Report on the revised version of the manuscript: "Cross-continental age calibration of the Jurassic/Cretaceous boundary"

Dear Handling Editor Silvia Gardin,

Structure of the Report on the revised manuscript version

Firstly, we present a bullet point list of all the relevant modifications made to the manuscript we felt would improve the manuscript. Other comments by the reviewers that we disagree or felt were inadequate where left out and we await the decision of the Editor and Handling Editor. Secondly, we present a point-by-point modifications relative to the reviewers comments structured as follows: (1)reviewer comment; (2) author reply; (3) author modification, starting with comments from reviewer #1 W. Wimbledon and subsequently reviewer #2 J. Pálfy. Reviewer's comments are in *italic* blue font, our reply in **black** regular font, and modification as in green regular font respectively. A marked up version of the manuscript to better aid the Editors and reviewers in proof the revised version. The revised Supplementary Material is also in this report. All modifications to the manuscript and Supplementary Material are high-lighted in green.

Main modifications

1. We have addressed the comment 2.13 which suggested that we compare out estimates for the duration for the Tithonian with that of the independent duration estimates of the Pacific M sequence of magnetic anomalies of Malinverno et al. (2012). This was incorporated into section 4.3.
2. The affirmation of that in p.6. 25 that there was a formal definition of the Kimmeridgian and Tithonian boundary was removed as suggested in comment 2.11

3. We have incorporated the suggestion by reviewer J. Pálfy in his comments 2.1 and 2.14 (see author's reply). As the reviewer suggested, we have refocused part of our discussion (section 4.5) to the embrace the mismatch between the ages of the JKB in the dated sections and discuss the pitfalls of regional and global biostratigraphical correlation. To accommodate the reviewers suggestion in comment 2.1 and 2.14 we have completely rewritten section 4.5.
4. In the interest of addressing the comments 2.9 and 1.2 which questioned the magnetostratigraphic correlation between Las Loicas and Arroyo Loconche, we have completely removed the correlation between both sections, since both reviewers took issues and we felt better to remove it from the manuscript.
5. Comment 2.15 was also addressed and incorporated into the *new* section 4.5
6. Comments 2.16 and 1.14. The concept of the JK interval was rephrased and explained the reasoning behind and can be found in section 4.5.
7. We have added a 4.6 section entitled: "A case for a younger J/K boundary age" where we specifically address our data and data from other publications that show that the age of the JKB is much younger than the one found in the ICS and the fragility of the biostratigraphy under which the ICS JKB age is grounded on.
8. We have written the section 5. Summary and conclusions to accommodate the new refocusing of sections 4.5 and 4.6
9. Figure 1: Title was modified; "distribution of continents" was replaced by "global paleogeography". We did not use a different base map, since no justification from the reviewer mas made as to why the maps map should be changed. Nor a suggestion as of which base map should be used. Migratory routes were left in the map because we do suggest that the rate migratory routes could be a possible explanation to the difference in age between Las Loicas and Mazatepec. Section that were not in the study were left in to convey the idea that the these section are contemporaneous.

10. Figure 2: Berriasian spelling was corrected. Fonts were made smaller, as requested; number of grain in LL10 was changed to 4 instead of 6.
11. Figure 3: We have not removed taxon names since we see this is a common practice in many publications. Additionally, the caption figure was rewritten to accommodate reviewer #2 requets to have the taxon names in the figures caption.
12. Figure 4: Names of species were corrected as pointed out. Some species names were uncapitalized and steinmannii spelling was corrected. A dashed green line was put in to connect and high-light the mismatch between Las Loicas and Mazapetec. Stage names were added to every section, i.e., Tithonian, Berriasian. References were put at the top of each panel to make clear what is being cited and what is not, although also in the caption figure, to address comment 2.3. Arroyo Loconche section from Iglesias Llanos et al., (2017) was removed from the figure as well as the manuscript and the templates were renamed accordingly throughout the manuscript.
13. Renaming of the Figure 4 was were carried out throughout the manuscript to coincide with the new figure 4
14. Supplementary Material: We have added the calcareous nannofossil chart to the Supplementary Material, now named F.S1, as pointed out in comment 2.5.

Modifications to the manuscript with respect to the comments by reviewer W. Wimbledon (reviewer #1) on the manuscript "Cross-continental age calibration of the Jurassic/Cretaceous boundary"

General Stratigraphic remarks – Magnetostratigraphy

1.1) The text should perhaps say that there is no possibility of magnetic calibration of Las Loicas with the many Tethyan sites where it has been documented.

A subset of the authors are pursuing the magnetic calibration in Las Loicas. The preliminary sampling has already been done, and some results are available yet not published. The main obstacle is that the basinal facies in Las Loicas which makes it difficult to have a dense suitable sampling for magnetostratigraphy. Therefore, efforts are being made to overcome this issue. Please see reply to comment 1.2 and 2.9 (i.e., in reply to reviewer #2 J. Pálfy) for further clarification on our attempt to correlate the magnetostratigraphic data from Arroyo Loconche with Las Loicas.

MODIFICATION: No modification was made since we feel we have answered this comment.

1.2) the ammonite zonations applied at the LL and AL do not agree – a big problem.

It needs to be made clear that we do not present any new magnetostratigraphic data, but instead use the magnetostratigraphy of Iglesias 2017 to aid marginally and back-up our age of the JKB in Las Loicas. Magnetostratigraphy is not the focus of the paper nor did we state in the manuscript that we aimed to do that, but rather an aside. Meaning, we use it as a reflection on how other substantial evidence for the JKB from the Neuquen Basin might agree with our data. We recognize that magnetostratigraphy is a significant component in calibrating and locating the JKB in sections that span the JKB. However, we are fully aware of the seemingly conflicting evidence from the ammonite zonation from Arroyo Loncoche and Las Loicas. We clearly stated that the ammonite zonation in Arroyo Loncoche is preliminary and also cited a discussion around the matter in López-Martínez et al. (2018). The main point discussed in López-Martínez et al. (2018) is that both discussions contain the different resolution of data. The ammonite biostratigraphy of Las Loicas is based on the bed by bed collection from 54 fossiliferous levels with 450 ammonite specimens. López-Martínez et al. (2017 Fig. 1) and Vennari et al. (2014) recorded 35 fossiliferous levels and studied 228 ammonite specimens. Therefore, we feel that the ammonite zonations in Las Loicas is well-defined and described.

On the other hand, in the Arroyo Loncoche region there is not a single published section with the ammonite levels, or the number of specimens collected, which renders the definition of the biozones unreliable. It is also evident that the boundaries of the biozones in Arroyo Loncoche have been changing along the years, as well as unit thickness, the presence of sills, etc. We invite the reviewer to take a closer look at the discussion in Lopez-Martinez et al. 2018 but include here an extraction from the paper to illustrate the issue. Iglesia Llanos et al. (2017), p. 194 state that "*The boundary between ammonite zones in Arroyo Loncoche was placed according to the first occurrence of the index species*." However, the range chart with vertical distribution of the taxa (their Fig. 2) and the ammonite biozones do not follow this criterion. For instance, the base of the Corongoceras alternans zone is placed at the first occurrence of *Corongoceras* sp. and the index species is not even recorded in this section. Furthermore, the base of the Substeueroceras koeneni zone is placed on the first occurrence of *Substeueroceras* sp. (at 150m of the base of the section) while the index species appears higher (above 180 m). This more than 30m discrepancy explains the different biozonation of the same section published by Kietzmann et al. (2011 Fig. 3) where they placed the base of the Substeueroceras koeneni zone at 190 m of the base of the Arroyo Loncoche section**. Lastly, it is important to point out that in the absence of a reliable biostratigraphic framework, such as the case of Arroyo Loconche, magnetostratigraphy is just a floating scale.**

In conclusion, the paper aims to calibrate the numerical age of the JKB using high-precision geochronology in Las Loicas and Mazatepec using the base on the base of the Calpionella alpine zone as the primary marker for the JKB. In Figure 4, we correlate the JKB Arroyo Loconche and Las Loicas based on more compelling evidence for the JKB which is the M19.2n (Arroyo Loconche) and the base of the Calpionella alpine Subzone (Las Loicas). Therefore, we avoided normalizing the two sections based on ammonite. Incidentally, in his 2017 review of the JKB, W. Wimbledon (Wimbledon, 2017) has also normalized Las Loicas and Arroyo Loncoche disregarding the apparent mismatch of the ammonite zones in the working model for correlating the regions for the JKB. Furthermore, in our Figure 4, the correlation between the M19.2n in Arroyo Loncoche and the base of the Calpionella alpine subzone in Las Loicas is a dashed red line, which suggests that the correlation is merely conjectural. As W. Wimbledon pointed out, Phanerozoic stage boundaries are not dependent on geochemistry, magnetostratigraphy or geochronology. These are just tools used to aid the calibration of stage boundaries, and mismatches are commonplace. Therefore, we do not see this first point as a big problem. The reviewer #2, J. Pálfy, also took an issue with this matter. We kindly ask the reviewer to also read the reply on comment 2.9 (i.e., in reply reviewer #2). Hopefully, it will supplement this reply and vice-versa.

MODIFICATION: We have removed the correlation of the magnetostratigraphy within the Neuquen Basin between Las Loicas and Arroyo Loconche since both reviewers took issue with our approach, and we acknowledge that there are many issues with the ammonite zonation in Iglesias Llanos et al., (2017)

1.3) The calpionellid assemblage noted at Las Loicas is anomalous: such a mixed assemblage (with apparently derived Tithonian calpionellids) does not define or mark the base of the Berriasian. It should be made clear what is definitively lower Berriasian and what is not.

First, it is essential to recognize that sections containing datable horizons close to boundaries, such as the Las Loicas and Mazatepec, are extremely rare which is a significant hindrance in calibrating the age of stage boundaries in general. Tethyan and Mediterranean sections do not contain datable horizons, because these sections are deposited in passive margins far from plate tectonic boundaries where a considerable amount of acidic-aerial volcanism output is produced allowing for the deposition of ash fall deposits (ash beds). Therefore, even though the issues surrounding the JKB have been concentrated in the Tethys region, its age, on the other hand, will not. Although the reviewer claims that the Las Loicas contains "anomalous" calpionellid assemblages, if we are ever to advance in the knowledge of the numerical age of the JKB, we have to use everything at our disposal.

Replying to the reviewer's comments, the only reported "anomalies" in Las Loicas are a) he presence of *Tintinnopsella remanei* in the upper part of the Crassicollaria Zone. This is a none typical appearance in the Mediterranean Tethys, but usual in western Tethys as discussed in López-Martínez et al., (2017), and b) the record of *Crassicollaria massutiniana* in the lowermost part of the Alpina Subzone. Even when it can be unusual the presence of this species in the Lowermost Berriasian, this does not affect the biozonation scheme as the Alpina Subzone is defined by the acme of *Calpionella alpina* small and globular form and not the Last Occurrence of any species. Then, the Alpina Subzone is defined in the same way as in the Mediterranean Tethys and can be used as a marker of the JKB in Las Loicas.

MODIFICATION: No modification was made since we feel we have answered this comment.

1.4) The nannofossil literature cited as the justification for some of the text's discussion and conclusions is rather old - Bralower and Casellato references are now 10 -30 years old. Many Tethyan sites have since been documented, and that make some of the species FADS and the zones discussed obsolete. Some Italian localities cited in the text are seen as anomalous in the positions of their nannofossil FADs. Thus it is not clear why these localities are selected by the authors for comparison with the LL and M sites, especially when they are not the best/most representative.

We, unfortunately, have to disagree with this comment. There are two standard calcareous nannofossils zonations for the studied interval. (Bralower et al., 1989) proposed a calcareous nannofossil zonation for the Jurassic and Cretaceous based on southern European land sections and the western North Atlantic, DSDP Sites 391C and 534A. (Casellato, 2010) proposed a new calcareous nannofossil biostratigraphic scheme for the Tithonian–Early Berriasian established for the Southern Alps in Northern Italy. Even though many recent papers deal with nannofossils of this time interval, there are no new zonations for this interval. Therefore, these two papers form the basis for newer studies, with many of the recent publications still citing the zonation in the classic papers of Bralower et al. (1989) and Casellato (2010). We agree with the reviewer that these publications might be considered old, but in no way, shape, or form, can they be considered outdated or overtaken since the zonation presented in them form the basis of the more recent works on calcareous nannofossils zonation of this period.

To illustrate, we take the liberty of copying below excerpts from the newer publications on calcareous nannofossil of this period that promptly cite the work of Bralower et al. (1989) and Casellato (2010), as we have.

a) Grabowski et al., (2017). Sedimentary Geology 360, p. 57, state:

"*For biostratigraphic purposes, the available biostratigraphic schemes of Bralower et al. (1989), Bown and Cooper (1998) and Casellato (2010) were considered. The latter was selected to apply for the Lókút section, as the most appropriate for nannofossil record in this Tethys location*".

b) Hoedemaeker et al. 2016. Revue de Paleobiologie 35, p. 190, state:

"*CALCAREOUS NANNOFOSSILS (C. E. Casellato and S. Gardin)…. Calcareous nannofossils are rare to common and poorly to well preserved, with overgrowth more pervasive than etching. Assemblages are of Tethyan affinity ……(and) the biostratigraphic schemes adopted in this study are those of Bralower et al. (1989) and Casellato (2010)….*"

c) Ogg et al., (2012). A Concise Time Scale, p. 170, state:

Use for defining the JK boundary in the Mediterranean Tethys similar FOs of calcareous nannofossils as those used in our paper (fig. 13.2.).

d) Schnabl et al., (2015). Geologica Carpathica 66, p. 491, state:

"*For several generations, apart from occasional aberrations, definitions of a J/K boundary have focused on one interval, between the base and top of one ammonite subzone (that of Berriasella jacobi), and, in the last thirty years, more and more, on the widespread and more consistently recognized turnover from Crassicollaria assemblages to small Calpionella…. Latterly this has been widely reinforced by the use of calcareous nannofossil FADs (references in Casellato 2010).*"

e) Sbodova and Kotsak 2016. Geologica Carpathica 67, p. 225 state:

"*Biostratigraphic data were interpreted with reference to the nannofossil zonation of Casellato (2010), commonly used for the Upper Jurassic and the Lower Cretaceous in the Tethyan/Mediterranean area".*

Regarding some anomalous positions of the nannofossils. p. 231. "*It should be noted, that the LO of N. kamptneri minor usually appears a little above the LO of N. steinmannii minor, but in this paper it occurs together with the LOs of N. steinmannii steinmannii and N. kamptneri kampteri in bed 35. This anomaly can be explained by the very poor preservation and extreme etching of calcareous* *nannofossils between beds 32 and 34. Moreover, the appearance of these four species together suggests the presence of a hiatus."*

f) Bakhmutov et al., (2018), Geological Quarterly, 62 p. 232, state:

"*The first appearances of species of significant calcareous nannofossils at Theodosia are shown in Figure 23. The appearances are not consistently equivalent to all records in western Tethys (Casellato, 2010; Schnabl et al., 2015), one reason being that in this preliminary study we did not sample beds below a level we believe to be assignable to the lower to middle part of M19n.2n. ……. However, the FADs in M19n of H. strictus, C. cuvillieri, N. wintereri, N. steinmannii minor and N.kamptneri minor appear to be consistent with other regions."*

MODIFICATION: No modification was made since we feel we have answered this comment.

1.5) The dating of the magnetozones needs to highlight and discussed at more length in the Discussion.

Very confusing comment. Also on magnetostratigraphy, the reviewer comments on the dating of magnetozones. Nowhere in the manuscript, it is stated that we have dated magnetozones, or implied doing so. This is clearly beyond the scope of the manuscript, and additionally, not even possible since we do not present any magnetostratigraphic new data in any of the studied sections. To date magnetozones, one would have to present magnetostratigraphic and geochronological data on the same section, which we have not done nor said we had. It would not be scientifically sound to do otherwise. Therefore, we feel the request of the reviewer is rather odd and unjustified.

MODIFICATION: No modification was made since we feel we have answered this comment. This study is a detailed study, at the 100 ka level. Gross stratigraphical correlations are not possible in this level of detail. This is the importance of high-precision geochronology. Correlations that were once possible in the past are no longer the case, because out understand if the geological time and stratigraphic record has and will improve dramatically due to this technique. Time equivalency of boundaries and markers need to be proven and not taken as a foregone conclusion. Our manuscript depicts this issue very clearly.

1.6) Also, the assumptions (as seen in most publications) about using the magnetostratigraphic scale as a time scale could be laid out fully in the Introduction

The reviewer also asks us to discuss the assumptions of using magnetostratigraphy, which again, is not the aim of the paper since we do not present any magnetostratigraphic data whatsoever. Therefore, to discourse about the use of magnetostratigraphy is beyond the scope of the dataset we present not to mention beyond the point of the problem we are trying to solve and the methods we use. Again, an odd comment from the reviewer.

MODIFICATION: No modification was made since we feel we have answered this comment.

1.7) Notably, Ogg et al 2016 is not at all 'official' and is not attributable to ICS, but this is not clear from the text.

The reviewer does have a point and will make the distinction clearer between the ICS and Ogg 2016.

MODIFICATION: We feel this has been made clearer in the revised version.

Structure

1.8) The chronostratigraphic and biostratigraphic background should be made clear before consideration of any new data on radiometric dates.

The issues and intricacies with fixating the JKB are well-documented in several publications which W. Wimbledon himself has authored and co-authored. The biostratigraphy in both sections we use has also been well-documented in other publications by some of the authors in this manuscript. Therefore, we feel that this request is somewhat unnecessary since the issue has been dealt with quite thoroughly in other publications and have been cited throughout the manuscript when necessary. Furthermore, we have taken Solid Earth's recommendation on the manuscript type, where manuscripts should be short, concise, and to the point which is a trend among high-impact journals. We feel that reviewing the biostratigraphic framework would make the manuscript unnecessarily long. In closing, the manuscript is not dedicated to reviewing any previous data, but rather presenting new data and building on pre-existing biostratigraphy.

MODIFICATION: No modification was made since we feel we have answered this comment.

1.9) The extrapolation of the GMPTS to onshore localities is central. The paper is concerned with attaching radiometric dates to a biostratigraphic framework. But it says very little about how radiometric dates match the timescale used by, for instance, Gradstein et al 2012: a time framework linked to the oceanic magnetostratigraphic record, the GMPTS. The last is hardly mentioned.

