Cross-continental age calibration of the Jurassic/Cretaceous boundary

Luis F. De Lena[1], Rafael López-Martínez[2], Marina Lescano[3], Beatriz Aguirre-Urrreta[3], Andrea Concheyro[3], Verónica Vennari[3], Maximiliano Naipauer[3], Elias Samankassou[1], Marcio Pimentel[4], Victor Ramos[3], Urs Schaltegger[1]

1Department of Earth Sciences, University of Geneva, Geneva, 1205, Switzerland
2Instituto de Geología, Universidad Nacional Autónoma de Mexico, Ciudad de Mexico, 02376, Mexico
3Instituto de Estudios Andinos Don Pablo Groeber (UBA-CONICET), Universidad de Buenos Aires, Buenos Aires, 1428, Argentina
4Instituto de Geociências, Universidade de Brasilia, Brasilia, DF, 70910-900, Brasil

Correspondence to: Luis F. De Lena (lena.luis@gmail.com; Luis.FortesDeLena@unige.ch)

Abstract. The age of the Jurassic/Cretaceous boundary has remained elusive for the past decades. evaluate how well the determined boundary age agrees between two distinct sections from different sedimen her we can constrain a globally valid Jurassic/Cretaceous boundary age. 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 section, Argentina, and the Mazatepec section in Mexico. These two sections display well-established primary and secondary stratigraphic markers as well as interbedded volcanic horizons that allow bracketing the Jurassic/Cretaceous boundary We also present the first age determinations in the early Tithonian and tentatively propose a minimum duration of ~7 Ma for the Tithonian stage.

1. Introduction

The age of the Jurassic/Cretaceous boundary (JKB) remains one of the last major Phanerozoic stage boundaries without an adequate age. e been made in the past to tackle the age of the JKB. varied from coupling of magnetostratigraphy with biostratigraphy (Larson and Hilde, 1975), and to the use of absolute radio-isotopic ages (Gradstein et al., 1995; Kent and Gradstein, 1985; Lowrie and Ogg, 1985; Ogg and Lowrie, 1986). These attempts were based on data compilations from different sections around the world to reach a grasp of the age scarcity of absolute ages for the late Jurassic and early Cretaceous, a lot of the available JKB age information was derived from interpolation between distant tie points for arguably large intervals of time (~25 Ma). This has led to unascertained errors in the final n et al., 1995; Kent and Gradstein, 1985; Lowrie and Ogg, 1985; Ogg and Lowrie, 1986; Pálfy et al., 2000b). Only few case studies presented geochronological information from several samples within one single section (Bralower et al., 1990; Vennari et al., 2014). Therefore, the different JKB age estimates poorly reproduce ages varying from 135 to 144 Ma with a high degree of uncertainty with no significant overlap. english Ok he main hindrance to finding an appropriate age for the JKB has been the difficulty in identifying a english Ok er 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 Zone has gained momentum as the most widespread candidate english: a zonal base does not gain momentum, and this level has been t allows to put JKB sections into a coherent framework. This advance also allows to compare the temporal record from sections that straddle the JKB, thus facilitating correlation and defining an age for the JKB.

Given the current elusive nature No. There are few radiometirc date available near a very well known and well documented stratigraphic level if we date two independent sections loose language =in two widely separated regions ablished JKB markers, do their markers overlap in radio-isotopic age? Furthermore, if the biostratigraphy and geochronology from two distant sections match, the inferred JKB age may potentially be of global correlation. English Ok ave used high-precision U-Pb zircon age determinations using chemical abrasion, isotope dilution, thermal ionisation mass spectrometry (CA-ID-TIMS) techniques to date volcanic ash layers in the Las Loicas section, Neuquén Basin, Argentina and the Mazatepec section, Mexico (Fig. 1, 2). The selected and dated volcanic ash beds are bracketing the JKB, English Ok to be the base of the Calpionella Zone (Alpina Subzone How can ash beds be the base of a calpionellid zone? precision U-Pb dates have proved to yield robust estimates for the timing of the stratigraphic record (e.g., Burge 2014), especially in combination with Bayesian age-depth modelling (e.g., Ovtcharova et al., 2015; Baresel et al., 2017). Ovtcharova et al., 2015). We have used the definition of the JKB as the base of the Calpionella Zone (Alpina Subzone) in both sections as it has been selected as the primary marker for the boundary in recent years delete Ok 2017; Wimbledon et al., 2011). In both sections, nannofossils are present, which are regarded as important secondary markers for the JKB (Wimbledon, 2017; Wimbledon et al., 2011). We also describe new results new nannofossil results assemblage of the Mazatepec section in Mexico, which allows definition of the FAD of *Nannoconus steinmanni steinmanni* and *Nannoconus Kamptneri minor*, respectively (Figs. 3, 4).

Additionally, we also present ages radiometric ages e *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 for an estimate the duration English ithonian, which in turn also enabl enables Ok eck the validity of our age informal and a bit sloppy? for the early Berriasian and the JKB. Ok

2. Studied areas

To investigate the age of the JKB, we have selected two sections where the JKB is well recognized and defined. The Las Loicas section is located in the Vaca Muerta Formation, Neuquén Basin, Argentina repetition ok i et al., 2014). 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 the Las Loicas section, Tedious to always have "LL section" every time At LL or at the site, or some other variation? *Argentiniceras noduliferum* ammonite biozone and calcareous nannofossils have been d We will try to vary wording

Recently, (López-Martínez et al., 2017) reported the occurrence of upper Tithonian-lower Berriasian calpionellids, which is the only known section where the three main markers for the JKB occur together. ...oicas also contains several ash beds which allowed a ... bracketing of the boundary using high-precision U-Pb geochronology. We also investigated the early Tithonian in the La Yesera Section, Vaca Muerta Fm., where the *Virgatosphinctes andesensis* outcrops ... a Muerta Fm. and Tordillo Fm.

The Mazatepec section spans the Pimienta and the lower Tamaulipas formations the ... ra Madre geological province, Mexico (Fig. 1). The Pimienta Fm. is composed of darkish clayey limestones and the Tamaulipas Fm is a gray ...tone (López-Martínez et al., 2013b). The section has a dense occurrence o... (Colomi Subzone) and Early Berriasian calpionellids from Calpionella Zone, (Alpina, ... Subzones) to Calpionellopsis Zone (Oblonga Subzone). In the upper part of the section, ash beds occur at distinct levels ...been reported by some authors ... d in the Lower Tamaulipas Fm. The dated ash bed ... in the Elliptica Subzone of 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 three to six youngest overlapping ^{206}Pb/^{238}U dates (Fig. 2), ... record prolonged residence of zircon ... magmatic systems as well as intramagmatic recycling. In the text, all quoted ages for the dated ash beds ... ^{206}Pb/^{238}U ages corrected for initial ^{230}Th disequilibrium. A detailed description of the techniques for 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 Mexican section ... ples 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 ... BAFC-NP: Nº 4190-4206. Optical images of selected species are shown in Fig. 4; the distribution chart for the calcareous nannofossil species is presented in supplementary Fig. 3.

