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Solid Earth Discussions

Cross-continental age calibration of the Jurassic/Cretaceous boundary

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Abstract. The age of the Jurassic/Cretaceous boundary has remained elusive for the past decades. In this study we evaluate how well the determined boundary age agrees between two distinct sections from different sedimentary basins, and whether 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 age of the Jurassic/Cretaceous boundary at 140.22 ± 0.13 Ma. 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. Many efforts have been made in the past to tackle the age of the JKB. Approaches have 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 of the JKB. Due to the 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 ages (Gradstein 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

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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 in 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 Zone has gained momentum as the most widespread candidate for the base of the Berriasian (Wimbledon, 2017), which 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 of the JKB age, we aim to test the following hypothesis: if we date two independent sections in distinct geological contexts that have well-established 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. To do so, we have 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, here assumed to be the base of the Calpionella Zone (Alpina Subzone). 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 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 (Wimbledon, 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 from the nannofossil 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 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 for an estimate the duration of the Tithonian, which in turn also enable us to cross-check the validity of our age for the early Berriasian and the JKB.

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 (Fig. 1) (Vennari 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, the *Substeueroceras koeneni* and *Argentiniceras noduliferum* ammonite biozone and calcareous nannofossils have been described by Vennari et al. (2014).

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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. Additionally, Las Loicas also contains several ash beds which allowed a precise age 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 at the contact between the Vaca Muerta Fm. and Tordillo Fm.

The Mazatepec section spans the Pimienta and the lower Tamaulipas formations the Eastern Sierra Madre geological province, Mexico (Fig. 1). The Pimienta Fm. is composed of darkish clayey limestones and the Tamaulipas Fm is a gray limestone (López-Martínez et al., 2013b). 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 occur at distinct levels and have been reported by some authors in the Pimienta Fm. and in the Lower Tamaulipas Fm. The dated ash bed is situation within 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), assuming that older grains record prolonged residence of zircon in the magmatic systems as well as intramagmatic recycling. In the text, all quoted ages for the dated ash beds are weighted mean $^{206}Pb/^{238}U$ 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 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. 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 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 age-depth model with the resulting uncertainty envelope is presented in Fig. 4A. The age-depth results are reported in TS.2 with age assigned to every meter of stratigraphic height. The Bchron code used in R statistical package environment (R Core Team 2013) is included in the Supplementary Materials.

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4. Results and discussion

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

The 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 dated ash beds found in the Las Loicas section 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., 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), the Bchron 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*.

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., 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., 2017a) (Fig. 4A). These assemblages are bracketed by ash beds LL9 (139.956 ± 0.063 Ma) and LL10 (140.338 ± 0.083 Ma) (Fig.SA). 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* (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 calculate that the age of the JKB in the Vaca Muerta Fm. to be 140.22 ± 0.13Ma (Fig. 4A).

When calibrating the age of stage boundaries, magnetochrons are extremely important because they impose a single work frame for all studied sections to be normalized 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, it has been shown that the base of the Calpionella Zone is, in many cases, appears to be coincident with the M19n.2n

(Schnabl et al., 2015; Wimbledon, 2017). Therefore, the magnetochron M19n.2n has lately emerged as a reliable tool in 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. Relative to the ammonite zonation the position of the JKB in the Las Loicas and 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.

4.2 The age of the Jurassic/Cretaceous Boundary in the Mazatepec section

The Mexican Mazatepec section has a dense and well-established calpionellid zonation with close ties to the 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, characterized by a moderate 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 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 in the Berriasian.

At stratigraphic height ca. 25m an increase in the diversity of nannofossils is identified, reaching 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 magnetocron 17r (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 Ellipitica 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). Unfortunately, the presence of *N. steinmanni minor* or *N. wintereri* (Wimbledon, 2017) have not been reported in the Mazatepec section. However, it is reasonable to assume that both

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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 paleontological markers 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 MZT-81 which 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 formations. Here we assume 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.

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 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 *Virgatosphinctes andesensis* Zone. This biozone is mostly equivalent to the Darwini Zone of the Tethys region, which is broadly regarded as early Tithonian in age and widely distributed in various other regions such as Pakistan, Mexico and Tibet (Riccardi, 2008, 2015; Vennari, 2016 for a thorough review on the subject). Consequently, the age of ash bed LY-5 (147.112 ± 0.078 Ma) is considered representative for the early Tithonian. This result is in close agreement with other studies that have dated the early Tithinon. For instance, 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 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 in fact 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 age of the base of the Berriasian to be at the base of the Calpionella Zone (Fig. 4A), then this would imply that the minimum duration of the Tithonian would be 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). Therefore, our new ages for the base of the Berriasian and the early Tithonian are with the expected duration of the Tithonian. Incidentally, this result also has direct implications for the age of the KmTB: Currently, the recommended boundary age is 152.1 Ma (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. However, if the age of the KmTB is in fact 152.1 Ma, it would imply that the Virgatosphinctes ammonite Zone itself would last more than ~5 Ma and that the total duration of the Tithonian would be ~12 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?

