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; Wotzlaw, et al., 2018). 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

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 modeling, we calculate the age of the JKB in the Vaca Muerta Fm. to be 140.22 ± 0.13Ma (Fig. 4A).

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.

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.

6. Acknowledgments

This paper is dedicated to the memory of Márcio Pimentel, which unfortunately passed away during the reviewing process. Márcio was a champion of isotope geochemistry and geochronology in Brazil and played a vital role in the development of personnel and analytical capabilities in the field in Brazil during the 90's and early 2000's. His passing is a great loss to the community and his presence will be sorely missed. L. Lena would like to thank CAPES (under project 1130-13-7) and University of Geneva for financial support. Sam Bowring (MIT) is kindly acknowledged for support during the initial stages of the project. This is contribution R-262 of the Instituto de Estudios Andinos Don Pablo Groeber.

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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

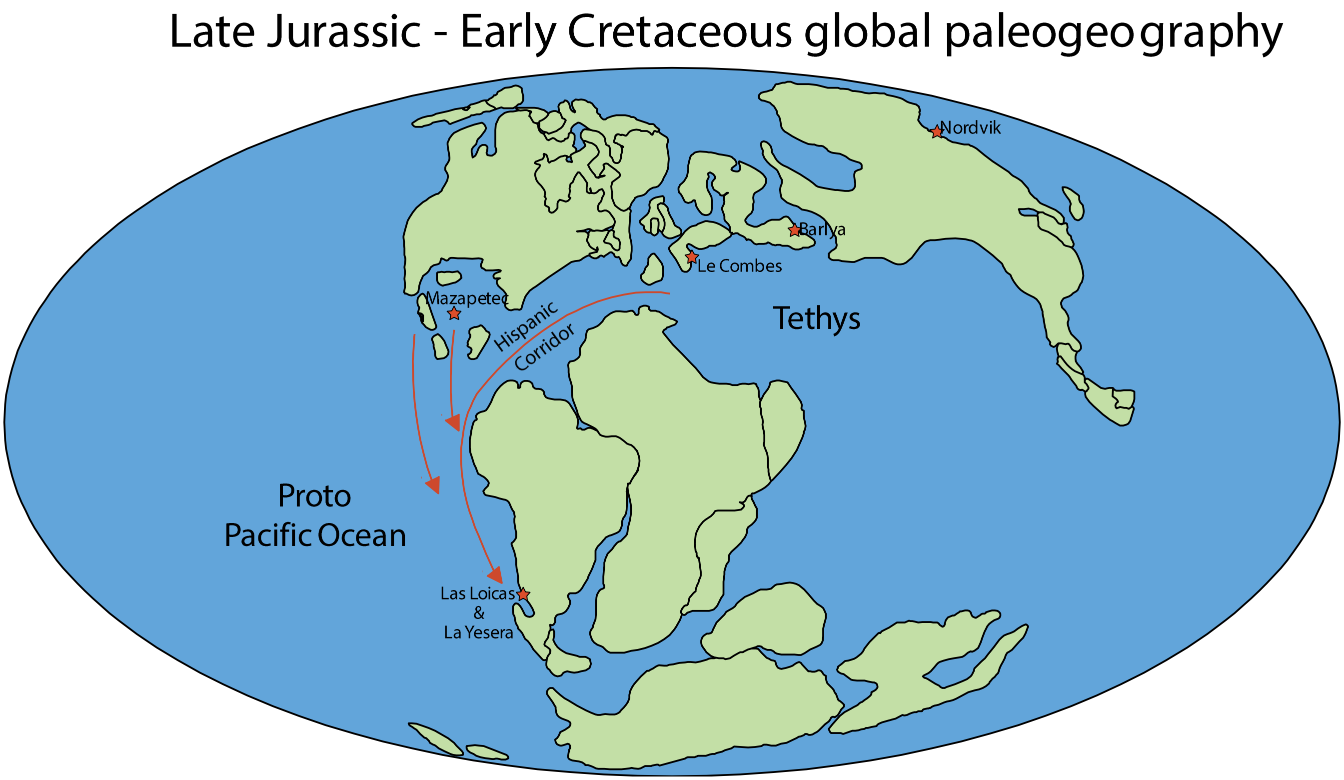

Late Jurassic - Early Cretaceous global paleogeography
Nordvik
Barlya
Le Combes
Mazapetec
Hispanic
Corridor
Tethys
Proto
Pacific Ocean
Las Loicas
&
La Yesera