The age of the various paleontological ... 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 age-depth model ... resulting uncertainty envelope is presented in Fig. 4A. The age-depth results are reported in TS.2 ... ned to every meter ...igraphic height. The Bchron code used in ... cal package environment (R Core Team 2013) is included in the Supplementary Materials.

4. Results and discussion

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

The The Las Loicas section Ok d 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 dated ash beds found in the Las Loicas section delete i Ok 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., 2013b, 2013a, 2015). This calpionellid assemblage occurs below the base of the NJK-B calcareous nannofossil Zone, characterized by the FAD of *Umbria granulosasa 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). More importantly, the occurrence of *Crassicollaria parvula* and *Crassicollaria colomi* and the FAD of *Umbria granulosasa granulosa* are located 13 meters above ash bed LL13, which has an age of 142.040 ± 0.058 Ma. Since the assemblage is situated 13 meters above from the dated ash bed (ca. 15 m stratigraphic height), model age is 141.31 ± 0.56 Ma (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 granulosasa granulosa*.

meaning?

In the Las Loicas section, there are several well-known early Berriasian markers. For instance, the FAD of *Nannoconus kamptneri minor* (Fig.SA) and *Nannoconus steinmannii minor* are considered trustworthy indicators of the early Berriasian (Bralower et al., 1 ere they overlap with the base of the *Argentiniceras noduliferum* ammonite Zone (López-Martí ri et al., 2014). The occurrence of the calpionellid assemblage dominated by *Calpionella alp* ns of *Crassicollaria massutiniana, Tintinnopsella remanei,* and *T. carpathica* confirms the early rtínez et al., 2017a) (Fi cketed by ash beds LL9 (139.956 ± 0.063 ± 0.083 Ma) (Fig.SA). e base of the Berriasian cannot be young 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* (Fig. SA) and *Nannoconus steinmannii minor* and the base of *Argentiniceras noduliferum* ammonite Zone (c.a 34 m stratigraphic height) (Fig. 3A). Using age-depth modeling, we ca 3Ma (Fig. 4A).

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

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

magnetozones is much better than chrons. "Chr Ok a very particular meaning in the ICS stratigraphic guidelines

When calibrating the age of stage boundaries, magnetochrons are extremely important because they impose a single work frame ormalized against. The use of magnetostratigraphy coupled with biostratigraphy has become a crucial tool for successfully correlating different JKB sections. Currently, in various sections that span the JKB, base of the Calpionella Zone is, in many cases, appears to be coincident with the M19n.2n

English, contruction, meaning

Need some publications cited here, to give substantiation

No. This is very very vague. In numerous sections the bas Please see Replies Sub e middle of M19n.2n

(Schnabl et al., 2015; Wimbledon, 2017). Therefore, the magnetochron M19n.2n has lately emerged as a [illegible] locating the JKB in different sections where the most important markers for the JKB might be absent, or where fossil density is not optimal. In the Neuquén Basin, Iglesia Llanos et al. (2017) has shown that the M19n.2n is recorded in the lower *Substeueroceras koeneni* Zone in the Arroyo Loncoche section. [illegible] the ammonite zonation the position of the JKB in the [illegible]nd the Arroyo Loncoche sections does not overlap (Fig. 4A). However, ammonite zonation in the Arroyo Loncoche lacks fossil density and is thus imprecise (see discussion in López-Martínez et al., (2018). It is impossible to locate or extrapolate the M19n.2n onto the Las Loicas section, but considering the preliminary nature of ammonite zonation in Arroyo Loncoche, we consider our results to be fairly close to that of Iglesia Llanos et al. (2017), thus giving further support for our age of the JKB in Las Loicas.

Rather unsafe. Authors present no evidence on Arroyo Loncoche. They cannot interpret what [illegible] at LL, as they say. How can the authors' results [illegible] of Inglesia Llanos when they have no magnetostratigraphy to present at Las Loicas and do not work on AL?

4.2 The age of the Jurassic/Cretaceous Bou[illegible]

The Mexican [illegible] section has a dense and well-established calpionellid zonation with close ties [illegible] classical western Tethys zonation (López-Martínez et al., 2013b) (Fig. 4B). The nannofossil assemblages recognized in the Mazatepec section exhibit low diversity compared to contemporary associations of the Tethyan realm and a relatively poor degree of preservation of the nannofossils, [illegible]erate to heavy dissolution etching (Fig. 3). At stratigraphic height ~16 m (bed MTZ-65; López-Martínez et al., 2013b), 18 nannofossil species have been recognized (Fig. 3): the heterococcoliths are mostly represented by Watznaueriaceae including *Watznaueria barnesae*, *W. britannica, W. manivitae, Cyclagelosphaera marrgerelii, 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 are indicative of a late Tithonian-early Berriasian age in the 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* [illegible]5 m above the base of the Alpina Subzone in the Berriasian.

This is rather late/high, compared to Tethys?

At stratigraphic height ca. 25m an increase in the diversity of nannofossils is identified, reaching 13 sp[illegible] (bed MZT-87 sample). Among the nannofossils, the presence of *N. [illegible]einmanni* stands out, a marker also used to define the base of the first biozone of the Berriasian (NK1) [illegible] DSDP 534, Colme di Vignola Bosso and Foza with magne[illegible] Channell et al., 2010) as well as the Elliptica Subzone (Schnabl et al., [illegible]nofossil 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 Ellipitica Subzone recognized here in Mazatepec which also coincides with the previously established relationship between these biozones in the [illegible]2010). Unfortunately, the presence of *N. steinmanni minor* or *N. wintereri* (Wim[illegible]azatepec section. However, it is reasonable to assume that both

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

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 Alpi[illegible]
You quote Wimbledon 20[illegible]

of these markers would be close to the base of the Alpina Zone since the FAD *N. steinmanni* is only 5 m above the base of the Alpina Zone. Therefore, the relative age of the pal[illegible]kers in the Mazatepec section is in full agreement with the working model of Wimbledon (2017) for the JKB.

To constrain the age of the JKB in the Mazatepec section, we have dated the ash bed in bed [illegible]h is located within the Elliptica Subzone and stratigraphically 10.1m above the base of the Alpina Subzone (Bed MTZ-45 Fig. SC), i.e., JKB (López-Martínez et al., 2013b) (Fig. 4B). The age of ash bed MZT-81 is 140.512 ± 0.036Ma (Fig.2). Unfortunately, in the Mazatepec section ash beds are scarce. Therefore, it was not possible to bracket the age of the JKB, as was the case in the Las Loicas section. Consequently, to estimate 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 forma[illegible]. Here we assume [illegible]tation 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.