Extrapolating the GMPTS would be over-interpreting our data and certainly beyond the scope of the manuscript. Nevertheless, we feel this is the main problem that the International Chronostratigraphic Chart of International Commission on Stratigraphy (2005 to 2018 versions) is facing. The 145 Ma age for the JKB boundary is based on the Shatsky Rise magnetozones. The main drawback for this assertion is the accepted age for the base of the Berriasian, supported by a poorly dated age of the Shatsky Rise in the Pacific Ocean. The radiometric Ar-Ar dating, even if only the best two samples were considered, have reduced plateaux that could indicate some ^{39}Ar recoil (Mahoney et al., 2005). The ages of these samples are 144.8 ± 1.2, 143.7 ± 3.0, and 142.2 ± 5.3 Ma, but 145 Ma was the preferred age as it coincides with the spreading rate assumed for this part of the Pacific Ocean floor (Ogg et al., 2012). Besides, when the biostratigraphic controls of the sediments of the Shatsky Rise intruded by the dated sills are taken in consideration, the results are not very well constrained (Mahoney et al. 2005 cited (Bown, 2005)):

Quoting Bown (2005) :

"*Zone NK1; Berriasian (Site 1213): The Jurassic/Cretaceous boundary interval zonation of Bralower et al. (1989) is based on a distinctive succession of nannolith appearances, notably Conusphaera and Nannoconus; however, these taxa were absent in this part of the section and the former was absent throughout. In addition, a number of important marker species of the family Cretarhabdaceae (C. cuvillieri, R. angustiforata, and Retecapsa octofenestrata) and genus Eiffellithus (E. primus, E. windii, and E. striatus), although present, are rare and restricted to a small number of samples, and their first and last occurrences may not be biostratigraphically reliable. The lowest Cretaceous zones are thus identified using marker species, where present, together with alternative datum events and aspects of the entire assemblages.*

The lowermost productive samples (Core 198-1213B-27R) yielded H. chiastia, L. carniolensis, Tubodiscus bellii, and R. laffittei, indicating Subzone NJKc or younger. The nannofossils do not unambiguously indicate a Cretaceous age, but correlation with Zone NK1 is inferred based on the presence of the genus Tubodiscus and absence of R. angustiforata, P. fenestrata, and R. wisei (Bralower et al., 1989). Support for this interpretation also comes from radiolarian fauna that also indicate a Berriasian age for the lowermost cores (H. Kano, pers. comm., 2003)".

In conclusion, Bown (2005) makes it clear that the nannofossils **do not unambiguously indicate a Cretaceous** age but also the **inferred** correlation with zone NK1 is based in the **presence of ONE GENUS and the ABSENCE of three species** (negative evidence!). There are not markers, no first appearances, etc. Regarding the radiolarians, the data are based only in personal communication. The facts stated above discredit the JKB extrapolation of the Global Magnetic Polarity Time Scale (GMTPS) based on the Shatsky Rise to onshore localities currently in use. In any case, it is not the focus of this paper to criticize the age of the magnetic polarity time scale used to define the boundary, which needs a deep revision in our opinion.

MODIFICATION: No modification was made since we feel we have answered this comment. Gross stratigraphical correlations are not possible in this level of detail. Please see modification comment to 1.5.

1.10) The core of the paper could usefully be a careful examination of the calibration of the dated ash horizons and the levels with the key biostratigraphic markers – listing them in sequence, level by level.

The detailed biostratigraphy of Las Loicas with an indication of the fossiliferous levels and relevant markers is indicated in Vennari et al., (2014) and López-Martínez et al. (2017). The objective of this paper is to date this biostratigraphy with accurate and precise ages in the relevant interbedded tuffs coupled with age-depth modeling. In the Mazatepec section, biostratigraphy based in calpionellids in found López-Martínez et al. (2013) is complemented by new calcareous nannofossil occurrences which are presented here and presented in figures and pictures.

MODIFICATION: No modification was made since we feel we have answered this comment.

Precision, accuracy, English Language

1.11) There are numerous examples of rather problematic phrases and sentences which are not written in good English. But more critical is the lack of precision or looseness in language and terminology. This lets down the submission very badly. It is the thing that needs the most attention in a revision by the authors.

We do admit that many of W. Wimbledon's suggestions on our English usage and grammar (or lack thereof) are correct and we welcome them. We incorporate all the suggested words, variations and rewrite all sentences pointed out that remain unclear and confusing. Names of species will be thoroughly revised. Specific replies to comments on the supplementary section are found below.

MODIFICATION: Reviewer's suggestion on English usage was made and can be found in the high-lighted revised version at the end of this report.

Corrections on some spelling mistakes are just differences between American and British English. Spellings such as gray, meter, catalog, paleontological, memorize, analog, analyze, defense, color, aging, inquiry, license among many other words are a correct and legitimate form of spelling in American English. Therefore, since Solid Earth does not dictate which kind of English is to be used in their publications, we chose to use American spelling. Furthermore, we feel we were consistent with our choice of spelling thought out the manuscript. Therefore, we have decided to disregard the reviewer's comments on these spelling mistakes.

MODIFICATION: No modification was made since we feel we have answered this comment.

1.12) The loose wording of the Abstract's and Introduction's first sentences. No, the age of the J/K boundary is very clear. Lena et al. talk only about radiometric dating. They should say that the start of Berriasian age/base of the Berriasian stage has been more or less fixed for some years [the authors actually quote several relevant papers that show this]

This comment is quite confusing, and we are not sure what the reviewer meant by this. We hypothesize it might have to do with how different fields in the Earth Sciences use the word "age" with subtle nuances, which is understandable. For instance, in the field of paleontology, an age of a fossil can sometimes be ascribed as an age of a stage. For instance, saying "fossil XY has a Tithonian age" or "is Tithonian" is perfectly acceptable when used in this context. However, in the matter of calibrating the numerical age of stage boundaries such usage of the word age is too loose because a stage boundary can last for millions of years; therefore, it lacks accuracy and precision. In the context of calibrating the age of a stage boundary, the word "age" needs necessarily to be taken as a numerical age (or radiometric age), usually arising from a physical measurement which carries a mean value and an error. Since this manuscript deals with the age calibration of stage boundary from a geochronological perspective, no other meaning of the word "age" is possible other than a numerical age. Therefore, every time the word age appears in the manuscript, it should necessarily be interpreted and understood as a numerical age.

Singling out what type of age we are talking about as radiometric age is redundant and unnecessary since no other meaning is possible. The main aim of the manuscript is to dispute the (numerical) age of the JKB, therefore "Berriasian age" is meaningless and confusing with the aim of calibrating the age of a boundary. Certainly, the sentence suggested by the reviewer "The base of the Berriasian stage has been fixed for some years" is 100% correct, which one would correctly interpret as the base of the Berriasian has been fixed at the base of the Calpionella alpine Subzone and has been for many years. However, the sentence does not bear any relation to the numerical age of the base of the Berriasian, aka the JKB, which is the foremost purpose of this manuscript. As described in the introduction, there have been many (numerical) ages for the base of the Berriasian over the years, 135 Ma, 140 Ma, 144 Ma, 145 Ma. This represents a span of 10 Ma, which begs the question: What is the age of the JKB after all? Having an age of a boundary that is floating around a span of 10 Ma is less the ideal. Therefore, by any standards, the age of the JKB has been contentious over the past years. Sure, one could suggest it to be Berriasian, but this is too loose of a definition for the sake of numerical calibrating the geological timescale. Since 2005, the ICS has the JKB at ~145 Ma, which means approximately 145 Ma. From a geochronological perspective this far from ideal for ascribing a numerical age to a boundary. Admittedly, for many outside the field of geochronology such nuance bears no meaning, but for an accurate division of the geological timescale is it is imperative to find a more realistic age for the JKB, where geochronological data from many sections seem to converge to a similar age. We are confident we have demonstrated this in the manuscript.

In short, geochronology is of the utmost importance to understand the rate of geological phenomena; for instance, duration magma magmatic processes, tectonic processes, duration of mass extinctions and recoveries. All this relies on the accurate and precise knowledge of the (numerical) age of rocks, paleontological markers, and stage boundaries. The latter two can only be resolved by using dating horizons that are close to boundaries using geochronological methods that are accurate and precise, which is methodology we have used in this manuscript.

MODIFICATION: No modification was made since we feel we have answered this comment.

1.13) "JKB" is not standard terminology. It appears hundreds of times in the text. "J/K boundary" is the norm. Alternatives for use are: the base of the Alpina Subzone, base of Berriasian Stage, Tithonian/Berriasian boundary, or, less precisely, the J/K interval, the boundary interval. . Care is required is using the phrase J/K boundary.

We feel that abbreviations can take any form, as long as it is clearly stated in the text and consistently used throughout. The use of the "J/K boundary" is just a personal preference of the reviewer as is our choice to use "JKB" just because something might be considered the norm hardly qualifies it to be mandatory. We see no problem with this abbreviation. However, if the reviewer or the Handling Editor feel adamant about this, we can certainly accommodate it since it is a frivolous matter and simple to adjust.

We have deliberately chosen not to vary the term JKB with its many analogs to avoid confusion, especially to that reader that is not familiar with the various synonyms that the term JKB takes. Since we aim to draw attention from a broader audience, we feel that the term JKB should stay fixed for clarity, even though it might come across as repetitive.

MODIFICATION: No modification was made since we feel we have answered this comment.

1.14) Anything that is not exactly correlated with the base of the Alpina Subzone can be said to be in the J/K interval, but not at the boundary. The reader is sometimes not sure what interval is referred to, or what horizon. Many times a fossil or date is somewhere in the J/K interval, but, to be accurate, nowhere near the actual boundary.

We do understand that we are introducing a new concept (the JKB interval) to a field that already has a plethora of analog terms. However, we want to make it clear that the JKB interval is NOT a substitute for the JKB and the JKB is not the JKB interval. The idea for the JKB interval mainly stems from the fact that the age of the JKB in both sections do not overlap within our analytical uncertainty, and are offset by ~670 ka (± 335 ka). Furthermore, as pointed out by the reviewer #2 in comment 2.1, the markers are offset in an age which, in our opinion, only builds a stronger case to leave the age of the JKB confined to an interval, the JKB interval. Nevertheless, we will try to make a great effort to make this distinction very clear in the revised version of the manuscript. To supplement this reply, we refer the reviewer to comment 2.16 (i.e., in reply to reviewer #2, J. Pálfy).

MODIFICATION: We hope to have addressed this comment in section 4.5, 4th paragraph.

Reply to W. Wimbledon - Supplementary Comments

Page 1, line 28

MODIFICATION: This is geochronological jargon: "final" usually means the reported age. We will replace the word "final" with "reported age".

Page 2, line 1 to 5

The reviewer pointed to a problem with the construction of the sentence. What we want to imply is that reported ages from a previous publication are imprecise and they do not overlap, which means that they do not match, agree, or have the same age. That is what is implied by no overlap.

The main difficulty in finding a (numerical) age for the JKB has been the choice for the base of the Berriasian. Of course, this has been solved, but back in the day when the first attempts to date the boundary (1985, 1995) this was still an issue, and this had significant implications towards the numerical age of the JKB. Maybe this has been clarified for the reviewer.

MODIFICATION: No modification was made since we feel we have answered this comment.

"*… and this level has been the most popular boundary marker for around 30 years*".

The Killian group in their 2014 report (Reboulet et al., 2014) still recommend the base of the Barriasella as a marker for the JKB. This might not be the case for the Berriasian Working Group, where 76% have chosen the base of the Calpionella alpine Subzone, but this is apparently not an overwhelming consensus within the entire community.

MODIFICATION: No modification was made since we feel we have answered this comment.

Page 2, line 13

What we are implying here is that the base of the JKB is assumed to the be the base of the Calpionella alpine subzone, not the ash bed. We will rephrase for clear meaning.

Page 2, line 16

MODIFICATION: "Recent years" was deleted.

Page 2, line 19

MODIFICATION: We will rephrase it to "We also report new nannofossil results from Mazatepec section."

Page 2, line 22

See reply above on the usage of the word "age" in reply to comment 1.12.

MODIFICATION: No modification was made since we feel we have answered this comment.

Page 2, line 24,25

MODIFICATION: We have rephrased it to "which in turn also validates our age for the early Berriasian and the JKB."

Page 2, line 27

MODIFICATION: We will replace "JKB" for "boundary" to avoid repetition. We want to avoid the use of the other many synonyms for JKB to prevent any confusion.

Page 3, line 3

MODIFICATION: "a" replaced by "the"

Page 3, line 5

MODIFICATION:.. of the Eastern… will be added

Page 3, line 6

MODIFICATION: Replaced outcrops by exposed, since fossils do not crop out.

Page 3, line 8

Gray is the American spelling. See comments on spelling in reply to comment 1.11

MODIFICATION: No modification was made since we feel we have answered this comment.

Page 3, line 15-16

We disagree with the reviewer. The sentence is well constructed. Zircon does not need to be pluralized since it related to the behavior of the mineral zircon in general.

MODIFICATION: No modification was made since we feel we have answered this comment.

Page 3, 17

MODIFICATION: Deleted the word dated as suggested, because of the precision of language.

Page 3, line 21

MODIFICATION: Mazatepec will be inserted instead of the vague term "the section in Mexico."

Page 3, line 30

MODIFICATION: comma added.

Page 3, line 31

MODIFICATION: The definite article "the" has been added before the noun R (as in the statistical package)

Page 4, line 3

MODIFICATION: "The section" replaced by "The Las Loicas section" as suggested

Page 4, line 4-5

MODIFICATION: "Found in the Las Loicas section" deleted for it was redundant, as pointed out by the reviewer.

Page 4, line 14

"(ca. 15m stratigraphic height)" is there to facilitate and aid the reader to locate the position in Figure 4.

MODIFICATION: No modification was made since we feel we have answered this comment.

Page 4, line 19

Bralower's thirty year old results must be seen as totally overtaken by more recent results, and to a lesser extent it is true of Casellato 2010. You quote Wimbledon 2017 which shows a more recent situation

Please see reply to comment 1.4

Page 4, line 19

T, remanei and C. massutiniana are decidedly not typically Berriasian

Please see reply to comment 1.3

Page 4, line 29

MODIFICATION: Magnetozones will replace Magnetochrons.

Page 4, line 30

No. This is very very vague. In numerous sections the base of the Alpina Subzone is proved in the middle of M19n.2n

MODIFICATION: We have removed any correlation with any magnetostratigraphic data

Page 5, line 5

Rather unsafe. Authors present no evidence on Arroyo Loncoche. They cannot interpret what is or is not M19n.2n at LL, as they say. How can the authors' results be close to those of Inglesia Llanos when they have no magnetostratigraphy to present at Las Loicas and do not work on AL?

Please see reply to comment 1.2 and also 2.9 (in reply to J. Pálfy)

MODIFICATION: We have removed any correlation with any magnetostratigraphic data

Page 5, line 25

Again, surely this is obsolete work to cite? More up to date references required. The Italian data has been superceded. By the way, Ogg et al. 2016 is not original resesrch but a compilation

The authors do not agree with Wimbledon (2017) where he said that N. kamptneri kamptneri and N. steinmannii steinmannii bioevents, previously used as infallible biozonal indicators in M17r, have been found widely in lower M18r and the upper half of M19n (Figs. 1, 2). Based on Wimbledon (2017) figure 2 only in Puerto Escano these bioevents are correlated with the upper part of C. alpina. (M19n). Besides, according to Svobodova and Kostak 2016 (cited by Wimbledon (2017) only in "one" sample they recognized this bioevent in M19n1r and other is correlated with M18r. The record of N. steinmanii steinmannii and the biozone NK1 are correlated with the Calpionella Zone without specifying the subzone and it is recorded nearly one meter above the acme of C. alpina.

MODIFICATION: No modification was made since we feel we have answered this comment.

Page 5, line 30

This does not match evidence from lots of sites N. steinmannii steinmannii is not a marker for the Elliptica Subzone, especially when it occurs as low as the Alpina Subzone.

N. steinmannii steinmannii defines the base of the NK1 zone and nowhere in the text have the authors considered this marker as a bioevent of the Elliptica Subzone. The authors explain that it is found associated with this calpionellid in the Mazatepec section of Mexico, in the same way of other sections cited and that the NK1 Zone has been correlated in different section with the Elliptica biozone. The authors does not state that this bioevent is a marker of this calpionellid biozone.

You quote Wimbledon 2017?

MODIFICATION: Citation was deleted

Comments

Page 6, line 9-11

No modification was made since we feel the sentence is fine.

Page 6, line 18

"loc" was supposed to be located

MODIFICATION: Located was corredted

Page 6, line 19

MODIFICATION: Tethys regions was replaced by Tethys Ocean

Page 6, line 23

We agree the sentence does not read well. What weant to imply is that the age of ash bed LY5 is an age in the Tithonian. We will rephrase to make it more clear.

MODIFICATION: can be regarded as an age in the early Tithonian

Page 7, line 1

MODIFICATION: Perhaps the sentence would read better if stated: "Therefore, our new ages for the base of the Berriasian and the early Tithonian yield an excepted duration for Tithonian."

Page 7, line 1

How is it "recommended"???? Ogg is just another publication. And not an ICS publication.

MODIFICATION: We have tried to make a clearer distinction between Ogg et al. 2016 and the ICS. Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Page 7, line 8 subsection title

We feel that this is a great subsection title, it instigates the reader to pose the question: Do the ages presented here present the age of the boundary globally? Meaning, if we could measure the age of the JKB in every section, would we find the same age everywhere? Although this is impractical because not every section has table horizons close to the boundary, we argue for the fact that the Las Loicas and the Mazatepec agree favorably our ages can be considered as the age of the JKB globally. As a hypothetical, suppose that the age of the Las Loicas was 140 Ma and that the age of the Mazatepec was 143 Ma, then it would be hard to argue that their age agrees. However, they are off by 600 ka, which is a short interval.

Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Page 7, line 29

The reviewer says the FAD of R. asper is much older. How older is the FAD R. asper? Can he precise how much older?

Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Page 8, 1st paragraph

"*And yet for 200 years geologists have divided up the geological column quite successfully, with no magnetic markers and with no geochemistry, nd the bulk of agreed GSSPs do not rely on these. Replace this sentence?*"

High-precision geochronology has enabled the understanding of Earth processes in great detail. The time scales at which we deal in the manuscript are in the order of 50 ka, in which preservation of the paleontological markers becomes of extreme importance. We never suggested that GSSPs do not rely on secondary markers, but rather a valuable tool. Additionally, we draw W. Wimbledon's attention to the comments of J. Pálfy (reviewer #2), where he suggests that we should use our high-precision ages in both sections to show how problematic it can be to assume time-equivalency of biozones. We also share Pálfy view. Our data clearly shows a slight mismatch at the sub 100 ka level. In this scenario, the diachroneity of FAD and LAD's becomes evident and thus the dating of the stratigraphic record using high-precision U-Pb geochronology becomes a powerful tool in unraveling such nuances. It is undebatable that paleontology has been successful in dividing the geological timescale in the past. However, integrating geochronology, stratigraphy, paleontology, geochemistry, and magnetostratigraphy can push the limits of correlations and calibrations of the geological timescale and is the best way forward. Perhaps, in the suggested sentence, we could state that in the context of calibrating the age of stage boundaries at the sub 100ka level, preservation of paleontological markers is an issue. Maybe this way it would be made clearer.

Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Page 8, line 5

meaning? one level but rest of sentence is about a set of biological events that took place across the Upper Tith-lower Berriasian interval

We did not understand the reviewer's comment.

Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Page 8, line 7

what 'explosions'? bloom of small C alpina? It comed after diversification of nannoconids

We meant the bloom of small Calpionell alpina

Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Page 8, line 19-20

Vague, no justification shown

Through out the paragraph we cite publications to support this last sentence.

Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Page 8, line 24

Its proper name is the "International Chronostratigraphuc Chart"?

Will make the modification to "International Chronostratigraphic Chart".

Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Page 8, line 24

meaning?

It is beyond the scope of the manuscript to go into detail on the issue of offset between Ar-Ar and U-Pb ages. However, it is an important statement to be made from a geochronological perspective.

Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Page 8, line 31

it is a hole in the sea bed, there is no section

We will refer to it as core, as was done previously in the paragraph, instead of section.

Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Page 8, line 31

vague

We will incorporate examples of the JKB markers in the sentence, even though at this point in the manuscript we are deep into the discussion and have stated and cited what the markers are and expect the reader to be following along.

Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Page 9, line 1

As a concluding sentence it is not effective. It says, more or less, our age agrees with othe ages. Not a very weighty ending

We disagree, this last sentence sums up that our age agrees with more recent ages for the JKB, and can be considered the age of the JKB globally. The sentence, in our opinion, is actually quite important sentence and carries a lot of weight. No other study dealing with the age of the JKB could make such a big claim.

Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Page 9, line 3 - comment of the title of section 5 – Conclusions and Summary

Cretaceous rock/time is base Berriasian stage and start Berriasian age. What you discuss is geochronology and radiometic dates

We are not sure what the reviewer meant by this comment. Not very clear.

Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Page 9, line 8

what interval, you just presented numbers

The reviewer missed the point of the the meaning of the JKB interval. We talk about the JKB interval previously in the manuscript. For clarification with regards to the JKB interval, we refer to comment 2.16.

Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Page 9, line 10-11

This ammonite biozone is enormously long, what can it bracket or corroborate? Precision?

We did not imply that we could bracket anything using an ammonite zones. Our bracketed interval is the JKB interval, which is bracketed with U-Pb ages which is staed in the manuscript.

Comments from page 7-9 have been disregarded since section 4.5, 4.6 and 5 have been completely rewritten.

Comments on Figures

Page 17, Figure 2

The main aim of figure 2 is to display our U-Pb data. The biozones are displayed merely conjecturally, since the exact age and duration of the biozones are not known. Therefore, adding boundaries to the biozones would be unrealistic and wrong. Spelling will be rectified.

MODIFICATION: Spelling rectified. The rest of the comment was disregarded since it not possible nor scientifically sound.

Page 19, Figure 4

MODIFICATION: Spelling of species names will be rectified. Boundary abbreviations have been commented on previously in this reply. Additionally, abbreviations were adopted to make the figures more clear, less clustered, and easier to read.

Modifications to the manuscript with respect to the comments by reviewer J. Pálfy (reviewer #2) on the manuscript "Cross-continental age calibration of the Jurassic/Cretaceous boundary"

General comments

2.1) "… I take several issues with the interpretation, and may suggest guidance for a revised version which could better avoid the pitfalls of confusing regional and global biostratigraphic correlation issues. Instead, a refocused discussion should emphasize the obvious significance of the radioisotopic dates in highlighting problems and contradictions in biostratigraphy."

REPLY: This is a significant point, and it highlights the importance of dating the stratigraphic record using high-precision geochronology to unravel its subtle nuances. If we have interpreted the reviewer's advice correctly, our ages clearly show that assuming time-equivalency of biostratigraphic zones can lead to erroneous correlations regarding the numerical ages of FAD and LOD. Possibly, this difference can arise from the migratory rates of these species resulting in the diachroneity of FDA and LOD. This is an interesting point to explore and discuss in the revised manuscript and will be incorporated into the revised version. Nevertheless, we feel that the essential aspect of our data is how younger the age of the JKB is with regards to the long-lasting age of 145 Ma. This is the most crucial contribution of the manuscript, and the discussion around how the age of the JKB in both sections favorably agree is still central to the manuscript.

MODIFICATION: We have incorporated the suggestion by reviewer J. Pálfy in his comments 2.1 and 2.14 (see author's reply). As the reviewer suggested, we have refocused part of our discussion to the embrace the mismatch between the ages of the JKB of the dated sections and discuss the pitfalls of regional and global biostratigraphical correlation. To accommodate the reviewers suggestion in comment 2.1 and 2.14 we have completely rewritten section 4.5.

Specific comments

2.2) The paper needs a proper "Geological and stratigraphic setting" chapter to augment and replace the "Studied areas" in the current version. Formation names, i.e. the bare bone lithostratigraphy should be complemented with brief characterization of basin evolution and depositional environments, to provide context for assessment of stratigraphic completeness and sedimentation rates in the section, the latter being crucial in the authors' arguments in comparing the JKB age of different sections.

REPLY: In the "Studies areas" chapter, we chose simply to give a brief description of where the studies sections are located and cite important publications relevant to where the sections are exposed. There are numerous publications on the tectonic architecture and basinal evolution where the sections are that are cited in the manuscript. As it stands, the manuscript is 4626 words long, which we feel is an adequate length for a publication. If we were to expand the "Studies areas" chapter with a detailed "Geological and stratigraphic setting" chapter, it would increase the manuscript to another 800-1000 words. Even then, it would not do justice to fully review the geological setting of both geological settings within 1000 words (e.g., 500 words each basin). The reviewer claims that such an expansion of the regional geology would be useful to understand better the sedimentation rate in Mazatepec, which is an integral part of our discussion. However, we make it pretty clear in the manuscript that the sedimentation rate in the Mazatepec section is **unknown**, and we further use both a low and high sedimentation rate to back-calculate the age of the JKB in the section. Even with a thorough knowledge of the sedimentological and stratigraphical background, there is no hard evidence for the rate of sedimentation rate in the Pimienta and Tamaulipas formations. Ultimately, this would inevitably leave us with a subjective choice of sedimentation rate based on the depositional environment and sedimentological structures present. Moreover, we also make the case that the choice of sedimentation rate is not that important. Nevertheless, we would not oppose slightly expanding the "Studies areas" chapter, or giving it a new title if the reviewer feels adamant about the subject. We leave this option to the discretion of the Handling Editor, because it influences the format with which publications in Solid Earth are communicated.

MODIFICATION: No modification was made, and we await the Editors decision.

2.3) Care should be taken to ensure consistency in terminology and usage of biozones. Much biostratigraphic information is presented both in the text and in Fig. 4. However, it is not clear to the reader what, if any of these is new here, what is taken unchanged from the references cited, and what is revised from published sources

REPLY: In the caption for figure 4, there is ample information on the information that is new and what is cited from other publications. We will try to make the figure 4 clearer at the request of the reviewer well as its caption.

MODIFICATION: Names of species were corrected as pointed out. Some species names were uncapitalized and steinmannii spelling was corrected. A dashed green line was put in to connect and high-light the mismatch between Las Loicas and Mazapetec. References were put at the top of each panel to make clear what is being cited and what is not, although also in the caption figure there is ample information on what was cited and what is new.

2.4) Cases where there is controversy in either the zonal subdivision of sections or their correlation, based on ammonoids, calpionellids and nannofossils (e.g., between Riccardi 2015 and Vennari et al. 2014) and the stance of the authors should be more clearly stated.

REPLY:

Ammonoids: There is no discrepancy among the biozonation of Riccardi, (2015), the Vennari et al., (2014), and the present manuscript regarding the sequence and names of index species of each biozone. It is worth to mention here that Riccardi explicitly states: "*There is no attempt to deal here with the precise definition of the Jurassic-Cretaceous limit, and therefore the use of terms such as "Tithonian," "Berriasian," "Upper/Late Jurassic" and "Lower/*

Early Cretaceous have been kept to a minimum and is usually adopted when quoting other sources. It is considered that once biostratigraphic correlations are well-established definition of Stage and System boundaries will follow by convention" (Riccardi 2015, p. 24).

Calpionellids: The data from this manuscript has been published by López-Martínez et al., (2013) for the Mexican section and López-Martínez et al., (2017) for the Argentine section.

Nannofossils: The data from this manuscript has been published by Vennari et al. (2014) for the Argentine section. The data presented here for the Mexican section is new, and a systematic paper is in preparation (Lescano et al. in prep.).

MODIFICATION: No modification was made since we feel we have answered the comment.

2.5) The reader might suspect that calcareous nannofossil occurrences are newly obtained as Supplementary Fig. 3 is promised to present them (p. 3, l. 26), but this figure is missing.

REPLY: Yes. Unfortunately, we have not placed the Supplementary Figure 3 (distribution chart for the calcareous nannofossil species) in the Supplementary Materials as stated in p.3, l. 26. We apologize and promise to rectify.

MODIFICATION: We have placed the calcareous nannofossil chat in the Supplementary Material as Fig. S1.

2.6) Details of reporting of the error and age interpretation would be better placed in the main text's Methods chapter rather than in the Supplementary Material.

REPLY: The detailed account of the geochronological data is intended for full disclosure of its meaning and interpretation; however, this would only be appealing to a specific subset of the geochronology community. The average reader, drawn by the interest of knowing the age of the JKB, in our opinion, would be distracted by an excessively detailed description of the geochronological U-Pb data in the main text. Moreover, this information is not further referred nor directly used in the discussion and conclusion chapters, i.e., the meaning of a depositional age for the ash beds, number of grains selected for weighted means, etc. These are not information that is central to the discussion of the data and conclusions. This is why we decided to keep it in the Supplementary Materials. Nevertheless, we leave it at the discretion of the Handling Editor do choose what best fits the format of the journal because it would be an easy adjustment to make to the revised manuscript.

MODIFICATION: No modification was made since we feel we have answered the comment.

2.7) For the aimed global relevance in time scale studies, the most conservative error (i.e., that including the tracer calibration and decay constant errors) needs to be quoted and used for each U-Pb dates throughout the paper. This is typically still within 0.2 Ma, a commendable high-precision.

REPLY: The reason high-precision ages are reported with three errors (as explained in the Supplementary Materials) is to allow for an appropriate propagation of errors when comparing different geochronological datasets that been acquired through different geochronological methods (e.g., $^{39}Ar/^{40}Ar$, U-Pb (SHRIMP, LA-ICP-MS)). In this manuscript, we do not directly compare datasets from other studies. We do, indeed, aim to challenge the JKB recommend age in the ICS is ~145 Ma, which mainly highlights the lack of precision and accuracy towards the JKB age. In any case, the JKB age in the ICS is based on the $^{39}Ar/^{40}Ar$ age of Mahoney et al. (2005). Nevertheless, our ages are so much younger than that of Mahoney et al. (2005), making precision, not such a big deal for the sake of challenging the ICS age. Hopefully, other sections that span the JKB will be dated in the future and most likely use U-Pb CA-ID-TIMS since it has become a gold-standard in dating the stratigraphic record. Therefore, how we quote precisely in the manuscript is not that big of a deal.

MODIFICATION: No modification was made since we feel we have answered the comment.

2.8) The chapter "Results and discussion" needs to be split into two, allowing results to be clearly separated from the interpretation.

REPLY: In the same vein as the reply to comment 2.6, we wanted to make a concise manuscript. In this sense, we feel that the nitty-gritty dissection of the geochronological data should not be moved to a separate "Results" chapter in the main text. Instead, we describe the data along with the discussion, which in our opinion reads better and is not unusual in scientific communications. As far as the Solid Earth's author guideline goes, it does not mandate that results be separated from the discussion. Moreover, we think that the lack of a specific "Results" chapter does not compromise any of the discussion or conclusions in the manuscript. Therefore, we thought it might be better to leave the results and discussion together. We believe that this comment is more of a personal preference of the reviewer than a weakness of the manuscript. Nevertheless, we leave it at the discretion of the Handling Editor do choose what best fits the format of the journal because it would be an easy adjustment to make to the revised manuscript.

MODIFICATION: No modification was made, and we await the Editors decision.

2.9) Even though it is widely accepted that magnetostratigraphy is very useful for global correlation in the JKB interval, projecting the magnetozones identified in the Arroyo Loncoche section in the Neuquén Basin (Iglesia Llanos et al. 2017) introduces additional confusion (p. 5, l. 1-9, Fig.

4) to the already complex web of stratigraphic correlation of the three studied sections. The new results from Las Loicas do not appear to be closely correlatable with Arroyo Loncoche, Fig. 4 reveals that the placement of the JKB is offset by nearly one ammonoid zone, being near the base or at the top of the Substeueroceras koeneni zone, respectively. It would suffice to say that magnetostratigraphy of the Las Loicas section will be desirable to enhance the utility of the newly obtained U-Pb ages and clarify contentious biostratigraphic correlation issues.

REPLY: In the manuscript, we do not project the magnetozones of the Arroyo Loncoche section to the Las Loicas or any other section. We merely attempt to correlate the JKB in the Arroyo Loncoche to the Las Loicas section using the Alpina Subzone and the M19.2n, which are the most compelling evidence for the JKB in either section. We admit that there is a mismatch between the ammonite zonations, which is clearly stated in the manuscript (p. 5, l. 8-9). Additionally, we also cited a discussion on the matter in López-Martínez et al., (2018). Nevertheless, the thickness of biozones changes as a function of facies, randomness of finding markers in the field, the latter hugely influenced by preservation, and paleogeographical position within a sedimentary basin. Therefore, although we do see that better understanding the mismatch between both sections as an incentive for future research, we do not, however, see this as a significant issue to be explained.

One needs to keep in mind that another principal aim of this manuscript is to try to show that the age of the JKB in ICS is too old. In an idealized case, one would find the age of the M19.2n and the base of the Calpionella alpina Subzone to be the same age (assuming these markers are exposed in different sections as is the case in this manuscript). This would require that both of these markers have a datable horizon very close by. However, in the real world, this scenario is quite hard to come by, and we need to try and reconcile the available data despite its shortcomings. In the context of trying to show that the ICS age of the JBK (145 Ma) is too old, the data from Las Loicas and Arroyo Loconche seems to be in reasonable agreement, in our opinion. That is, if we consider that the most trustworthy markers for the JKB are the M19.2n and the base of the Calpionella alpine Subzone, even with the mismatch of the ammonite zones between Las Loicas and Arroyo Loconche (which would be a couple 100 ka), the age markers for the JKB of these two sections would not be off by 5 Ma. **Furthermore, it is important to point out that in the absence of a reliable biostratigraphic framework, such as the case of Arroyo Loconche, magnetostratigraphy is just a floating scale (very important to bear in mind).** Therefore, from this perspective, even with the ambiguity in the correlation between these two sections, the age of the JKB at ~145 Ma is hard to reconcile. We do understand that the M19.2n in Arroyo Loconche might seem older than the base of the Calpionela alpine Subzone in Las Loicas when compared against the Substeueroceras koeneni biozone as a relative timescale. Nevertheless, this discrepancy would not allow, for instance, the interpretation that the age of the M19.2n in Arroyo Loconche to be as old as 145 Ma and the age of the Calpionella alpina Subzone in Las Loicas to be at ~140 Ma, which would be the alternative to invalidating our conclusion. Furthermore, our age in the *Virgatosphinctes andesensis* biozone (Early Tithonian) would certainly not allow this interpretation. In closing, the explanation above only exposes the how poorly constrained the current age of the JKB is, that even with a crude correlation (which is what is available at our disposable at this conjecture) the age of the JKB at 145 Ma seems implausible.

Additionally, in the manuscript, we cite many references that have also dated the JKB and found ages similar to ours. Furthermore, our goes for the base of the Berriasian are much easier to reconcile with the ages for the Early Cretaceous ages (see page 8, lines 10-10 in the manuscript). In closing, there is substantial evidence from different fields that point to an age of the JKB that is much younger than in the ICS (We would also like to refer the reviewer to the reply on comment 1.2, i.e., in reply to reviewer #1).

Having said this, we realize that both reviewers took issue with our attempt to correlate the M19.2n in Arroyo Loconche and the base of the Alpina Subzone in Las Loicas in an attempt to build a more solid case for our age of the JKB. If our arguments remain unconvincing, we will not oppose removing entirely this from the discussion and figure 4. Hopefully, our explanation was satisfactory.

We would, in this case, value comments and advice from the handling Editor on the matter for the revised manuscript.

MODIFICATION: Even though it we argued in favor of correlating our geochronological and data with the magnetostratigraphic data of Iglesia Llanos, et al., (2017), we have we have decided to remove this from the manuscript and figures since both reviewers took issues with this approach.

2.10) Discussion on the age of the JKB in the Mazatepec section includes an assumption on the FAD of a nannofossil taxon, Nannoconus steinmannii minor, not actually found in the section (p. 5, l. 31 – p. 6, l. 3). Such speculation is best avoided.

REPLY: Our consideration of the *N. Steinmannii* is speculative, very short. We certainly do not substantiate any conclusion on this comment. Nevertheless, the N. steinmannii defines the base of the biozone and is the main bioevent, and the others are defined as close and secondary with regards to this bioevent. Therefore, this was just to give the reader food for thought, as so to speak.

MODIFICATION: No modification was made since we feel we have answered the comment.

2.11) Beware of the lack of formal definition of base Tithonian. There is no agreed-upon GSSP decision yet, contrary to what is implied here (p. 6, l. 25). The attendant uncertainties of stage boundary placement and its correlation with the Andean sections make the time scale calibration use of La Yasera U-Pb date more problematic than admitted here.

REPLY: Indeed, there is no agreement on the GSSP for the Kimmeridgian-Tithonian boundary. We will remove the sentence in brackets that suggested otherwise (p.6, l 25), and will make it clear that the KmTB is not formally defined.

MODIFICATION: The affirmation of that in p.6. l 25 that there was a formal definition of the Kimmeridgian and Tithonian boundary was removed as suggested.

2.12) The discussion on the duration of the Tithonian is interesting but contains a factual error and misses some further opportunities. The Geological Time Scale 2016 (Ogg et al. 2016) is misquoted, it assigns 150.8 Ma to the base of Tithonian Stage and 145.5 Ma to the JKB.

REPLY: In the ICS chart 2018, the age of the KmTB is 152.1 ± 0.9 Ma. Please see http://www.stratigraphy.org/index.php/ics-chart-timescale. Additionally, in the compilation of Ogg et al., (2016), Chapter 12 – Jurassic, Figure 12.1 page 152, and Figure 12.4 page 157, the age quoted is 152.1 Ma for the base of the Tithonian.

MODIFICATION: No modification was made since we feel we have answered the comment.

2.13) It would be useful to compare two other, independent duration estimates. The Pacific M sequence of magnetic anomalies has long featured in time scale calibration. The recent work of Malinverno et al. (2012) (the MHTC12 scale) suggests 6 m.y. for the Tithonian, i.e., between magnetochrons M22An and M19n2n.

REPLY: We thank the reviewer for pointing this out to us, and we will undoubtedly discuss and compare Malinverno et al., (2012) timescale for the Tithonian in the discussion, especially since it is very close to our estimate for the duration of the Tithonian.

MODIFICATION: We have addressed the comment 2.13 which suggested that we compare out estimates for the duration for the Tithonian with that of the independent duration estimates of the Pacific M sequence of magnetic anomalies of Malinverno et al. (2012). This was incorporated into section 4.3.

