, 1997) to suppress the term “Volgian” and to use the standard names Tithonian and Berriasian; confirming an earlier decision by the Interdepartmental Stratigraphic Committee of the USSR to regard Berriasian as the standard basal stage of the Cretaceous System (Luppov, 1967; Rostovtsev and Prozorovsky 1977). However, an inheritance of confusion remains, because of the extensive use in Russia of “Volgian” with its several different meanings, and poor definition above. With “Volgian” defunct, an aberrant unit that straddled, at least, two standard stages (and possibly three - Scherzinger and Mitta, 2006) had been removed from the debate (Urman *et al.*, 2019).

3. Early Berriasian Palaeogeography

Palaeogeographic reconstructions of a truly Berriasian nature are few. The number of Late Jurassic-Early Cretaceous reconstructions that relate biostratigraphic information and depositional basins to plate tectonic and terrane reconstructions, rather than present-day base maps, are a rarity, and some nominal “J/K boundary” reconstructions tend to show either much earlier or much later geographical realities. Early Berriasian geography was markedly different to, for instance, the Kimmeridgian to Early Tithonian (or the later Early Cretaceous), because former wide Late Jurassic seaways became restricted, including the passage between Greenland and Britain, and the routes northward from Tethys across the Caspian and Black Sea regions were closed by earliest Cretaceous times. Later Berriasian connections from Tethys to the Russian Platform have been assumed based on supposed identifications of Tethyan ammonite taxa on the Russian Platform.

The reconstruction here (Fig 1; modified after Rees *et al.*, 2000) of earliest Berriasian geography illustrates perfectly the restricted seaways and the isolation of some basins, and the limitation of marine connections. But it also shows the enormous oceanic bodies of equatorial to subtropical regions, Panthallassa and Tethys. The sedimentary rocks of these two water bodies, actually and potentially, hold the majority of evidence for understanding palaeoenvironments and biota at and around the J/K boundary. Of Panthallassa, the northwest portion has the largest area with surviving submarine lowest Cretaceous rocks, with the most studied portion onland in the SE in Argentina. Biotic migration routes, with northward and southward movement, via western Canada and California (Jeletzky, 1984) and the Okhotsk region (Zakharov *et al.*, 1996b) are still much in need of study, as far as the exact timing of migrations and stratigraphic significance is concerned, and some regions are complicated by the emplacement of allochthonous terrains. Tethys affords the largest database of evidence for future study. As a water mass, including the Middle Atlantic, it has left dateable sediments on the south from Mexico and the Caribbean, to Africa and on to southern Tibet and Australasia, and on the north from offshore eastern Canada and Spain to, at least, Iran. This is not to mention fragments in non-carbonate marine facies in the Russian Far East and Japan. The Greenland/UK seaway appears to have been blocked after later Tithonian (=middle Portland) times, until the later Berriasian. The route across Poland closed even earlier, soon after Chitinoidea Zone times (=lowest Portland beds) (Pszczółkowski, 2016)

A multiplicity of profiles with calpionellids in western Tethys, via the Middle Atlantic to the Caribbean and Mexico, Kurdistan and the Arabian Peninsula, Iran and to the western edge of Panthallassa in the East Indies and on its eastern edge in the Andes, indicate geographical connections even when elements of the macrofauna were subject to marked provincialism. Taking into account areas lost through subduction (ocean floor of northern Laurasia, much of Panthallassa and the floor of Tethys), this thus includes most of the globe with recognisable J/K outcrops, excluding only some isolated, low-biodiversity boreal basins.

Tethyan Jacobi Zone ammonites have long been reported from the Russian Far East (where clastic facies have proved unsuitable for microfossils and palynology), as well as Japan. The

finding of nannofossils in the accretionary terrains of Japan (Shikoku Island) reinforces the connection. Of course, ‘Tethyan’ nannofossils are recorded also in California.

A key recent development with implications for palaeogeography has been the finding of a belemnite, an *Arctoteuthis* species, marking the mid-M19n boundary level in regions with mixed Tethyan and boreal biotas – California and Japan - and Siberia. It is apparent that, though ammonites did not travel north or south around Panthallassa in latest Tithonian to earliest Berriasian times, belemnites could.

In the Andes, ammonite provinciality is well known, but ‘Tethyan’ calcareous nannofossils, calcareous dinoflagellates and calpionellid species in the sequences there prove that consistent connections existed, via the Caribbean, and/or also via routes between the Arabian plate (Kurdistan, Oman and Yemen) and southern Tibet, where some of the same species have been recorded. Regardless of geographical divisions of the globe based on single fossil groups, Tethyan biotic elements extended to most areas; this is true for calpionellids, and even more so for nannofossils, both now proved to have geographical ranges far beyond those of the earlier-preferred neocomitid ammonites.

As an aside, herein we use terms such as boreal and subboreal informally; employing the former in the original way, to simply denote northern regions. Connections between boreal basins were intermittent, some fossil groups sometimes being able to migrate between (and to Tethys/Panthallassa) and some not – there were no long-lasting or uniform distributions, which argues against the use of terms such as “Boreal Realm”.

4. Wider J/K correlations employing different fossil groups and inorganic methods

Below we discuss possibilities for correlation of the Alpina Subzone, as the marker for the base of the Berriasian Stage, by direct correlation of calpionellids (plus magnetostratigraphy, nannofossils, ammonites or calcareous dinocysts) or by use of other fossil groups which accurately mark or approximate the boundary level, plus consideration of inorganic methods (geochronology, isotopes).

4.1. Calpionellids

Calpionellids are microfossils that are seen as the most significant for biostratigraphy in rocks of latest Jurassic to early Cretaceous age. In 1902, Lorenz gave the name *Calpionella alpina* to multitudes of minute *incertae sedis* organisms in the rocks of the Swiss Portlandian. Subsequently, most workers have assigned them to the ciliate Infusoria, but Remane consistently opposed this view on the basis that their loricae are made of calcite (Remane, 1989).

Early studies in the J/K interval were widespread, from Mexico to the Himalaya, and New Guinea (e.g. Andrusov and Koutek, 1927; Cadisch, 1932; Colom, 1934, 1939, 1950, 1965; Heim and Gansser, 1939; Brönnimann, 1953, 1955; Rickwood, 1955; Bonet, 1956; Embergere and Magne, 1956; Durand Delga, 1957, 1973; Hudson and Chatton, 1959; Remane, 1963, 1971; Doben, 1963; Furrázola-Bermúdez, 1965; Catalano, 1965; Catalano

and Lima, 1964; Le Hégarat and Remane, 1968; Magne and Sigal, 1965; Magne, 1965; Allemann *et al.*, 1971; Edgell, 1971; Catalano and Liguori, 1971; Kreisel and Furrázola-Bermúdez, 1971; Furrázola-Bermúdez and Kreisel, 1973). Le Hégarat and Remane (1968) and Le Hégarat (1973) set the scene for the use of calpionellids with their substantial efforts to calibrate them with ammonites. Ammonites and calpionellids (and nannofossils), were cited by Ogg and Lowrie (1986) and tied to magnetozones in the J/K boundary interval.

It is perhaps noteworthy that in a suite of key J/K and often-cited publications on other fossil groups, magnetostratigraphy and sea-level change, various authors have chosen to correlate their data with a standard calpionellid scale (*e.g.* Ogg and Lowrie, 1986; Bralower *et al.*, 1989; Weissert and Channell, 1989; Bown, 1998; Baumgartner *et al.*, 1995; Haq *et al.*, 1987).

Since the 1973 Jurassic/Cretaceous colloquium, there has been published an ever-increasing number of detailed calpionellid biostratigraphic studies in the boundary interval, often with precise integration with other biomarkers; and this over a widening geographical extent, most notably to include the Andes and Mexico; and, latterly, progress has been given impetus by the work of the Berriasian group and collaborating specialists (Pop, 1974, 1976; Allemann *et al.*, 1975; Makarieva, 1974, 1976, 1979; Micarelli *et al.*, 1977; Bakalova, 1977; Grandesso, 1977; Trejo, 1980; Jansa *et al.*, 1980; Durand-Delga and Rey, 1982; Atrops *et al.*, 1983; Ascoli *et al.*, 1984; Borza, 1984; Remane, 1986; Borza and Michalík, 1986; Bakalova-Ivanova, 1986; Mazaud *et al.*, 1986; Remane *et al.*, 1986; Pop, 1986a, 1986b, 1986c; Channell and Grandesso, 1987; Al-Rifaiy and Lemone, 1987; Memmi *et al.*, 1989; Cresta *et al.*, 1989; Weissert and Channell, 1989; Myczyński and Pszczółkowski, 1990, 1994; Altiner and Özkan, 1991; Taj Eddine, 1991; Özkan, 1993; Wierzbowski and Remane, 1992; Bucur, 1992; Lakova, 1993, 1994; Adatte *et al.*, 1994; Tavera *et al.*, 1994; Pop, 1994, 1997, 1998a, 1998b; Benzaggagh and Atrops, 1995a, 1995b, 1996, 1997; Reháková, 1995; Olóriz *et al.*, 1995; Reháková and Michalík, 1997; Grün and Blau, 1997; Lakova *et al.*, 1999; Pszczółkowski, 1996, 1999; Skourtsis-Coroneou and Solakius, 1999; Fernandez Carmona and Riccardi, 1998, 1999; Ivanova *et al.*, 2002; Reháková, 2000a; Houša *et al.*, 1999, 2004; Pszczółkowski *et al.*, 2005; Pszczółkowski *et al.*, 2005; Grabowski and Pszczółkowski, 2006; Boughdiri *et al.*, 2006; Andreini *et al.*, 2007; Lakova *et al.*, 2007; Pszczółkowski and Myczyński, 2004, 2010; Ben Abdesselam-Mahdaoui *et al.*, 2010, 2011; Azimi *et al.*, 2008; Michalík *et al.*, 2009; Grabowski *et al.*, 2010; Lukeneder *et al.*, 2010; Dragastan, 2011; Michalík and Reháková, 2011; Reháková *et al.*, 2009, 2011; Pruner *et al.*, 2010; Sallouhi *et al.*, 2011; Petrova *et al.*, 2012; Benzaggagh *et al.*, 2012; Lakova and Petrova, 2013; López-Martínez *et al.*, 2013a, 2013b; Wimbledon *et al.*, 2011, 2013; Platonov *et al.*, 2014; López-Martínez *et al.*, 2015a, 2015b; Wimbledon *et al.*, 2016; Hoedemaeker *et al.*, 2016; Michalík *et al.*, 2016; Svobodová and Košťák, 2016; Maalaoui and Zargouni, 2016; Wohlwend *et al.*, 2016; Celestino *et al.*, 2017; Kowal-Kasprzyk, 2018; Frau *et al.*, 2016a; Lakova *et al.*, 2017; Elbra *et al.*, 2018a, 2018b; Bakhmutov *et al.*, 2018; Carevic *et al.*, 2018; Kowal-Kasprzyk and Reháková, 2019; Svobodová *et al.*, 2019; Petrova *et al.*, 2019; Reháková and Rozic, 2019; Wimbledon *et al.*, 2020), and in many such projects calpionellid biostratigraphy has been closely coupled with magnetostratigraphy.

Calpionella has long been identified as a key zonal indicator. It shows diversity in size, and in the proportions of its loricae through time (Kowal-Kasprzyk and Reháková, 2019); and such morphological changes are especially noticeable between the Crassicollaria Zone and the Alpina Subzone (Calpionella Zone). The boundary between these two biozones has repeatedly been described as being indicated by the marked increase in small globular *Calpionella alpina*. The marked reduction in the size of *Calpionella* has recently been statistically analysed (Kowal-Kasprzyk and Reháková, 2019). This event (the “explosion” or “bloom” of some authors) coincided with the disappearance of most *Crassicollaria* species (Borza, 1984; Pop, 1986a; Remane, 1986). Based on the large database recounted above, recent generations of J/K workers have regarded calpionellids as the most consistent and useful fossil group to provide a Tithonian-Berriasian bio-event and a primary marker.

Studies conducted by the Berriasian WG since 2009 have built further on the considerable body of literature and have reinforced earlier opinions. The turnover from *Crassicollaria* and large *Calpionella* to small orbicular *Calpionella alpina*, accompanied by *Crassicollaria parvula* and *Tintinopsella carpathica*, has been documented as the most consistent and widespread marker, occurring in the middle of magnetic subzone M19n.2n. This fact was recognised by the clear consensus amongst specialists at the Warsaw J/K workshop (Wimbledon *et al.*, 2013). Ongoing work since has extended the identification of the Alpina Subzone further east in Tethys, to Arabia and Iran (references listed above), it has unambiguously confirmed disputed results in North America, expanded those in the Caribbean, and brought new results in South America (López-Martínez *et al.*, 2013a, 2013b, 2015a, 2015b, 2017).

In 2016, the choice of a primary marker for the base of the Berriasian Stage was decided. Because of the geographical extent noted above, and the consistency and frequency of its identification, the Alpina Subzone base was put forward to the Vienna Cretaceous Symposium as the primary marker for the Tithonian/Berriasian boundary by the Berriasian WG (Wimbledon *et al.*, 2017).

4.2 Calcareous nannofossils

The majority of Mesozoic nannofossil families originated in early Jurassic times. The Jurassic-Cretaceous boundary was marked by a large turnover at the family and species level. At the latter, there were approximately seventeen extinctions and fifteen first appearances, with the appearance of three nannolith families (Kanungo *et al.*, 2017). Under suitable conditions, nannoconids contributed considerably to the sedimentation of deeper water limestones. *Nannoconus* evolved just prior to the Berriasian, and a suite of species of this genus and other taxa have their first occurrences clustered around the stage base (references cited below).

Nannoconids and other coeval J-K nannofossils that are well documented in the Atlantic and Tethys, onshore and offshore, and though they have been considered lower-latitude forms, there are records that they extend into supposed boreal regions (*e.g.* North Sea, Jakubowski,

1987) and into both east and west sub-boreal Panthalassa (Aita and Okada, 1986; Bralower *et al.*, 1990) Sequences in boreal basins lack the nannofossil diversity seen in low latitudes and they are dominated by robust ubiquitous genera such as *Watznaueria* (Zanin *et al.*, 2012).

Distribution of calcareous nannofossils that mark the J/K boundary interval is thus extensive, in almost all regions, and having perhaps the greatest potential for future correlation in the boundary interval, given that practical techniques for obtaining nannofossils are amongst the most simple. The last thirty years have seen identification of J/K nannofossils at numerous DSDP sites, in Japan (Shikoku), in the Pacific (*e.g.* Shatsky Rise), California, Mexico, Arabia, the Andes, Australasia, as well as Siberia - far beyond the Atlantic-western Tethyan range where research was first focussed.

Biozonations of calcareous nannofossils in the Tithonian/Berriasian interval, notably in the middle Atlantic and Tethys, were developed from the 1970s (Worsley, 1971; Thierstein, 1975; Sissingh, 1977; Perch-Nielsen, 1985; Roth, 1978; Bralower *et al.*, 1989; Bown and Cooper, 1998). The last contribution defined several key species FOs in the Lower Berriasian (base of the ammonite Jacobi Zone, but enigmatically placed that level at the base of magnetic zone M18r), in sequence from the base: *Nannoconus steinmannii minor*, *N. steinmannii steinmannii*, *Cruciellipsis cuvillieri*, *Rhagodiscus nebulosus* and *Retacapsa angustiforata* (the last just into the ammonite Occitanica Zone). For the purposes of this J/K account, we can consider the pioneering broader study of Bralower *et al.* (1989), which considered a number of key onshore localities in western Tethys, as providing the starting point for recent consideration of nannofossil stratigraphy in the boundary interval, related to magnetostratigraphy.

Bralower *et al.* (1989, fig. 14) took the J/K boundary to be defined by the base of the calpionellid Alpina Subzone (showing it to be coincident with the ammonite Jacobi Subzone), but its level was placed (too high) in magnetosubzone M19n.1n, in the middle of a *Rotelapillus laffitei* Zone (NJK-C). Subsequently, *R. laffitei* has fallen into disuse as a marker, but other taxa have continued to be regarded as significant. In particular, Bralower chose as key indices *Nannoconus steinmannii minor* (FO lower M18n) and *N. steinmannii steinmannii* (FO lower M17r).

From 2009, a reconsideration was started of various nannofossils and other biotic markers and their calibration with magnetozones (Wimbledon *et al.*, 2011). Revising datums mooted in earlier accounts, Casellato (2010, fig 16) proposed a new nannofossil biozonation: biozones NJT17a, NJT17b, NKT and NK1 covering the interval between the top of magnetozones M20n and mid M17r. Casellato, kept *N. steinmannii steinmannii* as the marker for the NK1 zone in M17r, and founded a NKT zone on the FOs of *N. steinmannii minor* and *N. kamptneri minor* at the base of M18r (Channell *et al.*, 2010). Additionally, *Nannoconus wintereri* was recognised as the marker for a NJT 17b zone in M19n.2n, that is, close to the base of the Alpina calpionellid subzone.

The expansion in recent years of nannofossil studies has provided a suite of first occurrences that is a useful complement to, and proxy for, calpionellid zonal boundaries. This includes results from several sites, some of which have been considered as serious contenders to be the Berriasian GSSP (e.g. Brodno, Michalík *et al.*, 2009; Torre de' Busi, Casellato, 2010; Strapkova, Michalík *et al.*, 2016; Le Chouet, Wimbledon *et al.*, 2013; Puerto Escaño, Svobodová and Košťák, 2016; Banik, Wimbledon *et al.*, 2016; Rio Argos, Hoedemaeker *et al.*, 2016; Lókút, Grabowski *et al.*, 2010; Kopanitsa, Stoykova *et al.*, 2018; Theodosia, Bakhmutov *et al.*, 2018, Kurovice, Svobodová *et al.*, 2019; Bosso, Reháková and Svobodová (unpublished), Sidi Khalif, Gardin (unpublished), Vocontian Basin (Wimbledon *et al.*, 2020). Not forgetting that nannofossils (including *Nannoconus* species) are described from Europe, North Africa, Arabia, the Atlantic, North and South America, Panthallassa and Japan, and, minus *Nannoconus*, from the Arctic Russian regions also.

Though the same useful 'Tethyan' nannofossils have been proved in both Mexico (Lena *et al.*, 2019) and the Andes (Vennari *et al.*, 2014; Lopez *et al.*, 2017), extension of early work in California (Bralower *et al.*, 1990) has thus far proved disappointing, with only limited retrieval of typical late Tithonian and Berriasian marker species (Casellato, unpublished).