Figure 2

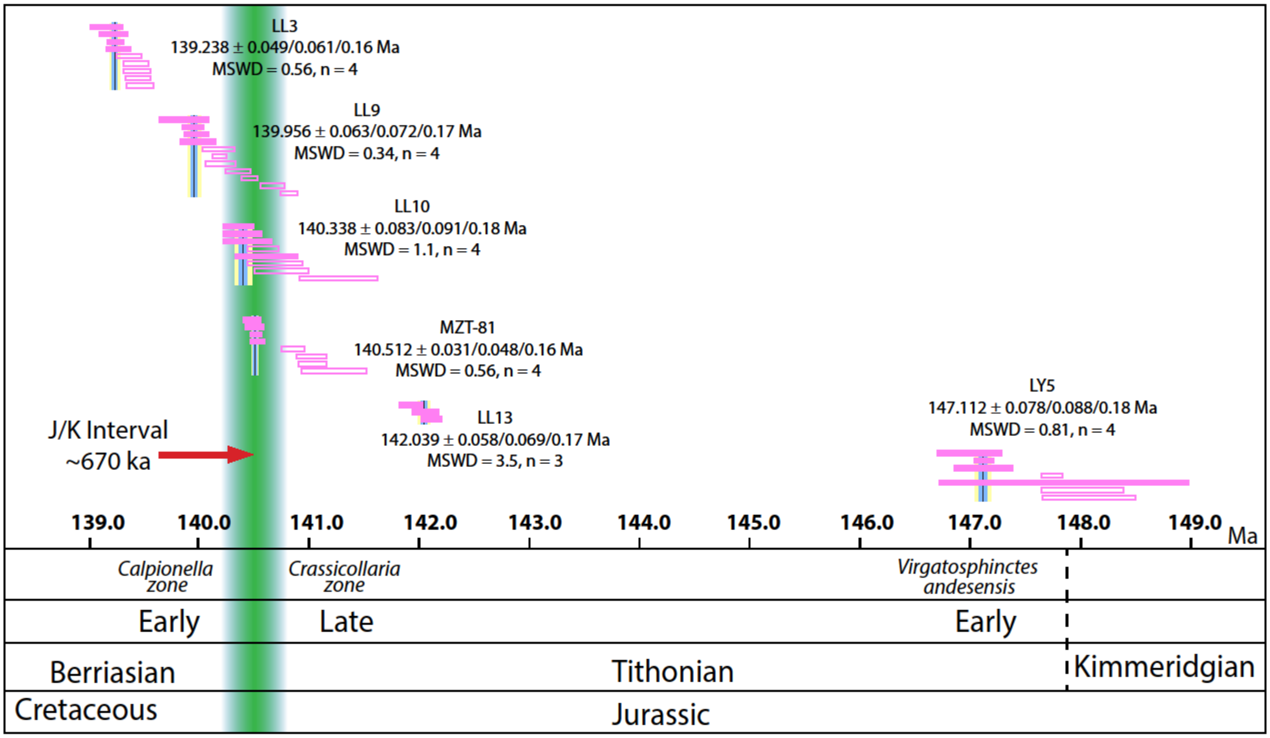

LL3
139.238 ± 0.049/0.061/0.16 Ma
MSWD = 0.56, n = 4
LL9
139.956 ± 0.063/0.072/0.17 Ma
MSWD = 0.34, n = 4
LL10
140.338 ± 0.083/0.091/0.18 Ma
MSWD = 1.1, n = 4
MZT-81
140.512 ± 0.031/0.048/0.16 Ma
MSWD = 0.56, n = 4
LY5
147.112 ± 0.078/0.088/0.18 Ma
MSWD = 0.81, n = 4
J/K Interval
~670 ka
LL13
142.039 ± 0.058/0.069/0.17 Ma
MSWD = 3.5, n = 3
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