2.14) The cyclostratigraphic analysis of Kietzmann et al. (2015; not cited by Lena et al.) identifies 10 long eccentricity cycles for almost the entire Tithonian, starting with the Virgatosphinctes mendozanus zone dated here at La Yesera, hence a duration of c. 4 m.y. The discussion should emphasize that the duration favored here is longer these previous estimates using other methods *and offer possible reasons to explain the difference, perhaps considering biostratigraphic correlation issues.*

REPLY: There are two issues here: First, in Kietzmann et al., (2011) the Tithonian was more than 210 m thick in Arroyo Loncoche; then in Kietzmann et al., (2015) the Tithonian is reported as 195 m thick; and finally in Iglesia Llanos et al., (2017) the Tithonian was reported with less than 160 m. This makes more inadequate the ten long eccentricity cycles for almost the entire Tithonian. The second issue is that following Vennari et al. (2014) and Riccardi et al. (2015), and in the present manuscript, the andesensis (former mendozanus) zone is correlated with the Tethyan ammonite zones, which are above the base of the Tithonian, i.e. the hybonotum zone is not represented in Vaca Muerta Formation.

MODIFICATION: No modification was made since we feel we have answered the comment.

2.15) Perhaps my most important criticism and suggestion pertains to the projection of a sedimentation rate-based JKB from the Mexican Mazatepec section into Las Loicas in Argentina. The authors can make a much stronger case and build a more logical argument by projecting the actual U-Pb date, expressing the stratigraphic height from the age-model calculation as ~28.5 m and note the mismatch in biostratigraphies. Reading from Fig. 4, beds of the same numeric age thus appear assigned to nannofossil zone NJK-B vs. high in NJK-D, to calpionellid Crassicollaria zone vs. Calpionella zone (and its third subzone, the Elliptica subzone, and ultimately to lower Berriasian vs. upper Tithonian at Las Loicas and at Mazatepec, respectively. The discussion could thus be refocused to use the newly obtained high-precision and high-resolution U-Pb age framework to highlight biostratigraphic correlation issues, most likely due to diachronous FAD-LADs of certain key taxa.

REPLY: We have partially addressed this inquiry in question 2.1. Nevertheless, we are happy with this comment because it further substantiates our arguments, especially for a JKB interval. We agree with J. Pàlfy that the mismatch in the age of the FAD-LAD in Las Loicas and Mazapetec is clear evidence that assuming age-equivalency of markers and stage boundaries is problematic when working at the sub-100 ka level and highlights the importance of high-precision geochronology to the stratigraphic record. Furthermore, in the context of the JKB, it stresses the importance of leaving **the age** of the JKB confined to an interval (we further explore this in reply to question 2.16). We welcome this comment and will surely incorporate this into the revised manuscript because we see this as an essential implication from our data.

MODIFICATION: Comment 2.15 was also addressed and incorporated into section 4.5. Also see modification to comment 2.1.

2.16) To strengthen the argument for potential problems in biostratigraphic correlation, the authors might comment on the discrepancy of ammonoid-based correlation, and striking differences of thickness of zones in different sections even within the Vaca Muerta Fm. (e.g. Argenticeras noduliferum zone: ~27 m in Las Loicas vs. 5 m in La Yesera section).

There are important facies and thickness changes between Las Loicas and La Yesera sections due to their different paleogeographic positions within the Neuquén Basin. La Yesera section is further east (see paleogeographic sections for example in Kietzmann et al. (2015).

MODIFICATION: Comment 2.15 was also addressed and incorporated into section 4.5. Also see modification to comment 2.1.

2.17) It the "Global correlation" chapter, the suggestion of understanding the JKB as an interval (p. 8, l. 1-10) is conceptually flawed and needs to be rephrased. By definition, the JKB boundary (as any other chronostratigraphic boundary) is a time line. It does indeed carry an uncertainty of our numeric calibration but it cannot be equated with an actual time interval in which different "boundary events" took place.

The reviewer may not have understood what we meant by the term Jurassic/Cretaceous interval. We want to make it clear the JKB is not tantamount to JKB interval; in other words, they are not the same thing. We did not suggest that the JKB be understood as an interval (at least that was not our intention), but rather the age of the JKB be left within a bracketed interval, thus the idea of the JKB interval. This mainly stems from the fact that the age of the JKB in both sections do not overlap within our analytical uncertainty, and are offset by ~670 ka (± 335 ka). Furthermore, as pointed out by the reviewer in comment 2.1, the markers are offset in an age which, in our opinion, only builds a stronger case to leave the age of the JKB confined to an interval, the JKB interval. In other words, what we propose here is that the interval constrained by our geochronology is short enough that the JKB can be placed somewhere in that interval because a single age is yet out of our reach. We feel confident that this interval can get tighter as newer sections are dated in the future. Even though they do not overlap, the ages presented here highlight a discrepancy between the age of the JKB in the ICS and the ages that we have measured.

MODIFICATION: Comments 2.17 and 1.14 regarding the concept of the JK interval was rewritten in section 4.5. Hopefully, the concept of the JKB interval is clearer.

2.18) Also in this final chapter, consider the significance of your argument for a significantly younger JKB together with Martinez et al. (2015) suggested age for the base Valanginian at 137 Ma. This would make for a shorter than previously understood Berriasian Stage of a -3 m.y. duration. This in turn contradicts with the astrochronology of Kietzmann et al. (2015), who identify more than 10 long eccentricity cycles in the Berriasian part of the Vaca Muerta Fm.

The issue with Valanginian boundary is presently in the discussion as well as the Hauterivian and Barremian ages by new high precision U-Pb CA-ID-TIMS dating together with cyclostratigraphy and the ammonoid and nannofossil biostratigraphy in the Neuquén Basin by Beatriz Aguirre Urreta and Mathieu Martinez (in prep.). Some results already published also show several million-year discrepancies with the ICS Time Table.

MODIFICATION: No modification was made since we feel we have answered the comment.

2.19) The statement in chapter "6. Data availability" suggests that some of the raw data will be withheld until completion of the thesis of the first author. Instead, all data should be made available at the publication of this paper. Understandable practice is not to release data in a thesis prior to publication, but there should be no reason to justify an embargo the other way around.

We will remove this section since all the data is reported in the data table in the supplementary materials. The reported U-Pb table data can easily be copied and pasted on the excel sheet, where it can easily be manipulated in Isoplot in Excel and or R Studio, for instance. Or instead, we can state the latter in chapter 6.

MODIFICATION: We have removed this section since we initially misinterpreted the data availability requirement. As stated in the reply, we do not withhold any data, and every data we use is presented in the manuscript and in the supplementary materials.

2.20) Table S1 contains the essential data for the U-Pb geochronology, it should be placed in the main part of the paper.

We disagree with the reviewer to place the U-Pb data Table, T.S1 to the main text. With the aim of keeping the manuscript more appealing, we feel that by putting raw data tables cuts the flow of the written text and distracts the reader. Therefore, we think that the data table T.S1 is better viewed separately from the main text, especially when reading in a digital format (which we encourage). It allows going back and forth from the text to the data table more readily if the reader deems necessary. Nevertheless, we leave it at the discretion of the Handling Editor do choose what best fits the format of the journal, and also because it would be an easy adjustment to make in the revised manuscript.

MODIFICATION: No modification was made and we await the decision of the Handling Editor

2.21) *Fig. S is also worth transferring from the Supplementary Material to the main part. (However, its labeling needs re-coloring so it be legible in black and white print, panel C might be more informative to show the dated ash bed, D needs labels, and the figure needs a caption.)*

In trying to keep the manuscript short, concise and to the point, we have opted to leave field figures (Fig. S) in the Supplementary Materials. We feel that figures that do not directly support any of the discussion or conclusion and are best kept in the supplementary material. Nevertheless, we leave it up to the Handling Editor to advise us on what better suits the format of the journal. We thank the reviewer for pointing out that the figure was, unfortunately, left out the caption and we will incorporate his advice on how to better the figures such as recoloring for printing and better labeling.

MODIFICATION: Fig. S is now Fig. S2 (because the nannofossil chart is now Fig. S1). No modification was made as where the Fig. S2 where should be placed Supplementary Materials or the main manuscript. Ee await the decision of the Handling Editor.

Recoloring of Fig. S2 was not made since printing in black-white inevitably leads to loss in quality. Furthermore, the pictures will be in color in the online version and can be better viewed on a digital platform (computer, laptop, tablet, phone etc), which also avoid printing.

Closing remarks from the authors

In closing, we would like once more to show our appreciation to J.Páfly for reviewing our manuscript and accepting it for publication after the revision. Many of the reviewer's suggestions we agree and will fully accept, with only a very few where we disagree or would not favor the change. For instance, there where two comments that, in our opinion, that standout and substantially add to the manuscript. First, the refocusing the discussion around the apparent mismatch between the ages of the biozones in Las Loicas and Mazatepec, which we address in question 2.1 and 2.14. This is the most critical comment from the reviewer, and we welcome it and assure we will incorporate this will be added to the discussion in the revised version. Second, the renaming of the "Studies areas" section for a "Geological and Stratigraphical Setting" and an expansion of both sections. On this comment, we argue as to why we felt it was essential to leave the Studies areas section short, but did not oppose to reviewer's suggestion. In any case, leave it to the decision of the Handling Editor for the revised version.

All other comments from J. Pálfy, albeit pertinent, we feel that they are minor and straightforward to adjust. For instance, the reviewer suggests a "Results" section separate from the Discussion section, which would imply moving the description of the results found in the Supplementary Material to a new chapter entitled Results in the main text. Another similar request is to place the raw data tables in the Supplementary Material in the main text. Even though we oppose such changes in the structure, we do not see it as a significant modification to the manuscript, and we leave it to the Handling Editor to decide what would best fit the journal's format. Other requests pertain to improving the readability and clarity of the figures, adding a caption to one of the supplementary figures. Modification in the grammar usage, word choice, style, and spelling will promptly modify since they will improve the manuscript. In short, we feel that we have dealt with all of the reviewer's comments adequately and hopefully, the answers fulfill the requirements for publications by both the reviewer and the Handling Editor.

Technical corrections

The comments below also include several suggestions for better English language, style and word choice.

p. 1, l. 12 (and elsewhere): age ! numeric age

We discuss this in reply to comment 1.10 to reviewer #1 W. Wimbledon. Since this is a paper that discusses the age of a boundary from a geochronological perspective age is necessarily a numerical age. In our view, it would be some tedious to specify age every time. In the introduction, however, we use the "absolute age" nomenclature to distinguish it from the more older ages derived from statistical interpolation. Therefore, in that context, we felt it was necessary to make the distinction. However, throughout the text when we mention "ages", it can only be numerical ages or numeric ages because what we present are U-Pb ages, which are numerical by definition. Therefore, we feel a distinction is not necessary.

MODIFICATION: We have deleted the adjective "absolute" to qualify the noun "age" as requested reviewer #2 and replaced it with "numerical". Especially in the abstract, introduction wherever the distinction felt necessary as was pointed out by reviewer #2 in his technical comments. However, whenever the word age referred to our results or any of the data presented we did not qualify it as numerical since this would be redundant, because our results are necessarily numerical ages.

elusive ! difficult to determine

OK. Agreed

MODIFICATION made and can be found high-lighted version of the revised manuscript.

l. 16: display ! contain

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised manuscript.

l. 21: one of the last major Phanerozoic stage boundaries ! last Phanerozoic system boundary

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised manuscript.

l. 23: absolute ! [delete, avoid "absolute age" altogether]

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised manuscript.

p. 2, l. 3: Calpionella alpina subzone (cf. l. 16) [ensure consistency in zonal names and terminology]

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised manuscript.

l. 17: selected ! suggested

OK. Agreed.

MODIFICATION: fell it is not suggested because the base of the Aplina Subzone as the base of the Berriasian was voted on, and consequently selected not suggested.

l. 21: Kamptneri ! kamptneri

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised manuscript.

p. 3, l. 6: spans ! exposes

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised manuscript.

l. 12: out of sequence numbering of figures (not as they appear in text)

OK. Agreed. We will modify.

MODIFCATION: Figures are no in order of appearance, Fig. 1 page 2 line 10, Fig. 2 page 2 line 15, Fig. 3 and 4 page 2 line 23.

l. 26: optical images ! photomicrographs

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised manuscript.

p. 4, l. 3: The section ! The Las Loicas section

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised manuscript.

l. 29: impose ! may provide

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised manuscript.

p. 5, l. 2, 6: fossil density ! abundance of fossils

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised manuscript.

p. 6, l 24: Tithonian

OK. Agreed.

Comment no longer relevant since this part of the manuscript has been removed from the manuscript been rewritten.

p. 9, l. 22: thank

OK. Agreed.

Comment no longer relevant since this part of the manuscript has been removed from the manuscript been rewritten.

p. 10, l. 3: Neuquén

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised manuscript.

p. 11, l. 11: [delete] February

OK. Agreed.

MODIFICATION made

p. 12, l. 6: Potosí [+spell out journal name]

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised manuscript.

l. 13: &amp [delete]

OK. Agreed.

MODIFICATION made.

p. 14, l. 4: Episodes [delete the rest of name]

OK. Agreed.

MODIFICATION made .

l. 14: Aguirre-Urreta

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised manuscript.

l. 22: [provide doi instead of URL]

References cited in text but not listed in reference list: Edwards, 1963 R Core Team, 2013

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised manuscript.

p. 15, l. 3: Distribution of continents ! Global paleogeography

OK. Agreed.

MODIFICATION made

l. 9-15 (Fig. 3): Give stratigraphic horizon of occurrence (e.g. m from base) fo each specimen photographed

OK. Agreed.

MODIFICATION: Fig. S1 (nannofossil chart) should supplement this request.

p. 16, Fig. 1: delete title, consider using different base map, do not show migrazion routes and sections not discussed in text.

OK. Agreed. We will consider just leaving only the two sections studied. However, it is quite common to add sections that are of the same age to a paleogeographical maps to give a to give the sense of the time equivalent between sections even though they are not discussed in the text.

MODIFICATION: Title was modified, "distribution of continents" was replaced by "global paleogeography". We did not use a different base map, since no justification from the reviewer mas made as to why the maps map should be changed. Nor a suggestion as of which base map should be used. Migratory routes were left in the map because we do suggest that the rate migratory routes could be a possible explanation to the difference in age between Las Loicas and Mazatepec. Section that were not in the study were left in to convey the idea that the these section are contemporaneous.

p. 17, Fig. 2: Barriasian ! Berriasian

[J/K boundary interval – see comments about conceptual flaw here]

[fonts too small in the upper part, too large in the lower part]

OK. Agreed.

MODIFICATION made

p. 18, Fig. 3: [it is redundant to show taxon names here, it is customary to give them in the caption only]

OK. Agreed.

MOFIFICATION: We have not removed taxon names since we do not see it as redundant, nor is this relevant.

p. 19, Fig. 4: [this is the key figure of the paper, already need to refer to in the Geological setting, so make it Fig. 2; A: show meters; put Las Loicas section to a separate panel B, making the others C and D; La Yesera: indicate placement of JKB; some lettering uses illegibly small font]

Here we disagree with the reviewer. There is no sedimentological or geological consideration is figure 4, but rather a comparison between the ages of markers from each section. Furthermore, Figure 4 should be within the discussion chapter as the bulk of the discussion pertains to this figure. Therefore, we do not see the purpose of it being placed at the beging on the manuscript.

MODIFICATION: Arroyo Loconche section from Iglesias Llanos et al., (2017) was put in its own panel A, and the other panels were renamed accordingly, B, C, D. Stratigraphic height was add to the Arroyo Loconche section, as requested.

Supplementary Material

p. 1, l. 1: Ash beds were crushed ! Samples were crushed

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised Supplementary Materials.

p. 3, part 5

Give weight of each sample so zircon yield can be assessed in this context.

Grains discarded as too old are erroneously quoted as >_150 Ma for each sample, *provide true cut-off age of grains not included in age calculation.*

Weight of the samples was not made because it is not customary to do so. Grains 150 Ma were discarded. The cut-off age for grains included in the weighted mean is sample dependent and are usually the youngest overlapping grains.

MODIFICATION : no modification was made since we feel the comment was answered.

5.3 (p. 4): Ash bed LL10 has n=6 grains in Fig. 2, four in text

OK. Agreed, will change it to 4, not 6.

MODIFICATION made and can be found high-lighted version of the revised Supplementary Materials.

5.4. Ash bed LL13: include date of discarded grains in Table S1 (really older than 450 Ma?)

We do not see the point of reporting the age of grains that are significantly older than the weighted mean of the ash bed. It serves no purpose. Ages much older than the weighted mean are hard to evaluate if they are detrital of inherited from older basement rocks volcanic source.

MODIFICATION : no modification was made since we feel the comment was answered.

5.5. "Due to its proximity to the Tordillo Fm." [it is from the Tordillo Fm.] inherited grains or detrital grains?

OK. Agreed.

MODIFICATION made and can be found high-lighted version of the revised Supplementary Materials.

5.6. MZT-81 (p. 5): check this descriptions, there are errors here. four discarded grains (not five), the grain numbers are in error (belong to sample LL10)

OK. Agreed. Thanks for pointing this out. Will be rectified.

MODIFICATION made and can be found high-lighted version of the revised Supplementary Materials.

Fig. S needs a caption and should be transferred to the main part of the paper. The labels of the figures need to be recolored so they are legible in black and white print as well.

OK. Agreed.

MODIFICATION: Caption has been given. No coloring was made. Transfer to the main text was not made since await the Editor's decision on the issue.

Table TS.1 is essential to assess the U-Pb dates reported so it should be transferred to the main part of the paper.

Please see the discussion to comment 2.19.

MODIFICATION: No modification was made since we await the Editor's decision since we disagree with the reviewer.

Sample LY5 in Table TS.1: why discard grain z67 and keep z10, when the first one is not older and its error is not larger? This and similar issues of only marginally different aged grains undermine the credibility of unbiased and rigorous selection of grains for the age interpretation.

Weighted mean ages are nothing other than the average mean value of set of dates (youngest grains). In this case, grain LY z67 has a mean value of 147.740 Ma and the precision with what we know the true age of the grain is 93 ka. In figure 2, it is quite clear that LY z67 does not overlap with the weighted mean age of the youngest grains, which means it has little to no chance of statistically belonging to the subset of youngest grains of the population. On the other hand, LY z10 has a mean value of 147.8 Ma and the precision with which we know the age of the 1.1 Ma (much lower precision), and from Fig. 2 it clearly overlaps with the weighted mean age of the sample, which implies that it does have some probability of being a part of the subset of younger grains. In short, LY z10 statistically has a better chance of belonging to the subset of the youngest grains than LY z67, even though the mean value of LY z67 is slightly younger than LY z10. This is just a question of precision, or how well-known is the confidence interval for a particular physical measurement. We draw the attention of the reviewer to compare the Pb* concentration of these two grains. Here, precision is mainly limited by the amount of sample. If the sample size was any bigger, the precision would be higher. Thus the confidence interval reduced. And in that case, grain LY10 would have possibly been excluded from the weighted mean age of the ash bed.

MODIFICATION : no modification was made since we feel the comment was answered.

8.2 (p. 11), Table TS.2: Why is the age value of 2 m any different from the age of LL13 taken from this level?

This is because the stratigraphic height of LL13 is in fact at height three m and not two m. This will be rectified in the main text. Notice that the age of LL13 is 142.039 ± 0.058 Ma and the age of stratigraphic height 3 m is 142.04 ± 0.06 Ma, which is because we have rounded the numbered to two decimal places rather than three. Thank you for pointing that out.

MODIFICATION: made and can be found high-lighted version of the revised Supplementary Materials.