The string of publications from an increasing number of stratigraphic profiles has led to a re-assessment of nannofossil first occurrences, and biozones (summarised in Wimbledon, 2017). Fig. 2 herein shows the latest situation with FOs recorded from recently documented sites, with a suite of FOs of key species that are almost all stratigraphically lower than were recorded prior to 2010. Concentrating here on the J/K boundary interval, this affects several key *Nannoconus* and other markers, as well the biozones founded upon them. In summary, this means that, because of the changes with positions of the FOs of the index species, three nannofossil zones - NJT17b, NKT and NK1 - all occur in M19n (not between the top of magnetozone M19n and M17r). It impacts the biozones previously in use (Bralower *et al.*, 1989; Casellato, 2010), so that:

- Biozone NK1 (marker the FO of *N. steinmannii steinmannii*), formerly was in the mid M17r, but is now in upper M19n.2n;
- Biozone NKT (markers the FOs of *N. steinmannii minor* and *N. kamptneri minor*) was formerly at the base M18r, but occurrences of the first species now form a cluster in mid M19n.2n, and the second appear in upper M19n (though there is one aberrant record in mid M19n.2n)
- Biozone NJT17b (marker the FO of *Nannoconus wintereri*) was formerly high in M19n.2n, but is now in lower M19n.2n (see Fig. 2)

This does not detract at all from the usefulness of the marker species, but the compression of the zones raises doubts about their continued efficacy. The artefact of biozonations in no way inhibits the great potential that nannofossils have for extending correlations at or close to the boundary level. In fact, the proliferation of recent studies has led to the stabilisation in first occurrences, and the recognition of the best nannofossil markers in the immediate boundary interval: notably *Cruciellipsis cuvillieri* and *Nannoconus globulus globulus* (lower M19n.2n),

Nannoconus steinmannii minor (base of the Alpina Subzone), *Nannoconus wintereri* (mid M19n.2n), *Hexalithus strictus* (mid M19n.2n), and *Cretarhabdus octofenestrata*, *Nannoconus kamptneri minor*, *N. kamptneri kamptneri* and *N. steinmannii steinmannii* (M19n.1r-M19n.1n).

In the Andes, Vennari *et al.* (2014) suggested that the calcareous nannofossil zones NJK-A, NJK-B, NJK-C and lower NJK-D (see Casellato, 2010 for equivalents) could be recognised in the ammonite *Substeueroceras koeneni* (=Koeneni) Zone. Observing key species in other regions raises a few questions. The NJK-C zone (= *N. laffittei* Subzone), is a supposed equivalent to the upper Andreaei to lower Jacobi zones, with the FO of *N. wintereri*. This last-mentioned occurrence may be early, as its FO elsewhere (except for a doubtful record at Nutzhof) is predominantly in the middle part of magnetosubzone M19n.2n (still within the Jacobi Subzone of authors). The NJK-D Zone at Las Loicas (?= upper Jacobi - lower Grandis ammonite subzones, Bralower *et al.*, 1989) was defined by the FO of *N. kamptneri minor*, close to the ammonites *Substeueroceras* sp., *Blanfordiceras* sp. and *Berriasella* aff. *gerthi*. In western Tethys, including the Vocontian sites (Fig. 2), the FO of *N. kamptneri minor* is above the base of the Jacobi Subzone (*circa* the base of magnetozone M19n.2n) and close to the base of the *Calpionella alpina* (Alpina) calpionellid subzone. Lopez-Martinez *et al.* (2017) note the same nannofossil taxa as Vennari *et al.* (2014) bracketing the base of the Alpina Subzone, and they make that level exactly coincident with the base of the ammonite *Noduliferum* Zone. The potential for more precise calibrations is obviously considerable.

4.3. Ammonites

In later Tithonian and earliest Berriasian times, no Tethyan immigrants migrated into the boreal regions and no boreal species have been recorded from Tethyan profiles (Rawson, 1995; Bulot, 1996; Lehmann *et al.*, 2015). After mid Portland bed times, marine connections appear to have been intermittent even within the boreal ‘realm’: the Late Tithonian seaway across Poland was blocked, the J/K interval is in non-marine facies in Dorset and NW Europe, it is lost in a hiatus in much of East Greenland, and each other region (Russian Platform, Siberia, North Sea) has its own distinct ammonite biozonation, reflecting provincialism. Though Svalbard has a condensed “Taimyrensis Zone”, in common with Siberia, that seems to straddles the J/K boundary. These are some of the reasons that, although the definition of the Jurassic/Cretaceous boundary, founded on ammonites, has been debated *in extenso*, correlations between Tethys and boreal areas remain at a preliminary stage (Wimbledon *et al.*, 2011).

In recent years, integrated magneto- and biostratigraphy have allowed the first correlation between Tethys and one high-boreal region - Siberia (Houša *et al.*, 2007; Schnabl *et al.*, 2015), apparently confirming that the latest “Volgian” correlates with the earliest Berriasian (following Casey, 1973). No significant ammonite turnover above the suprageneric level equates to the Jurassic/Cretaceous boundary, neither in boreal basins nor in Tethys, or further south. In Siberia, the approximation of the lower boundary of the ammonite Taimyrensis Zone (Dzyuba, 2010) to the base of the calpionellid Alpina Subzone (and the belemnite Tehamaensis Zone) has been suggested (Schnabl *et al.*, 2015), though the lack of ammonites

remains a problem. Better calibration in the Andes awaits more elucidation of magnetostratigraphic results (see below). The family Polyptychitidae, notably *Craspedites*, *Praetollia* and *Chetaites* (Baraboshkin, 2002; Rogov and Zakharov, 2009) are dominant in Russian basins, with *Subcraspedites* widespread in other regions. Tethyan Early Berriasian ammonite faunas are very much more diverse, and are dominated by ammonites of the family Neocomitidae. The distributions of *Berriasella*, *Pseudosubplanites*, *Malbosiceras*, *Delphinella*, *Dalmasiceras*, *Strambergella* and *Pseudoneocomites* are seemingly restricted to a Mediterranean to Caucasian “subrealm” (Le Hégarat, 1973; Kotetishvili, 1988; Wimbledon *et al.*, 2013).

Earliest Berriasian *Berriasella sensu stricto* is only known from SW to central Europe, North Africa, Ukraine, the Caucasus and northern Iran. The putative much wider geographical distribution has been due to a more lax definition of the genus. In the north, after a period of strong provincialism, a change in ammonite distribution came about during the later Berriasian, with the decline of the Craspeditinae and Dorsoplanitinae and the diversification of the Tolliinae (Baraboshkin, 1999). The widespread appearance of *Hectoroceras* (Casey, 1973; Birkelund *et al.*, 1983; Baraboshkin, 1999) is a noteworthy event in all basins from Greenland to the Russian northern Far East, tentatively in magnetozone M16r.

In austral regions and around Panthallassa, an Indo-Pacific subrealm has been recognised. In Argentina and Chile, the faunas are dominated by *Andiceras*, *Argentiniceras*, *Frenguellliceras*, *Hemispiticeras*, *Cuyaniceras* and *Pseudoblanfordia* (Riccardi, 1988; Parent *et al.*, 2011; Vennari *et al.*, 2012). Endemic *Kossmatia*, *Durangites* and *Substeueroceras* in Mexico are now considered to extend into the Berriasian (Olóriz *et al.*, 1999; Villaseñor and Olóriz, 2019). The conspecificity of the Berriasian ammonites described by Collignon (1962) from Madagascar with western Tethyan taxa is still unsolved, at least regarding *Berriasella*; and *Subthurmannia* from Pakistan (Spath, 1939; Fatmi, 1977) are fully distinct from *Fauriella* of northern western Tethys (Bulot, 1996). Endemism of Berriasian Neocomitidae at the genus level was much higher than has been supposed in the literature, and homeomorphy has led to erroneous taxonomic interpretations.

Spiticeras was one of the few taxa that ranged throughout the whole of Tethys and beyond (Lehmann *et al.*, 2015). It links the Mediterranean and the Indo-Pacific regions, with populations reported from the west coast of America (Jeletzky, 1965; Imlay and Jones, 1970), Madagascar (Collignon, 1962) and the shelf basins of South America and Antarctica (Thomson, 1979; Riccardi, 1988). As stated, the core area for earliest Berriasian *Berriasella* is western Tethys, as far east as Iran and Iraq; and the efficacy of the taxa previously used to define a J/K boundary (Mazenot, 1939, Le Hégarat, 1973) is limited to a similar geographical area.

4.3.1. Jacobi Subzone

In western Tethys, the inability to separate ammonite faunas in the lowest Berriasian has led to various usages for the stage's first biozone. A Euxinus Zone (Wiedmann, 1975; Howarth, 1992) has been used to cover the combined Jacobi and Grandis subzones (Le Hégarat, 1973),

that is, the supposed post-“Durangites Zone” (=Andreaei Zone, Wimbledon *et al.*, 2013) and pre-Subalpina Subzone interval. Alternatively, a “Jacobi Zone” has been applied as a label for this interval, following earlier factual work (*e.g.* Le Hégarat, 1973; Hoedemaeker, 1982; Tavera, 1985), though sometimes it has been repeated with no new primary results and thus no substantive definition. Riccardi (2015), importantly, has reviewed correlative ammonite faunas in this interval in the New World.

There is no doubt that a substantial turnover in ammonites, Himalayitidae to Neocomitidae, (Wimbledon *et al.*, 2013; Bulot *et al.*, 2014; Frau *et al.*, 2015) occurs at the level of the base of the *Berriasella jacobi* Subzone/Zone of authors (Tavera *et al.*, 1994). This is an important event, and this level was previously promoted and selected as the best level for the base of the Berriasian (1973 Jurassic/Cretaceous Colloquium decision). However, though we can recognise this ammonite turnover, and its coincidence more or less with the base of magnetozone M19n (within the calpionellid *Crassicollaria colomi* Subzone), it is not easily definable at multiple sites, and there have been issues both with recognition of the earliest Berriasian ammonites (systematic and stratigraphic), the use of a *Berriasella jacobi* Zone/Subzone, and its limited areal extent.

These are issues which previously have sometimes been hinted at, but not fully addressed. Additionally, there are nomenclatorial problems with the Mazenot’s type material of *Berriasella jacobi*: *B. jacobi* is not a *Berriasella* (Frau *et al.*, 2016a), but a microconch *Strambergella*, and many of the specimens assigned to “*Berriasella jacobi*” have been misidentified, notably, specimens from Bulgaria, Crimea, Iraq, Tibet and South America (*e.g.* Nikolov, 1982; Arkad’ev and Bogdanova, 2004; Arkad’ev *et al.*, 2005, 2012; Howarth, 1992; Liu, 1988; Salazar, 2012). Additionally, the true stratigraphic origin of the type material of Mazenot (1939) for *Strambergella jacobi* is now proven to be well above basal Berriasian levels - in fact, occurring in the calpionellid Ferasini-Elliptica subzones (Frau *et al.*, 2016a).

These facts have rendered *Strambergella jacobi* problematical as a marker for the lowest Berriasian, and unsuitable as an index species for the lowest zone of the stage. Further, the species and the Jacobi Subzone can play no useful part in the definition of a lower boundary for the Berriasian. Moreover, recent studies have revealed that the base of the calpionellid Alpina and ammonite Jacobi biozones are not coincident (as has often been stated to be the case in the past), and neither of them is seen to lie close to the base of magnetozone M18r (*e.g.* Tavera *et al.*, 1994; Pruner *et al.*, 2010; Wimbledon *et al.*, 2013)

The earliest post-*Protacanthodiscus* (Tithonian) ammonite fauna is not characterised by *S. jacobi*, but by other species, notably *Praedalmasiceras* (pars *Dalmasiceras*) and *Delphinella*, as in Spain, France, Bulgaria and Ukraine. The preliminary results from the expanded sections of the Vocontian Basin (Le Chouet, St Bertrand, *etc.*) suggest that four successive assemblages can be identified there in the lowest Berriasian, as detailed in the Tré Maroua description in Part 2. This has potential for wider correlations.

One key observation is that the first occurrences of *Delphinella* approximate the base of the Calpionella Zone in the Vocontian basin sections (Wimbledon *et al.*, 2020). This is of great interest in approximating the boundary using ammonites as secondary markers in other regions.

4.3.2. Grandis Subzone

The problem of making a distinction between putative Jacobi and Grandis subzone ammonite assemblages has been apparent in the work of various authors, and it was highlighted in the range charts in Le Hégarat's (1973) seminal study, where a number of species were recorded spanning the two subzones. It is clear, for instance, that the genus *Pseudosubplanites* occurs low down, in levels assigned to the Jacobi Subzone of authors. There have been concerns that some of the patterns of distribution of larger forms of *Pseudosubplanites* were ecologically controlled, and the incoming of large forms of the genus have not always been consistent. Work is in progress on the matching of presumed macro- and microconchs. Thus it is still premature to try to make any statement on retaining a putative Grandis Subzone while work is in progress on critical French localities (Berrias, Le Chouet, Font de St Bertrand, Beaume, Tré Maroua). Outside France, thus far, no clear base for the subzone has been fixed (*e.g.* Spain - Hoedemaeker *et al.*, 2016; Crimea – Arkad'ev *et al.*, 2012, Bakhmutov *et al.*, 2018). Therefore, the unambiguous separation of “Jacobi” and Grandis” faunas has yet to be satisfactorily resolved (see Frau discussion in Reboulet *et al.*, 2018).

However, ammonite data from France that has been calibrated with magnetostratigraphy, calpionellid and nannofossil data is informative, as discussed by Wimbledon *et al.* (2020) and shown here in Fig. 3.

4.4. Belemnites

Belemnites are not prominent in most well-documented Mediterranean to Alpine J/K sections, or in North Africa, and thus have been little employed for biostratigraphy. At well-known Berriasian sites, in more recent times, accounts of belemnites have appeared: at Rio Argos (Hoedemaeker *et al.*, 2016), Stramberk and Kurovice (Eliš *et al.*, 1996), though no belemnite biozonation can be applied over a wider Tethyan area. Belemnites are uncommon in the studied outcrops of the Vocontian Basin.

However, in boreal and sub-boreal regions the potential for correlation appears to be substantial.

Doyle and Kelly (1988) and Mutterlose *et al.* (2019) have reviewed the distribution of Jurassic-Cretaceous boreal belemnites. Exchange between Tethys and boreal regions was almost non-existent in Berriasian times: Tethyan genera such as *Hibolithes*, *Pseudobelus* and *Duvalia* did not penetrate significantly into higher boreal basins: the first reached the Russian Platform and California in Tithonian times, and it alone persisted in the latter into the

Berriasian. All other basins lack any representation of these three genera. In the Berriasian, the genera *Liobelus* and *Acroteuthis* had the greatest geographical spread.

In boreal regions and those areas where boreal and Tethyan biotic elements are mixed, some very substantial stratigraphic advances have been made in recent times. Notably on the correlation, precisely at the J/K boundary level, between Siberia and California (Dzyuba, 2010, 2012, 2013) and Japan (Sano *et al.*, 2015; Haggart and Matsukawa, 2019).

4.5. Calcareous dinoflagellates

Calcareous dinoflagellate cysts are common fossils in the Tithonian to Berriasian of European and North African Tethys. Many sites documented for calpionellids and nannofossils in Mediterranean and Alpine regions have also been studied for calcareous dinoflagellates. Borza (1984) and, later, Lakova *et al.* (1999) gave a biozonation applicable to European Tethys.

Cysts appear to have much potential as accessories to the calpionellids, but the stratigraphic ranges of some species have yet to be resolved (*e.g.* *Stomiosphaera moluccana* and *Colomisphaera pieniensis* (Wimbledon *et al.*, 2013; and below). Of notably useful species, in the Balkans, the first appearance of *Stomiosphaerina proxima* has been recorded in the calpionellid upper Crassicollaria Zone, and is said to have its FAD at the base of the Colomi Subzone, though it appears earlier in SE France. This restriction to the Crassicollaria Zone was emphasized by Reháková (2000a) (see also Lukeneder *et al.*, 2010: but see Lopez *et al.*, 2013b). *C. fortis* only just pre-dates *S. proxima* (appearing pre-Crassicollaria Zone), and its range straddles the upper Crassicollaria and Calpionella zones, affording a wider stratigraphic bracket: this proves to be the case in some French sites (*e.g.* Tré Maroua and St Bertrand: Wimbledon *et al.*, 2020). If such occurrences could be confirmed and consistently proven in Siberia (and perhaps the Russian Platform), it would be a step forward in accuracy when trying to correlate with the calpionellid Crassicollaria/Calpionella zonal boundary. Vishnevskaya's (2017) FAD of *C. ? fortis* in Siberia appears to be very high (ammonite Analogus Zone) and that of *S. proxima* is shown lower than one might expect (ammonite Exoticus Zone, ?M20n magnetozone) as compared to Tethys, as the calpionellid Alpina J/K boundary (M19n.2n) has been correlated with the middle of the Siberian ammonite zone of *Craspedites taimyrensis*. However, the original assignment of magnetozone numbers in Siberia, at Nordvik, may merit reconsideration, as may the specific identifications of dinocysts. That being as it may, more research on calcareous dinoflagellates is an absolute priority in boreal regions.

Recently, sampling in the Tithonian to Valanginian of southern Mendoza at Arroyo Loncoche, Río Seco del Altar and Tres Esquinas has revealed a relatively rich calcareous dinoflagellate cyst assemblage (with poorly preserved calpionellids and benthic foraminiferans) of some twenty species (Ivanova and Kietzmann, 2016). Ivanova and Kietzmann (2017) and Kietzmann *et al.* (2018b) have recorded, in particular: *Colomisphaera tenuis*, *Col. fortis*, *Stomiosphaerina proxima* (lower part of the ammonite Noduliferum Zone)

and *Stomiosphaera wanneri* (upper part of the Noduliferum Zone). The *S. wanneri* biozone (Arroyo Loncoche) they take to be “Late Berriasian” (equating it with the Noduliferum to Damesii ammonite zones). *S. wanneri* has been found in the Upper Berriasian in the Carpathians, but it has also been collected in the Lower Berriasian in southern Ukraine (Bakmutov *et al.*, 2018), and it seems that it appears similarly early in France (see Wimbledon, 2017; Wimbledon *et al.*, 2020).

4.6. Palynology

4.6.1. Organic-walled dinoflagellates

Dinoflagellate cysts are microfossils of planktonic organisms. They are widely distributed and are often used for biostratigraphy in the Mesozoic and Cenozoic, particularly in petrochemical exploration. Tithonian to Valanginian dinoflagellate cyst associations are demonstrably provincial. Cosmopolitan taxa in the Tithonian to Berriasian interval are relatively rare, especially in the Arctic and the Southern Hemisphere. Jurassic-Cretaceous boundary beds in southern Europe and the North Atlantic region include significant proportions of taxa which are present in northwest Europe and the Volga Basin, but they are matched with biostratigraphies based on fossil groups which are endemic. Thus, the calibration of bioevents is possible locally, but it only has limited geographical significance. Within individual basins, the incoming, and in particular the range-tops of species have great stratigraphic utility and various compilations of ranges close to the Jurassic-Cretaceous boundary have been made (e.g. Davey, 1979; Woolam and Riding, 1983; Riding, 1984; Powell, 1992; Poulsen and Riding, 2003; Stover *et al.*, 1996; Monteil, 1992, 1993; Leereveld, 1997; Harding *et al.*, 2011). Typically, ranges have been compiled against standard ammonite zonations and have become somewhat removed from the rock-intervals in which the cysts occur. Many of the sections and boreholes used as the basis of these compilations have limited age-control and few have been subjected to the intensive multidisciplinary study carried out by the Working Group. It is, however, apparent as more becomes known that individual species sometimes have different ranges in different basins, so it is necessary to establish ranges at multiple sites with strong age-control from multiple indicators.