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. SB). We have dated an ash bed (LY-5) loc[illegible]ntact 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 *Virgatosphinctes andesensis* Zone[illegible]he Darwini Zone [illegible] which is broadly regarded as early Tithonian in age and widely distributed [illegible] other regions such as [illegible]n, [illegible]co and Tibet (Riccardi, 2008, 2015; Vennari, 2016 for a thorough review on [illegible] subject). Consequently, the age of ash bed LY-5 (147.112 ± 0.078 Ma) is considered representative for the early Tithonian. [illegible] is in close agreement with other studies that have dated the early Tithinon. [illegible]nstance, Malinverno et al. (2012) quote an age 147.95 ± 1.95 Ma for the M22An chron (i.e., a formal definition of the Kimmeridgian-Tithonian boundary (KmTB) (Ogg et al., 2016b). Muttoni et al. (2018) suggests [illegible] 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 [illegible] (147.112 ± 0.078 Ma) in the La Yesera section being in fact [illegible] and coupling it with the age for the base of the Berriasian in [illegible]as (140.22 ± 0.13 Ma), we can calculate a minimum duration for the Tithonian. If we assume the age [illegible]base of the Berriasian to be at the base of the Calpionella Zone (Fig. 4A), then this would imply that the minimum duration [illegible] Tithonian would be of 6.90 ± 0.15 Ma (Fig. 4C). This is in good agreement with the current full duration of the Tit[illegible]n estimated at ~7 Ma (Ogg et al., 2016b). Therefore, our new incomplete sentence

ages for the base of the Berriasian and the early Tithonian are with the expected duration of the Tithonian. Incidentally, this resu How is it "recommended"???? Ogg is just another publication. And not an ICS publication. ndary age is 152.1 Ma (Ogg et al., 2016b). Admittedly, the ash bed LY-5 is not at the KmTB albeit close; , albeit that it is close Ok that the age of KmTB would have to be older than bed LY-5. However, if the age of the KmTB is in fact , in fact, a Ok ould imply that the Virgatosphinctes ammonite delete Ok would last tenses - last not would last Ok duration of the Tithonian would be would have been Ok Ma. In short, it is reasonable to assume that our results are in agreement with other studies that dated the KmTB, but also suggesting that the KmTB age estimate may still be inaccurate.

4.5 A global correlation for the Jurassic/Cretaceous boundary age? re-word? meaning

The main aim of this study is to evaluate whether our biochronological and radio-isotopic data from two distant sections in 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); for the Las Loicas section the Bchron age model yields an age of 140.22 ± 0.13 Ma for the JKB (Fig. 4A). The projection of the 140.9-140.7 Ma age range from the Mazatepec section onto the Las Loicas section places it at a stratigraphic height at 22 to 25 m of =in Ok (Fig. 4A). However, with the relatively high uncertainty of the age-depth model in this part of the section (~±500 ka), the 22 and 25 m levels are indistinguishable in age. Consequently, for the projection of the JKB age from the Mazatepec section onto the Las Loicas section the choice of sedimentation rate used to back-calculate the age of the JKB in the Mazatepec section is not that important, Long and awkward sentence for the reader Ok 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. Incorrect, see Wimbledon 2017, Fig 2. Ok the base of the Alpina Subzone in the Las Loicas section could be old Meaning? re (possibly ca 26 m). This would make the age of the JKB in Las Loicas within range with age estimated in the Mazatepec section, suggesting that the results from both sections do converge. meaning? re-phrase?

We may stress the point that the use of secondary markers is very important when calibrating the age of stage No.. Base of Alpina Subzone falls in the middle of M19n.2n n has been shown to be coincident with the base of the Alpina Subzone globally. Magnetostratigraphic data has been reported in the Neu Imprecise, it was at Arroyo Loncoche No magnetostratigraphy at Las Loicas so how can you directly "relate" to it. It is an approximation? Yes. important to evaluate how well the M19n.2n chron reported in Ig The FAD of *R* much older! *asper* (ca. 26 m height, ~147 Ma) which in the working model for the JKB markers of Schnabl et al. (2015) is older than the Alpina Subzone in western Tethys and thus considered late Tithonian. delete, it says nothing Ok Furthermore, the FAD of *R. asper* is commonly placed in the M19r, and thus older than the M19n.2n (Schnabl et al., 2015). Therefore, it is reasonable to suggest that the M19n.2n could be encompassed within our bracketed time interval for the JKB in the Las Loicas section (Fig. 4A). re-write? - not sure what this is trying to say

Taken at face value, age [the ages of] of the JKB in the in the Neuquén Basin and the Eastern Sierra Madre do not overlap and [but are] are offset by as much as ~670 [illegible] stratigraphic record is a major u[illegible] absence of geochemical proxies or a paleomagnetic timescale. Taking into account that the working models for the relative ag[what does this mean] [illegible]tion of the JKB markers are not yet fully resolved, we are confident that the age bracket between 140.22±0.13 Ma and ~140.7-140.9 Ma is robust. This interva[illegible] understood as an uncertainty interval of the JKB, during which the important events of the JKB (i[illegible] calcareous nannofossil explosions) took place. Given these circumstances, it seems more plausible, at the cu[illegible] strain the JKB to a time interval rather than a single age.

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

[what 'explosions'? bloom of small C [Please see reply] It comed after diversification of nannoconids]

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

Other studies have published geochronological data for the JKB using different dating approaches (e.g., Re-Os isochron ages from shales, or laser ablation ICP-MS U-Pb ages from zircons) that agree with our ages within uncertainties (López-Martínez et al., 2015, 2017; Pálfy et al., 2000a; Tripathy et al., 2018). Additionally, our resu[Ok] [methodologically] t with other studies that have calibrated the age of younger stage boundaries such as the Valanginian, Hauterivian, and Barremian. For instance, Aguirre-Urreta et al. (2015, 2017) presented high-resolution U-Pb geochronology data together with precise biostratigraphy for the late Hauterivian in the Neuquén Basin at 131.96 ± 1.0 Ma and the base of the Barremian at 126.02 ± 1.0 Ma. For instance, Martinez et al. (2015) anchored astrochronological data from two classic sections of the Tethys with the Neuquén Basin U-Pb geochronology using the base of the Valanginian at 137.05 ± 1.0 Ma, and the U-Pb ages Aguirre-Urreta et al. (2015, 2017) for the Hauterivian and Barremian as tie points. The ages of the early Cretaceous stage boundaries of [=in] these studies seem to agree with the tempo of our estimates [meaning? re-word] for the early Tithonian to the earliest Cretaceous, which further adds to the reliability and robusteness of our ages for the JKB. [Whole sentence is vague and not to the point]