REVISED MANUSCRIPT

Cross-continental age calibration of the Jurassic/Cretaceous boundary

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Abstract. The numerical age of the Jurassic/Cretaceous boundary has been controversial and difficult to determine. In this study, we cross calibrate biostratigraphical and geochronological data from the Jurassic/Cretaceous boundary between two distinct sections from different sedimentary basins and evaluate whether we can constrain a globally valid numerical age for the Jurassic/Cretaceous boundary. Here we present high-precision U-Pb zircon age determinations on single grains of

volcanic zircon of two sections that span the Jurassic/Cretaceous: the Las Loicas in Argentina, and the Mazatepec in Mexico. These two sections contain well-established primary and secondary stratigraphic markers as well as interbedded volcanic horizons allowing the age of the Jurassic/Cretaceous boundary to be bracketed. We also present the first age determinations in the early Tithonian and tentatively propose a minimum duration for the stage as a cross check for our ages in the early Berriasian.

1. Introduction

The age of the Jurassic/Cretaceous boundary (JKB) remains one of the last Phanerozoic system boundaries without an adequate numerical age. Many efforts have been made in the past to tackle the age of the JKB. Approaches have varied from the coupling of magnetostratigraphy with biostratigraphy (Larson and Hilde, 1975), and to the use of radio-isotopic ages (Gradstein et al., 1995; Kent and Gradstein, 1985; Lowrie and Ogg, 1985; Ogg and Lowrie, 1986). These were based on data compilations from different sections that span the JKB. Due to the scarcity of numerical ages for the Late Jurassic and Early Cretaceous, a lot of the available JKB age data was derived from interpolating distant tie points for arguably large intervals of time (~25 Ma). This approach yet valid, can lead to unascertained errors in the reported ages (Gradstein et al., 1995; Kent and Gradstein, 1985; Lowrie and Ogg, 1985; Ogg and Lowrie, 1986; Pálfy et al., 2000b). Only a few case studies presented geochronological data from several samples within single sections (Bralower et al., 1990; Vennari et al., 2014), thus allowing a direct calibration of the numerical age of the key JKB taxa. Therefore, the different estimates for the age of the boundary lack reproducibility varying from 135 to 144 Ma with a high degree of uncertainty with no significant overlap. Admittedly, the main hindrance to finding an appropriate age for the JKB has been the difficulty of identifying a primary marker that is globally recognized (Wimbledon et al., 2011), a problem that has plagued the matter for decades. Recently, the base of the Calpionella alpina Subzone has become the most widespread candidate for the base of the Berriasian (Wimbledon, 2017), which allows putting sections that span the boundary in a coherent framework. This advance also allows comparing the temporal record from sections that straddle the JKB, thus facilitating correlation and defining a numerical age for the JKB.

Given the current contentious nature of the JKB age, we aim to test the following hypothesis: if the primary markers for the JKB are dated using radio-isotopic methods in two independent sections in distinct geological contexts (Fig. 1), do the ages of these markers overlap? Moreover, if the data (biostratigraphy and geochronology) from two distant sections converge to similar results, it might lead to a more reliable numerical age to the JKB. To do so, we have used high-precision U-Pb zircon age determinations using chemical abrasion, isotope dilution, thermal ionization mass spectrometry (CA-ID-TIMS) techniques to date interbedded volcanic ash layers in the Las Loicas section, Neuquén Basin, Argentina and the Mazatepec section, Mexico (Fig. 2). High-precision U-Pb dates have proved to yield robust estimates for the timing of the stratigraphic record (e.g., Burgess et al. 2014), especially in combination with Bayesian age-depth modeling (e.g., Ovtcharova et al., 2015; Baresel et al., 2017). The coupling of high-precision U-Pb geochronology and age-depth modeling permit ascribing specific numerical ages to key taxa in the Early Berriasian, Late Tithonian. We have assumed the definition of the JKB as the base of the Calpionella Zone (i.e., the Alpina Subzone) in both sections as it has been selected as the primary marker for the boundary (Wimbledon, 2017; Wimbledon et al., 2011, Ogg et al., 2016a). In both sections, nannofossils are also present, which are regarded as important secondary markers (Wimbledon, 2017; Wimbledon et al., 2011). We also report new nannofossil data from the section in Mexico, which allows the definition of the FAD of *Nannoconus steinmannii steinmannii* and *Nannoconus kamptneri minor*, respectively (Fig. 3 & 4). Additionally, we also present an age at the base of the *Virgatosphinctes andesensis* biozone in the La Yesera section, Neuquén basin, very close to the Kimmeridgian/Tithonian boundary (KmTB) (Riccardi, 2008, 2015; Vennari, 2016). This age allows an estimation of the duration of the Tithonian, which in turn also validates our age for the JKB. Additionally, our results allowed us to identify a few pitfalls when trying to correlate seemingly contemporaneous basin deposits over thousands of kilometers. More importantly, the data presented here permits to put o the test the currently ICS accepted age of the JKB.

2. Studied areas

To investigate the numerical age of the JKB, we have selected two sections where the boundary is well recognized and defined with the presence of the most prominent markers for the boundary. The Las Loicas section is located in the Vaca Muerta Formation, Neuquén Basin, Argentina (Vennari et al., 2014) (Fig. 4A) The Vaca Muerta Formation is a 217 m thick sedimentary sequence of marine shales and mudstones, which spans an interval from the Lower Tithonian (*Virgatosphinctes andesensis* biozone) to the upper Berriasian (*Spiticeras damesi* biozone) (Aguirre-Urreta et al., 2005; Kietzmann et al., 2016; Riccardi, 2008, 2015). In Las Loicas, the *Substeueroceras koeneni* and *Argentiniceras noduliferum* ammonite biozone and calcareous nannofossils have been described by Vennari et al. (2014). Recently, (López-Martínez et al., 2017) reported the occurrence of upper Tithonian to lower Berriasian calpionellids, which is the only known section where the main markers for the JKB occur together in Argentinian Andes. The section contains several ash beds which allowed precise age bracketing of the boundary using high-precision U-Pb geochronology. We also investigated the Early Tithonian in the La Yesera Section, also in the Vaca Muerta Fm., where the *Virgatosphinctes andesensis* is exposed above the contact between the Vaca Muerta Fm. and Tordillo Fm.

The Mazatepec section exposes the Pimienta and the lower Tamaulipas formations of the Eastern Sierra Madre geological province, Mexico. The Pimienta Fm. is composed of darkish clayey limestones and the Tamaulipas Fm is a gray limestone (López-Martínez et al., 2013). The section has a dense occurrence of Late Tithonian Crassicollaria Zone (Colomi

Subzone) and Early Berriasian calpionellids from Calpionella Zone, (Alpina, Ferasini, and Elliptica Subzones) to Calpionellopsis Zone (Oblonga Subzone). In the upper part of the section, ash beds are scarce and occur at distinct levels. Ash bed MZT-81 is situated within the Elliptica Subzone in the lower Tamaulipas Formation (Fig. 4B).

3. Material and Methods

We have applied U-Pb zircon CA-ID-TIMS dating techniques to single zircon grains, which yields ^{206}Pb/^{238}U dates at 0.1-0.05% precision. The depositional age of ash beds has been calculated from the weighted means of the four youngest overlapping ^{206}Pb/^{238}U dates (Fig. 2), assuming that older grains record prolonged residence of zircon in the magmatic systems as well as intramagmatic recycling. In the text, all quoted ages of ash beds are weighted mean ^{206}Pb/^{238}U ages corrected for initial ^{230}Th disequilibrium. A detailed description of the techniques of sample preparation, laboratory procedures, data acquisition, as well as data treatment are provided in the Supplementary Materials. The full U-Pb data set is reported in Table S1.

The nannofossil biostratigraphy for the Mazatepec section was based on 17 samples from the Pimienta and Tamaulipas formations. For detailed calcareous nannofossil examination, simple smear slides were prepared using standard procedures (Edwards, 1963). Observations and photographs were taken using a polarizing microscope Leica DMLP with increased 1000X and accessories such as λ one sheet of plaster and blue filter. The slides are deposited in the Repository of Paleontology, Department of Geological Sciences, University of Buenos Aires, under the catalog numbers BAFC-NP: Nº 4190-4206 photomicrographs of selected species are shown in Fig. 3; the distribution chart for the calcareous nannofossil species is presented in Supplementary Fig. S1.

The age of the various paleontological markers, as well as the age of JKB in the Las Loicas, have been modeled using the Bayesian age-depth model Bchron of Haslett and Parnell (2008) and Parnell et al. (2008). The model outputs an uncertainty envelope which is presented in Fig. 4B. The age-depth results are reported in TS.2, with age assigned to every meter of stratigraphic height. The Bchron code used in the R statistical package environment (R Core Team 2013) is included in the Supplementary Materials section 6.

4. Results and discussion

[redacted] 4.1 The age of the Jurassic/Cretaceous Boundary in the Vaca Muerta Formation

The Las Loicas section contains ammonites and calcareous nannofossils (Vennari et al., 2014) as well as calpionellids (López-Martínez et al., 2017). In Fig. 4A, the various primary marker assemblages and the age of the ash beds are indicated. The Late Tithonian Crassicollaria Zone, Colomi Subzone (Upper Tithonian) is composed of *Calpionella alpina* Lorenz, *Crassicollaria colomi* Doben, *Crassicollaria parvula* Remane, *Crassicollaria massutiniana* (Colom), *Crassicollaria brevis* Remane, *Tintinnopsella remanei* (Borza) and *Tintinnopsella carpathica* (Murgeanu and Filipescu) (López-Martínez et al., 2013, 2015). This calpionellid assemblage occurs below the base of the NJK-B calcareous nannofossil Zone, characterized by the FAD of *Umbria granulosa granulosa* (Bralower et al., 1989) and well within the *Substeueroceras koeneni* ammonite Zone (Vennari et al., 2014). All these markers have been considered Late Tithonian in age (Bralower et al., 1989; Casellato, 2010; Riccardi, 2015). Importantly, the occurrence of *Crassicollaria parvula* and *Crassicollaria colomi* and the FAD of *Umbria granulosa granulosa* are situated 13 meters above ash bed LL13 (142.040 ± 0.058 Ma; ca., 15 m stratigraphic height). The calculated Bchron model age is 141.31 ± 0.56 Ma for the faunal assemblage (Fig. 4A). Therefore, this age can be considered a minimum age for the Late Tithonian based on the association of *Crassicollaria parvula* and *Crassicollaria colomi* in close occurrence with the FAD of *Umbria granulosa granulosa*.

In the Las Loicas section, there are several well-known Early Berriasian markers. For instance, the FAD of *Nannoconus kamptneri minor* (Fig. 4A, Fig.S1) and *Nannoconus steinmannii minor* are considered trustworthy indicators of the Early Berriasian (Bralower et al., 1989; Casellato, 2010). Here they overlap with the base of the *Argentiniceras noduliferum* ammonite Zone (López-Martínez et al., 2017; Vennari et al., 2014). The occurrence of the calpionellid assemblage dominated by *Calpionella alpina* over scarce specimens of *Crassicollaria massutiniana*, *Tintinnopsella remanei,* and *T. carpathica* confirms the Early Berriasian age (López-Martínez et al., 2017) (Fig. 4A). These assemblages are bracketed by ash beds LL9 (139.956 ± 0.063 Ma) and LL10 (140.338 ± 0.083 Ma) (Fig. 4A). From our data, we can state that the base of the Berriasian cannot be younger than 139.956 ± 0.063 Ma, because ash bed LL9 is located 8 meters above the base of the *Argentiniceras noduliferum* Zone. The Early Berriasian calpionellid assemblage described in López-Martínez et al. (2017) overlaps with the FAD of *Nannoconus kampteri minor* and *Nannoconus steinmannii minor* and the base of *Argentiniceras noduliferum* ammonite Zone (ca., 34 m stratigraphic height) (Fig. 4A). Using age-depth modelling, we calculate the age of the JKB in the Vaca Muerta Fm. to be 140.22 ± 0.13Ma (Fig. 4A).

[redacted]4.2 The age of the Jurassic/Cretaceous Boundary in the Pimienta Formation

The Mazatepec section has a dense and well-established calpionellid zonation like that of classical western Tethyan zonation (López-Martínez et al., 2013) (Fig. 4B). Compared to Tethys, the nannofossil assemblages in Mazatepec exhibits low diversity and a relatively poor degree of preservation of the nannofossils, which are characterized by a moderate to heavy dissolution etching (Fig. 3). At bed MTZ-65 (López-Martínez et al., 2013), 18 nannofossil species have been recognized (Fig. S1): the heterococcoliths are mostly represented by Watznaueriaceae including *Watznaueria barnesae, W. britannica, W. manivitae, Cyclagelosphaera margerelii, and C. deflandrei; Zeugrhabdotus embergeri* is another frequent constituent. The nannoliths are represented by *Conusphaera mexicana, Polycostella senaria, Hexalithus noeliae, Nannoconus globulus* and *N. kamptneri minor*. These nannofossils indicate Late Tithonian to Early Berriasian age for the Pimienta Formation and the lower part of the Tampaulipas Formation. The assemblage composed by *Conusphaera mexicana*, *Polycostella senaria*, and *Hexalithus noeliae*, indicates a Late Tithonian age. The only useful biological event recognized is the FAD of *N. kamptneri minor* documented in the base of Ferasini Subzone, 5 m above the base of the Alpina Subzone. At bed MTZ-65 (López-Martínez et al., 2013) the FAD of *Remaniella ferasini* (Catalano) and the FAD of *Nannoconus kamptneri minor* are situated 5 meters above ash bed MZT-45 (base of alpine Subzone) (ca., 11 m stratigraphic height).

At stratigraphic height ca. 25m an increase in the diversity of nannofossils is identified, with 13 species (bed MZT-87 sample). Among the nannofossils, the presence of *N. steinmanni steinmanni* stands out; a marker also used to define the base of the first biozone of the Berriasian (NK1) (Bralower et al., 1989). The NK1 biozone has been correlated in DSDP 534, Colme di Vignola Bosso and Foza with magnetozone 17t (Bralower et al., 1989; Casellato, 2010; Channell et al., 2010) as well as the Elliptica Subzone (Schnabl et al., 2015; Ogg et al., 2016a). The calibration of nannofossil datums with magnetostratigraphy has been a very useful development (e.g., Channell et al., 2010), although the integration of nannofossils with calpionellids ranges has been less exploited. Noteworthy is the correlation between NK1 and the Elliptica Subzone recognized here in Mazatepec which also coincides with the previously established relationship between these biozones in the Nutzhof section in Austria (Lukeneder et al., 2010). Therefore, the relative age of the paleontological markers in the Mazatepec section is in full agreement with the working model of Wimbledon (2017). Unfortunately, the presence of *N. steinmannii minor* or *N. wintereri* have not been reported in Mazatepec.

To constrain the age of the JKB in Mazatepec, we dated the ash bed in bed MZT-81 which is located within the Elliptica Subzone and stratigraphically 11.1m above the base of the Alpina Subzone (Bed MTZ-45 Fig. S2C), i.e., JKB (López-Martínez et al., 2013) (Fig. 4B). The age of ash bed MZT-81 is 140.512 ± 0.031Ma (Fig. 2). Unfortunately, in Mazatepec ash beds are scarce, so it was not possible to bracket the age of the JKB, as was the case in Las Loicas. Consequently, to calculate the age of the boundary, we have to resort to assumed sedimentation rates to back-calculate the age of the JKB. Since the sedimentation rate in the Pimienta and Tampaulipas formations is unknown, we use both high and low sedimentation rate because this takes into account our conjectural knowledge of the sedimentation rate in the Pimienta and Tampaulipas formations. Here we assume a low sedimentation rate to be 2.5 cm/ka and a high sedimentation rate to be 4.5 cm/ka. Therefore, the age of the JKB is estimated to be 140.7 Ma and 140.9 Ma, respectively.

[redacted] **4.3 The Early Tithonian and the base of the Vaca Muerta Formation**

The base of the Vaca Muerta Formation contains a well-established Early Tithonian ammonite assemblage of the *Virgatosphinctes andesensis* Zone (Riccardi, 2008, 2015; Vennari, 2016). Fortunately, the gradational contact between the Vaca Muerta and the Tordillo formations is very well exposed in the La Yasera section and contains ash beds very close to the contact (Fig. S2B). We have dated an ash bed (LY-5) located below the contact, and it yielded an age of 147.112 ± 0.078 Ma (Fig. 4C). The ash bed is located in the Tordillo Fm, 1.5m below the contact with the Vaca Muerta Formation, thus very close to the base of the *Virgatosphinctes andesensis* Zone. This biozone is mostly equivalent to the Darwini Zone of the Tethys ocean, which is broadly regarded as Early Tithonian in age and widely distributed such as in various other regions like Mexico and Tibet (Riccardi, 2008, 2015; Vennari, 2016 for a thorough review of the subject). Consequently, the age of ash bed LY-5 (147.112 ± 0.078 Ma) can be regarded as an age in the Early Tithonian. This result is in close agreement with other studies that have dated the Early Tithonian. For instance, Malinverno et al. (2012) quote an age 147.95 ± 1.95 Ma for the M22An magnetozone and Muttoni et al. (2018) suggest that the base of the Tethyan Tithonian (top Kimmeridgian) falls in the lower part of M22n at a nominal age of ~146.5 Ma based on the FO of the nannofossil *Conusphaera mexicana minor*.

Assuming the age of our ash bed LY-5 (147.112 ± 0.078 Ma) in the La Yesera section being Early Tithonian and coupling it with the age for the base of the Berriasian in Las Loicas (140.22 ± 0.13 Ma), we can calculate a minimum duration for the Tithonian. If we assume the base of the Berriasian to be at the base of the Calpionella Zone (Fig. 4A), then this would imply that the minimum duration for the Tithonian of 6.90 ± 0.15 Ma (Fig. 4C). This is in good agreement with the current full duration of the Tithonian estimated at ~7 Ma (Ogg et al., 2016b). Furthermore, the M-sequence geomagnetic polarity time scale (MHTC12) of Malinverno et al. (2012) suggests a duration for the Tithonian of 5.75 ±2.47 Ma (i.e., between magnetozones M22An and M19n.2n, a proxie for the base of the Berriasian). Therefore, our new ages for the base of the Berriasian and the Early Tithonian are in good agreement of other independent timescale estimates for the duration of the Tithonian. Incidentally, this result also has direct implications for the age of the KmTB. Currently, the age of the KmTB is 152.1±0.9 Ma in the International Commission on Stratigraphy (ICS) (see also Ogg et al., 2016b). Admittedly, the ash bed LY-5 is not at the KmTB, albeit close; therefore, we acknowledge that the age of KmTB would have to be older than bed LY-5. Nevertheless, if the age of the KmTB is 152.1 Ma, it would imply that the *Virgatosphinctes* ammonite Zone itself lasts more than ~5 Ma and that the total duration of the Tithonian would have been ~12 Ma. In short, it is reasonable to assume that our results for the Early Tithonian are in agreement with other studies that dated the KmTB, and also suggests that the current ICS KmTB age may need revision.