Few palynological publications have appeared on Tethyan marine sequences in recent times, but much work in boreal/sub-boreal regions has been undertaken (e.g. Harding *et al.*, 2011; Turner *et al.*, 2019; Peshchevitskaya *et al.*, 2011; Schneider *et al.*, 2017; Nøhr-Hansen *et al.*, 2019), which affords limited possibilities for consistent correlation with Tethyan profiles.

The proposed GSSP at Tré Maroua (and St Bertrand) has only been the subject of preliminary sampling for palynology. Several zonation schemes exist for the boundary interval in other parts of the world, but few have much resolution in the latest Jurassic/earliest Cretaceous, and in many areas there are non-marine facies or non-sequences within the latest Jurassic and earliest Cretaceous marine rocks. So far, few palynological studies have been carried out on sequences with calpionellid control. Dinoflagellate cyst zonal schemes elsewhere vary in the solidity of macrofossil control, which close to the boundary is rather intensely provincial in reach, with many uncertainties in correlation. Thus, effectively, most biostratigraphic

schemes ‘float’ against the Jurassic-Cretaceous boundary and it is thus still unclear how regional dinoflagellate cyst zonations equate to one another, and whether incomings and outgoings of some key dinoflagellate cyst species are diachronous between regions, as has been suggested, for instance, by Harding *et al.* (2011), or whether some are, in fact, good time planes.

In Tethys, very few sampled marine calpionellid-controlled sequences have yielded palynological assemblages across this interval. There is a hiatus, with no palynology between the Tithonian and Berriasian at Berrias and other sampled sections in the Vocontian Basin of SE France, and thus in the zonations based on them (*e.g.* Monteil, 1993; Leereveld, 1997; Hunt, 2004). In the European Tethys, only a suite of boreholes in northern Bulgaria and the Bruzovice section in the Outer Western Carpathians have yielded assemblages that can unequivocally be assigned to the calpionellid Alpina Subzone (Pavlishina and Feist-Burkhardt, 2004; Dodekova, 2004; Skupien and Doupovcova, 2019). The sequences, however, may contain non-sequences and were apparently sampled only at reconnaissance level.

Here, critical range tops and range bases of stratigraphically significant dinoflagellate cyst species close to the proposed boundary are compiled from key literature (Fig. 4). These are plotted against the available biostratigraphy. The *Biorbifera johnewingii* (Bjo) Interval Zone of Leereveld (1997) covers the Late Tithonian to the Late Berriasian and is defined as the interval between the first appearance of *Biorbifera johnewingii* and the first appearance of *Pseudoceratium pelliferum*. Several major events lie within this interval zone, most notably the first appearance of the genus *Spiniferites*, but also the last occurrence of *Senoniasphaera jurassica* and the evolution of the diverse forms in the *Amphorula* lineage (*e.g.* Monteil 1990). It would appear that high-resolution palynological biostratigraphy will be possible around the base of the Berriasian, based on close sampling.

Sources used are as follows:

Locality	Section(s)	Biostratigraphic control	Author(s)
Vocontian Trough	Berrias, Broyon, Angles	ammonites	Monteil, 1992, 1993; Hunt, 2004
Bruzovice, Czech Republic	Bruzovice	calpionellids	Skupien and Doupovcová, 2019
North Bulgaria	R-6, R-7, R-8 Sultanice	calpionellids, ammonites	Dodekova, 2004; Pavlishina and Feist-Burkhardt, 2004
Volga Basin, Russia	Gorodishche, Kashpir	ammonites	Harding <i>et al.</i> , 2011
Dorset Basin, UK	St Aldhelm’s Head, Durlston Head, Durlston Bay	ammonites, miospores	Hunt, 2004
Terschelling Basin, Netherlands	Wells L06-2, L06-3	ammonites, miospores	Abbink <i>et al.</i> , 2001b

Herein (see Fig. 4), the ranges of some species, chosen because they are widely used in biostratigraphy and feature in the compilations cited in the figure, are plotted where there is some measure of biostratigraphic control. The relative positions of the biostratigraphies against which they are plotted follows the work and correlations of the Working Group, but it is possible that some of these will be subject to revision in the future.

Given the uncertainties with the correlation of these sections and the different sampling intervals, sample sizes and taxonomic approaches between studies, there are some interesting commonalities between some ranges at different sites.

Late Tithonian markers: *Prolixosphaeridium anasilum*, *Dichadogonyaulax cumula* and *Senoniasphaera jurassica* all become extinct in the very latest Tithonian in European Tethyan sites, although *D. cumula* runs significantly higher in the boreal Terschelling Basin and *S. jurassica* runs higher in the Volga Basin and may run higher in Dorset, if its occurrence in the upper Purbeck Limestone Formation is not the result of recycling.

Late Tithonian/Early Berriasian markers; *Impletosphaeridium tribuliferum* has a long range in the Late Jurassic and becomes extinct early in the Berriasian in the Vocontian Basin and in Dorset. The short range of *Amphorula monteiliae* spans the Tithonian/Berriasian boundary interval in Tethyan sites where it occurs and it may lie close to the boundary in Dorset. The range-bases of *Biorbifera johnewingi* and *Warrenia californica* start below the basal Berriasian in Tethyan sites and they range high into the Berriasian.

Early Berriasian markers: the most important of the taxa incoming in the earliest Berriasian in Tethys are the *Spiniferites* spp. Other taxa starting close to the base of the Berriasian in Tethys include *Ctenidodinium elegantulum*, *Muderongia tabulata* and *M. longicornuta*. The incoming of *Dichadogonyaulax bensonii* appears to be a reliable marker a short time after the beginning of the Berriasian.

Dinoflagellate cyst biostratigraphy potentially offers an important tool for the correlation of sequences in the latest Jurassic and lowest Cretaceous. New work on the GSSP candidate sections and other sections across this interval is urgently necessary.

4.6.2. Pollen and Spores

The term ‘miospores’ denotes pollen and spores and is often preferred in palaeopalynology since the botanical affinities of many form-taxa are uncertain. Although many Upper Jurassic and Lower Cretaceous sequences have been studied for palynology, many – if not most - studies of marine sequences have focussed only on dinoflagellate cysts, while studies of non-marine sequences have perforce focussed on miospores, many of which have been shown to have extremely long ranges. During the later Jurassic, provincialism of floras became more marked and changing climates drove migration of the parent plants, and so miospore ranges in any given section are usually less than the total range of the species. As a result of the facies on which most studies have taken place, miospore ranges are difficult to calibrate against the several markers used by the Working Group.

In NW Europe, climatic change close to the Jurassic-Cretaceous boundary led to decline of arid-land floras dominated by gymnosperms. A change to a moister semi-arid regime facilitated the rise of a diverse vegetation of gymnosperms, ferns, bryophytes and lycopsids

(Norris, 1969; Hunt, 1985; Abbink, 2001a). Existing taxa expanded their ranges into the region, but there was also a burst of evolution and many new miospore forms appeared. Few, however, became extinct at this time.

Miospores with ammonite or other marine control close to the base of the Berriasian have been reported in NW Europe from the Wessex Basin, UK (Hunt, 1985) and Terschelling Basin (Abbink *et al.*, 2001b). Correlations using available ammonites and dinoflagellate cysts suggest that the range bases of *Apiculatisporis verbitskayae* Dörhöfer and *Cicatricosisporites purbeckensis* Norris lie in the latest Tithonian, while the range bases of *Matonisporites elegans* Hunt and *Aequitriradites spinulosus* (Cookson and Dettmann) lie close to or just above the base of the Berriasian in these basins. Secure range-tops in the interval are not available. Further work on sections with ammonite and/or calpionellid control is urgently necessary, but it is rather likely that miospore floras, although useful for biostratigraphy within regions, will have little significance for inter-regional correlation around the Jurassic-Cretaceous boundary.

4.7. Radiolarians

From latest Jurassic to early Cretaceous times several distinct regions have been described with their own radiolarian associations: Tethyan (lower latitudes - Mediterranean, Alps, Caucasus; Baumgartner *et al.*, 1995), northern Panthalassic (Vishnevskaya, 2001), and arcto-boreal (Vishnevskaya and Kozlova, 2012; Vishnevskaya, 2013). Boreal elements such as the genus *Parvicingula* also occur in austral regions (Argentina, Antarctica, southern eastern Tethys; Kiessling, 1999). California, Mexico and the Caribbean have received special attention (summarised by Pessagno *et al.*, 2009), and this region falls in the second association above, and has a grouping of largely non-Tethyan taxa and some Tethyan species. Radiolarian provincialism hinders the correlation of radiolarian faunas between northern Eurasia and America, and “subboreal” Panthalassa and Tethys during late Jurassic-early Cretaceous times. (Vishnevskaya, 2013). The integration of zonal schemes between the several radiolarian provinces is ongoing.

Radiolarians are widespread in the Tithonian to Berriasian, but often in facies with little other biota (*e.g.* Russian Far East, Caribbean, Arctic), or they are calcified and not suitable for study using normal techniques, or are richly developed in some levels, but absent through adjacent intervals. For instance, the Nordvik section has yielded no radiolarian from the zones of ammonites *Craspedites okensis* (=Okensis Zone) or *C. taimyrensis* (=Taimyrensis Zone) (Bragin, 2011). Few profiles have been documented in detail with exact ranges documented relative to a lithostratigraphy and to other significant biota. The last, co-occurrences of occasional radiolarians with other biota, are key. Opportunities to calibrate radiolarians with other microfossil groups have sometimes been overlooked (Pessagno *et al.*, 2009.) In the Vocontian Basin profiles, radiolarians are not uncommon, and are typical in some microfacies (see microfacies of Tré Maroua), but of low diversity and mostly calcified.

The radiolaria research group, studying multiple sites (Baumgartner *et al.*, 1995), recognised two biozones (13 and 14), the boundary between which they closely delimited relative to calpionellid and nannofossil events: it is close to the base of the Calpionella Zone. In their

“unitary zone” (UAZ) 13 they recorded fifty taxa whose first appearances mark the beginning of the biozone [*Angulobracchia* (?) *portmanni*, *A.* (?) *portmanni* s.l., *Archaeospongoprunum patricki*, *Artocapsa* (?) *amphorella*, *Bistarkum valdorbiense*, *B. brevilatum*, *Canoptum banale*, *Crucella collina*, *Cyrtocapsa* (?) *grutterinki*, *Ditrabs* (?) *osteosa*, *Emiluvia chica decussata*, *Halesium* (?) *lineatum*, *Homoeoparonaella* sp. aff. *H. irregularis*, *Homoeoparonaella speciose*, *Hsuum feliformis*, *H. raricostatum*, *Katroma milloti*, *Milax adrianae*, *Mirifusus odoghertyi*, *Obesacapsula rusconensis umbriensis*, *O. breggiensis*, *O. polyhedra*, *O. rusconensis*, *O. bullata*, *O. rusconensis* s.l., *Pantanellium berriasianum*, *P.* sp. aff. *P. cantuchapai*, *Parapodocapsa furcate*, *Paronaella* (?) *tubulata*, *Parvicingula sphaerica*, *P. longa*, *P. cosmoconica*, *Pseudoaulophacus* (?) *pauliani*, *Pseudocrucella* (?) *elisabethae*, *Pseudoeucyrtis* (?) *fuscus*, *P. sceptrum*, *Sethocapsa* (?) *concentrica*, *S. kitoi*, *S. tricornis*, *S.* sp. aff. *S. karninogoensis*, *Syringocapsa coronata*, *S. lucifer*, *S. longitubus*, *S. vicetina*, *S. agolarium*, *Stylosphaera* (?) *macroxiphus*, *Triactoma luciae*, *Wrangellium puga*, *W. columnum*, and *W. depressum*]. They next recognised the first appearances of twelve taxa as marking the base of their “unitary zone” 14 [*Bernouillius* (?) *monoceros*, *B. spelae*, *Cyclastrum rarum*, *Dicroa periosa*, *Godia lenticulata*, *Jacus* (?) *italicus*, *Parvicingula usotanensis*, *Pseudoeucyrtis acus*, *Ristola asparagus*, *Stichomitra* sp. aff. *S. asymbatos*, *Thanarla pulchra*, and *Xitus sandovali*].

Biozone 13 is unambiguous in its definition: the FAD of *Tintinopsella carpathica*, which marks the base of the calpionellid Crassicollaria Zone, was recognised at the bottom of unitary zone 13. The critical information on the positioning of the junction between this zone and zone 14 (Baumgartner *et al.*, 1995) was that it was placed just above the base of the calpionellid B zone, that is, the base of the Calpionella Zone. This makes unitary zone 13 more or less equivalent to the Crassicollaria Zone. Zone 14 is now somewhat less well defined, mainly because of improved knowledge of nannofossil ranges. Baumgartner *et al.* relied on Bralower *et al.* (1989) and other earlier references, when they identified the nannofossils *Nannoconus steinmannii steinmannii* and *N. steinmannii minor* in radiolarian zone 14. This was perhaps why unitary zone 14 was said to also cover magnetozones M18 and M17. Nevertheless, the earliest occurrences of both these long-ranging species are now recorded in M19n, and this is consistent with the base of zone 14 being just above the base of the *Calpionella alpina* Subzone, *i.e.* in magnetosubzone M19n.2n.

Pessagno *et al.*'s (2009) scheme for radiolaria was focussed on eastern Panthalassa and southern North America. These authors were critical of the Baumgartner *et al.* (1995) results: that they were typical mostly of “Central Tethys”, that some taxa were over-lumped, and that others had been ignored (*e.g.*, Pantanelliidae Pessagno and Blome, species of *Perispyridium*). However, none of this precludes attempts to apply the scheme.

Pessagno *et al.* (2009) used radiolarian species markers for the base of the Berriasian that are mostly not in the range charts of Baumgartner *et al.* (1995) The base of the Berriasian they identified with the FO of *Archaeocenosphaera boria* as the primary indicator, supported by the species *Obesacapsula rotundata*. Four species were recorded as having their LOs at the same level: *Ristola altissima*, *Complexapora kozuri*, *Loopus primitivus* and *Hsuum*

mclaughlini. Unfortunately, Pessagno *et al.* worked where there was no magnetostratigraphy available, preferring to calibrate their results with a combination of endemic ammonites and occasional nannofossil datums: not taking opportunities to calibrate radiolaria with calpionellids that had already been identified in Mexico.

In the Great Valley of California, Pessagno *et al.* (2009) placed the base of their radiolarian zone 5 (sample Grin 94-20), just below the thick sandstone formation at Grindstone Creek, that is, low in the bivalve *Buchia uncitoides* Zone (=Uncitoides Zone). They also noted there the occurrence of a UAZ 13 species, *Obesacapsula polyhedral*, in the same profile, calibrating it with the nannofossil “*Nannoconus steinmanni* [sic] s.s. Zone: upper Berriasian”. This sample (Grin 94-37) with *O. polyhedra* is 50 metres above the base of Pessagno’s Zone 5, just above the thick sandstone formation (mid Uncitoides Zone). The Bralower *et al.* (1990) nannofossil assemblage is probably Berriasian, but no more accuracy can be achieved than that.

A rare instance where radiolarians have been collected in some numbers and directly calibrated with calpionellid zones was given by Mekik *et al.* (1999, fig 4) from NW Anatolia. Immediately above the base of the Calpionella Zone at Kel, they indicate the appearance of the radiolarians *Acaeniotyle diaphorogona*, *Alievium nodulosum*, *Archaeodictyomitra apiarium*, *Dicerosaturnalis dicranacanthos*, *Deviatus diamphidius*, *Halesium* sp., *Emiluvia pessagnoii*, *Pyramispongia barmsteinensis*, and *Thanarla* sp; and some metres above of *Pantanellium berriasianum*, *Hsuum raricostatum*, *Tethysetta* cf. *boesii*, *Tricolocapsa campana*, *Podobursa* cf. *multispina* *Ristola altissima altissima* and *Zhamoidellum* cf. *ventricosum*. Of all these, only *Pantanellium berriasianum* and *Hsuum raricostatum* are given as indicator species by Baumgartner *et al.* (1995), in unitary assemblage 13. However, *Ristola altissima* was used by Pessagno *et al.* (2009) to mark the top of their Zone 4.

Of the many J/K localities documented in detail in recent years, only Grindstone Creek (already mentioned), Fiume Bosso and Torre de’ Busi have figured in accounts of radiolarians (Baumgartner *et al.*, 1995). No details have been obtainable on radiolarian results from Torre de’ Busi, nor, particularly, on how these might relate to published magnetostatigraphy or the biostratigraphy of other fossil groups. At Fiume Bosso, the base of the calpionellid Alpina Subzone was formerly placed in bed 78 by Houša *et al.* (2004), and Matsuoka *et al.* (2019) sampled that part of the sequence (now placed in the calpionellid Colomi Subzone), and work is ongoing at higher levels to bracket the J/K boundary.

4.8. Foraminifera

Foraminifera are a long-lived group of Protozoa which first appeared in the fossil record in the Ordovician. By latest Jurassic/earliest Cretaceous times, a number of different groups and assemblages of foraminifera had developed, that reflect the different palaeoenvironmental realms existing at the time, including both benthonic and planktonic forms.

One of the significant evolutionary developments in benthonic foraminifera was a symbiotic relationship with algae, which allowed foraminiferal tests to develop significant size. This relationship required high light levels and such “larger foraminifera” typically occurred in shallow, warm-water carbonate platforms during Jurassic-earliest Cretaceous times (as described by many authors, including Hottinger (1967), Bassoulet and Fourcade (1979) and Boudagher-Fadel (2018)). In contrast, cooler, deeper-water settings lack these larger foraminifera, and are also poor in smaller benthonic foraminifera. The result is that although shallow marine (to upper slope) foraminiferal associations are well known, and ages may be inferred for them, it is difficult to precisely correlate key appearances and extinctions of key marker taxa in these groups with the succession of calpionellids, nannofossil or ammonite markers that traditionally define divisions of the Tithonian-Berriasian interval. Therefore, it is difficult to recognise this boundary in shallow marine depositional settings. The challenge in assessing the value of foraminifera to aid the recognition of the Jurassic/Cretaceous boundary is to find good quality data sets from depositional settings in which both calpionellids and larger foraminifera, which are largely mutually exclusive palaeoenvironmentally, are present. Such settings include upper slope locations where associations of abundant foraminifera and less common calpionellids may both occur.

In Tethyan shallow-marine shelf depositional settings a number of biozonal schemes have been developed based on a similar succession of key larger foraminiferal taxa, spanning the Tithonian-Berriasian boundary interval. These include the species *Anchispirocyclus lusitanica*, *Montsalevia salevensis*, *Pseudocyclamina lituus* and *Protopenneroplis ultragranulata* (senior synonym of *P. trochangulata* Septfontaine, 1974). They are the most widespread, cosmopolitan taxa that have been recorded by many authors across the Tethyan region, for example, Kuznetsova and Gorbachik (1985, Ukraine), Rojay and Altiner (1998, Turkey), Arkad'ev *et al.* (2006, Ukraine), Olszewska (2010, SE Poland) and Granier (2019, S. France - Middle East), among others.