[Vague, no justification shown] [illegible]unt several studies using different approaches to report an age for the JKB around the world allow us to suggest that our proposed age for the JKB does indeed carry a global significance. However, it is important to point out that our JKB age [repetition] does not agree with the current recommendation in the Time Scale of the International Commission on Stratigraphy (TSICS), but is ~5 Ma younger. The current age in the TSICS taken to be that of Mahoney et al. (2005) at 144.2± 2.6 Ma (^{40}Ar/^{39}Ar) [comma] wa[Ok] corrected by Gradstein et al. (2012) to 145.5±0.8 Ma with the recalibrated ^{40}K decay constant of Renne et al. (2010). Mahoney et al. (2005) 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. [delete, not needed] Since the ^{40}Ar/^{39}Ar dates of Mahoney et al. (2005) are corrected for any systematic offset towards U-Pb [meaning?] [Please see reply] [illegible]lytical quality, the offset would be better explained by the poor biostratigraphic constraints in the drill core 1213: 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 [comma] [Ok] [illegible]ccurrences. Additionally, the [it is a hole in the sea bed, there is no section] [illegible] nannofossils considered [to be] [Ok] markers (Wimbledon, 2017) and lack [lacks] [Ok] [illegible]y markers. These facts collectively [render] [Ok] section biostratigraphically [vague] [illegible]ds to the JKB markers. In closing, we feel that the results

[Its proper name is the "International Chronostratigraphuc Chart"?] [Ok] presented in this study are in good agreement with several other studies of the age of the JKB and thus it allows our bracketed interval to be considered as the age of the JKB globally.

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

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

The age of the JKB has been contentious for the past decades with a spread of ages of ~10 Ma with varying approaches and geochronological methods being employed. Recent developments in high-precision U-Pb geochronology have proven to be a powerful tool in dating the stratigraphic record, allowing and allowing the accurate Ok on of stage boundaries. We have constrained the age of the JKB to an in before the numbers not at the end of sentence 40.9-140.7 Ma by dating two independent sections that span the JKB using high-precision U-Pb geochronology. This interval is what interval, you just prese ammonite zonation, calcareous nannofossil, and calpionellid as well as in both sections. We consider the magnetochron M19n.2n at Arroyo Loncoche Ok 7) as the most important secondary marker This ammonite Please see reply usly long, what can it bra ? Precision? within the late Tithonian *Substeueroceras koeneni* in the Neuquén Basin, close en especially when the relative age between the various markers for the boundary is still not fully resolved. The agreement between high-precision U-Pb ages If this OGG et al it is not the official ICS timescale Ok ns allows us to contest the current age for the JKB in the TSISC 2016 of 145.5 ± 0.8 Ma. Additionally, our radiometric age *tosphinctes andesensis* Zone, close to the Kimmeridgian-Tithonian Boundary, is in agreement with recent estimates for the age of the CM22An polarity interval ...interval. This preserves ,,, Ok ation of delete Ok he Tithonian and thus corroborate our ages for the JKB. In conclusion, we consider our results for the JKB to carry a global significance and should be viewed as a positive step forward in resolving the age of the JKB. delete Ok

6. Data availability

All the raw data will be made available in the University of Geneva's website upon the graduation of Luis F. De Lena.

7. Acknowledgements

We did not understand why the reviewer highlighted sections 6 and 7

Lena would like to than CAPES under project 1130-13-7 and University of Geneva for financial support. Sam Bowring, MIT, for support during the initial stages of the project is kindly acknowledged. This is contribution R-262 of the Instituto de Estudios Andinos Don Pablo Grober.

8. References

Aguirre-Urreta, B., Rawson, P. F., Concheyro, G. A., Bown, P. R. and Ottone, E. G.: Lower Cretaceous (Berriasian-Aptian) biostratigraphy of the Neuqurn Basin, Neuquén Basin, Argentina A case study Seq. Stratigr. Basin Dyn., 57–81, 2005.

Aguirre-Urreta, B., Lescano, M., Schmitz, M. D., Tunik, M., Concheyro, A., Rawson, P. F. and Ramos, V. A.: Filling the gap: new precise Early Cretaceous radioisotopic ages from the Andes, Geol. Mag., 152(03), 557–564, doi:10.1017/S001675681400082X, 2015.

Aguirre-Urreta, B., Schmitz, M., Lescano, M., Tunik, M., Rawson, P. F., Concheyro, A., Buhler, M. and Ramos, V. A.: A high precision U–Pb radioisotopic age for the Agrio Formation, Neuquén Basin, Argentina: Implications for the chronology of the Hauterivian Stage, Cretac. Res., doi:10.1016/j.cretres.2017.03.027, 2017.

Baresel, B., Bucher, H., Brosse, M., Cordey, F., Guodun, K. and Schaltegger, U.: Precise age for the Permian-Triassic boundary in South China from high-precision U-Pb geochronology and Bayesian age-depth modeling, Solid Earth, 8(2), 361–378, doi:10.5194/se-8-361-2017, 2017.

Bown, P. R.: Early to Mid-Cretaceous calcareous nannoplankton from the northwest Pacific Ocean, Leg 198, Shatsky Rise, Proc. Ocean Drill. Program, Sci. Results, Vol 198, 198(December), 1–82, 2005.

Bralower, T. J., Monechi, S. and Thierstein, H. R.: Calcareous nannofossil zonation of the Jurassic-Cretaceous boundary interval and correlation with the geomagnetic polarity timescale, Mar. Micropaleontol., 14(1–3), 153–235, doi:10.1016/0377-8398(89)90035-2, 1989.

Bralower, T. J., Ludwig, K. R. and Obradovich, J. D.: Berriasian (Early Cretaceous) radiometric ages from the Grindstone Creek Section, Sacramento Valley, California, Earth Planet. Sci. Lett., 98(1), 62–73, doi:10.1016/0012-821X(90)90088-F, 1990.

Burgess, S. D., Bowring, S. A. and Shen, S.: High-precision timeline for Earth ’ s most severe extinction, Proc. Natl. Acad. Sci., 111(9), 3316–3321, doi:10.1073/pnas.1403228111, 2014.

Casellato, C. E.: Calcareous nannofossil biostratigraphy of upper Callovian-lower Berriasian successions from the southern Alps, north Italy, Riv. Ital. di Paleontol. e Stratigr., 116(3), 357–404, 2010.