4.5 A global correlation for the Jurassic/Cretaceous boundary age?

The principal aim of this study is to evaluate whether our biochronological and geochronological data from two disparate sections (Argentina and Mexico) match well enough to infer a global calibration for the JKB age. In the Mazatepec section, we have estimated the age of the JKB to be ~140.9-140.7 Ma (Fig. 4B), and in Las Loicas the Bchron age model coupled with high-precision geochronology yields an age of 140.22 ± 0.13 Ma (Fig. 4A). Clearly, there is an offset between the age of the JKB in both sections of ~670 ka (±335 ka) (Fig. 4A). In Mazatepec the ash bed MZT-81 (140.512±0.031 Ma) is in the middle of the Elliptica Subzone, well within the Calpionella Zone, in the NJK-D, and consequently of lower Berriasian age (Fig. 4B). Conversely, in the Las Loicas section, the JKB Bchron model age of 140.54±0.37 Ma (ca. 28.5 m, see TS.2) is high in the Crassicollaria Zone and the NJK-B, thus Late Tithonian (Fig. 4A). In other words, the age of ~140.5 Ma in one section is coincident with Late Tithonian fauna, and in the other, it yields an age coincident with Early Berriasian fauna. It becomes apparent that both sections are offset by ~670 ka. The rate of migration of key taxa could be a possible explanation for the difference in age between FAD and LAD of key taxa in the Late Tithonian to Early Berriasian. For instance, Calpionellids are thought to have originated in the tropical waters of Tethys and spread globally during the transition from the Jurassic to Cretaceous (Rehákova & Michalik, 1997). As such, the discrepancy in age between the fauna of the studied sections may represent the time it took for the key taxa of this time to migrate globally. However, the discrepancy seems quite long (670 ka) to represent the rate of migration of key taxa, so other avenues need to be explored to explain the offset.

The preservation of the geological record is a significant challenge when correlating sections at the 100 ka level. To examine if preservation affects are data, we project the JKB age from the Mazatepec section onto the Las Loicas section. Using our Bchron model age in Las Loicas the age of 140.7-140.9 Ma (i.e., the age of the JKB in Mazapetec) is found at a stratigraphic height at 22 to 25 m (Fig. 4A). However, with the relatively high uncertainty of the age-depth model in this part of the section (~±500 ka), these level (22 and 25 m) levels are virtually indistinguishable in age. Consequently, for the projection of the JKB age from the Mazatepec section onto the Las Loicas section show that the choice of sedimentation rate used to back-calculate the age of the JKB in the Mazatepec section is not that important, because the interval ~140.9-140.7 Ma is statistically indistinguishable in the Las Loicas section. In López-Martínez et al. (2017), the FAD of *N. kampteri minor* and the FAD *N. steinmannii minor* and Alpina Subzone occur very close to each other. However, in working models of Schnabl et al. (2015) and Wimbledon (2017), the FAD of *N. kampteri minor* and the FAD *N. steinmannii minor* are considered to be younger than the base of the Alpina Subzone in the Western Tethys. From this perspective, it is conceivable that the base of the Alpina Subzone in the Las Loicas section is older (possibly ca. 26 m), which would make the age of the JKB in Las Loicas within range with the calculated age in the Mazatepec section, suggesting that the geochronology results from both sections might converge to similar results if preservation is an issue.

In summary, it is possible that FAD and LAD of key taxa of the Late Tithonian to Early Berriasian are apparently not time-equivalent and thus not allowing global correlations during the Late Tithonian to Early Berriasian. However, global correlations between stratigraphic sections based on FAD and LAD are dependent on: (1) different degrees of sample density, (2) preservation of the geological record, (3) different environmental and depositional setting between the correlated sections. Additionally, other processes that occur at the 100 ka level in the marine record such as migratory rates can also affect and create discrepancy in age of key markers; however, such a process is hard to quantify. Difference in rate of migration between different taxa might also complicate matters. Nevertheless, these parameters ultimately result in a different thickness of biozones in the sedimentary record and this can become quite a confusing when correlating bioevents globally. For instance, the different thickness of the *Argentiniceras noduliferum* between Las Loicas (~27m) and La Yesera (~5 m) (see Fig. 4) is an example of how these parameters need to be taken into account. Therefore, defining the age of stage or substage boundaries on the bases of FAD, especially in the light of these latter limitations, leads to weak correlations between biochronology and other time series of possible global importance as, e.g., magnetostratigraphy or chemostratigraphy. These facts make the correlation of biozones at the 100 ka level quite challenging and only reliable when high-resolution age models based on high-precision geochronology are available from different sections. Furthermore, the effort in documenting biodiversity has to be on the same level of resolution at the same level as the gechronological methods being used. From this perspective, it is hard to evaluate how these parameters affect our data in both sections, and we suggest bracketing the age of the JKB between 140.22 ± 0.13 Ma (in Las Loicas) and ~140.9-140.7 Ma (in Mazatepec) and define it as the JKB interval.

4.6 A case for a younger J/K boundary age

Another principal aim of this study is to show that the current age of the JKB in ICS is demonstrably too old. As of now, the age of the JKB in the ICS is ~145 Ma, which is significantly older than our bracket interval for the JKB. As we have explored in the previous section, there is significant ambiguity between of the most prominent markers for the JKB, which has prevented us to constrain the age of the JKB to a precise age. Nevertheless, our data are sufficiently conclusive to challenge the age of ~145 Ma for the JKB. For instance, our age for the base of the Berriasian is anchored by Calpionellids, calcareous nannofossils, and ammonites, which are the most prominent paleontological markers for the boundary. Furthermore, an assemblage of *Crassicollaria parvula*, *Crassicollaria colomi* and the FAD of *Umbria granulosa granulosa* in Las Loicas has an age of 141.31 ± 0.56 Ma (Fig. 4A), which is decidedly Late Tithonian. Lastly, the age in the *Virgatosphinctes andesensis* biozone (Early Tithonian) at 147.112 ± 0.078 Ma also makes it implausible for the base of the Berriasian to be ~145 Ma. From our geochronological data, ~145 Ma would be most likely an age in the middle of the Tithonian rather than the base of the Berriasian (Fig. 2).

Analytical and biostratigraphical issues further add to the inconsistency of the current age of the JKB. The age is based on the work of Mahoney et al. (2005). These authors dated a basaltic intrusion in Early Cretaceous (NK1) sediments and made the case that the age of the basalt would be close to the age of the JKB. Their age for the intruded basalt is 144.2± 2.6 Ma ($^{40}Ar/^{39}Ar$), which was later corrected by Gradstein et al. (2012) to 145.5±0.8 Ma with the recalibrated ^{40}K decay constant of Renne et al. (2010). It is worth pointing out that Mahoney et al., (2005) report the dated basalts to be slightly altered which could have consequences to the accuracy and precision of their age. The biostratigraphy of drill core 1213 also poses problems. Bown (2005) pointed out that the sediments of this core were devoid of indicative NK1 nannofossils such as *Conusphaera* and *Nannoconus*. Important markers such as the Cretarhabdaceae family are present but in rare occurrences. Additionally, drill cores 1213 is limited to the occurrences of nannofossils considered secondary markers and lack any primary markers. Collectively, these facts expose how poorly the current age of the JKB is anchored.

Other recent geochronological studies on JKB using different dating approaches (e.g., Re-Os isochron ages from shales, or laser ablation ICP-MS U-Pb ages from zircons) and in the Early Cretaceous make the age of the boundary at 145 Ma complicated. López-Martínez et al., (2015, 2017); Pálfy et al., (2000a); Tripathy et al., (2018) all have published geochronological results that overlap within uncertainty with our ages for the JKB, which further adds to the reliability and robustness of our bracketed interval for the JKB and ultimately a younger age for the JKB.

5. Summary and conclusions

The age of the JKB has been controversial and difficult to determine for the past decades. Recent developments in high-precision U-Pb geochronology have proven this technique to be a powerful tool in dating the stratigraphic record, allowing an accurate and precise calibration of stage boundaries. Our geochronological and biostratigraphical data have not permitted the age of the JKB to be constrained to a single age. However, we were able to restrict the boundary to an interval, here coined as the JKB interval 140.22 ± 0.13 Ma to 140.7-140.9 Ma. The idea of the JKB interval stems from the fact that key paleontological markers from both sections are apparently not time-equivalent and present difficulties to global correlations with regards to their age. We hypothesize that this might be because: (1) very different degrees of sample density, sampling effort, (2) preservation of the geological record, and (3) environmental-depositional differences. Therefore, defining the age of stage or substage boundaries assuming that first and last appearance datum's are of global validity, especially in the light of these limitations outlined above leads to weak age correlations between paleontological markers during this time frame (Late Tithonian to Early Berriasian). This fact makes the correlation of biozones at the 100 ka level only valid when high-resolution age models based on high-precision geochronology are available from the different sections, and if the effort in documenting biodiversity is at the same level as the geochronology. Another significant implication of our results is that it challenges the current age of the JKB. In addition to finding a much younger age for the base of the Berriasian, our data impose other constraints against a JKB age at 145 Ma. For instance, the Late Tithonian assemblage of *Crassicollaria parvula, Crassicollaria colomi* and the FAD of *Umbria granulosa granulosa* have an age of 141.31 ± 0.56 Ma, and the *Virgatosphinctes andesensis* Zone one at 147.112 ± 0.078 Ma, both rendering the JKB age at 145 Ma implausible. Collectively, this facts render our revised age interval for the JKB better-anchored and more reliable than the one currently held by the ICS.

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Figure 1: Global paleogeography during the Late Jurassic to Early Cretaceous after Smith et al. (1994), with various JKB sections located globally. Red arrows indicate possible migratory routes of the Calpionellid from Tethys to the proto Pacific Ocean (López-Martinez et al., 2017)

Figure 2: U-Pb weighted mean ages of the dated ash beds and the ages and the projected ages of the JKB interval, base of the Calpionella alpina Zone, top of the Crassicolaria Zone, *Virgatosphinctes andesesis* Zone, and the KmTB at ~148 Ma. Colour bars represet grains considered in the weighted mean age.

Figure 3: A-H. Representative calcareous nannofossils from Mazatepec section, Mexico. A-B) *Conusphaera mexicana* Trejo, C) *Hexalithus noeliae* Loeblich and Tappan, D) *Hexalithus geometricus* Casellato, E) *Nannoconus kamptneri minor* Bralower, F) *Nannoconus globulus* Brönnimann, G-H) *Nannoconus steinmannii* subsp. *steinmannii* Kamptner, I-P Calcareous nannofossils from Las Loicas section, Argentine Andes. I-J) *Polycostella senaria* Thierstein, K) *Umbria granulosa* Bralower and Thierstein, L) *Eiffellithus primus* Applegate and Bergen, M-N) *Rhagodiscus asper* (Stradner) Reinhardt, O) *Nannoconus kamptneri minor* Bralower, P) *Nannoconus wintereri* Bralower and Thierstein. All photomicrographs under crossed nicols (polarized light), white scale bar 1μm.

Figure 4: Age correlation between the Las Loicas, Mazatepec, La Yesera section. (A) Las Loicas section: Ash beds in light blue with respective name and U-Pb dates in black font; age-depth modeling ages are in red font next to green stars (this study); ammonites and nannofossils zonation Vennari, et al. (2014); calpionellid zonation Lopez-Martinez et al. (2017);. (B) Mazatepec section: ash bed in light blue with respective name and U-Pb age in black font, age calculated from sedimentation rate red font (this study); calcareous nannofossils (this study); calpionellid zonation Lopez-Martinez et al. (2013). (C) La Yesera section: ash bed in light blue with U-Pb age.

Figure 1

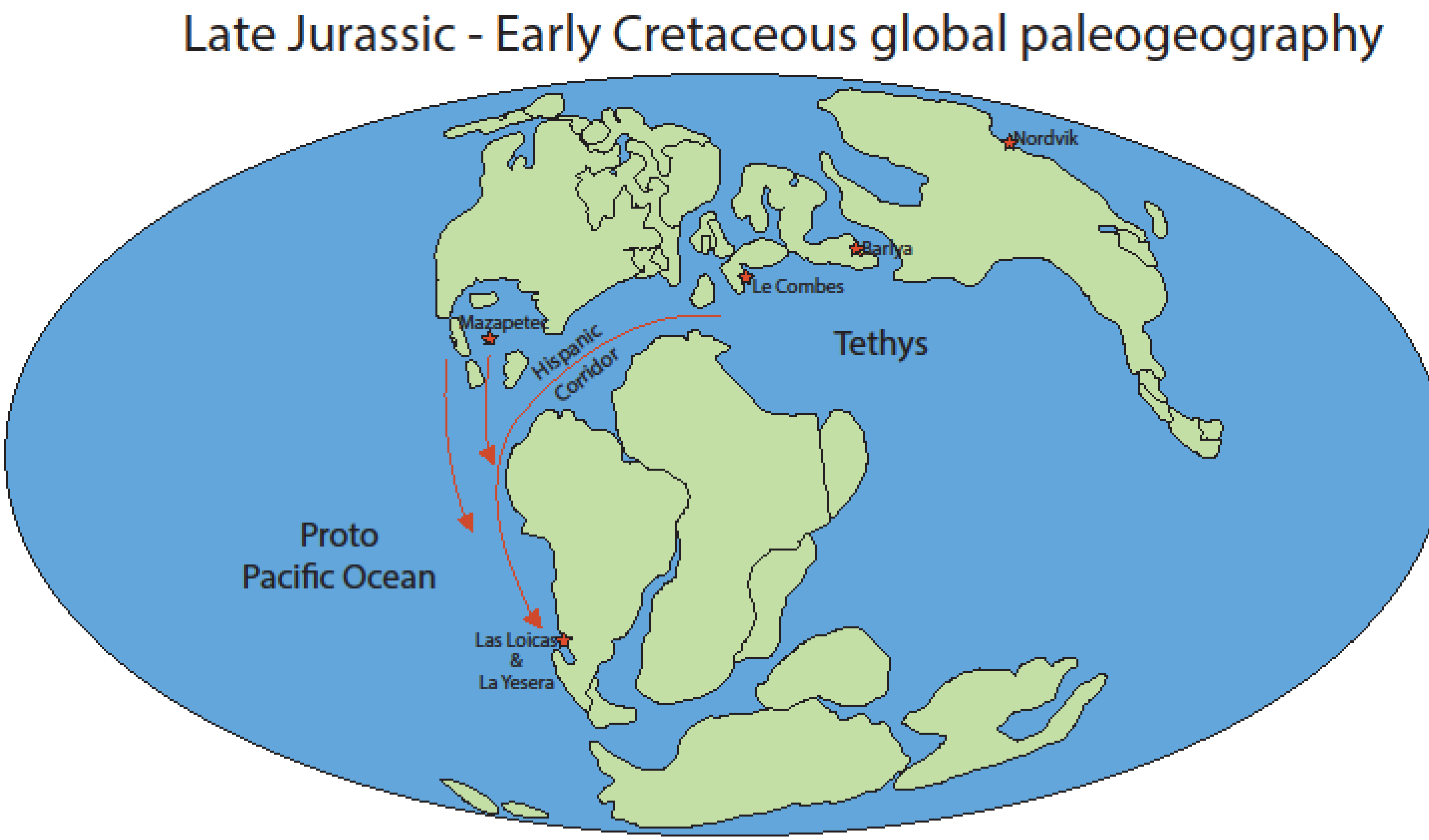

Late Jurassic - Early Cretaceous global paleogeography
Nordvik
Bariya
Le Combes
Mazapetec
Hispanic
Corridor
Tethys
Proto
Pacific Ocean
Las Loicas
&
La Yesera

Figure 2

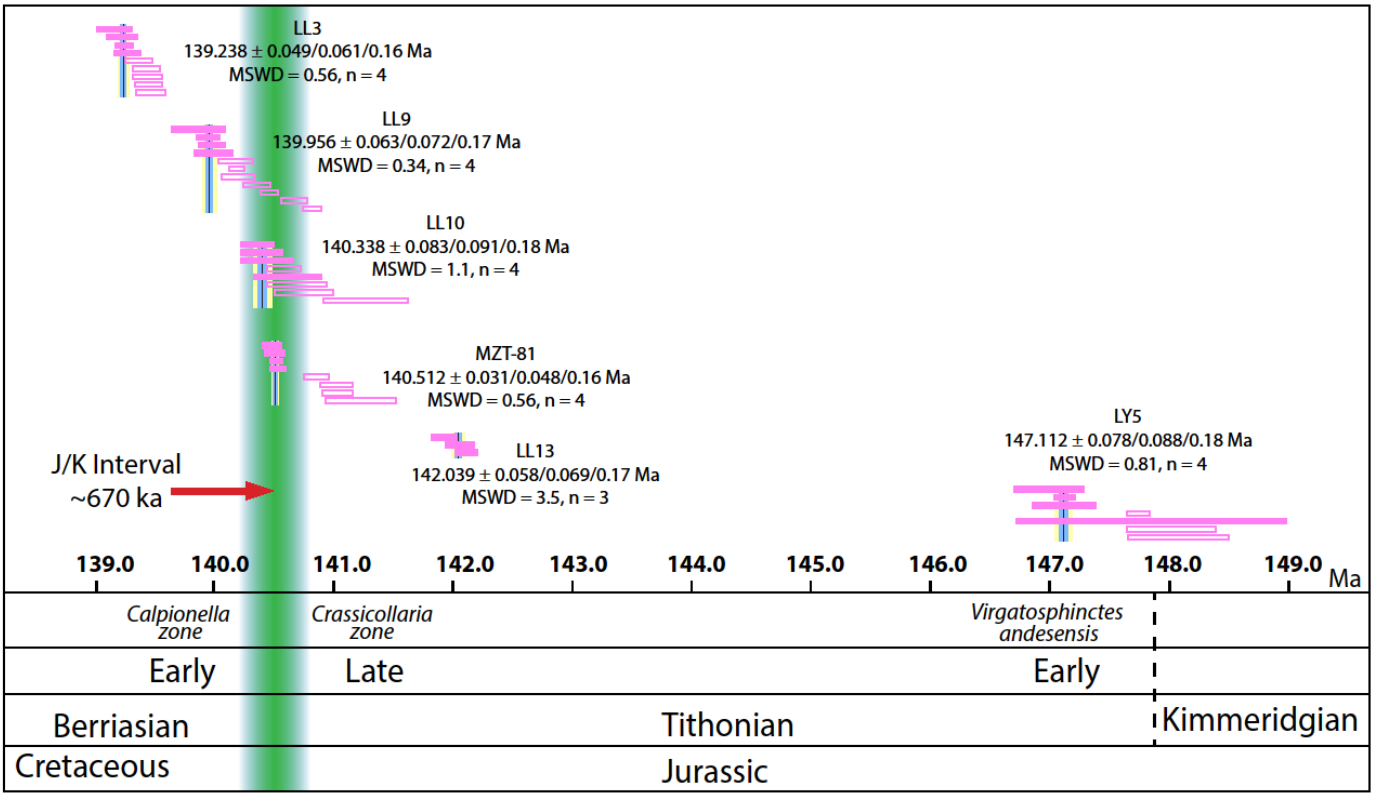

LL3
139.238 ± 0.049/0.061/0.16 Ma
MSWD = 0.56, n = 4
LL9
139.956 ± 0.063/0.072/0.17 Ma
MSWD = 0.34, n = 4
LL10
140.338 ± 0.083/0.091/0.18 Ma
MSWD = 1.1, n = 4
MZT-81
140.512 ± 0.031/0.048/0.16 Ma
MSWD = 0.56, n = 4
LL13
142.039 ± 0.058/0.069/0.17 Ma
MSWD = 3.5, n = 3
LY5
147.112 ± 0.078/0.088/0.18 Ma
MSWD = 0.81, n = 4
J/K Interval
~670 ka
139.0
140.0
141.0
142.0
143.0
144.0
145.0
146.0
147.0
148.0
149.0
Ma
Calpionella zone
Crassicollaria zone
Virgatosphinctes andesensis
Early
Late
Early
Berriasian
Tithonian
Kimmeridgian
Cretaceous
Jurassic