Altiner and Ozkan (1991) studied calpionellids in Anatolia (Turkey), and found foraminifera associated with calpionellids, which had been either transported (approximately contemporaneously) from shallower marine environments in carbonate turbidites or as *in situ* elements. They reported the first occurrence of *Protopenneroplis ultragranulata* (as *P. trochangulata*), in association with calpionellid Subzone A2 (*Crassicollaria*) assemblage. Additionally, in Turkey (central Pontides), Rojay and Altiner (1998) recorded the incoming of *P. ultragranulata* (as *P. trochangulata*) as latest Tithonian by correlation with the work of Altiner and Ozkan (1991).

Of the key foraminifera taxa listed above, the shortest ranging form, *Anchispirocyclus lusitanica*, has been considered in several studies to be Tithonian restricted (see references below). However, it has been recorded in a supposed ammonite Jacobi Zone (?earliest Berriasian) of Portugal (Granier and Bucur, 2011) (in association with magnetozone M18). The species' extinction has been recognised as high as the top of the Jacobi Zone by Granier (2019), who defined an *A. lusitanica* biozone for the Tithonian to earliest Berriasian (based on the total range of the nominate taxon), succeeded by a *P. ultragranulata* biozone for the Berriasian (representing the lower part of the range of the nominate taxon). The evolutionary

appearance of *P. ultragranulata* has been recorded in several biozonal schemes in shallow marine platform areas, across a wide region including France, Italy and Iran. Granier (2019) discussed the record of *P. ultragranulata* by several authors in the latest Tithonian, however, it is uncertain whether these occurrences would now fall in the Berriasian using the new definition of the base of the stage. Bucur (1997) had previously described the species as occurring in the Tithonian of Romania, and other areas, and showed the widespread distribution of the species across Europe, together with records from Tanzania and Pakistan. Bucur and Sasaran (2005) noted that *P. ultragranulata*, though first appearing in the latest Tithonian, became more abundant from Berriasian times onwards in the Trascau Mountains, Romania.

Arkad'ev *et al.* (2006) described the Tithonian-Berriasian succession (with ammonites, foraminifera and ostracoda) at Theodosia in eastern Crimea. In this section, the extinction of *A. lusitanica* and the appearance of *P. ultragranulata* coincided with a level they interpreted as the base of the Jacobi Zone. The depositional setting was interpreted as slope, with many of the carbonates (and contained foraminifera) showing signs of contemporaneous re-sedimentation. In the same Theodosia cliffs, Bakhmutov *et al.* (2018) documented nannofossils and magnetostratigraphy, together with ammonites, foraminifera, calcareous dinocysts and calpionellids. These authors noted the extinction of *A. lusitanica* much higher, in the lowermost part of the Berriasian. Bakhmutov *et al.* recorded *A. lusitanica* in the same samples as *P. ultragranulata*; and interpreted the specimens of *A. lusitanica* to be derived from a shallow marine setting, within lowermost Berriasian deep-water sediments, but that the reworking was contemporaneous, there being no abrasion or damage on the specimens. The authors also recorded rare planktonic foraminifera in the section. Also in southern Ukraine, Krajewski and Olszewska (2007) recorded *A. lusitanica* ranging into the early Berriasian and *P. ultragranulata* occurring in the latest Tithonian.

Olszewska (2010) recorded rich foraminiferal associations, of both smaller and larger taxa, in Tithonian/Berriasian boundary beds (of the Babczyn Formation) in boreholes in south eastern Poland, with limited calibration to calpionellids and calcareous dinocysts (but not to ammonites). She identified a change from her *Andersenolina alpina* Zone to the overlying *Protopenneroplis ultragranulata*-*Protomarsonella kummi* Zone as marking the base of the Berriasian. A key link to other authors' biozonations is the incoming of *P. ultragranulata* at the boundary, correlated with calpionellid biozone B (*Alpina* Subzone). Notably, she did not record the presence of *A. lusitanica* in her studies. She used the extinction of *Protopenneroplis striata* to define the top of the Tithonian and tied this bioevent to a *C. alpina* occurrence in one of the boreholes.

Boudagher-Fadel (2018) defined a biozonation scheme for the Upper Jurassic that included a *Freixialina planispiralis* biozone corresponding to the Tithonian, marked by the presence of *A. lusitanica*, *A. neumanni*, *Everticyclammina virguliana*, *E. praekelleri* and *Pseudocyclammina lituus*. Several of these taxa range into the overlying Berriasian. This author noted that the top of the biozone is marked by the disappearance of the genera *Parurgonina*, *Pseudospirocyclina*, *Kastamonina* and *Labyrinthina*.

Granier (2019) subdivided the Tithonian-Berriasian interval of Tethyan shallow-water carbonates in the unconformity-bounded formations of the Jura (plus Spain, Morocco and offshore Abu Dhabi) into three biozones (zones and subzones), combining mostly large benthic foraminifera and "calcareous" green algae (Dasycladales). Within this biozonation, however, there are no clear bioevents in the biostratigraphic succession that appear to correlate with the Tithonian/Berriasian boundary. Notably, Granier (2019) considers that the first appearance of *P. ultragranulata* occurs in the latest Tithonian and the extinction of *A. lusitanica* in the earliest Berriasian. The same succession was also documented by Neamtu *et al.* (2019) in the eastern Carpathians, Romania.

In offshore east Canada and north eastern USA, calpionellids, foraminifera and dinoflagellate cysts have been recorded from a number of wells and boreholes. Ascoli *et al.* (1984) and Ascoli (1990), among others, have reported the association of a *Calpionella alpina* acme biozone with the top occurrence of the foraminifer *A. lusitanica* at the Tithonian/Berriasian boundary in multiple hydrocarbon exploration and stratigraphic test wells across a large region from Baltimore Canyon to offshore Nova Scotia and Newfoundland. More recently, in offshore Nova Scotia, the extinction of *A. lusitanica* has been recognised as marking the top of the Tithonian in shallow-marine settings, where it is correlated with the appearance of the nannofossil *Nannoconus steinmannii* (Weston *et al.*, 2012). Calpionellid assemblages defining the base of the Berriasian are recorded by these authors from the Mohican I-100 and Moheida P-15 wells.

Smaller benthonic foraminifera may also be common in Tethyan shallow-water settings: however, their use as regional biostratigraphic markers around the boundary level over a wide region of Tethys is less well established. Olszewska (2010) recorded an abundance of smaller foraminifera both below and above the base of the Berriasian, including species such as *P. kummi* (which ranges as high as the Barremian). It remains to be seen whether any of these taxa, and her local biozonation scheme based on them (which she was able to tie to other parts of Poland, including the Holy Cross Mountains and Krakow areas and attempted a correlation with SW Ukraine), prove to be correlatable with the base of the Berriasian over a wider area.

Planktonic foraminifera occurred in Late Jurassic-Berriasian slope settings along the continental margins of Tethys (Gradstein *et al.* 2018), but were rare and of low diversity; this contrasts markedly with their abundance and diversity in deep marine settings from Barremian/Aptian times onwards, where they are of great value for biostratigraphic subdivision and correlation. Gradstein *et al.* (2018) defined the appearance of a rich assemblage of planktonic foraminifera, including *Favusella hoterivica*, *Conoglobigerina gulekhensis*, *Lilliputianella eocretacea*, *L. aff. similis* and *Hedbergella aff. handousi*, defining Zone Cr1, from the Tonas road section, in Crimea. This assemblage was interpreted as approximating to the base of the Berriasian and was related to calcareous nannofossils and ammonites (of the Jacobi Zone), though not to calpionellids

Within cosmopolitan foraminiferal assemblages located in shallow-marine settings, the extinction of *Anchispirocyclina lusitanica* and the appearance of *Protopenneroplis ultragranulata* occur in the Tithonian/Berriasian boundary interval. In some sections, this

change matches the boundary precisely, whereas in some it occurs in the lowermost Berriasian as defined by rare, co-occurring calpionellids. Other authors claim that the two species overlap in ranges over the boundary interval. However, it is possible that this mixing of shallow marine (larger foraminifera) and calpionellid faunas (slope to deep marine), is affected by reworking of shallow water specimens into deeper water settings - such reworking not being contemporaneous. It is therefore possible that some of the derived occurrences of *A. lusitanica* in lowermost Berriasian sediments represent reworking and erosion of older, late Tithonian sediments rather than genuine earliest Berriasian occurrences reworked contemporaneously. Further work is required to resolve this question.

Smaller benthonic and planktonic foraminifera may have some potential for the definition of the Tithonian/Berriasian boundary in Tethyan deeper marine areas, however, more research is required to define biostratigraphically important assemblages over a wider area.

4.9. Magnetostratigraphy

Though today it is universally accepted as an essential tool, when integrated with biostratigraphy, promotion of magnetostratigraphy in the Tithonian/Berriasian interval was first systematically undertaken only a little over thirty years ago. The method relies on matching a sequence of magnetozones in a given profile with the unique pattern of magnetic polarity zones of the ocean floor GPTS (Butler, 1992). One of the first studies, fittingly, was on the historical type section at Berrias, in France (Galbrun, 1984, 1985; Galbrun and Rasplus, 1984), followed by another, in Spain, at Sierra de Lugar.

Magnetostratigraphy as a correlative tool has been widely seen as amongst the most significant, and this is very true in the global definition of Jurassic/Cretaceous (J/K) boundary. It must be recognised that not all rocks preserve their primary magnetization (*e.g.* McCabe and Elmore, 1989) and that magnetostratigraphy must be integrated with other stratigraphical methods. In the context of the lithologically and environmentally varied J/K interval, magnetostratigraphy works equally well in oceanic, shallow marine and non-marine sediments, and may be applied also in radiometrically-dated volcanic rocks. For magnetostratigraphy, fine-grained lithologies (limestones, claystones, and fine siltstones) are generally preferred, which is opportune when studying many Tithonian-Berriasian profiles. Results in recent times have been required to meet at least six out of ten reliability criteria for palaeomagnetic data in magnetostratigraphic studies (Opdyke and Channell, 1996) and pass the reversal test (McFadden and McElhinny, 1990) for sections containing both normal and reverse polarization. Complete thermal or alternating field demagnetization is performed and analysis of magnetization components (Wilson, 1961; Zijderveld, 1967). Directions are determined from line-fitting least squares analysis (Kirschvink, 1980), statistical parameters (*e.g.* Fisher, 1953) should be fully documented, and magnetic mineralogy determined. These criteria were applied in studies of the French sites (Wimbledon *et al.*, 2020): see Part 2 of this publication.

The distinctive magnetozone pattern around the J/K boundary may be recognised in both marine and non-marine profiles, in different latitudes and basins (Tethys, Panthallassa, austral, boreal, non-marine), and, of course, it is unaffected by biotic provincialism and independent of independent biostratigraphical schemes, as well as providing a constraint on the timing of paleoenvironmental change. In regions where endemism and low diversity have hindered wider correlation, magnetostratigraphy has become a primary indicator in the boundary interval.

Through the 1980s there was an early developmental phase of geomagnetic study in the Tithonian-Berriasian (Nairn *et al.*, 1981; Lowrie and Channell, 1983; Cirilli *et al.*, 1984; Ogg *et al.*, 1984; Marton, 1986; Mazaud *et al.*, 1986; Ogg and Lowrie, 1986; Lowrie and Ogg, 1986; Channell and Grandesso, 1987; Galbrun *et al.*, 1990) on marine strata in North Africa, Spain, Italy, England and Portugal, and on the Purbeck Formation of southern England (Ogg *et al.*, 1991, 1994): all founded on recognition of ocean-floor magnetic anomalies (Vogt and Einwich, 1979). Some studies were allied to limited or still-evolving biostratigraphic data. With more data it became clear that, with integrated close-frequency collecting, a succession of magnetozone boundaries had the potential to give far greater accuracy and certainty, to constrain fossil markers, to help detect deficiencies in the fossil record, and, occasionally, sedimentary phenomena such as condensation and non-sequence. Even so, some key J/K sites have been found to be re-magnetised (*e.g.* Rio Argos, Mupe Bay), or even where original magnetisation was well developed, calibration with calpionellids could not be attained (*e.g.* Theodosia).

As ammonite biostratigraphic methods were judged imperfect in providing a comprehensive inter-regional correlation in the Tithonian-Berriasian interval, magnetostratigraphy was developed as a useful constraint and complement to macro- and microfossil biozonations. Houša *et al.* led the way in a new era with precise integration of calpionellid species ranges and magnetozones at Brodno and Bosso (Houša *et al.*, 1996a, 1996b, 1999, 2004). More recent work revises some of the details at these sites (references in Pruner *et al.*, 2010). Studies then moved to the more biotically challenging Arctic, to Siberia, where correlation of that boreal basin to the M-sequence was achieved in one Tithonian and Berriasian sequence (Houša *et al.*, 2007), at Nordvik. As the sole Russian high-latitude site with a reasonably extended magnetostratigraphy in the Tithonian/Berriasian interval, this site, for a time, uniquely fitted with the GPTS and the stratigraphic pattern determined in Tethys (Houša *et al.*, 2007): but see alternative interpretations of Bragin *et al.* (2013) and Schnabl *et al.* (2015). A study was also carried out in Svalbard (Rogov and Guzhikov, 2009). Unfortunately, the hoped-for expansion of magnetic studies in boreal and sub-boreal regions, notably in Russia, where correlation is difficult, have not materialised. New sites with better biostratigraphic control have not been identified: though the often-described, broken siliciclastic sequences at Gorodishche and Kashpir have been subject to preliminary magnetic documentation (Baraboshkin *et al.*, 2015).

Studies on the J/K interval still expand in number (*e.g.* Guzhikov and Eremin, 1999; Speranza *et al.*, 2005; Grabowski and Pszczółkowski, 2006; Michalík *et al.*, 2009; Guzhikov

and Baraboshkin, 2008; Channell *et al.*, 2010; Grabowski, 2010; Grabowski *et al.*, 2014; Guzhikov *et al.*, 2012; Wimbledon *et al.*, 2013; Salminen *et al.*, 2014; Bragin *et al.*, 2013; Schnabl *et al.*, 2015; Guzhikov *et al.*, 2016; Satolli *et al.*, 2015; Satolli and Turtu, 2016; Arkad'ev *et al.*, 2015; Michalík *et al.*, 2016; Bakhmutov *et al.*, 2018; Elbra *et al.*, 2018a, 2018b; Grabowski *et al.*, 2019; Wimbledon *et al.*, 2020)

Exciting new developments and prospects appear: the first North African magnetostratigraphy in a J/K interval at Beni Kleb (tied to a calpionellid biozonation; Schnabl unpublished) and the first magnetostratigraphic records in North America - results obtained from the lower Great Valley Sequence of the Sacramento Valley at Elder Creek. Further, new, ongoing work in Mexico is integrated with recent calpionellids advances, and, most recently, the first palaeomagnetic results have been published for the Andes (Iglesia Llanos *et al.*, 2015, 2017) and the non-marine of NE China (Schnabl *et al.*, 2019).

4.10. Radio-isotopic age constraints on the Jurassic/Cretaceous boundary

The base of the Berriasian, and thus the Cretaceous, though well-defined biostratigraphically, lacks a clearly defined numerical age. Though radiometric dates have been obtained from several regions with Berriasian strata (N. California, Andes, Tibet, Caribbean, Mexico, Japan and others), the classical sedimentary sequences through the J/K interval in Tethys are mostly without datable materials, as is the case with both the Tithonian Stage below and the Valanginian above. Consequently, though no radiometric data can be cited from the Vocontian Basin, a discussion is given here of recent dating results in regions where fossils occur that allow a direct correlation with Tethys, and a direct connection to the proposed GSSP. More recent results derived from the application of modern methods are shown in Fig. 5.

There are some often-quoted instances where useful widespread micro- or nannofossils are associated with datable minerals in the boundary interval: one example of note is Shatsky Rise. Mahoney *et al.* (2005) provided an age of 144.6 ± 0.8 Ma as a minimum estimate for the Jurassic-Cretaceous boundary there. This relied in part on nannofossils that suggested Bralower *et al.*'s NK1 zone (*N. steinmannii steinmannii* zone). Bralower *et al.* (1989) placed the base of this zone in magnetozone M17r. (Though this does not cohere with present knowledge: see above). In any case, M17r could not be in the "earliest Berriasian", as mooted by Mahoney *et al.* (2005).

As can be seen, assigning a numerical age for the J-K boundary can be difficult. Over the last twenty-five years, dating has relied on different approaches and on some repeated assumptions, which have yielded a large range of ages: from 135 Ma to 145 Ma (Bralower *et al.*, 1990; Gradstein *et al.*, 1995; Liu *et al.*, 2013; López-Martínez *et al.*, 2015a; Lowrie and Ogg, 1986; Mahoney *et al.*, 2005; Vennari *et al.*, 2014). Currently (2019), the base of the Berriasian in the International Commission on Stratigraphy's chart is given an age of ~ 145.0 Ma. This age has been the most enduring one for the boundary, due to the agreement between of the M-sequence model of Ogg *et al.* (2012) and the Ar-Ar age of Mahoney *et al.* (2005).

The model (Ogg *et al.*, 2012) is based on a spline-fitting model that predicts the ages of stage boundaries from the Early Cretaceous (Aptian) to the Late Jurassic (Oxfordian). The model is a combination of astronomically calibrated durations (Huang *et al.*, 2010a) for some of the magnetozones and the distances between magnetic anomalies in the NW Pacific (Channell *et al.*, 1995; Larson and Hilde, 1975; Tamaki and Larson, 1988), with the aim of determining a spreading rate for the region

This complex web of correlations has been combined with a astronomically calibrated durations for the Kimmeridgian-Oxfordian and the Aptian to produce a decreasing sea-floor spreading rate for the north-western Pacific (Huang *et al.*, 2010a, 2010b). On this basis, the age of each stage boundary was back-calculated from the base of the Aptian M0 (base age 126.3 ± 0.4 Ma) to the Oxfordian. In the case of the J-K boundary the projected age was placed at 145.0 ± 0.8 Ma. Mahoney *et al.* (2005) measured an Ar-Ar age of 144.2 ± 2.6 Ma from the M19-M20 anomalies in the Shatsky Rise, which was used as a rough estimate for the base of the Cretaceous (Ogg and Lowrie, 1986; it is now more accurately placed in the middle of the M19.2n (Wimbledon, 2017). This was later corrected to 145.5 ± 0.8 Ma, because of the recalibrated ^{40}K decay constant (Renne *et al.*, 2010). Thus, both of these studies have taken different and independent approaches, but have yielded similar ages

In contrast, when radio-isotopic dating has been directly applied to rocks that were closely associated with boundary markers the results have been significantly different. Bralower *et al.* (1990) dated volcanic horizons in the Great Valley Group at Grindstone Creek (California), placing them in an *Assipetra infracretacea* (Upper Berriasian) nannofossil subzone (Angustiforatus Zone) at *circa* 137.1 Ma (ID-TIMS). The authors back-calculated the age of the Berriasian base 141.1 Ma, using an arbitrary duration of 4-6 Myr for the biozones and their presumed age in the Upper Berriasian as an anchor. However, the nannofossil assemblage appears, at best, to indicate an age no older than the calpionellid Elliptica Subzone: *C. angustiforatus* occurs at this level in Tunisia, and *A. infracretacea* is a common Lower Berriasian nannofossil. Surpless *et al.* (2006), still in the Great Valley Group, reported depositional ages of 132.6 to 143.6 Ma in a range of J/K strata. Liu *et al.* (2013) dated interbedded bentonites in four sections in the Sangxiu Fm. of Tibet. The ages cluster around 140-142 Ma (U-Pb, SIMS), but the ages violated stratigraphic superposition, and a single age for the boundary is not quoted. Lopez *et al.* (2015b) dated a volcanic unit in the Pimienta Formation (Mexico) at 139.1 ± 2 Ma (U-Pb LA-ICP-MS). The unit lies between the calpionellid Colomi (uppermost Tithonian) and the Elliptica subzones (Lower Berriasian), thus bracketing the J-K boundary, though the base of the Alpina Subzone is not present, so that a very precise constraint on the boundary age is not possible. Vennari *et al.* (2014) sampled an ash bed at Las Loicas (Neuquen Basin, Argentina), at a level 20m above the J-K boundary and within the Andean upper part of the Noduliferum ammonite zone (placed in the NJK-D nannofossil zone), with an age of 139.55 ± 0.03 Ma (CA-ID-TIMS). The authors used a constant sedimentation rate of 0.5 cm/kyr to back-calculate the age of the boundary to *circa* 140 Ma. Lena *et al.* (2019) presented geochronological constraints (U-Pb CA-ID-TIMS) on Late Tithonian to Early Berriasian deposits at Las Loicas and on the later Berriasian in the Tamaulipas Fm. at Mazatepec (Mexico). The age of the boundary (*i.e.* the base of the calpionellid Alpina Subzone) at Las Loicas was set at 140.22 ± 0.14 Ma (U-Pb CA-ID-TIMS)

and the age in the Elliptica Subzone at Mazatepec at 140.512 ± 0.036 Ma (U-Pb CA-ID-TIMS).