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 the latter (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, 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 could be old (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.

We may stress the point that the use of secondary markers is very important when calibrating the age of stage boundaries. In the case of the JKB, the M19n.2n has been shown to be coincident with the base of the Alpina Subzone globally. Magnetostratigraphic data has been reported in the Neuquén Basin by (Iglesia Llanos et al., 2017). Therefore, it is important to evaluate how well the M19n.2n chron reported in Iglesias Llanos et al. (2017) relates to the Las Loicas section. The FAD of *Rhagosdiscus 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. 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).

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Taken at face value, age of the JKB in the in the Neuquén Basin and the Eastern Sierra Madre do not overlap and are offset by as much as ~670 ka (±335 ka). However, the degree of preservation of paleontological markers in the stratigraphic record is a major uncertainty in the calibration of stage boundaries from different sections, especially in the absence of geochemical proxies or a paleomagnetic timescale. Taking into account that the working models for the relative age and tempo of evolution 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 interval of ~670 ka can be understood as an uncertainty interval of the JKB, during which the important events of the JKB (i.e., calpionellid and calcareous nannofossil explosions) took place. Given these circumstances, it seems more plausible, at the current stage, to constrain the JKB to a time interval rather than a single age.

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 results are also in agreement 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 these studies seem to agree with the tempo of our estimates for the early Tithonian to the earliest Cretaceous, which further adds to the reliability and robusteness of our ages for the JKB.

Taking into account 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 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 ($^{40}Ar/^{39}Ar$) 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). 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. Since the $^{40}Ar/^{39}Ar$ dates of Mahoney et al. (2005) are corrected for any systematic offset towards U-Pb and are of unquestionable analytical 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 but in rare occurrences. Additionally, the section is limited to the occurrences of nannofossils considered secondary markers (Wimbledon, 2017) and lack any primary markers. These facts collectively renders the section biostratigraphically unreliable with regards to the JKB markers. In closing, we feel that the results 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.

5. Summary and conclusions

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 accurate and precise calibration of stage boundaries. We have constrained the age of the JKB to an interval of ~670 ka between 140.22 ± 0.13 and 140.9-140.7 Ma by dating two independent sections that span the JKB using high-precision U-Pb geochronology. This interval is supported by ammonite zonation, calcareous nannofossil, and calpionellid as well as in both sections. We consider the magnetochron M19n.2n (Iglesia Llanos et el., 2017) as the most important secondary marker for the JKB, which has been shown to be within the late Tithonian *Substeueroceras koeneni* in the Neuquén Basin, close enough to corroborate our bracketed interval 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 and the various markers for the boundary in both sections allows us to contest the current age for the JKB in the TSISC 2016 of 145.5 ± 0.8 Ma. Additionally, our age in the *Virgatosphinctes andesensis* Zone, close to the Kimmeridgian-Tithonian Boundary, is in agreement with recent estimates for the age of the CM22An polarity interval and preserves a duration of ~7 Ma for the 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.

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

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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)