Channell, J. E. T., Casellato, C. E., Muttoni, G. and Erba, E.: Magnetostratigraphy, nannofossil stratigraphy and apparent polar wander for Adria-Africa in the Jurassic-Cretaceous boundary interval, Palaeogeogr. Palaeoclimatol. Palaeoecol., 293(1–2), 51–75, doi:10.1016/j.palaeo.2010.04.030, 2010.

Gradstein, F. M., Agterberg, F. P., Ogg, J. G., Hardenbol, J., Veen, P. V, Thierry, J. and Huang, Z.: Comparison of Cretaceous Time Scales, Geochronol. Time Scales Glob. Stratigr. Correl., 54, 95–126, 1995.

Haslett, J. and Parnell, A.: A simple monotone process with application to radiocarbon-dated depth chronologies, J. R. Stat. Soc. Ser. C Appl. Stat., 57(4), 399–418, doi:10.1111/j.1467-9876.2008.00623.x, 2008.

Iglesia Llanos, M. P., Kietzmann, D. A., Martinez, M. K. and Palma, R. M.: Magnetostratigraphy of the Upper Jurassic–Lower Cretaceous from Argentina: Implications for the J-K boundary in the Neuquén Basin, Cretac. Res., 70(February), 189–208, doi:10.1016/j.cretres.2016.10.011, 2017.

Kent, D. V and Gradstein, F. M.: A Cretaceous and Jurassic geochronology, Geol. Soc. Am. Bull., 96, 1419–1427, 1985.

Kietzmann, D. A., Ambrosio, A. L., Suriano, J., Alonso, S., Gonz, F., Depine, G. and Repol, D.: The Vaca Muerta – Quintuco system (Tithonian – Valanginian) in the Neuquén Basin, Argentina: a view from the outcrops in the Chos Malal fold and thrust belt, Am. Assoc. Pet. Geol. Bull., 5(5), 743–771, doi:10.1306/02101615121, 2016.

Larson, R. L. and Hilde, T. W. C.: A revised time scale of magnetic reversals for the Early Cretaceous and Late Jurassic, J. Geophys. Res., 80(17), 2586, doi:10.1029/JB080i017p02586, 1975.

López-Martínez, R., Barragán, R., Reháková, D. and Cobiella-Reguera, J. L.: Calpionellid distribution and microfacies across the Jurassic/ Cretaceous boundary in western Cuba (Sierra de los Órganos), Geol. Carpathica, 64(3), 195–208, doi:10.2478/geoca-2013-0014, 2013a.

López-Martínez, R., Barragán, R. and Reháková, D.: The Jurassic/Cretaceous boundary in the Apulco area by means of calpionellids and calcareous dinoflagellates: An alternative to the classical Mazatepec section in eastern Mexico, J. South Am. Earth Sci., 47, 142–151, doi:10.1016/j.jsames.2013.07.009, 2013b.

López-Martínez, R., Barragán, R., Reháková, D., Martini, M. and de Antuñano, S. E.: Calpionellid biostratigraphy, U-Pb geochronology and microfacies of the Upper Jurassic-Lower Cretaceous Pimienta Formation (Tamazunchale, San Luis Potos??, central-eastern Mexico), Bol. la Soc. Geol. Mex., 67(1), 75–86, 2015.

López-Martínez, R., Aguirre-Urreta, B., Lescano, M., Concheyro, A., Vennari, V. and Ramos, V. A.: Tethyan calpionellids in the Neuquén Basin (Argentine Andes), their significance in defining the Jurassic/Cretaceous boundary and pathways for Tethyan-Eastern Pacific connections, J. South Am. Earth Sci., 78, 1–10, doi:10.1016/j.jsames.2017.06.007, 2017.

López-Martínez, R., Aguirre-Urreta, B., Lescano, M., Concheyro, A., Vennari, V. and Ramos, V. A.: Reply to comments on: "Tethyan calpionellids in the Neuquén Basin (Argentine Andes), their significance in defining the Jurassic/Cretaceous boundary and pathways for Tethyan-Eastern Pacific connections" by Kietzmann & Iglesia Llanos, J. South Am. Earth Sci., 84, 448–453, doi:10.1016/j.jsames.2017.12.003, 2018.

Lowrie, W. and Ogg, J. G.: A magnetic polarity time scale for the Early Cretaceous and Late Jurassic, Earth Planet. Sci. Lett., 76, 341–349, 1985.

Lukeneder, A., Halásová, E., Kroh, A., Mayrhofer, S., Pruner, P., Reháková, D., Schnabl, P., Sprovieri, M. and Wagreich, M.: High resolution stratigraphy of the Jurassic-Cretaceous boundary interval in the Gresten Klippenbelt (Austria), Geol. Carpathica, 61(5), 365–381, doi:10.2478/v10096-010-0022-3, 2010.

Mahoney, J. J., Duncan, R. A., Tejada, M. L. G., Sager, W. W. and Bralower, T. J.: Jurassic-Cretaceous boundary age and mid-ocean-ridge-type mantle source for Shatsky Rise, Geology, 33(3), 185–188, doi:Doi 10.1130/G21378.1, 2005.

Malinverno, A., Hildebrandt, J., Tominaga, M. and Channell, J. E. T.: M-sequence geomagnetic polarity time scale (MHTC12) that steadies global spreading rates and incorporates astrochronology constraints, J. Geophys. Res. Solid Earth, 117(6), 1–17, doi:10.1029/2012JB009260, 2012.

Martinez, M., Deconinck, J. F., Pellenard, P., Riquier, L., Company, M., Reboulet, S. and Moiroud, M.: Astrochronology of the Valanginian-Hauterivian stages (Early Cretaceous): Chronological relationships between the Paraná-Etendeka large igneous province and the Weissert and the Faraoni events, Glob. Planet. Change, doi:10.1016/j.gloplacha.2015.06.001, 2015.

Muttoni, G., Visconti, A., Channell, J. E. T., Casellato, C. E., Maron, M. and Jadoul, F.: An expanded Tethyan Kimmeridgian magneto-biostratigraphy from the S'Adde section (Sardinia): Implications for the Jurassic timescale, Palaeogeogr. Palaeoclimatol. Palaeoecol., 503(January), 90–101, doi:10.1016/j.palaeo.2018.04.019, 2018.

Ogg, J. G. and Lowrie, W.: Magnetostratigraphy of the Jurassic / Cretaceous boundary, Geology, 14, 547–550, 1986.

Ogg, J. G., Ogg, G. M. and Gradstein, F. M.: Cretaceous, in A Concise Geologic Time Scale, pp. 167–186, Elsevier., 2016a.

Ogg, J. G., Ogg, G. M. and Gradstein, F. M.: Jurassic, in A Concise Geologic Time Scale, pp. 151–166, Elsevier., 2016b.