One of the drawbacks of studies on Jurassic/Cretaceous radio-isotopic ages is that the dated horizons are often stratigraphically distant from the level of the stage base. This has forced the use of calculations that involve arbitrary constant sedimentation rates, or durations of magnetozones and biozones to back-calculate the age of the boundary, which inevitably introduces unknown errors in the age. Another issue is that geochronological data has seldom been calibrated with magnetozones, and thus the boundary level in magnetosubzone M19n.2n is hard to prove. As a result, the correlation between well-studied J-K sections in western Tethys and radio-isotopic ages around the boundary have been based on biostratigraphic data. However, in many of the radiometrically dated sections, the biotic boundary markers (primary and secondary) are rare. Lastly, the majority of the analytical techniques employed to date the boundary (*e.g.* SIMS, LA-ICP-MS) lack precision and accuracy, usually within limits of 1-3% of their age, which in the case of the J-K transition (*circa* 140-145 Ma) yields a precision in the order of 1-3 Myr. Overall, the analytical techniques used to measure the age of the boundary are unsuitable to date the appearance of key taxa in the geological record. In addition, these analytical techniques (U-Pb SIMS and U-Pb LA-ICP-MS) do not address the effects of Pb-loss, thus compromising the accuracy of the measurements. Recently, Lena *et al.* (2019) were able to bracket the primary and secondary markers using U-Pb CA-ID-TIMS at Las Loicas; however, fossil markers occur in low resolution, in addition to some anomalous calpionellids around the putative boundary level; and further investigation is required. Nevertheless, the assemblage of the calpionellids *Crassicollaria parvula* and *C. colomi* and the FO of the nannofossil *Umbria granulosa granulosa* from Las Loicas was dated at 141.31 ± 0.56 Ma, considered to be a valid age for the Late Tithonian. The age from the Lower Berriasian Elliptica Subzone at Mazatepec of 140.512 ± 0.031 Ma is robustly calibrated, since the calpionellid zonation there is closely comparable to that proven in western Tethys. As a result, Lena *et al.* (2019) has suggested a best boundary estimate to be between 140.7 and 141 Ma, though still without magnetostratigraphy. In summary, even given the issues and concerns described above, radio-isotopic ages tend to broadly cluster around 140-141 Ma, differing by *circa* 4 Ma from Ogg *et al.* (2012).

The comparison between studies that have calibrated the age of the base of the Berriasian and the M-sequence (Ogg *et al.*, 2012) is not a simple one. The absence of integrated radio-isotopic ages, biostratigraphy and magnetostratigraphy is a major challenge for dateable global correlations. Geochronological studies that lack magnetostratigraphy effectively prevent dating of Tithonian-Berriasian magnetozones, and thus an accurate age assessment for the base of the Berriasian (*i.e.* the base of the calpionellid Alpina Subzone) and magnetosubzone M19.2n is not possible. Nevertheless, it is worth pointing out that the accuracy of the M-sequence age model of Ogg *et al.* (2012) is ultimately dependent on the quality of available radio-isotopic ages and cyclostratigraphic data at and or around stage boundaries between the Oxfordian and the Aptian. New geochronological data from the late Jurassic to early Cretaceous suggest that the ages of the stage boundaries in this interval could be younger than those used in the M-sequence model of Ogg *et al.* (2012). For

instance, Zhang *et al.* (2018) provided magnetostratigraphic data allied to the U–Pb ages of Midtkandal *et al.* (2016) from Svalbard cores, which suggest that the age of the M0 (Aptian base) is 121–122 Ma, rather than ~126 Ma. Aguirre-Urreta *et al.* (2015) presented a high-precision U–Pb age of 127.24 ± 0.03 Ma for the highest Hauterivian Agrio Fm. (Neuquén Basin, Argentina): which Martinez *et al.* (2015) used to anchor cyclostratigraphic studies at Río Argos, and calculate an age for the base of the Hauterivian at 131.96 ± 1 Ma, and the base of the Barremian at 126.02 ± 1 Ma. Aguirre-Urreta *et al.* (2017) later reported a U–Pb high-precision age for the lower Hauterivian at 130.394 ± 0.037 Ma, which is fairly close to that of Martinez *et al.* (2015). Therefore, new geochronological constraints in the Early Cretaceous suggest an apparent consistent offset and younger ages: that is, of ~3–4 Myr less than those predicted by the M-sequence age model. Thus, future updates of the M-sequence model are likely to predict younger numerical ages for Late Jurassic to Early Cretaceous stage boundaries, and there is likely to be a change in the crucial apparent agreement between the M-sequence model of Ogg *et al.* (2012) and that of Mahoney *et al.* (2005).

4.11. Sea Level

Information on sea-level change calibrated to the detailed biostratigraphy of the Berriasian is limited.

Previous widely-quoted global accounts have not always been closely related to either traditional biozonal schemes or accurate biostratigraphy: *e.g.* with the base of the Cretaceous in some unusual positions, such as within M16n (Haq *et al.*, 1987, fig. 3).

Hoedemaeker (1987, 2002) related sea-level fluctuations to ammonite diversity. He recognised the lowest stands of sea level during the earliest Cretaceous in (1) the uppermost Grandis Subzone (Jacobi Zone), (2) upper Boissieri Zone - the uppermost Berriasella picteti Subzone – in the latest Berriasian. The highest sea-level stands were correlated with (1) the Jacobi Subzone, and (2) approximately with the Berriasella paramimounum/ Berriasella picteti subzonal boundary. A relatively rapid sea-level rise approximately coincided with the base of the Paramimounum Subzone.

Correlation of ammonite and calpionellid biostratigraphy presented in Hoedemaeker *et al.* (2016; fig. 1A) shows that periods of ammonite and calpionellid diversification coincided, confirming the results of Reháková (1998, 2000b). Reháková, (1998, 2000b) tried to correlate bioevents, of calcareous dinoflagellates and calpionellids, in pelagic West Carpathian deposits with sea-level fluctuations *sensu* Haq *et al.* (1987). Radiation and diversification phases in calpionellids coincided with intervals of the ongoing transgression: whereas stagnant phases in their evolution coincided with sea-level falls and siliciclastic inputs. The acme concentrations of some cyst taxa were controlled by sea-level highstand phases, or perhaps with increasing surface-water temperatures (Jach and Reháková, 2019).

The latest general account of sea-level variations (Haq, 2017) takes the base of the Berriasian to be in mid M19n.2n, at the base of the Alpina Subzone. In the late Tithonian to early Berriasian, sea-level fluctuations are plotted against parallel scales - with a western Tethyan

ammonite and English ammonite biozonations: the latter being composite, and based on the more expanded Portland units of the Dorset sequence together with the broken and condensed siliciclastic interval in the North Sea basin (Wimbledon, 1980).

Haq (2017) notes five successive highstand events, tied to magnetozones:

- 1) middle Microcanthum Zone (=Kerberus Zone) – mid M20n.2n
- 2) base Jacobi/ “Durangites” Zone (shown as equivalent) (=base Preplicomphalus Zone) – lowest M19n.2n
- 3) middle Jacobi/ “Durangites” Zone (= base Lamplughii Zone) – M18r
- 4) upper Jacobi/ “Durangites” Zone (= lowest Runctoni) – base M17r
- 5) lowest Boissieri Zone (= base Icenii Zone) – low M16r

The supposed equivalence (item 1) of the Kerberus Zone to the Microcanthum Zone in M20n is undermined by the presence of earlier ‘English’ ammonites, Fittoni/Albani zone, associated with *Chitinoidea* in Poland: *Chitinoidea* marks M20n in Tethys. Of course, the Jacobi and “Durangites” ammonite zones are in no part equivalent: the Andreaei Zone (=“Durangites” Zone) underlies the Jacobi Zone (see Ammonite chapter). Therefore, it is not clear how the lower, middle and upper Jacobi Zone of Haq (2017) might be interpreted. However, event two is apparently closest to the base of the calpionellid Alpina Subzone, notwithstanding the application of ammonite zones.

Of the English biozones, only the lower ammonite zones in Dorset (up to the Anguiformis Zone) have been subjected to a magnetostratigraphic study, so the higher cited zones (Preplicomphalus-Icenii) are not relatable to magnetozones (nor to the Tethyan ammonite zones mentioned by Haq). No publications are cited by Haq (2017) which elucidate this matter: nor on how the assumed equivalence of the Tethyan and two English ammonite stratigraphies was derived. Therefore, it is not possible, with any degree of certainty, to relate the sea-level curve to the fossil markers in magnetozone M19n which define and constrain the base of the Berriasian - ammonite, calpionellid, nannofossil etc. A Jurassic-Cretaceous sea-level curve matched accurately to key biotic markers would be an interesting topic for investigation, if it took into account both regional tectonic and eustatic effects.

4.12. Stable Isotopes

4.12.1. Tethys: carbon isotopes and cyclostratigraphy

Carbon-isotope ratios measured on bulk carbonate rocks (*e.g.* Föllmi *et al.*, 1994; Weissert and Mohr, 1996), calcitic shells and tests of foraminifera, bivalves or brachiopods (*e.g.* Carpenter and Lohmann, 1995; Pellenard *et al.*, 2014), pedogenic nodules (*e.g.* Cerling *et al.*, 1989) and dispersed organic carbon and wood fragments (*e.g.* Yans *et al.*, 2010) are widely used chemostratigraphic tools. They can help to better correlate sedimentary successions in combination with a bio- and magnetostratigraphic scheme. This is because carbon isotope trends and anomalies through time may reflect the ocean–atmosphere reservoir via their connection to the global carbon cycle. Alternatively, carbon isotope ratios measured on marine and continental materials may also (at least partly) reflect local/regional

palaeoenvironmental controls. Thanks to their global or near global character, some major carbon isotope anomalies (positive or negative peaks) are well known in the geological record, and correspond to major, geologically, short-lived palaeoenvironmental/palaeoclimatic events that can be precisely pinpointed in various sections. This is the case, as an example, for the negative peak event recorded globally at the base of the Toarcian (Jenkyns *et al.*, 2002). Some isotopic events match major geological boundaries and are used as markers for those boundaries, e.g. the Paleocene-Eocene boundary, defined by the onset of a negative $\delta^{13}\text{C}$ anomaly (Aubry *et al.*, 2002).

This carbon isotope approach for long-distance correlations can be tested around the Jurassic-Cretaceous boundary. In this time-interval, a steady carbon isotopes decrease is recorded from the ammonite *Microcanthum* Zone (Upper Tithonian) to the calpionellid *Alpina* Subzone (basal Berrasian) in the Vocontian Basin (*e.g.* Le Chouet road section, Wimbledon *et al.*, 2020). This represents a large scale (global?) trend that has been recorded in Tethys, boreal regions and in the Middle Atlantic (Weissert and Mohr, 1996; Price and Rogov, 2009; Žak *et al.*, 2011; Price *et al.*, 2016). However, some regional differences may occur. As an example, the amplitude of the carbon isotope decrease is roughly of 1.00‰ at the Lókút Hill section in Hungary (see review in Price *et al.*, 2016), whereas the amplitude is only 0.40‰ at Le Chouet. Having probably interesting palaeoceanographic/palaeoclimatic roots, this Late Jurassic steady carbon isotope trend is, however, of no use currently for stratigraphic correlation purposes in the Tithonian to Berriasian, and more studies are needed to build a fine understanding of carbon isotope evolution in the Vocontian Basin, and elsewhere.

In recent years, efforts have been made to increase the number of studies dealing with carbon isotopes in Russian boreal basins and a distinct positive carbon isotope excursion has been mooted. However, it is still unclear if this isotopic event can be properly recognised in Tethyan regions. As an example, it is not evidenced in the Vocontian Basin, although this may be due to a lack of high resolution isotopic data. Our preliminary work in the Vocontian Basin suggests a smooth evolution of carbon isotope ratios through Berriasian time, which is recognised to be of regional/global significance. Therefore, it is of major importance to increase detailed records in Tethys, in order to help build global isotopic stratigraphic correlations: and this includes the area of the proposed GSSP, St Bertrand, Charens, *etc.*, where a detailed biostratigraphic and magnetostratigraphic scheme is already available.

Furthermore, a preliminary cyclostratigraphic study (by Schnyder and Galbrun) has been undertaken using magnetic susceptibility (MS) variations in several J/K sections in the Vocontian Basin. However, though a cyclostratigraphic study generally gives good results in a succession with marl-limestone alternations, this is not often the case for well bedded/massive bedded limestone successions, such as at Le Chouet. MS is a palaeoclimatic proxy used to identify astronomical-paced cycles. First results have revealed astronomical cycles of 20 kyrs, 40 kyrs, 100 kyrs or 400 kyrs duration (Milankovitch cycles). This establishment of astronomical forcing paves the way for an estimation of the duration of biostratigraphic intervals and magnetozones in the Vocontian sections. It is hoped to apply this cyclostratigraphic approach, particularly, to the Tré Maroua and Saint Bertrand profiles.

4.12.2. Isotope records across the Jurassic/Cretaceous boundary in boreal regions: carbon and oxygen isotopes

Reconstructions of carbon-, oxygen- and strontium-isotope curves for boreal palaeobasins are based on the analysis of sedimentary organic matter or molluscan shell material, especially belemnites, which are best preserved in northern sections. Near the J/K boundary, thus far, the most detailed chemostratigraphic data have been obtained from belemnites. These data, taking into account their calibration with bio- and magnetostratigraphic data, allow us to recognise event levels for a correlation of J/K boundary beds across some boreal basins, and between boreal regions and Tethys.

Stable isotope data come from a number of boreal sections. In most of these, the J/K transition beds are poorly represented: Voskresensk in the Russian Platform basin and an uncertain locality in northern Germany (Podlaha *et al.*, 1998); Gorodishche, Kashpir and Marievka on the Russian Platform (Ruffell *et al.*, 2002; Gröcke *et al.*, 2003; Price and Rogov, 2009); Yatriya in Western Siberia (Price and Mutterlose, 2004); Janusfjellet and Knorringfjellet in central Spitsbergen (Hammer *et al.*, 2012). Nevertheless, in Siberia there are two sites characterized by a continuous sedimentary succession across the J/K boundary. Both Nordvik on the Laptev Sea coast (Eastern Siberia) and Maurynya in the foothills of the Northern Urals (Western Siberia) have detailed carbon and oxygen isotope records (Žák *et al.*, 2011; Dzyuba *et al.*, 2013).

Based on the data from the Tithonian-Berriasian (“Upper Volgian”) and Upper Berriasian (“Ryazanian”) in the Nordvik, Maurynya and other Siberian sections, a composite boreal $\delta^{13}\text{C}$ curve has been recently created (Dzyuba *et al.*, 2013). This curve is well-correlated with bio- and magnetostratigraphic zones. In the J/K boundary interval, two positive $\delta^{13}\text{C}$ excursions were recorded. A significant positive $\delta^{13}\text{C}$ shift is defined in the middle part of the ammonite *Craspedites okensis* (=Okensis) Zone at Nordvik, confined to the upper part of magnetozone M20n. This shift correlates well with a positive excursion found close to the base of the *Boreioteuthis explorata* belemnite beds at Maurynya. Furthermore, it is coeval with a positive excursion in the *Kachpurites fulgens* (=Fulgens) – *Craspedites subditus* (=Subditus) ammonite zone transition in the Gorodishche section (Gröcke *et al.*, 2003; Dzyuba *et al.*, 2013), and with a positive excursion in the lower part of the “Upper Volgian” in the Janusfjellet section, Spitsbergen (Hammer *et al.*, 2012). A positive excursion has also been observed in the composite Tethyan $\delta^{13}\text{C}$ curve (Weissert *et al.*, 2008) within the uppermost part of M20n. The second positive $\delta^{13}\text{C}$ excursion is most pronounced in the upper part of the *Craspedites taimyrensis* (=Taimyrensis) ammonite Zone in the Maurynya section, and it is observed in the Nordvik section in the same interval, high in magnetozone M19n, confined to the co-interval of the *Arctoteuthis tehamaensis* belemnite Zone and the nominal Taimyrensis Zone. The same excursion has been observed within the upper part of the *Craspedites nodiger* (=Nodiger) Zone in the Marievka section (Price and Rogov, 2009; Dzyuba *et al.*, 2013). Therefore, the J/K boundary is located in boreal sections between these two positive $\delta^{13}\text{C}$ excursions, but closer to the upper one. Both excursions are interpreted as records of increased rates of organic carbon burial (Dzyuba *et al.*, 2013).

The intensive accumulation of organic-rich sediments at that time is evident from a wide, almost global, distribution of black organic-rich shales in the Upper Jurassic and part of the Berriasian interval (Föllmi, 2012).

The composite Tethyan $\delta^{13}\text{C}$ curve that is based on bulk carbonate analyses is relatively smooth in the Upper Tithonian–Berriasian interval (cf. Weissert *et al.*, 2008). This is probably the result of the mixing of different biogenic components in a given sample, and the fact that such a sample could span tens or hundreds of years, which averages out natural variations in habitat, vital effects, time and preservation (cf. Nunn *et al.*, 2009, 2010; Dzyuba *et al.*, 2013). In the case of belemnites, individuals that are used for isotope analysis commonly have an estimated age of no more than two years.