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Figure 1

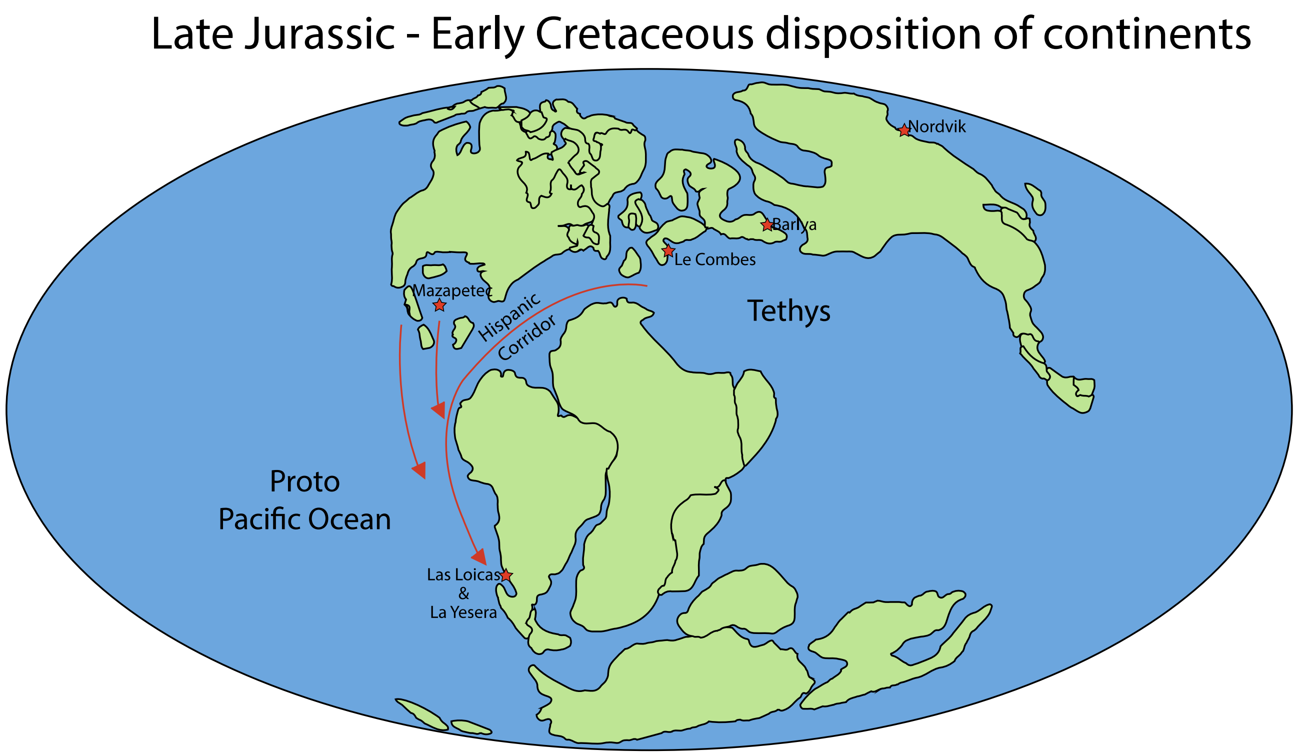

Figure 2

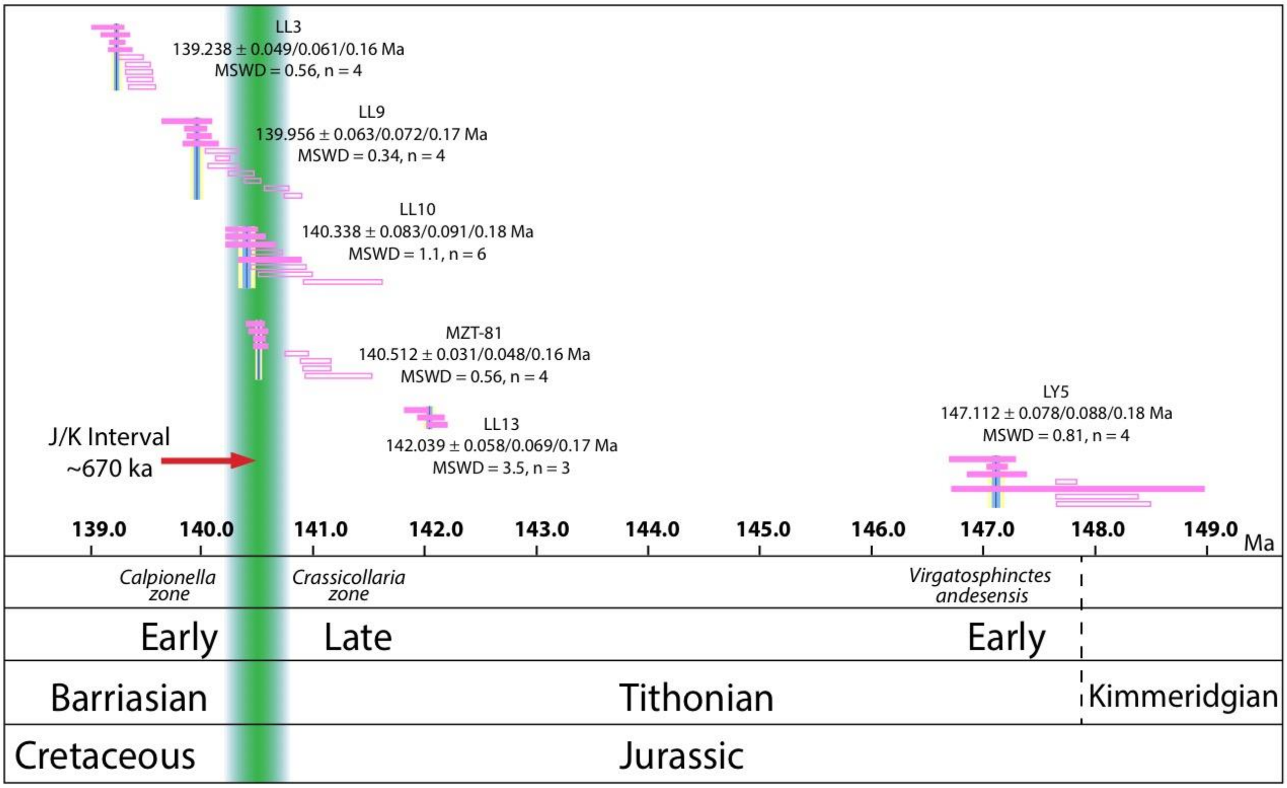
LL3
139.238 ± 0.049/0.061/0.16 Ma
MSWD = 0.56, n = 4
LL9
139.956 ± 0.063/0.072/0.17 Ma
MSWD = 0.34, n = 4
LL10
140.338 ± 0.083/0.091/0.18 Ma
MSWD = 1.1, n = 6
MZT-81
140.512 ± 0.031/0.048/0.16 Ma
MSWD = 0.56, n = 4
LL13
142.039 ± 0.058/0.069/0.17 Ma
MSWD = 3.5, n = 3
LY5
147.112 ± 0.078/0.088/0.18 Ma
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
Barriasian
Tithonian
Kimmeridgian
Cretaceous
Jurassic