Figure 3

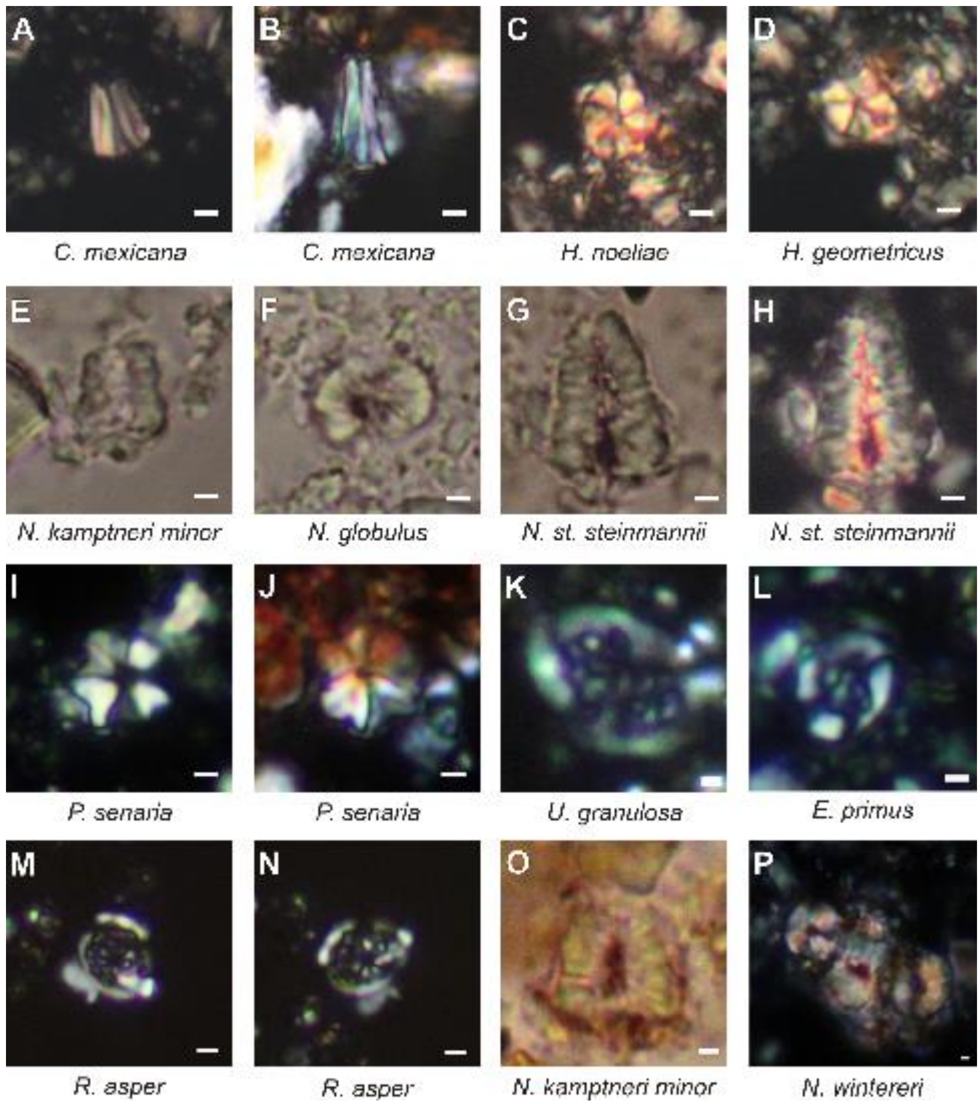
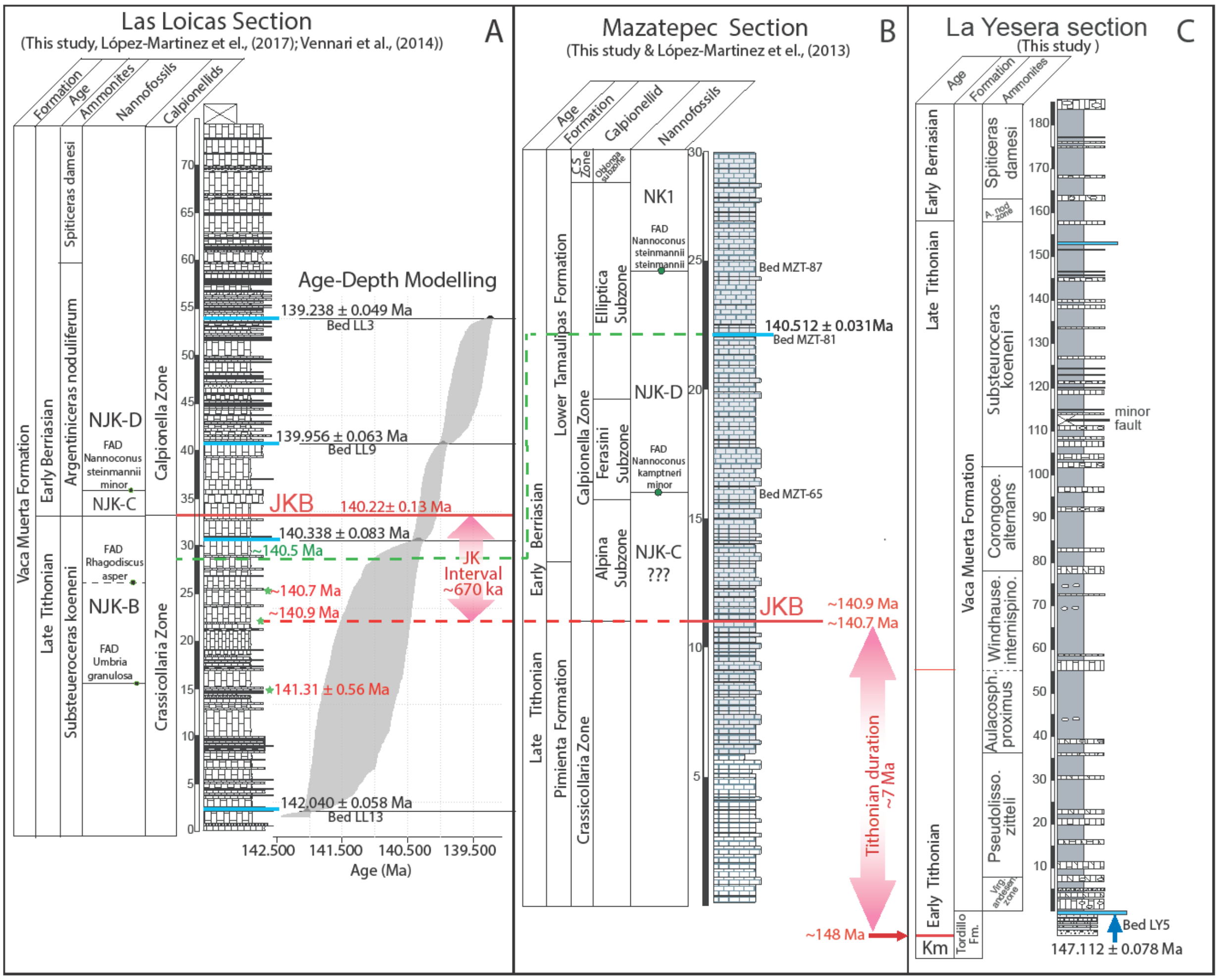

A
C. mexicana
B
C. mexicana
C
H. noeliae
D
H. geometricus
E
N. kamptneri minor
F
N. globulus
G
N. st. steinmannii
H
N. st. steinmannii
I
P. senaria
J
P. senaria
K
U. granulosa
L
E. primus
M
R. asper
N
R. asper
O
N. kamptneri minor
P
N. wintereri

Figure 4


Las Loicas Section
(This study, López-Martinez et el., (2017); Vennari et al., (2014))
A
Formation
Age
Ammonites
Nannofossils
Calpionellids
Vaca Muerta Formation
Early Berriasian
Late Tithonian
Spiticeras damesi
Argentiniceras noduliferum
Substeueroceras koeneni
NJK-D
FAD Nannoconus steinmannii minor
NJK-C
FAD Rhagodiscus asper
NJK-B
FAD Umbria granulosa
Calpionella Zone
Crassicollaria Zone
Age-Depth Modelling
139.238 ± 0.049 Ma
Bed LL3
139.956 ± 0.063 Ma
Bed LL9
JKB
140.22± 0.13 Ma
140.338 ± 0.083 Ma
~140.5 Ma
~140.7 Ma
~140.9 Ma
JK Interval ~670 ka
141.31 ± 0.56 Ma
142.040 ± 0.058 Ma
Bed LL13
142.500
141.500
140.500
139.500
Age (Ma)
Mazatepec Section
B
(This study & López-Martinez et el., (2013)
Age
Formation
Calpionellid
Nannofossils
Lower Tamaulipas Formation
Pimienta Formation
Early Berriasian
Late Tithonian
Calpionella Zone
Crassicollaria Zone
Elliptica Subzone
Ferasini Subzone
Alpina Subzone
NK1
FAD Nannoconus steinmannii steinmannii
NJK-D
FAD Nannoconus kamptneri minor
NJK-C
???
Bed MZT-87
140.512 ± 0.031Ma
Bed MZT-81
Bed MZT-65
JKB
~140.9 Ma
~140.7 Ma
Tithonian duration ~7 Ma
~148 Ma
La Yesera section
C
(This study)
Age
Formation
Ammonites
Early Berriasian
Late Tithonian
Early Tithonian
Km
Vaca Muerta Formation
Tordillo Fm.
Spiticeras damesi
Substeueroceras koeneni
Corongoce. alternans
Windhause. internispino.
Aulacosph. proximus
Pseudolisso. zitteli
minor fault
Bed LY5
147.112 ± 0.078 Ma

Revised - Supplementary Material

1. Sample preparation

Ash beds were crushed using a tungsten mill. The crushed samples were then sieved at 300 μm. A water flotation method was used to separate and remove the very fine grain size material (less than 20 microns), resulting in a fine material with mineral grains ranging from 20 to 300 μm. The material was then separated with a magnetic separator at a current of 1.8A using a Frantz unit. The non-magnetic material was then run through heavy liquid density separation method using Methyl Iodide from Geoliquids Inc. Minerals denser than 3.33g/cm^3 sank and collected, were zircons were expected to be found. Single grains zircons were then hand-picked using a transmitted light microscope.

2. Laboratorial procedures

Ten to twenty grains were selected for annealed at 900^{o}C for 48 hours. Grains from each sample were then separately chemically abraded, in bulk, for 12 hours in 3 ml Teflon beakers at 210^{o}C with 12N HF inside a pressure dissolution vessel. Following chemical abrasion, the grains were then individually placed inside 3ml Teflon beakers rinsed and cleaned. The cleaning of grains consisted of several steps. In the first step, grains are left for 12 hours (overnight) in 6.2N HCl inside 3ml Savilex beaker at 80^{o}C on a hot plate. In the second step, the grains were cleaned using 7N HNO_3, which consisted of a 45 min hot bath on a sonicator with and an additional 60 min hot bath on hotplate at 80^{o}C. The 7N HNO_3 was then removed from the beakers and the process repeated three times before moving to total dissolution of the grains. Total dissolution consisted of grains being placed individually in microcapsules in 12N HF for 48 hours at 210^{o}C. After total dissolution, microcapsules were then placed on a hotplate at 120^{o}C uncapped to evaporate the remaining HF remaining from the total dissolution. Subsequently, 6.2N HCl was added to the microcapsules and put back in the oven for 12 hours at 180^{o}C for total conversion. After the conversion of acids, the microcapsules were then placed on a hot at 80^{o}C to evaporate the 6.2N HCl remaining from conversion. After evaporation, 3.1N HCl was added to the microcapsules before eluting Pb and U using micro columns. The micro columns were first cleaned using four steps alternating 6.2N HCl and ultrapure H_2O. Samples were collected in 7ml savillex beakers.

Cleaning of 7 ml beakers are done in a three-step process of 12h in 6.2N HCl, 12h in 12N HF, and 12h of 6.2N HCl on the hotplate at 80^{o}C. General chemical abrasion procedures are followed after Mattinson (2005).

3. Data acquisition

After the full laboratorial procedures, the samples were dissolved into a silica gel and gently placed on outgassed Re filaments. Isotopic ratios were acquired using Thermal Ionization Mass Spectrometry. Samples were run using a either the Thermo Finnigan TRITON or Isotopx Phoenix in the Department of Earth Sciences, University of Geneva, Switzerland. Lead (Pb) measurements were acquired in dynamic mode on the SEM (Triton) or the Daly (Pheonix). Auto focusing and Peak centering were performed at the beginning of each block, which consisted of 20 cycles each. Lead baseline was monitored by mass 203.5. Interferences on mass ^{202}Pb and ^{205}Pb were monitored by masses 201 and 203, respectively. EARTHTIME ^{202}Pb-^{205}Pb-^{235}U-^{233}U and EARTHTIME ^{205}Pb-^{235}U-^{233}U were used as spikes (Parrish et al., 2006; Parrish and Krogh, 1987). Each measured ratio was corrected for fractionation using a ^{202}Pb/^{205}Pb of 0.99989 when the ^{202}Pb-^{205}Pb-^{235}U-^{233}U and EARTHTIME was used. When EARTHTIME ^{205}Pb-^{235}U-^{233}U was used Pb fractionation was assumed to be 0.13±0.5 % a.m.u (2 S.D). All common Pb measured was assumed to be from laboratorial blanks. Any sample that contained over 1pg of common Pb was considered to be contaminated and discarded.

Uranium measurements were made in static mode on Faraday cups 10^{12} Ω resistors as UO_2^+. Auto focusing and peak centering was performed at the beginning of every block, with each block consisting of 20 cycles each. Baselines were monitored on ±0.5 mass units. ^{238}U/^{235}U of the sample and blank was assumed to be 137.88 (Chen and Wasserburg, 1980). The oxide correction in U measurements was assumed ^{16}OU/^{18}OU = 0.002. Uranium decay constant values were used from Jaffey et al. (1971).

Raw U-Pb data was reduced using U-Pb Redux (Bowring et al., 2012) and the data reported in TS.1. Uncertainty and error propagation algorithm used in Redux software is described in McLean et al. (2011). For the initial Th disequilibrium deviation was calculated using ^{208}Pb and a Th/U of the magma was assumed to be 3.5 (Blackburn et al., 2013).

4. Ash bed age interpretation

All zircons considered in the age distribution of the ash are interpreted as ash-fall deposits from near-by volcanic eruptions, even though the exact source cannot be known. Individual zircon grains from each sample were analyzed and subsequently the youngest subset of grains from the age distribution of each sample were selected for the final weighted mean age. Ages reported in Fig. 2 and throughout the text are $^{206}Pb/^{238}U$ weighted mean Th-corrected ages. Uncertainties are reported as X/Y/Z; X includes analytical uncertainty, Y includes additional tracer (ET2535) calibration uncertainty, and Z includes additional ^{238}U decay constant uncertainty. The final weighted mean ages are interpreted as a depositional age for the ash beds. Chemical abrasion is assumed to eliminate the effect of Pb loss in individual grains. Therefore, dispersion of individual grains bigger than the analytical uncertainty in individual grains were assumed to record prolonged residence of zircon in the magmatic systems as well as intramagmatic recycling.

5. Sample Description

5.1. Ash bed LL3

Ash bed LL3 is located at stratigraphic height 54 m in the Las Loicas section. Zircon yield was moderate to high ca. > 50 grains. Zircons crystals ranged from 40-80 μm in size. Grains were mainly rounded with aspect ratio of 1:3 with rare prismatic crystals being rare. Radiogenic Pb ranged from 3 to 10 pg (TS.1). A total of nine grains were selected to represent the age distribution of the sample, with 5 grains being discarded for being too old (>~150 Ma) and considered either inherited grains or prolonged magmatic residence, or magmatic recycling. A total of four younger grains (z23, z25, z26, z32) that overlapped were considered for the final weighted mean age of the ash bed. The final weighted mean age of the ash bed is 139.238 ± 0.049/0.061/0.16 Ma, MSWD = 0.56

5.2.Ash bed LL9

Ash bed LL9 is located in stratigraphic height 41 m in the Las Loicas section. Zircon yield was moderate to high ca. > 50 grains. Zircons crystals ranged from 40-80 μm in size. Grains were mainly prismatic with aspect ratio of 1:8. Radiogenic Pb ranged from 2.5 to 14 pg (TS.1). A total of eleven grains were selected to represent the age distribution of the sample, with 7 grains being discarded for being too old (>~150 Ma) and considered either inherited grains or prolonged magmatic residence, or magmatic recycling. A total of four younger grains (z2, z12, z51, z55) that overlapped were considered for the final weighted mean age of the ash bed of 139.956 ± 0.063/0.072/0.17 Ma, MSDW 0.34

5.3. Ash bed LL10

Ash bed LL10 is located in stratigraphic height 31 m in the Las Loicas section. Zircon yield was moderate to high ca. > 50 grains. Zircons crystals ranged from 40-80 μm in size. Grains were mainly prismatic with aspect ratio of 1:8. Radiogenic Pb ranged from 1 to 6 pg (TS.1), notably lower than other the other samples. A total of eight grains were selected to represent the age distribution of the sample, with 4 grains being discarded for being too old (>~150 Ma) and considered either inherited grains or prolonged magmatic residence, or magmatic recycling. A total of four younger grains (z41, z42, z44, z45) that overlapped were considered for the final weighted mean age of the ash bed of 140.338 ± 0.083/0/091/0.18 Ma, MSWD = 1.1

5.4. Ash bed LL13

Ash bed LL13 is located in stratigraphic height 2 m in the Las Loicas section. Zircon yield very low ca. > 10 grains. Zircons crystals ranged from 40-80 μm in size. Grains were mainly prismatic with aspect ratio of 1:8. Radiogenic Pb ranged from 7 to 8 pg (TS.1). The only three three grains that overlapped and reasonably respecting stratigraphic superposition were selected to represent the age of the sample, with 7 grains being discarded for being too (>~450 Ma) and having no geological meaning to the age of the sample. Grains that are much older than the youngest population are hard to interpret if they are inherited grains or detrital, therefore they were discarded. A total of 3 younger grains (z9, z33, z34) that overlapped were considered for the final weighted mean age of the ash bed of 142.039 ± 0.058/0.069/0.17 Ma, MSWD 3.5.