A comparison of the $\delta^{18}\text{O}$ curves obtained from the Maurynya and Nordvik sections show an agreement with the general trend in oxygen isotopic composition in the J–K boundary interval (Žák *et al.*, 2011; Dzyuba *et al.*, 2013). The negative trend in the $\delta^{18}\text{O}$ curves established for both these sections had previously been recorded in the Russian Platform Basin (Price and Rogov, 2009). The same trend is expressed more or less prominently in Deep Sea Drilling Project Hole 534A section in the central Atlantic Ocean (Tremolada *et al.*, 2006) and in the Puerto Escaño section of southern Spain (Žák *et al.*, 2011), where $\delta^{18}\text{O}$ data were obtained from bulk carbonates. This negative $\delta^{18}\text{O}$ trend is associated with a gradual climatic warming (mid Oxfordian to the mid Berriasian - “early Ryazanian”) (e.g., Abbink *et al.*, 2001a; Price and Rogov, 2009; Zakharov *et al.*, 2014. According to Dera *et al.*, (2011), the $\delta^{18}\text{O}$ decrease during the Late Jurassic corresponded approximately to a period of prolonged and intense magmatism in the northeast Asian igneous provinces (Wang *et al.*, 2006) that could have caused high pCO₂ levels, which in turn could have maintained warmer climatic conditions.

Galloway *et al.* (2019) have recently identified a positive excursion at two localities in Canada’s Arctic islands, on Axel Heiberg Island. It forms the top of a prominent negative excursion (VOICE), with a minor positive reversal within it. The excursion occupies a stratigraphic interval that previously produced “mid-Volgian” dorsoplinitid ammonites and bivalve *Buchia fischeriana*, and it is overlain by a newly collected Berriasian sequence containing the ammonite *Borealites (Pseudocraspedites)* and *Buchia okensis*.

4.12.3. Strontium isotopes

The majority of sections in Tethys where integrated methods have been successfully applied tend to be in hemi-pelagic to pelagic, deeper-water environments, often suggesting sedimentation below the calcitic CCD. Documented belemnite-yielding sites with shallow-water sediments (or having originated above the calcitic CCD) and with stratigraphically important bio-markers – *i.e.* ammonites, calcareous nannofossils - are quite rare. There are several localities where they are present together with calpionellids (e.g. France, Turkey, Spain – Puerto Escaño).

The majority of published data used for the global Sr isotope ratio curve close to the Jurassic/Cretaceous boundary are from boreal regions and not Tethys and elsewhere The

global $^{87}\text{Sr}/^{86}\text{Sr}$ curve (summarized in Price and Gröcke, 2002; Price *et al.*, 2016; Kuznetsov *et al.*, 2017) used data obtained from various regions, including localities at higher latitudes: Falkland Plateau, New Zealand, Great Britain and the Russian Platform, as well as western Siberia.

The Late Jurassic and earliest Early Cretaceous are characterized by a global increase in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in the ocean (*e.g.* Howarth and McArthur, 1997; Jones and Jenkyns, 2001; Price *et al.*, 2016). Late Jurassic data have been published (Jones *et al.*, 1994; Podlaha *et al.*, 1998, and others) and also for the Early Cretaceous (Van de Schootbrugge *et al.*, 2000; McArthur *et al.*, 2004, 2007a, 2007b; Vaňková *et al.*, 2019, and others), whereas, the immediate Tithonian–Berriasian boundary interval before 2017 was poorly supported by relevant data (Jones *et al.*, 1994; Podlaha *et al.*, 1998; Price and Gröcke, 2002). For a long time, the Sr isotopic characteristics of the uppermost Tithonian and Berriasian were based only on data from sections in NW Europe and the Russian Platform, representing the boreal palaeobasins (Jones *et al.*, 1994; Veizer *et al.*, 1999; Gröcke *et al.*, 2003), as well as on results from the Tethyan Upper Berriasian sections of Spain and France (McArthur *et al.*, 2007a).

Strontium isotope data recently obtained from belemnites from the Maurynya section (Western Siberia) filled the data gap of the $^{87}\text{Sr}/^{86}\text{Sr}$ variation curve in the ocean at the J/K boundary (Kuznetsov *et al.*, 2017).

Judging by the fact that the Maurynya section encompasses the Upper Tithonian–Upper Berriasian (“Upper Volgian”- lowermost “Ryazanian”), up to the lower part of the ammonite *Hectoroceras kochi* (=Kochi) Zone, the Sr isotope values obtained (0.707172–0.707242) characterize an interval from the upper part of the magnetozone M20n to the lower part of the M16r, and hence the interval, in Mediterranean ammonite terms, from the upper part of the Microcanthum Zone to the Occitanica Zone, and probably the lowest horizons of the Boissieri Zone (Kuznetsov *et al.*, 2017).

Within the “Upper Volgian”, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the Maurynya belemnites varies from 0.707172 to 0.707222, whereas near a level which corresponds approximately to the J/K boundary, the ratios are in the range 0.707189–0.707195 (Kuznetsov *et al.*, 2017), which can serve as a useful characteristic for the boundary. New Sr data obtained by Rud'ko *et al.* (2017) from the Crimean carbonate platform, on the northern periphery of Tethys, fit the trend established at Maurynya. Despite the fact that these authors noted a decrease in the resolution of the method within the Tithonian–Lower Berriasian due to the relatively small number of well-dated determinations and the general flattening of the profile of the $^{87}\text{Sr}/^{86}\text{Sr}$ curve, they obtained close $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.70717–0.70722) approximately in the J/K boundary interval.

The gradual increase in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio observed in the Maurynya section coincides with the general increase in this ratio in the Late Jurassic and Early Cretaceous world ocean. This indicates large-scale geodynamic causes that led to an increase in the content of radiogenic ^{87}Sr during the Jurassic-Cretaceous transition. In general, the analysis of

available Sr isotope data shows that during the Late Tithonian and Berriasian the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio increased from 0.70716 to 0.70730 (Kuznetsov *et al.*, 2017).

5. Wider Stratigraphical Correlations

Here are considered some of the possibilities for correlations between the Alpina Subzone's base in Tethys and wider geographical regions in Patalallassa, and boreal basins, noting opportunities and limitations. This examines the distribution and availability of Tethyan markers and their co-occurrences with endemic biotic elements (such as belemnites), and how the wider application of calpionellids, nannofossils and magnetostratigraphy has improved global correlations.

5.1. Boreal regions

Despite such terms as “Panboreal Realm” or “Superrealm” relating to ammonites, each boreal or subboreal region has its own independent ammonite biozonal scheme: there is no such thing as a boreal realm with one zonal ammonite fauna that has a uniform distribution: the faunal uniformity lost in earlier Tithonian times only reappears in the later Berriasian times (with some taxa widespread, *e.g. Hectoroceras kochi* in Greenland, England and Siberia), and the same is true of *Buchia* (bivalve) zonations (*e.g. Inflata Zone*).

Previously, low diversity, sparse and regionally restricted ammonites were almost the only tool being used to achieve a correlation with other regions, but this now changes somewhat. In Siberia and Svalbard the boundary interval yields few ammonites, and the same is even more the case in Arctic Canada. Much reliance has been placed on a single ammonite taxon, or the inferred presence of zone when ammonites are absent. With *Buchia* species being long-ranging (see below) attention has moved to more indicative belemnite species, as well as palynology and calcareous dinocysts.

5.1.1. Eastern England/North Sea basin

Little can be added to accounts of the Spilsby and Sandringham formation by Casey (1973), as the few outcrops are in a state of decay. Of relevance here, Casey recorded the Preplicomphalus Zone's fauna as *Subcraspedites* (*S.*) *sowerbyi*, *S.* (*S.*) *preplicomphalus*, *S.* (*S.*) *cf. claxbiensis*, *S.* (*S.*) spp. nov., *Craspedites plicomphalus* and *C. thurrelli* sp. nov. He correlated this Preplicomphalus Zone with the Nodiger Zone (Russian Platform) and the Taimyrensis Zone (Siberia).

Rogov and Zakharov (2009) record *Subcraspedites* species, including *S. sowerbyi* and *S. cf. preplicomphalus* in the Nikitini Zone at Gorodishche, apparently indicating a correlation with the Preplicomphalus Zone. These authors also drew a comparison between *Craspedites* of the *nodiger* group morphology and the remarkable nodes near the umbilical seam in one English species, *C. preplicomphalus*. The occurrence of *C. pseudonodiger* in the middle part of the Nodiger Zone at Kashpir was seen as supporting a correlation between the Taimyrensis and

the Nodiger zones, and indicating an upper limit for the eastern English Preplicomphalus Zone.

5.1.2. Greenland

The Tithonian/Berriasian boundary interval is absent in East Greenland. A *Tenuicostatus* Zone (Upper Tithonian) fauna sits within a large hiatus between the *Vogulicus* and *Chetaites ammonite* zones (Callomon and Birkelund, 1982).

5.1.3. Siberia and Russian Platform

The biostratigraphic literature depends much on the NE Siberian section at Nordvik, which has become a kind of standard for Russian colleagues, with its magnetostratigraphic account (Bragin *et al.*, 2013). Only the interpreted match with Tithonian-Berriasian magnetostratigraphy fixes the boundary interval (Houša *et al.*, 2007), by means of the identification of upper M19r, M19n and lower M18 magnetic zones in the Taimyrensis Zone. The profile's ammonite record is sparse (Schnabl *et al.*, 2015), and, even with a subsequent update of finds from higher zones, it remains almost barren near the boundary. However, finds of the belemnite *Arctoteuthis tehamaensis*, a Californian species, in the ammonite Taimyrensis Zone at Nordvik allows a more precise correlation of the middle of magnetozone M19n with levels in California and Japan (Dzyuba, 2012; Haggart and Matsukawa, 2019). Thus, the base of the Tehamaensis Zone approximates to the base of the calpionellid Alpina Subzone. Further, Dzyuba (2013) equates the *Arctoteuthis tehamaensis* Zone with the *Simnobelus compactus* Zone on the River Maurynya (W. Siberia), expanding possibilities for correlation in Russia.

That notwithstanding, a very great deal hinges on the putative numbering of magnetozones at Nordvik. The three reversed intervals (identified as M19n.1r, M18r and M17r) were numbered with no calibration with fossils that could afford a wider correlation. All three are similarly thinly developed (Schnabl *et al.*, 2015). With a fresh mind and no preconceptions, the original magnetozone notation of Houša *et al.* (2007) might warrant reconsideration.

5.1.4 Svalbard

Palynology from Jurassic/Cretaceous boundary units in Svalbard has proven to have limited utility for wider correlation (Dalseg *et al.*, 2016). The most recent assessment of ammonite biostratigraphy near the Tithonian/Berriasian boundary in Svalbard is that of Rogov (2010). At Festningen, discontinuous occurrences of Upper Tithonian ammonites were recorded, and later faunas are limited to three horizons near the putative Tithonian/Berriasian boundary. The Okensis Zone appears to be truncated, and, above, the 1m assigned to the Taimyrensis Zone has only one faunal horizon with one species, *Craspedites* cf. *mosquensis*. At Myklegarfjellet ("AD" profile), an interval of 7m has no ammonites, then a monospecific *Craspedites okensis* fauna is overlain, above a gap, by 1m of strata with *C. agardensis* and *C. cf. canadensis*. These last two species were used to identify a putative Taimyrensis Zone. The remaining interval (4m), though it was assigned to the Taimyrensis Zone, is unexposed.

Thus, the Taimyrensis Zone, as at Nordvik, does not contain the zonal index. Guzhikov (Rogov and Guzhikov, 2009) gave preliminary results on magnetostratigraphy at Myklegarfjellet (“AB” section). Ammonites are absent in most of the interval assigned to the Okensis Zone and through the entirety of the Taimyrensis and Chetae zones. Nevertheless, Guzhikov interpreted a ‘normal’ magnetozone (with a short reversed subzone near its top) overlain by a short reversal (<1m), placing these in a Taimyrensis Zone, and identifying magnetozones M19n and M18r, respectively.

The isotopic studies of Koevoets *et al.* (2016) in Svalbard offer new precise data that should reinforce the limited biostratigraphy. In the Agardhfjellet Formation of central Spitsbergen, two $\delta^{13}\text{C}$ excursions have been recorded in the mid to late Tithonian. The extension of this study into the Berriasian is anticipated (Maayke Koevoets pers. comm.)

5.1.5. Canada

Considering the difficulties in correlating between the various boreal regions, Canadian usage has been to correlate Canadian zones with relative confidence only with northern Siberia (“high boreal”). Long-ongoing questions about correlations of the late Jurassic-early Cretaceous endemic ammonite zones among the various boreal and sub-boreal subprovinces are highlighted by the juxtaposition of the various “standard” columns (Ogg *et al.*, 2016).

Tithonian (“Middle Volgian”) dorsoplanitid ammonites have been reported from several localities on Ellesmere and Axel Heiberg Islands (Friebold, 1961; Jeletzky, 1966, 1984; Callomon, 1984; Schneider *et al.*, 2018). The ammonites *Dorsoplanites* ex gr. *panderi* Michalski and associated ?*Pavlovia* were figured from northern Ellesmere Island by Friebold (1961); the latter re-interpreted as *Pavlovia* (?*Paravirgatites*) by Callomon (1984), and as *Taimyrosphinctes* (Rogov, 2019, unpublished). Schneider *et al.* (2018) reported the co-occurrence of *Dorsoplanites maximus* Spath and *D. sachsi* Michailov, confirming the presence of the boreal Maximus Zone on Ellesmere Island. Galloway *et al.* (2019) suggested that Jeletzky’s (1984) report of specifically unidentified dorsoplanitids, occurring with large *Buchia fischeriana* (d’Orbigny), provides a “Middle Volgian” age for a newly discovered Arctic regional ^{13}C negative excursion.

The ammonites *Craspedites* (*Subcraspedites*) cf. *sowerbyi* Spath and *C. (Craspedites)* n. sp. aff. *subditus* (Trautschold) were illustrated from northern Ellesmere Island by Jeletzky (1984). They were re-assigned (Rogov and Zakharov, 2009) to *Subcraspedites sowerbyi* Spath and *Craspedites* cf. *thurrelli* Casey respectively. A higher fauna in the same section with *Craspedites (Subcraspedites)* n. sp. aff. *praeplicomphalus* [sic] Swinnerton and *C. (Craspedites)* n. sp. aff. *subditus* illustrated by Jeletzky (1984), has been updated to *Subcraspedites* cf. *preplicomphalus* and *C. cf. thurrelli* (Rogov, 2019). These faunas were interpreted as corresponding to the regional Preplicomphalus and Okensis zones of eastern England and Siberia, respectively (Jeletzky, 1984; Rogov, 2019).

Presumed Early Berriasian (“Late Volgian”) *Craspedites (Taimyroceras) canadensis* Jeletzky (1966) from Slidre Fiord, northern Ellesmere Island, appear to indicate a correlation with

the *Craspedites taimyrensis* (Taimyrensis) Zone of northern Siberia (Jeletzky, 1984; Rogov and Zakharov, 2009).

Canadian *Subcraspedites-Craspedites* ammonite assemblages and the overlying single taxon *Craspedites canadensis* (Jeletzky, 1984) appear to correspond to the northern Siberian Okensis - Taimyrensis zones, and the central Russian Fulgens - Nodiger zones (Rogov and Zakharov, 2009). The depiction (Ogg et al., 2016) of their mainly older age compared with the Preplicomphalus Zone in eastern England is particularly interpretive, however, and Wimbledon (2017) placed the Russian Taimyrensis Zone (and equivalent Nodiger Zone) almost entirely within the Cretaceous.

5.1.6. *Buchia* Zones

Species of the bivalve genus *Buchia* have been used for correlation in the J-K interval, within the constraint of their zones encompassing very long stratigraphic intervals and thus having comparatively low resolution. Biozonations are well established in boreal regions such as Siberia (Zakharov, 1987, 1990), as well as in subboreal NE China (Sha and Fürsich, 1993) and the Great Valley of California (Jones *et al.*, 1969: see Zakharov and Rogov (2020) on Grindstone Creek), western and Arctic Canada (Jeletzky, 1984) and the Russian Far East (Urman *et al.*, 2014). Formerly, the *Buchia unshensis* (=Unshensis) Zone was said to have a base exactly coincident with the base of the ammonite Taimyrensis Zone (Rogov and Zakharov, 2009). The Unshensis Zone (and its equivalent zones in other regions) now has a slightly greater vertical extent, covering the latest Tithonian and a large part of Berriasian time: in terms of Siberian ammonite zones, from the Okensis Zone to the Kochi Zone (Schnabl *et al.*, 2015). Thus the J/K boundary would fall in the lower Unshensis Zone.

5.2. The Americas (excluding Arctic Canada)

In the Americas, the resolution of correlations in the Tithonian-Berriasian interval, notably in Mexico and the Andes, has been improved beyond recognition in recent years. However, the great potential of thick marine sequences in California and western Canada is not yet realised (Jones *et al.*, 1969; Jeletzky, 1984). Recent work on palynology, nannofossils, belemnites and magnetostratigraphy of the Great Valley sequence at Elder, Thomes, Watson and Grindstone creeks has still to be published.

In Mexico, early studies had been characterized and dominated by work of endemic ammonites, as with California and the Andes. However, pioneering research on calpionellids by Bonet (1956) was followed by that of Trejo (1960, 1975, 1980) and Adatte *et al.* (1994). More recently, a crop of results from López-Martínez *et al.* (2013b, 2015a, 2015b), from Apulco, Tamazunchale and San José de Iturbide have revealed a full complement of biozones across the Tithonian-Berriasian boundary, with calcareous dinocysts, as well as accessory data on radiometric dates, and, most recently, calcareous nannofossils (Lena *et al.*, 2019).

This widespread evidence refutes uninformed criticisms of the work of Bonet and Trejo, and provides unequivocal correlations with Tethys and the Crassicollaria and Calpionella zones of other regions

In western Cuba, calpionellids were described two decades ago from the Guaniguanico terrane (Pszczółkowski, 1999, Pszczółkowski and Myczyński, 2010), and both calpionellids and nannoconids from the Sierra del Infierno (Pszczółkowski *et al.*, 2005). Latterly, López-Martínez *et al.* (2013a) has given an account of further calpionellid finds in the Sierra Los Organos, debated by Pszczółkowski (2013) and López-Martínez *et al.* (2013c).

The biostratigraphy of the Jurassic-Cretaceous interval in Argentina has been fully discussed by Riccardi (2015). The potential there for the application of calcareous nannofossils in the Neuquén Basin was earlier demonstrated (Concheyro and Bown, 2004), but it has not yet been realized extensively. Early calpionellids finds by Fernandez Carmona and Riccardi (1999) were key, and they were followed by those of Kietzmann (2017: Chitinoidea/Crassicollaria zones), and identification of the Alpina Subzone at Las Loicas (Lopez-Martinez *et al.*, 2017). Those last authors identified both the Crassicollaria and Calpionella zones, with the appearance of predominant small *Calpionella alpina* marking the base of the latter. They noted the same nannofossil taxa bracketing the base of the Alpina Subzone as Vennari *et al.* (2014), and they made that level exactly coincident with the base of the ammonite Noduliferum Zone. More work is anticipated, on longer productive intervals, with more beds yielding calpionellids, and the same is necessary for nannofossils. At Las Loicas, Vennari *et al.* (2014) suggested that calcareous nannofossils in the *Substeueroceeras koeneni* (=Koeneni) Zone could be zoned (zones NJK-A, NJK-B, NJK-C, and lower NJK-D), but this was based on impersistent occurrences of nannofossils (see Nannofossil chapter, and Andes).