Ovtcharova, M., Goudemand, N., Hammer, Ø., Guodun, K., Cordey, F., Galfetti, T., Schaltegger, U. and Bucher, H.: Developing a strategy for accurate definition of a geological boundary through radio-isotopic and biochronological dating: The Early-Middle Triassic boundary (South China), Earth-Science Rev., doi:10.1016/j.earscirev.2015.03.006, 2015.

Pálfy, J., Smith, P. L. and Mortensen, J. K.: A U – Pb and 40 Ar / 39 Ar time scale for the Jurassic, Can. J. Earth Sci., 37, 923–944, 2000a.

Pálfy, J., Mortensen, J. K., Carter, E. S., Smith, P. L., Friedman, R. M. and Tipper, H. W.: Timing the end-Triassic mass extinction: First on land, then in the sea?, Geology, 28(1), 39–42, doi:10.1130/0091-7613(2000)28<39:TTEMEF>2.0.CO, 2000b.

Parnell, A. C., Haslett, J., Allen, J. R. M., Buck, C. E. and Huntley, B.: A flexible approach to assessing synchroneity of past events using Bayesian reconstructions of sedimentation history, Quat. Sci. Rev., 27(19–20), 1872–1885, doi:10.1016/j.quascirev.2008.07.009, 2008.

Renne, P. R., Mundil, R., Balco, G., Min, K. and Ludwig, K. R.: Joint determination of 40K decay constants and 40Ar*/40K for the Fish Canyon sanidine standard, and improved accuracy for 40Ar/39Ar geochronology, Geochim. Cosmochim. Acta, 74(18), 5349–5367, doi:10.1016/j.gca.2010.06.017, 2010.

Riccardi, A. C.: The marine Jurassic of Argentina : a biostratigraphic framework, Episodes - Newsmag. Int. Union Geol. Sci., (September), 326–335, 2008.

Riccardi, A. C.: Remarks on the Tithonian-Berriasian ammonite biostratigraphy of west central Argentina, Vol. Jurassica, XIII(2), 23–52, doi:10.5604/17313708, 2015.

Schnabl, P., Pruner, P. and Wimbledon, W. A. P.: A review of magnetostratigraphic results from the Tithonian–Berriasian of Nordvik (Siberia) and possible biostratigraphic constraints, Geol. Carpathica, 66(6), doi:10.1515/geoca-2015-0040, 2015.

Tripathy, G. R., Hannah, J. L. and Stein, H. J.: Refining the Jurassic-Cretaceous boundary: Re-Os geochronology and depositional environment of Upper Jurassic shales from the Norwegian Sea, Palaeogeogr. Palaeoclimatol. Palaeoecol., 503(May), 13–25, doi:10.1016/j.palaeo.2018.05.005, 2018.

Vennari, V. V.: Tithonian ammonoids (Cephalopoda, Ammonoidea) from the Vaca Muerta Formation, Neuquén Basin, West-Central Argentina, Palaeontogr. Abteilung A, 306(1–6), 85–165, doi:10.1127/pala/306/2016/85, 2016.

Vennari, V. V., Lescano, M., Naipauer, M., Aguirre-urreta, B., Concheyro, A., Schaltegger, U., Armstrong, R., Pimentel, M. and Ramos, V. a.: New constraints on the Jurassic-Cretaceous boundary in the High Andes using high-precision U-Pb data, Gondwana Res., 26(1), 374–385, doi:10.1016/j.gr.2013.07.005, 2014.

Wimbledon, W. A. P.: Developments with fixing a Tithonian/Berriasian (J/K) boundary, Vol. Jurassica, 15(1), 0–0, doi:10.5604/01.3001.0010.7467, 2017.

Wimbledon, W. A. P., Casellato, C. E., Reháková, D., Bulot, L. G., Erba, E., Gardin, S., Verreussel, R. M. C. H., Munsterman, D. K. and Hunt, C. O.: Fixing a basal Berriasian and Jurassic/Cretaceous (J/K) boundary - Is there perhaps some light at the end of the tunnel?, Riv. Ital. di Paleontol. e Stratigr., 117(2), 295–307 [online] Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-80053273759&partnerID=tZOtx3y1, 2011.

9.

Figure 1: Distribution of the continents 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 and Arroyo Lonconche section. (A) Las Loicas section: Ash beds in light blue with respective name and U-Pb dates; green stars represent age-depth modelling dates, this study; ammonites and nannofossils zonation Vennari, et al. (2014); calpionellid zonation Lopez-Martinez et al. (2017); Arroyo Lonchonce section: ammonite zonation and magnetostratigraphy (Iglesia Llanos et al., 2017). (B) Mazatepec section: ash bed in light blue with respective name and U-Pb date this study; calcareous nannofossils this study; calpionellid zonation Lopez-Martinez et al. (2013). (C) La Yesera section: ash bed in light blue with corresponding age. Calcareous nannofossil zonation after Bralower et al. (1989)