5.5. Ash bed LY5

Ash bed LY5 is located 1.5 m below the contact of the Vaca Muerta Fm. and the Tordillo Fm (FS. 1B). Zircon yield was high ca. > 150 grains. Zircons crystals ranged from 20-100 μm in size. Grains were mainly prismatic with aspect ratio of 1:8 and rounded grains with aspect ratio of 1:3 were also very common. The ash bed is located in the Tordillo Fm, a silisiclastic unit. This sample had a significant amount of inherited and or detrital grains in the sample distribution. In a first batch of dated grains by CA-ID-TIMS the age distribution had a very large interval 180-450 Ma. Therefore, to optimize time we scanned the distribution of ages of the sample via LA-ICP-MS U-Pb geochronology. Grains were imaged via Cathodoluminescence and 250 grains were analyzed. Subsequently, the twenty youngest grains (135-145 Ma), based on Concordia ages, were selected to be analyzed via CA-ID-TIMS to obtain a reliable depositional age for the ash bed. A total of seven grains were selected to represent the age distribution of the sample, with thirteen grains being discarded for being too old (>~150 Ma) and considered either inherited grains or prolonged magmatic residence or magmatic recycling. A total of four younger grains (z10, z20, z38, z44) that overlapped were considered for the final weighted mean age of the ash bed of 147.112 ± 0.078/0/088/0.18 Ma, MSWD = 0.81. Radiogenic Pb ranged from 1 to 6 pg (TS.1).

5.6. Ash bed MZT-81

Ash bed MZT-81 is located in stratigraphic height ca. 22.5 m in the Mazatepec section. Zircon yield high ca. > 100 grains. Zircons crystals ranged from 40-80 μm in size. Grains were mainly prismatic with aspect ratio of 1:8. Radiogenic Pb ranged from 1 to 6 pg (TS.1), notably lower than other the other samples. A total of eight grains were selected to represent the age distribution of the sample, with 4 grains being discarded for being too old (>~150 Ma) and considered either inherited grains or prolonged magmatic residence, or magmatic recycling. A total of four younger grains (z4, z6, z8, z10) that overlapped were considered for the final weighted mean age of the ash bed of 140.512 ± 0.031/0/048/0.16 Ma, MSWD = 0.56

6. Age-depth modelling - Bchron Code

```
library(Bchron)

mydata2 = read.table(file='\\Users\\fortesd0\\Documents\\R\\win-
library\\3.4\\Bchron\\OregonPliens.txt', header=TRUE)
GlenOut = Bchronology(ages=mydata2$ages,
                ageSds=mydata2$ageSds,
                calCurves=mydata2$calCurves,
                positions=mydata2$position,
                positionThicknesses=mydata2$thickness,
                ids=mydata2$id
                predictPositions=seq(0,8400,by=10),iterations = 10000)
plot(GlenOut,main="NeuquenBchron",xlab='Age (Ma)',ylab='Depth (cm)',las=1)
summary(GlenOut)
```

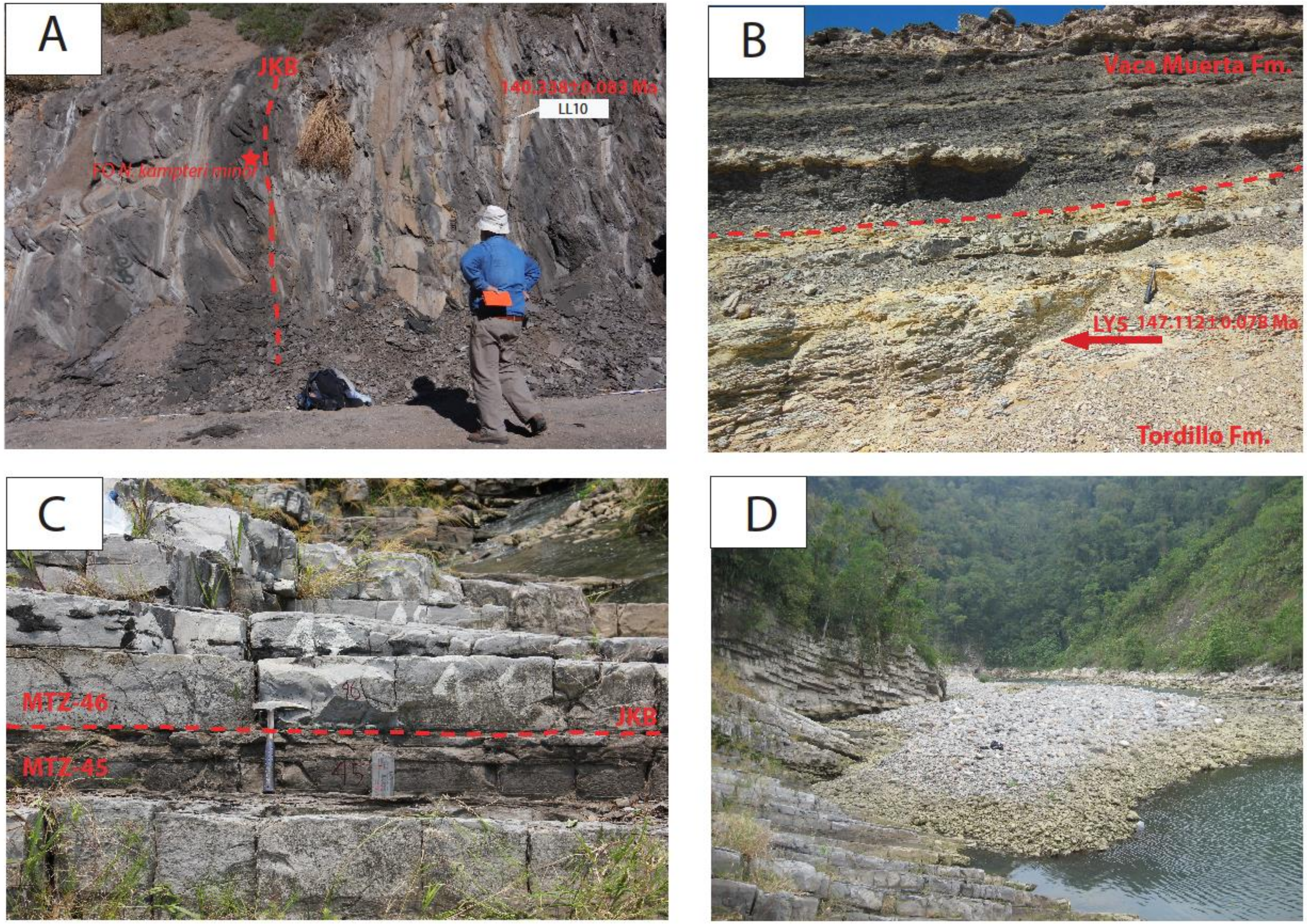
```
summary(GlenOut, type='convergence')
summary(GlenOut, type='outliers')


Output <- cbind(apply(GlenOut$thetaPredict, 2, quantile,  probs = c(.0025)),
     apply(GlenOut$thetaPredict, 2, quantile,  probs = c(.5)),
     apply(GlenOut$thetaPredict, 2, quantile,  probs = c(.975)))
write.csv(Output, file = 'whatever.csv', quote=FALSE, row.names = FALSE)


acc_rate = summary(GlenOut, type = 'acc_rate')
plot(acc_rate[,'age_grid'], acc_rate[,'50%'], type='l', ylab = 'cm per year', xlab = 'Age (k cal
years BP)', ylim = range(acc_rate[,-1]))
lines(acc_rate[,'age_grid'], acc_rate[,'2.5%'], lty='dotted')
lines(acc_rate[,'age_grid'], acc_rate[,'97.5%'], lty='dotted')
sed_rate = summary(GlenOut, type = 'sed_rate', useExisting = FALSE)
plot(sed_rate[,'position_grid'], sed_rate[,'50%'], type='l', ylab = 'Years per cm', xlab = 'Depth
(cm)', ylim = range(sed_rate[,-1]))
lines(sed_rate[,'position_grid'], sed_rate[,'2.5%'], lty='dotted')
lines(sed_rate[,'position_grid'], sed_rate[,'97.5%'], lty='dotted')

write.csv(sed_rate, file = 'NeuquenBchron_sed_rates.csv', quote=FALSE, row.names =
FALSE)
write.csv(GlenOut, file = 'NeuquenBchron_sed_rates.csv', quote=FALSE, row.names = FALSE)
```

7. Supplementary Figure 1 – Fig. S1

	Conusphaera mexicana	*Watznaueria barnesiae*	*Watznaueria fossacincta*	*Cyclagelosphaera margerelii*	*Watznaueria britannica*	*Cyclagelosphaera deflandrei*	*Watznaueria communis*	*Hexalithus noeliae*	*Zeugrhabdotus embergeri*	*Polycostella senaria*	*Cocosfera*	*Helenea chiastia*	*Watznaueria manivitiae*	*Nannoconus kamptneri minor*	*Nanoconus sp.*	*Retecapsa octofenestrata*	*Retecapsa surirella*	*Nannoconus steinmannii*	*Nannoconus globulus*	*Zeugrhabdotus erectus*
MZT-92		X		X														X		
MZT-87		X	X	X	X								X	X	X		X	**X**	X	X
MZT-84		X														X				
MZT-69		X		X						X										
MZT-68				X	X				X	X					X					
MZT-65		X	X					X		X		X	X	**X**						
MZT-58		X	X	X					X		X									
MZT-55		X		X						X										
MZT-51		X	X																	
MZT-47		X		X	X	X														
MZT-45	**X**	X	X						X											
MZT-30	X	X		X	X	X	X	X												
MZT-25		X																		
MZT-16		X	X																	
MZT-15	X	X	X	X																
MZT-12	X	X	X	X																
MZT-6	**X**	X	X	X	X															

Supplementary Figure 1. Stratigraphic distribution of calcareous nannofossils of Mazatepec section, Mexico.

8. Supplementary Figure 2 – Fig. S2



Supplementary Figure 2 – Field photos. A) Field figure from the Las Loicas section. Location of ash bed LL10 and the location of the JKB in the section. B) Field figure of the lower part of the La Yesera section where the contact between the Vaca Muerta and the Tordillo formations, and the location of ash bed LY5. C) location of the JKB in the Mazatepec section in Mexico, see bed MTZ-46 and MTY-45 (see Lopey-Matinez et al. 2013) D) Outcrop view of the Mazatepec section.

9. Data tables

9.1. U-Pb geochronology data table TS.1

Fraction	Dates (Ma) 206Pb/238U <Th> a	±2σ abs	207Pb/235U b	±2σ abs	Composition Th/U c	Pb* (pg) d	Pbc (pg) e	206Pb/238U f	±2σ %	207Pb/235U f	±2σ %
LL3											
z1	139.43	0.11	138.0	1.1	0.97	10.4	0.75	0.021852	0.080	0.1456	0.88
z2	139.36	0.11	138.75	0.76	0.88	9.76	0.43	0.021842	0.079	0.14642	0.59
z11	139.47	0.12	138.7	1.3	0.80	3.37	0.27	0.021858	0.088	0.1464	0.98
z21	139.45	0.11	139.8	1.1	0.97	7.21	0.48	0.021856	0.082	0.1476	0.84
z22	139.44	0.12	139.2	1.2	0.79	4.10	0.22	0.021853	0.086	0.1469	0.93
z23	**139.16**	**0.14**	**136.4**	**1.5**	**0.90**	**4.68**	**0.42**	**0.021809**	**0.10**	**0.1437**	**1.2**
z25	**139.244**	**0.067**	**136.71**	**0.70**	**0.75**	**5.08**	**0.21**	**0.021822**	**0.048**	**0.14413**	**0.55**
z26	**139.27**	**0.10**	**139.45**	**0.77**	**0.79**	**7.78**	**0.37**	**0.021826**	**0.075**	**0.14721**	**0.59**
z32	**139.23**	**0.13**	**139.2**	**1.1**	**0.90**	**6.41**	**0.37**	**0.021820**	**0.093**	**0.1469**	**0.88**
LL9											
z2	**139.98**	**0.11**	**144.6**	**5.2**	**0.73**	**8.68**	**1.02**	**0.021938**	**0.077**	**0.1531**	**3.9**
z5	140.191	0.063	141.2	1.2	0.47	14.0	0.40	0.0219707	0.045	0.1492	0.90
z7	140.19	0.14	141.7	2.3	0.53	8.56	0.46	0.021971	0.097	0.1498	1.8
z12	**139.99**	**0.16**	**150**	**11**	**0.37**	**1.94**	**0.55**	**0.021938**	**0.11**	**0.159**	**8.2**
z33	140.456	0.071	141.3	1.0	0.47	10.3	0.24	0.022013	0.051	0.1493	0.78
z34	140.814	0.078	141.5	1.7	0.78	5.62	0.21	0.022071	0.056	0.1495	1.3
z51	**139.87**	**0.22**	**153**	**15**	**0.37**	**2.54**	**0.96**	**0.021919**	**0.16**	**0.162**	**11**
z52	140.67	0.11	143.6	5.0	0.81	3.13	0.34	0.022048	0.078	0.1519	3.7
z53	140.18	0.14	140.7	2.5	0.65	5.33	0.29	0.021970	0.10	0.1486	1.9
z54	140.35	0.11	142.4	3.3	0.71	3.72	0.27	0.021997	0.080	0.1506	2.5
z55	**139.945**	**0.097**	**141.5**	**2.5**	**0.50**	**6.57**	**0.39**	**0.021932**	**0.070**	**0.1495**	**1.9**
LL10											
z11	140.51	0.13	140.1	1.4	0.82	4.08	0.37	0.022023	0.096	0.1479	1.1
z12	141.20	0.35	140.2	3.8	0.93	1.01	0.24	0.022134	0.25	0.1481	2.9

	z13	140.61	0.26	139.6	3.0	0.93	2.57	0.49	0.022039	0.18	0.1474	2.3
	z14	140.68	0.23	139.5	2.6	1.10	2.78	0.45	0.022052	0.16	0.1473	2.0
	z41	**140.37**	**0.21**	**138.0**	**2.2**	**0.84**	**2.17**	**0.28**	**0.022001**	**0.15**	**0.1456**	**1.7**
	z42	**140.29**	**0.12**	**140.3**	**1.2**	**1.14**	**6.31**	**0.45**	**0.021990**	**0.085**	**0.1481**	**0.94**
	z44	**140.32**	**0.16**	**139.8**	**1.2**	**1.02**	**4.86**	**0.32**	**0.021994**	**0.12**	**0.1476**	**0.96**
	z45	**140.55**	**0.27**	**138.3**	**2.8**	**0.87**	**1.42**	**0.19**	**0.022029**	**0.19**	**0.1459**	**2.2**
MZT-81												
	z4	**140.478**	**0.079**	**140.57**	**0.74**	**0.42**	**10.4**	**0.54**	**0.022016**	**0.057**	**0.14848**	**0.57**
	z6	**140.504**	**0.083**	**140.41**	**0.85**	**0.53**	**9.91**	**0.60**	**0.022021**	**0.060**	**0.14830**	**0.65**
	z7	141.03	0.12	141.7	1.3	0.43	3.31	0.30	0.022103	0.088	0.1498	0.97
	z8	**140.518**	**0.047**	**140.39**	**0.25**	**0.53**	**11.1**	**0.17**	**0.0220228**	**0.033**	**0.14828**	**0.19**
	z10	**140.528**	**0.061**	**140.22**	**0.45**	**0.53**	**10.9**	**0.33**	**0.0220243**	**0.044**	**0.14809**	**0.34**
	z11	140.85	0.10	140.4	1.1	0.48	6.49	0.51	0.022075	0.075	0.1483	0.83
	z12	141.22	0.29	141.4	3.4	0.47	2.47	0.60	0.022134	0.21	0.1494	2.6
	z15	141.02	0.14	140.1	1.4	0.53	5.98	0.58	0.022102	0.099	0.1479	1.1
LL13												
	z9	**142.106**	**0.085**	**142.49**	**0.76**	**0.64**	**8.39**	**0.41**	**0.022275**	**0.060**	**0.15066**	**0.57**
	z33	**141.93**	**0.11**	**142.2**	**1.2**	**0.76**	**7.49**	**0.51**	**0.022247**	**0.076**	**0.1503**	**0.88**
	z34	**142.05**	**0.12**	**142.6**	**1.1**	**0.93**	**7.09**	**0.39**	**0.022267**	**0.081**	**0.1508**	**0.80**
LY5												
	z10	**147.8**	**1.1**	**144**	**13**	**0.71**	**0.665**	**0.56**	**0.02319**	**0.77**	**0.152**	**9.7**
	z19	148.07	0.42	146.8	4.9	0.51	1.49	0.51	0.023221	0.29	0.1556	3.6
	z20	**147.12**	**0.26**	**144.5**	**3.0**	**0.77**	**3.92**	**0.75**	**0.023071**	**0.18**	**0.1529**	**2.2**
	z22	148.01	0.36	147.0	3.8	0.39	1.34	0.34	0.023211	0.25	0.1558	2.8
	z38	**146.99**	**0.29**	**145.3**	**3.3**	**0.74**	**2.07**	**0.45**	**0.023050**	**0.20**	**0.1539**	**2.5**
	z44	**147.118**	**0.086**	**146.49**	**0.82**	**0.75**	**3.37**	**0.15**	**0.023071**	**0.058**	**0.15520**	**0.60**
	z67	147.740	0.093	147.09	0.96	0.49	6.20	0.41	0.023168	0.064	0.1559	0.70

Legend T.S1

a) Corrected for initial Th/U disequilibrium using the radiogenic 208Pb and Th/U (magma)= 3.5
b) Isotopic dates calculated using 238= 1.55125 E-10 (Jaffey et al. 1971) and 235=9.8485E-10 (Jaffey et al. 1971)
c) Th contents calculated from radiogenic 208Pb and 239^{Th}-corrected 206Pb/207Pb date of the sample, assuming concordance between U-Pb and Th-Pb systems
d) Total mass of radiogenic Pb
e) Total mass of common Pb
f) Measured ratios correct for fractionation, tracer and blank.

9.2. Age-depth model data table TS.2

Stratigraphic Height (m)	Age (Ma)	Std Err (2 S.D) (Ma)
54	139.24	0.05
53	139.30	0.15
52	139.35	0.20
51	139.41	0.22
50	139.46	0.23
49	139.51	0.23
48	139.57	0.24
47	139.62	0.23
46	139.68	0.24
45	139.73	0.23
44	139.79	0.22
43	139.84	0.21
42	139.90	0.17
41	139.96	0.07
40	140.00	0.10
39	140.03	0.12
38	140.07	0.12
37	140.11	0.13
36	140.15	0.13
35	140.18	0.13
34	140.22	0.13
33	140.27	0.12
32	140.31	0.11
31	140.35	0.08
30	140.42	0.23
29	140.48	0.30
28	140.54	0.37
27	140.60	0.41
15	141.31	0.56
14	141.37	0.56
13	141.43	0.52
12	141.50	0.51
11	141.56	0.50
10	141.62	0.49
9	141.68	0.47
8	141.74	0.44
7	141.80	0.40
6	141.86	0.36
5	141.92	0.33
4	141.97	0.23
3	142.04	0.06
2	142.10	0.32
1	142.15	0.42

26	140.66	0.43
25	140.72	0.46
24	140.78	0.50
23	140.84	0.50
22	140.90	0.52
21	140.96	0.53
20	141.02	0.55
19	141.08	0.56
18	141.14	0.55
17	141.20	0.56
16	141.26	0.56

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