Recent key work on palaeomagnetism at Arroyo Loncoche (Argentina) by Iglesia Llanos *et al.* (2016, 2017) is discussed immediately below.

5.2.1. Andes

A Tithonian-Berriasian marine succession is well developed in the foothills of the Andes in west central Argentina, consisting of about 200 to 1700 metres of fossiliferous black shales and micritic limestones, *i.e.* the Vaca Muerta Formation. Ammonites present there were used during the first half of the XXth century (Burckhardt, 1900, 1903; Gerth, 1925; Krantz, 1928; Weaver, 1931; Leanza, 1945; see Riccardi, 2015) to develop a biostratigraphic scheme comprising eight biozones. The most complex study being that of Weaver (1931), based on ammonites collected from different sections along almost 500 km of outcrop.

Since then, new studies on the ammonites have been mainly focused on selected parts of the stratigraphic succession and on specific localities. Thus modern systematic studies on the Upper Tithonian-Berriasian, based on collections coming from carefully sampled sections, distributed through the entire exposed marine succession, are wanting. These circumstances

and the provinciality of the ammonite fauna have made it difficult to make a proper correlation with elements of the standard southern European ammonite biozonation.

In recent years, however, new studies have resulted in the finding of chitinoideids, calpionellids, nannofossils, dinoflagellates and radiolarians, which together with magnetostratigraphy and cyclostratigraphy, all tied to ammonite biostratigraphy, have introduced new possibilities for improving correlations with western Tethys (see Riccardi 2015).

Most recent studies were carried out on only two sections: Las Loicas (Vennari *et al.*, 2014; López Martínez *et al.*, 2017) and Arroyo Loncoche (Kietzmann *et al.*, 2011; Iglesia Llanos *et al.*, 2017; Ivanova and Kietzmann, 2017; Kietzmann, 2017; Kietzmann *et al.*, 2018b), although subsequently other sections were also added (Kietzmann *et al.*, 2018a; Aguirre Urreta *et al.*, 2019). These studies have resulted in some conflicting conclusions on the proposed correlation of the Andean-Tethyan ammonite zones, especially on those assigned to the Tithonian-Berriasian transition (see Kietzmann and Iglesia Llanos, 2018).

This is most probably related to the fact that there have been no modern regional studies of the entire ammonite fauna, and the ammonite identifications for most sections are not backed up by proper systematic studies, and thus the recognition of faunal stratigraphic ranges and biozones is not accurate enough. This comment is valid for the definition of the *Argentiniceras noduliferum* Biozone in the Las Loicas and Loncoche sections and the conflicting correlation between them. That is, with the biozone in magnetozone M19 at the former and M16 at the latter. At Las Loicas, the base of the Noduliferum Zone was defined (Vennari *et al.*, 2014) by an occurrence of *Argentiniceras cf. fasciculatum* (Steuer) - material not figured - 3.4 m above the base of the authors' nannofossil zone NJK-D (see below), although *A. noduliferum*, with material figured, was recorded *circa* 13 m above that base

Later (López Martínez *et al.* (2017, fig. 1) placed the first record of *A. noduliferum* (material not figured) *circa* 6-7 m below the previous record of *A. cf. fasciculatum* and the lower boundary of the biozone was moved down to coincide with the base of nannofossil subzone NJK-D. Further, a previous record of *A. noduliferum?* from a level *circa* 66 m above base was deleted and the lower boundary of the *Spiticeras damesi* (=Damesi) Zone was moved down to a level *circa* 58 m above base. Here it is relevant that referral of the base of the Noduliferum Zone at Las Loicas to the middle of magnetozone M19n (Lopez Martinez *et al.*, 2017, fig. 4) was not based on direct magnetostratigraphic studies, but on nannofossil correlation of the supposedly lower boundary of an ammonite biozonal boundary, whose definition needs to be clarified by a proper study of the ammonite fauna.

In the Loncoche section, the Noduliferum Zone was defined on the occurrence of *A. noduliferum*: this was apparently a single record, not illustrated, and one of two co-occurring long-ranging species (Iglesia Llanos *et al.*, 2017, fig. 2). Here the base and the whole zone were placed in magnetozone M16r, but, again, the ammonite zone was poorly defined.

Further, the associated microfossil evidence is too patchy to be certain of vertical distributions and the recognition of Tethyan bioevents. It is therefore evident, that more

detailed studies are needed in order to arrive at uncontroversial conclusions on the correlation of both macro- and microfauna with J/K sections with better resolution in Tethys, Mexico *etc.*

6. Berriasian Working Group methods, decisions and votes

The background geological facts that allow comparisons of prospective GSSP sites are laid out here, and we summarise below the progression towards making a decision on a GSSP locality. The Berriasian Working Group has held fifteen meetings for the purposes of comparing results, reaching a consensus and making decisions on preferred markers and a GSSP locality (See Appendix 2)

In the traditional J/K boundary interval, there existed several salient prospects for the primary stage marker. The working group in early discussions, considered prospects for fieldwork and the potential of various biotic and magnetic events, essentially in and at the top of magnetozone M19n - where all earlier suggested boundary levels had been located. Their usefulness would depend on their being consistently developed and widespread, and if there were supporting markers to calibrate the prospective level. Those with no concentration of markers and no possibilities for calibration would be disregarded.

At the Milan WG meeting in 2009, the following horizons were considered as salient prospects for study:

- Base of magnetozone M18r
- Base of ammonite Grandis Subzone (Symposium decision 1963)
- Base of magnetosubzone M19n.1r
- Base of calpionellid Alpina Subzone
- Base of ammonite Jacobi Subzone (Symposium decision 1973)
- Base of magnetosubzone M19n.2n

In addition, a suite of calcareous nannofossil events had been suggested as marking the levels of most of the biozone and magnetozone boundaries listed above. These also were subject to examination and testing.

As an aside, the base of the ammonite Occitanica Zone (base of Subalpina Subzone) was previously suggested by Hoedemaeker (1987) as an alternative to the Jacobi Zone. This idea was picked up by some (particularly Russian) authors on the basis that Tethyan taxa of this age had been recorded in Russia. However, the base of the Occitanica Zone, as seen in the Vocontian Basin, for instance, could not be considered as a leading contender because of the impersistent development of its basal subzone, the Subalpina Subzone, in Tethys, not to mention its geographically limited range. This rejection of the Occitanica Zone (and Subalpina Subzone) has latterly been endorsed by Hoedemaeker (Hoedemaeker *et al.*, 2016). In the Russian region most closely bordering Tethys, the Caucasus, the Cretaceous is interpreted as starting with a sub-Occitanica unconformity (Sey and Kalacheva, 2000), but with no Subalpina assemblage present, and on the Russian Platform ammonites have thus far

not been proven convincingly to have precise affinities with French or other Tethyan Occitanica Zone taxa (Frau *et al.*, 2016b; Frau *et al.*, in press)

In our early Working Group discussions, the magnetic subzone M19n.1r was ruled out as a prospective primary marker because it is such a very short subzone, and thus difficult to locate. It was agreed that the bases of M19n and M18r would be assessed as candidates, and biotic markers sought that coincided with them. The result of this would remain unclear until a reasonable number of localities had been documented. At the outset it appeared that no calpionellid zone or event coincided with either magnetozone, but that had to be shown for nannofossils and ammonites. To date, site documentation has proven that at only two sites (Puerto Escaño - Pruner *et al.*, 2010; Le Chouet - Wimbledon *et al.*, 2013) is the Jacobi Subzone's base demonstrably close to or at the base of magnetozone M19n. Further, it has been shown that no nannofossil has its FO at the base of either M19n or M18r (summarised Wimbledon, 2017; see nannofossil zones). Species of nannofossil previously recorded at or close to the base of M18r are now seen to have their earliest FOs in M19n (Fig. 2).

Salient amongst fossil markers were the two levels based on ammonites, selected by successive international conferences, the Grandis Subzone (1963 colloquium) and the Jacobi Subzone (1973 colloquium), and the base of the calpionellid Alpina Subzone, which in recent decades has largely replaced any ammonite datum as the primary marker in multiple publications. These have already been discussed above. The problems with definition of the base of the Jacobi Zone, and the identification and vertical range of the nominal index (*Strambergella jacobi*) have been fully discussed (Frau *et al.*, 2016b). The Grandis Subzone is discussed in the Ammonite chapter herein. Suffice it to say that, in documenting dozens of localities (and literature sources), we have not found it possible to easily define either subzone in a clear-cut fashion and in the traditional way. This only discusses sequences that yield ammonites: the lack of ammonites in multiple key sections across Tethys has made them even less of an option for stage definition.

At multiple WG meetings we have re-affirmed our early decision that the group should seek a GSSP that yielded, at least, ammonites, calpionellids, nannofossils and magnetostratigraphy, so as to give the greatest correlation potential. This opinion was last confirmed during our meeting at the Vienna Cretaceous Symposium in 2017.

These investigations, results and conclusions led the Working Group to the determination that the consensus of recent years was correct: that a calpionellid datum linked to magnetostratigraphy, and supported by nannofossils and ammonites, where present, was the best option to define the stage base. The fact that the group had documented and assessed so many localities gave the assurance that this conclusion was founded on the strongest factual basis. By the time of our 2014 WG meeting in Warsaw, there was a clear consensus that *Calpionella alpina* was the best candidate as a primary stage marker (Wimbledon, 2014).

In summary, the correlative framework for the base of the Berriasian can be shown as in Figure 6. This is the latest iteration of the table, the earliest (2011) version of which was used

by Gradstein *et al.* 2013. In the latest version, a range of fossil groups are used for definition of the boundary: calpionellids, supported by calcareous nannofossils, ammonites, belemnites and radiolaria. The widespread level chosen as the primary marker for the stage base is the base of the Alpina Subzone (and the calpionellid turnover it indicates) in mid M19n.2n, and it is closely matched by the FO of *Nannoconus steinmannii minor*. Several taxa of nannofossil (*N. wintereri*, *H. strictus*, *C. cuvillieri* and *N. globulus globulus*) make their first appearances just below, in M19n.2n. The base of the subzone is precisely dated in the Andes, at 140.22 ± 0.14 Ma. In boreal and subboreal basins the *Arctoteuthis tehamaensis* Zone has its base in the middle of M19n.2n. This and the base of radiolarian zone UZ 14, close above the base of the Alpina Subzone, provide widespread key proxies for the primary stage marker. And though the basal ammonites of the Jacobi Zone cannot be helpful in defining a mid-M19n.2n boundary, the first appearance of *Delphinella* there already provides a useful surrogate for the Alpina base in western Tethys; and it is hoped this observation may be extended to other regions where the genus has been recorded.

6.1.1 Selection of the primary marker for the base of the Berriasian Stage- June 2016

In 2016, after documentation and consideration of sites in Europe, North Africa, North and South America and Asia, the Berriasian Working Group held a formal vote. The proposal was that the base of the *Calpionella alpina* Zone be selected as the primary marker for the Tithonian/Berriasian boundary. This level was proposed on the judgement that it provided the best marker, and one that it allowed correlation over the greatest part of the globe. 75 people voted: with 2 abstaining, 16 voting “no” and 57 voting “yes”. That is, a 76% majority.

6.1.2. Kroměříž meeting - May 2018

The purpose of this meeting was to consider a shortlist of contender GSSP candidates. After individual presentations on particular sites, consideration of the International Commission on Stratigraphy’s guidelines for selection of chronostratigraphic units, and mention of the already agreed parameters for a preferred Berriasian GSSP, there followed a discussion of localities showing a good magnetostratigraphic record and the calpionellid primary marker, (small orbicular) *C. alpina*, with supporting nannofossil and ammonite datums. Key documented localities were demonstrated in Tithonian/Berriasian correlation charts. The discussion, in particular, included mention of the locality of Berrias, and the more useful localities of Puerto Escaño, Brodno, Fiume Bosso, the Drôme/Hautes-Alpes (Vocontian Basin) plexus of complementary sites (Tré Maroua , Le Chouet, Font de St Bertrand, Haute Beaume, and Charens), Torre de’ Busi, Rio Argos, and Kurovice. The pros and cons of these localities, some of which had been recently published, were discussed, and are (briefly) as follows.

The locality of Berrias was earlier ruled out as a contender: the outcrop ends before the base of either the Alpina Subzone or the ammonite Jacobi Zone is reached: though the site is still being studied by the Working Group for the upper Lower, Middle and Upper Berriasian. The

adverse *rosso ammonitico* facies at Puerto Escaño were noted, as were earlier comments (C. Casellato) about the condensation of the FADs of nannofossil marker species, supported in the discussion (K. Stoykova), though the very good palaeontological record still was emphasised (M. Košťák). Brodno is well documented, but had been understood since our earliest WG meetings to lack much of magnetozone M18r, and to have a weaker record of nannofossils in the upper part of M19n. Fiume Bosso remained a strong contender: there calpionellids have been re-collected and revised in the Chitinoidea-Ferasini interval described by Houša et al. (2004), and a nannofossil revision was at the time still in progress. The top and base of the Alpina Subzone show slight changes in position from those published previously. Torre de' Busi appeared to be a good prospect in 2010, but its calpionellid zonation shows some aberrant features, notably the very high placing of the base of the Alpina Subzone. The Vocontian plexus of sites are geographically closely spaced and show a detailed composite record, with good calpionellid preservation, essentially showing the same Tithonian-Berriasian facies succession and overlapping stratigraphic intervals within the pre-Chitinoidea Zone to Oblonga Subzone biozonal range so far documented. The need for description of the local sedimentary context was stressed (Grabowski), and the fact that Haute Beaume (near to Le Chouet) lacks breccias, as does most of the more distant Tré Maroua section was noted (C. Frau).

Two sites where great hopes were entertained in earlier times have proved to be a considerable disappointment: Theodosia, because, though it has ammonites, nannofossils and magnetostratigraphy, no coherent calpionellid zonation can be constructed; whereas Rio Argos yields ammonites, nannofossils and calpionellids, but is entirely remagnetised. Kurovice shows a good fossil record, though it has three tectonised intervals which closely bracket the calpionellid Alpina zonal base, and it lacks ammonites (M. Košťák); calpionellid preservation is poorer than, for instance, France (D. Reháková).

Veliky Kamianets, then being documented, was also mentioned (J. Grabowski): though some uncertainty over the position of the Alpina/Ferasini subzonal boundary meant that it did not qualify as a contender site.

Therefore, in summary, Berrias (France), Theodosia (Ukraine), Torre de' Busi (Italy), Brodno (Slovakia) and Rio Argos (Spain) were considered less suitable; Fiume Bosso (Italy) and the Vocontian Basin sites (France) were judged to be better candidates; and question marks remained over the localities of Puerto Escaño and Kurovice.

This is tabulated below:

	Pros	Cons
Theodosia	nannos, ammonites, magnetostrat (M19n.1r, M18r)	No calpionellid zonation, base of Alpina Sbz. and M19n not detected
Rio Argos	calpionellids, nannos, ammonites	No magnetostrat. - remagnetised
Torre de' Busi	nannos, calpionellids, magnetostrat. (M19r, M19n.1r and M18r)	Alpina Sbz. base in M19n.1n is anomalous. No ammonites

Brodno	calpionellids, nannos, magnetostrat. (M19r, M19n.1r)	Incomplete M18R, Limited nannofossil record
Puerto Escaño	ammonites, nannos, calpionellids magnetostrat. (M19r, M19n.1r and M18r)	Rosso Ammonitico facies Compressed nannofossil FADs
Kurovice	calpionellids, nannos, magnetostrat. (M19r, M19n.1r and M18r)	Tectonics in Alpina Sbz. No ammonites. Limited outcrop.
Fiume Bosso	calpionellids, nannos, magnetostrat (M19r, M19n.1r and M18r)	No ammonites Nannofossil revision in progress
Drôme/Hautes-Alpes composite	calpionellids, nannos, ammonites, magnetostrat. (M19r, M19n.1r and M18r)	M19r unproved at Tré Maroua, but M19n.1r is present

Subsequent to the group discussion, J. Grabowski wrote suggesting we should include mention of a site not proposed and discussed at the Kroměříž business meeting - Lókút, and P. Pruner suggested another - Nutzhof. And these additional notes in the same format were circulated to the Working Group.

	Pros	Cons
Lókút	calpionellids, nannos, magnetostrat. (M19r, M19n.1r)	Top of Alpina sbz. not detected. Incomplete M18r. No ammonites. Late FADs for key nannofossil markers. Poor outcrop.
Nutzhof	calpionellids, nannos, magnetostrat. (M19r, M19n.1r, M18r)	Abnormally thin M19n.2n. No ammonites. Abnormal level of base of Elliptica Sbz. in M18r. Late FADs for key nannofossil markers.

In the consultation of the whole group that followed, no adverse comment was lodged on the shortlisting of Fiume Bosso and the Vocontian Basin sites as the rival GSSP contenders. In conclusion, it is perhaps worth stating that during the consultation on the GSSP vote, no other site from any other region was suggested or proposed.

6.1.3. GSSP vote

By May 2019 documentation of Fiume Bosso and Tré Maroua (with complementary local sites) had been completed, and a one-month consultation was held within the Working Group to consider the site data that had been circulated. Next followed a one-month voting period. In the ballot, 52 people voted: with 5 abstaining, 9 voting for Fiume Bosso and 38 voting for Tré Maroua. That is, a 73% majority.

The documentation available on Tré Maroua will be presented in Part 2 of this work.

Acknowledgements:

Though this proposal focuses on a particular chosen site, the conclusions drawn here are based on work over the course of ten years, at many localities by many friends in the Berriasian WG and outside. It is the greatest pleasure to acknowledge their indispensable contributions and to sincerely thank them for this and the many publications cited below. It is impossible to put into words the debt owed to so many dear colleagues for their positive comradeship in discussion, in the writing of publications, in the lab and in the field.

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Figure captions

Fig 1. Early Berriasian palaeogeography.

Tithonian-Berriasian localities: A – Apulco, AA – Argo Abyss, AL – Arroyo Loncoche, B – Berrias, Bo – Fiume Bosso, D – Durlston Bay, Er – Eriksdal, E – Ellesmere Island, ET – East Timor, G – Grand Banks, Ga – Garagu, GL – Graham Land, Gr – Grindstone Creek, U – Ussuri Bay, H – Honshu, K – Kurovice, L – Liaoning, LO – Los Organos, M – Milne Land, Ma – Maurynya, N – Nagirze, No – Nordvik, O – Oman, P – Puerto Escaño, S – Shal, SK – Sidi Khalif, Sv – Svalbard, TP – Tepe Kel, Th – Theodosia, T – Tré Maroua, Y – Yemen.