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Figure 3

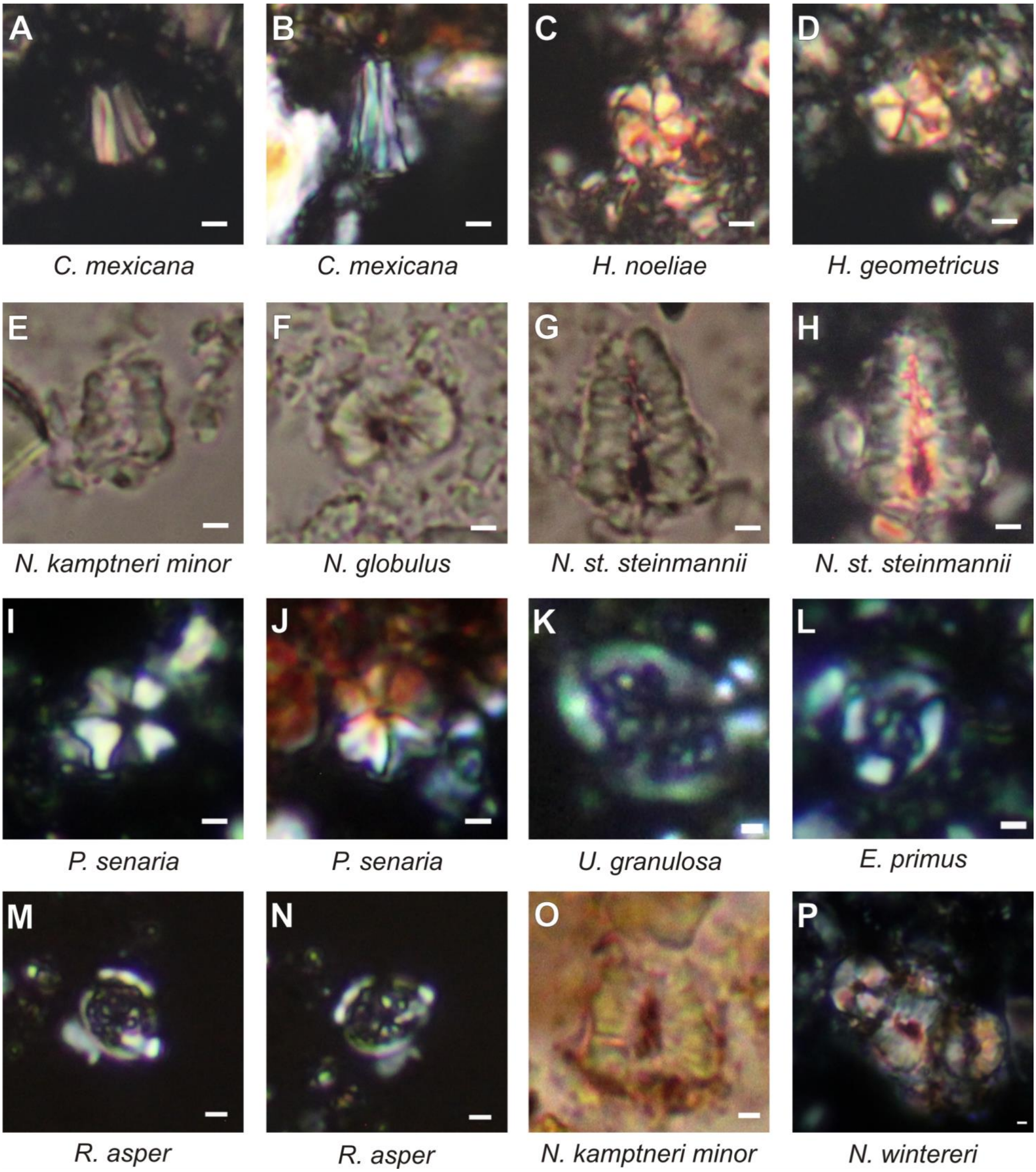

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Figure 4