Figure 1

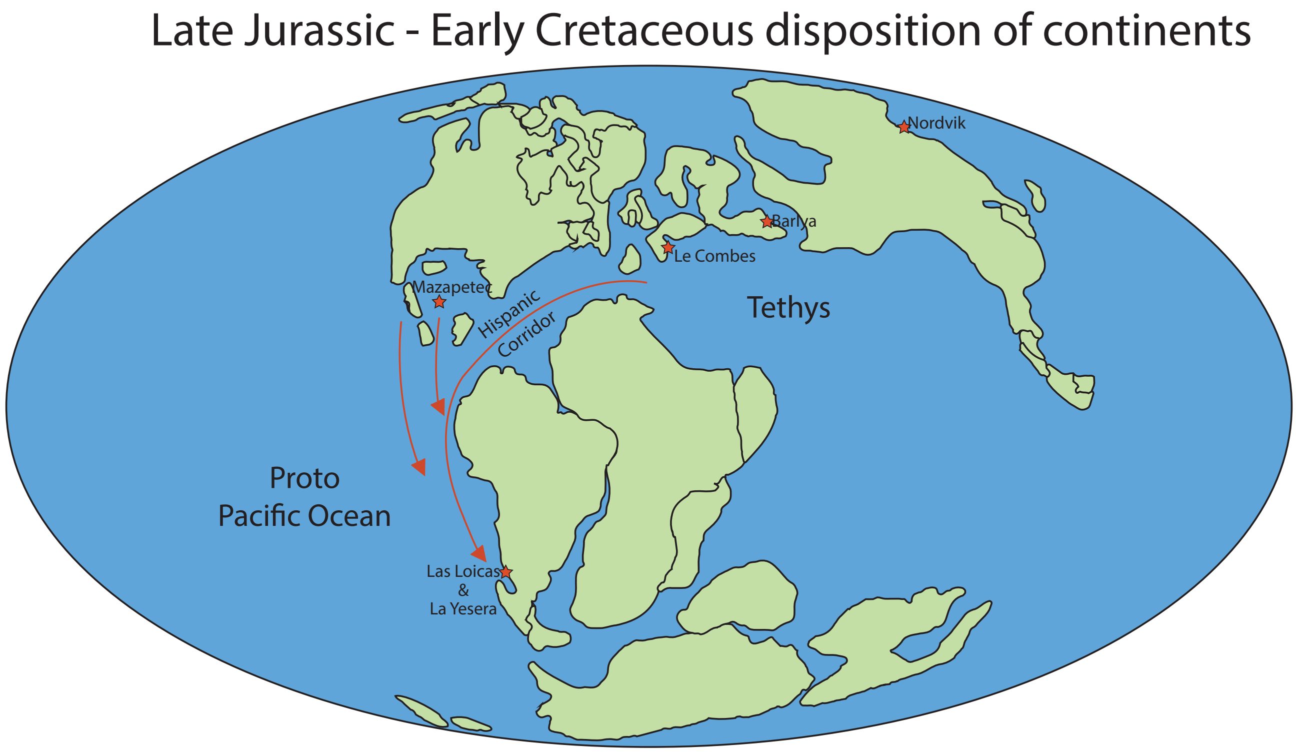
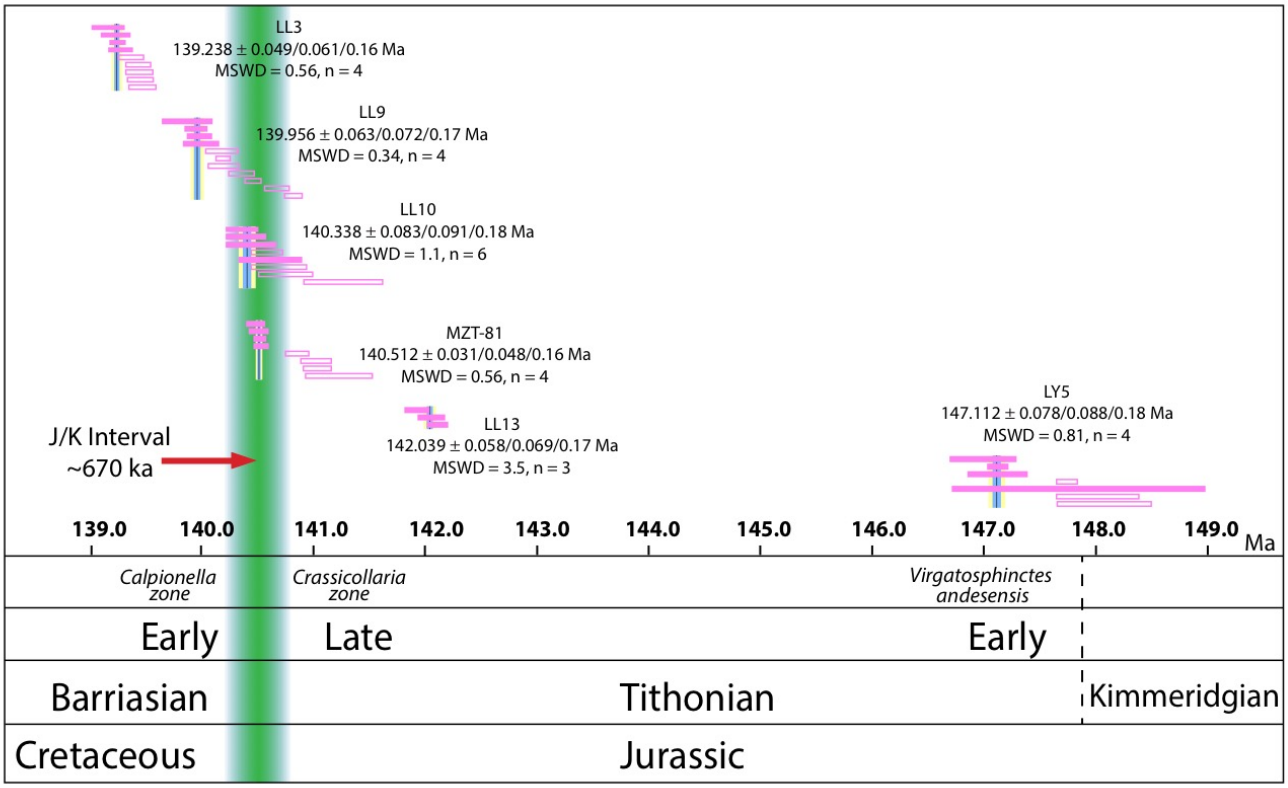

Late Jurassic - Early Cretaceous disposition of continents
Nordvik
Barlya
Le Combes
Mazapetec
Hispanic
Corridor
Tethys
Proto
Pacific Ocean
Las Loicas
&
La Yesera

Figure 2



Berriasian - spelling. There are no limits for any of the biozones. How can they be related to the dates?