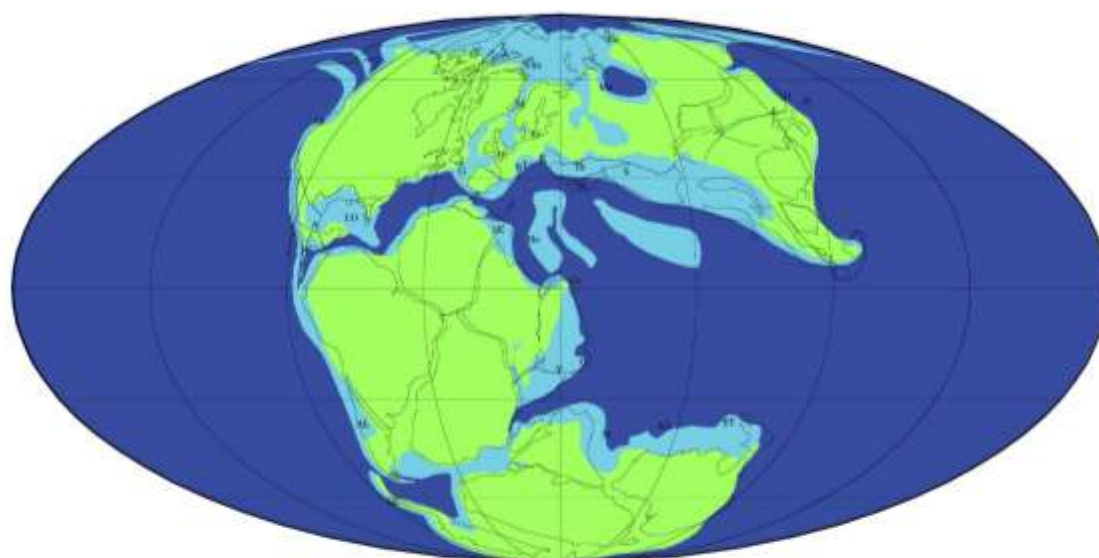


Fig. 2. Calcareous nannofossil FOs against magnetostratigraphy and calpionellid and ammonite biozonations (modified from Wimbledon, 2017, and bibliographic sources given therein, plus Wimbledon *et al.*, 2020). Abbreviations of biozones: Chitin – Chitinoidella; Rem - Remanei; Inter - Intermedia.

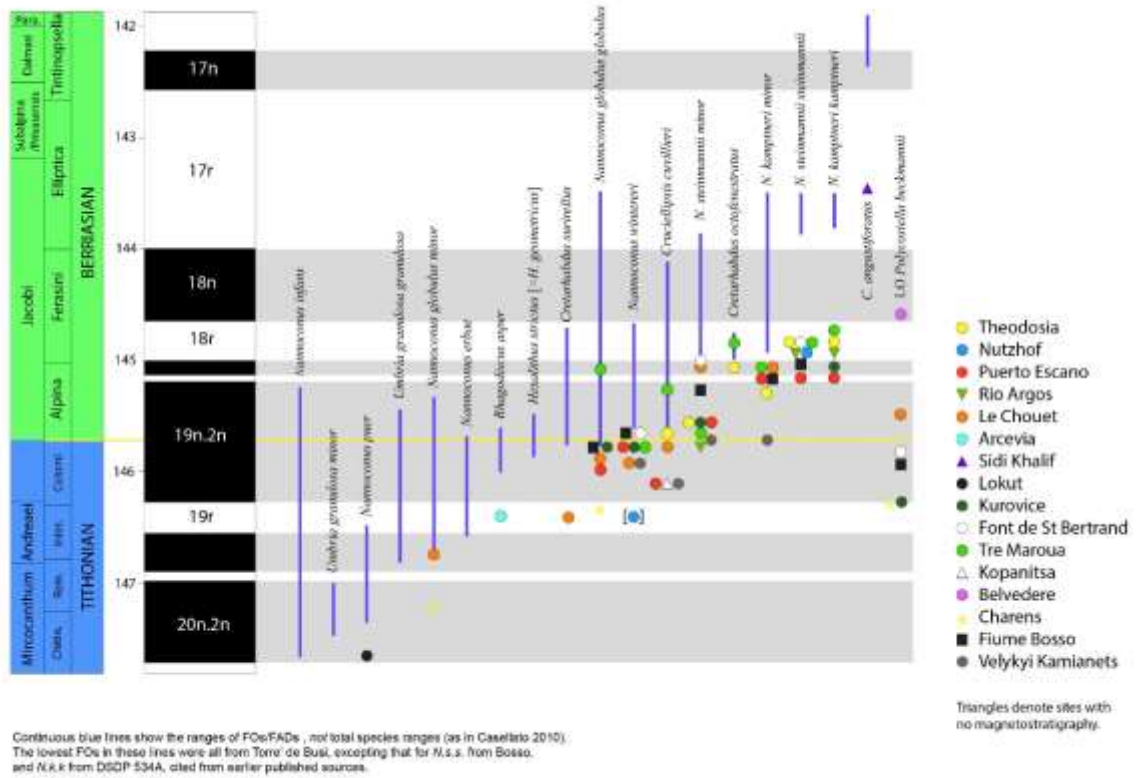


Fig. 3. Comparison of magnetozones, ammonite and calpionellid biozones and nannofossil FOs at Tré Maroua, Le Chouet, Charens, Saint Bertrand and Haute Beume (Belvedere).

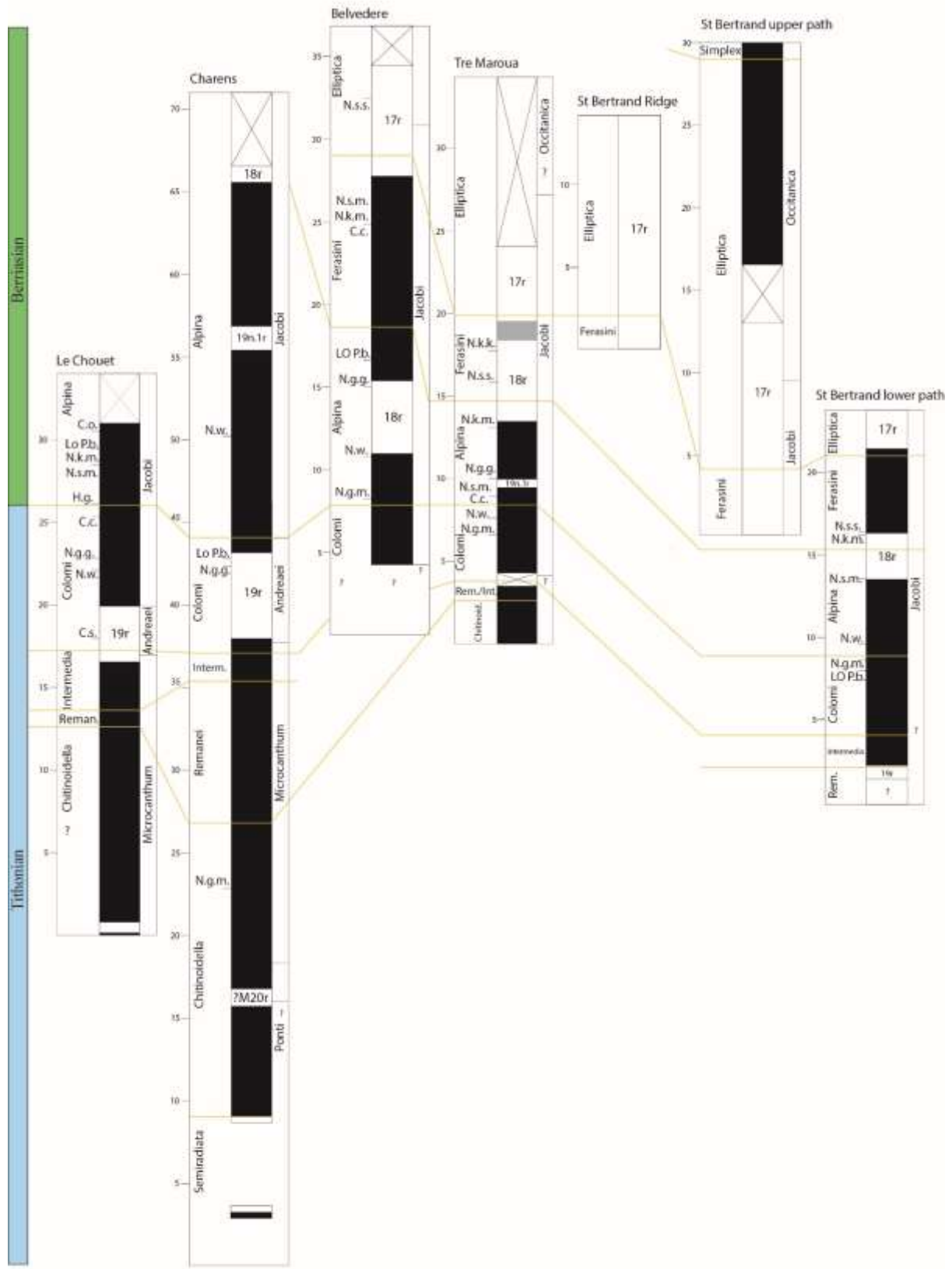


Fig. 4. Ranges of key taxa of organic-walled dinoflagellate cysts close to the Jurassic/Cretaceous boundary against calpionellid and ammonite zonation in the Vocontian Basin, Dorset, North Sea, Carpathians, northern Bulgaria, and Volga (compiled from Monteil (1992, 1993), Hunt (2004), Abbink *et al.* (2001b), Skupien and Doupovcova (2019), Dodekova (2004), and Harding *et al.* (2011)). It should be noted that the equivalence of the timescales between regions is an approximation.

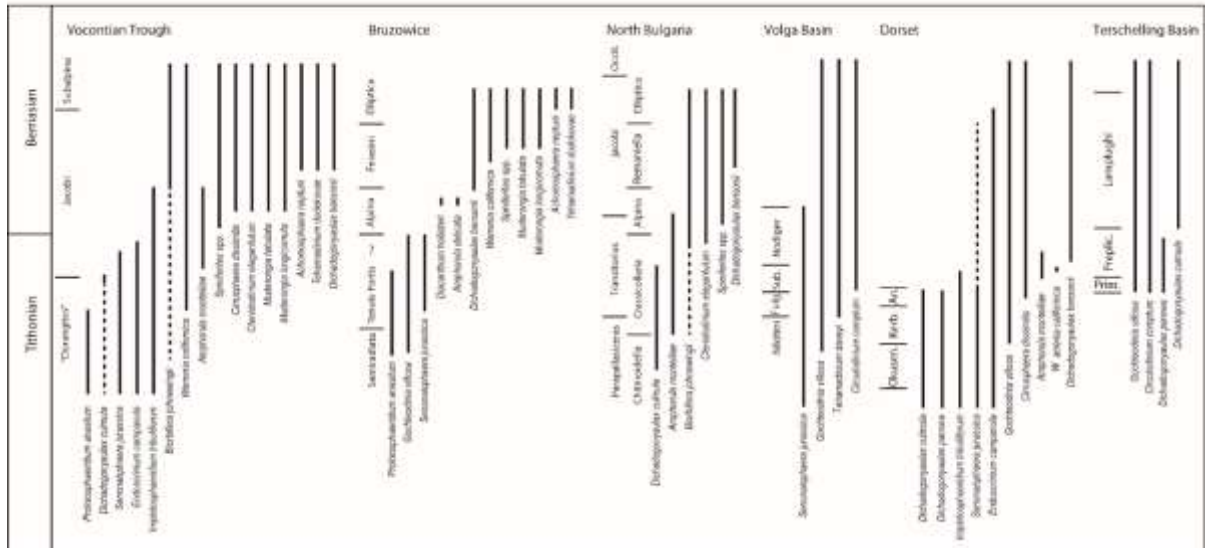
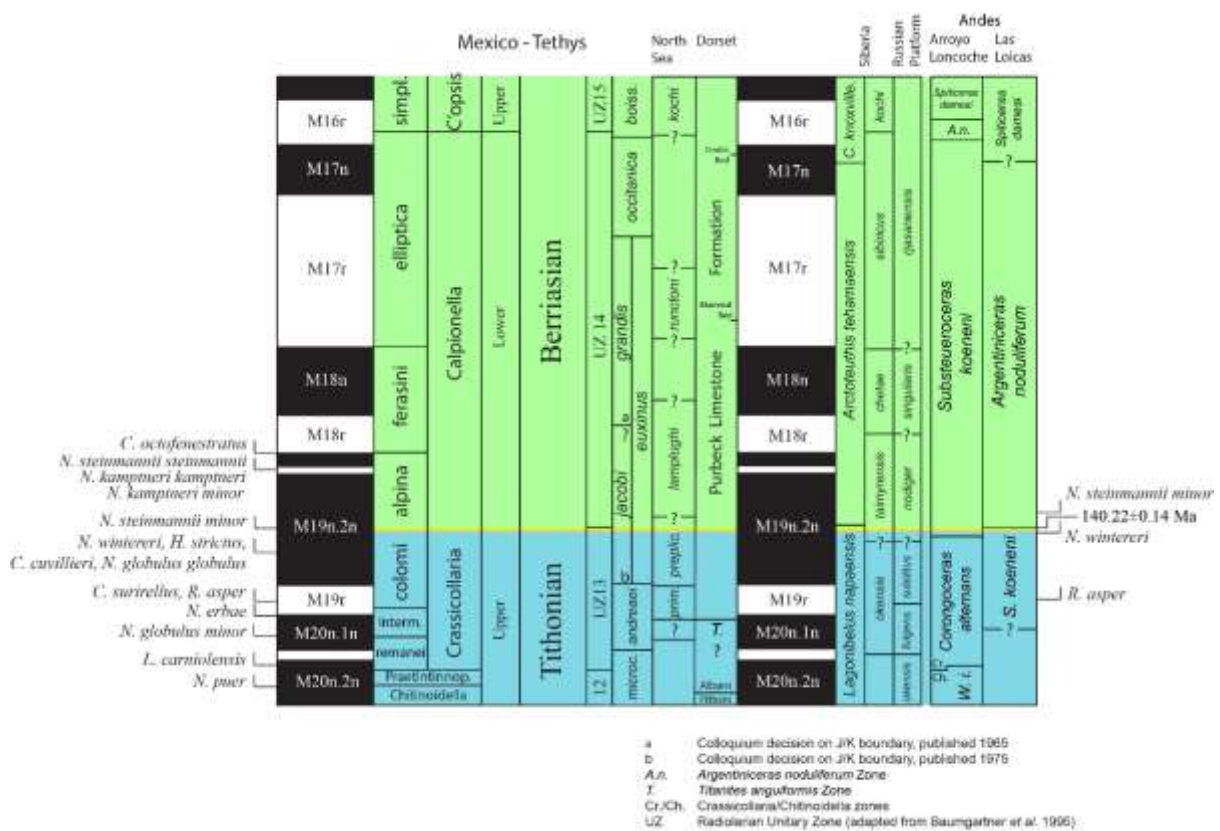


Fig. 5. Radiometric dating in the J/K boundary interval.

1, 3, 4, 5, 7, 8. after Lena *et al.*, 2019; 2. Pessagno *et al.*, 2009; 6. López-Martínez *et al.*, 2015; 9. Vennari *et al.*, 2014; 10. Gradstein *et al.*, 2012, modified after Mahoney *et al.*, 2005; 11. Liu *et al.*, 2013; 12. Bralower *et al.*, 1990.

Stage	Biostratigraphy	Geological Context	Numerical Age (Ma)	Dating Method
Berriasian lower	Infracretacea Zone	Great Valley Sequence, Grindstone Creek, California (12)	137.1±0.6	U-Pb, ID-TIMS
	early Berriasian nannofossils	Sangxiu Fm., Tibet (11)	140-142	U-Pb, SIMS
	?	Basaltic intrusion in M19 sediments, Shatsky Rise (10)	145.5±0.8	Ar-Ar
	upper Noduliferum Zone	Vaca Muerta Fm., Las Loicas, Argentina (9)	139.55±0.03	U-Pb, CA-ID-TIMS
	upper Noduliferum Zone	Vaca Muerta Fm., Las Loicas (8)	139.238±0.049	U-Pb, CA-ID-TIMS
	Elliptica Subzone	Pimienta Fm., Mexico (7)	140.512±0.031	U-Pb, CA-ID-TIMS
	Ferasini to Alpina Subzones	Pimienta Fm., Mexico (6)	139.1±2.6	U-Pb, LA-ICP-MS
Tithonian lower	base Alpina Subzone	Vaca Muerta Fm., Las Loicas (5)	140.22±0.13	U-Pb, CA-ID-TIMS
	& base Noduliferum Zone			
	Koeneri Zone & FO R. asper	Vaca Muerta Fm., Las Loicas (4)	140.6±0.4	U-Pb, CA-ID-TIMS
Tithonian upper	Koeneri Zone	Vaca Muerta Fm., Las Loicas (3)	141.31±0.56	U-Pb, CA-ID-TIMS
	& FO U. granulosa			
	Buchia piochii Zone	La Désirade Igneous complex (2)	143.734±0.060	U-Pb, CA-ID-TIMS
	Andesensis Zone	Vaca Muerta Fm., La Yesera, Argentina (1)	147.112±0.078	U-Pb, CA-ID-TIMS

Fig. 6. Correlative framework for the Upper Tithonian to Berriasian interval, with directly correlatable primary and secondary markers for the boundary level indicated, as well as proxies.



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Appendix 1 – Localities studied by the Berriasian WG

Argentina	Las Loicas Arroyo Loncoche
Bulgaria	Barlya Berende Kopanitsa Gintsi
California	Elder Creek Grindstone Creek Thomes Creek Watson Creek Hull Road
Czech Rep.	Kurovice Štramberk
France	Le Chouet Font de St Bertrand Charens Haute Beaume Tré Maroua Berrias
Hungary	Lókút
Iraq	Garagu Banik
Iran	Shal
Italy	Torre de' Busi Fonte de Giordano Fiume Bosso Arcevia (Col Santino) (Cortese quarry)
Mexico	Apulco Mazatepec San Jose de Iturbide Tamazanchule St Mateus, Zacatecas San Pedro de Gallo

Russia	Ussuri Bay Nordvik River Maurynya River Yatria Gorodishche Kashpir
Slovakia	Strapkova Brodno Hlboča Snežnica
Spain	Puerto Escaño Rio Argos
Tibet	Tingri Gyangze Nagarze
Tunisia	Beni Kleb Sidi Kralif Rheouis
Poland	Pośredni
Ukraine	Theodosia Ili Burnu Krasnosilivka Yuzhnoe Velykyi Kamianets Balki
Yemen	Wadi Arus Mintaq Salt Dome
Australia	Broome peninsula
China	Beipiao, (western Liaoning) Pingquan (northern Hebei)
UK	Durlston Bay Mupe Bay Lulworth Cove Portland quarries Freshwater Bay

Appendix 2 - Locations and dates of Berriasian Working Group meetings

2007 - Bristol (United Kingdom) - working group first convened
2008 - Marseille (France)
2009 - Milan (Italy) and Plymouth (United Kingdom)
2010 - Smolenice (Slovakia) and Paris (France)
2011 - Sofia (Bulgaria)
2012 - Tunis (Tunisia) and Prague (Czech Republic)
2013 - Warsaw (Poland)
2014 – Copenhagen (cancelled)
2015 - St Privat, Gard (France)
2016 - Smolenice (Slovakia)
2017 - Vienna(Austria) (part of the Vienna Cretaceous Symposium)
2018 - Kroměříž (Czech Republic)
2019 - Bratislava (Slovakia)