Please see reply

Figure 3

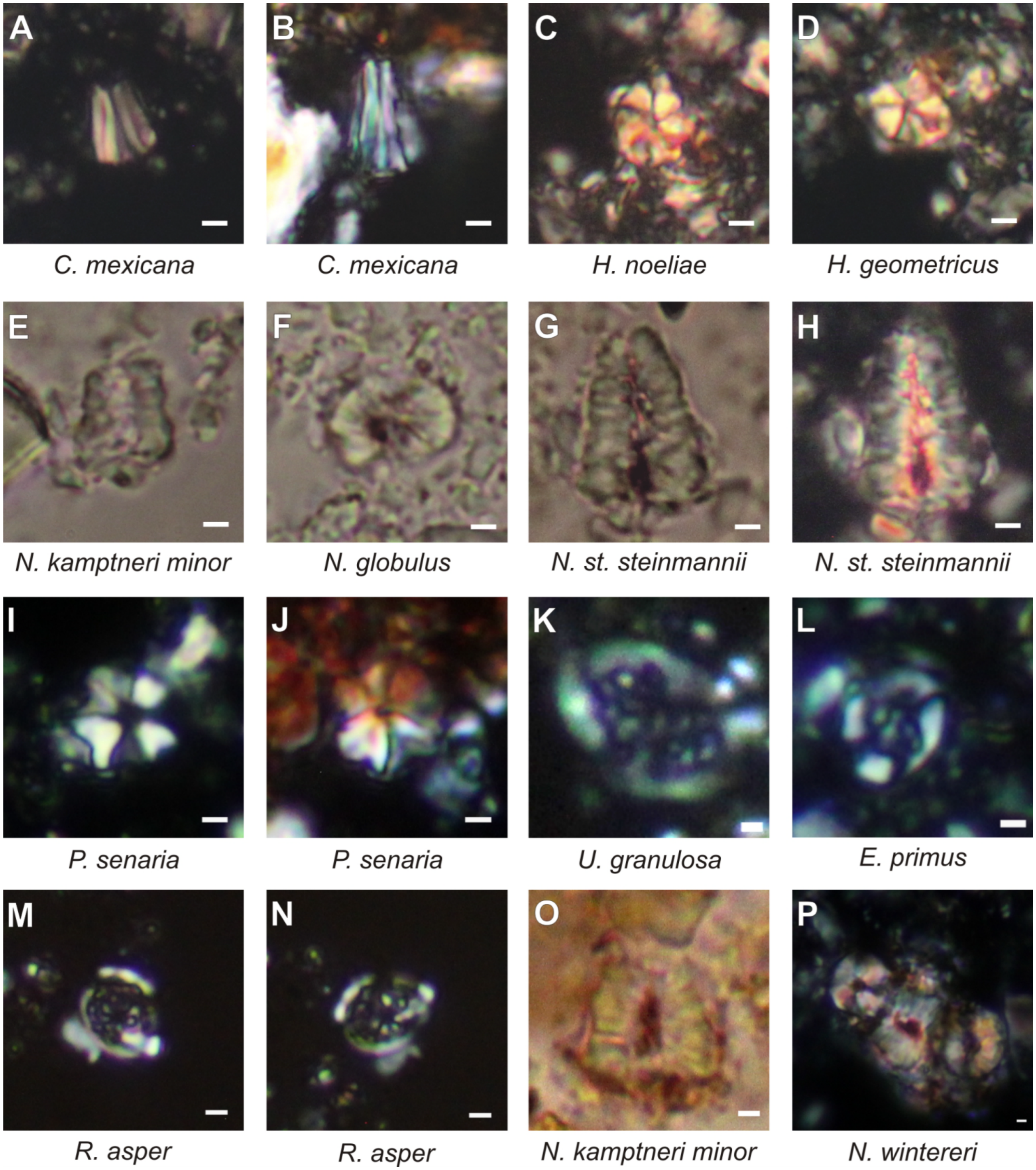
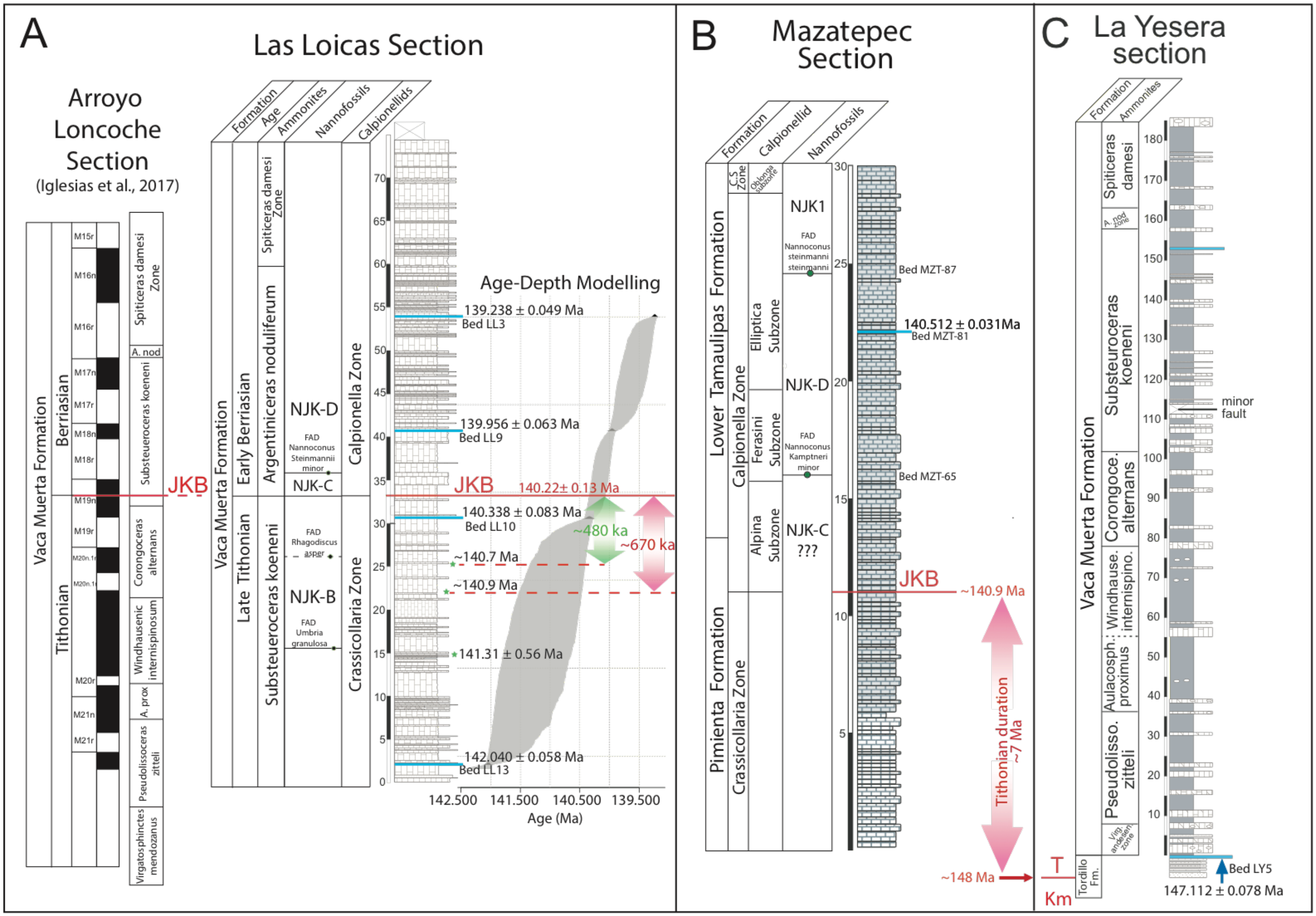

A
C. mexicana
B
C. mexicana
C
H. noeliae
D
H. geometricus
E
N. kamptneri minor
F
N. globulus
G
N. st. steinmannii
H
N. st. steinmannii
I
P. senaria
J
P. senaria
K
U. granulosa
L
E. primus
M
R. asper
N
R. asper
O
N. kamptneri minor
P
N. wintereri

Figure 4



JKB as in the text. J/K boundary or Tithonian/ Berriasian boundary
Species names should not have a calital letter

OK