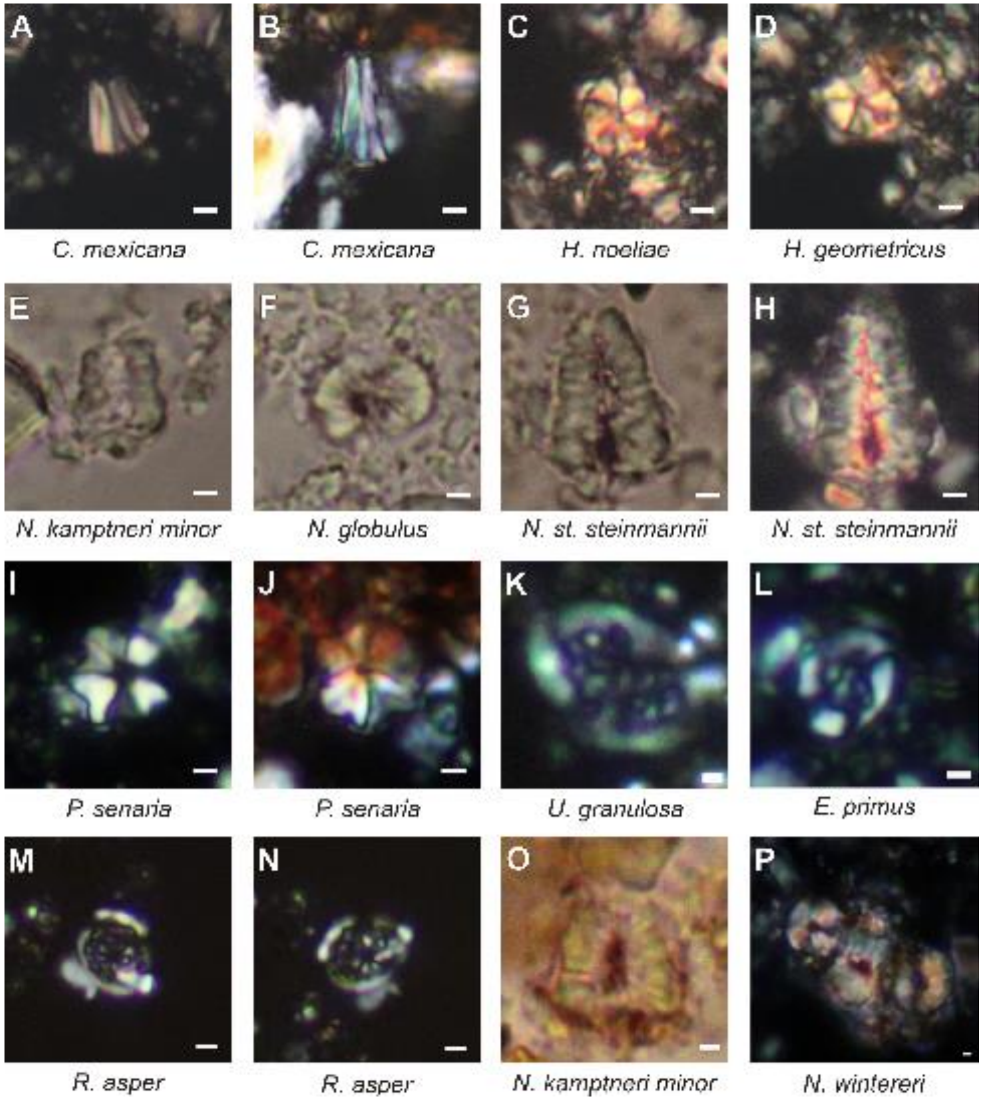
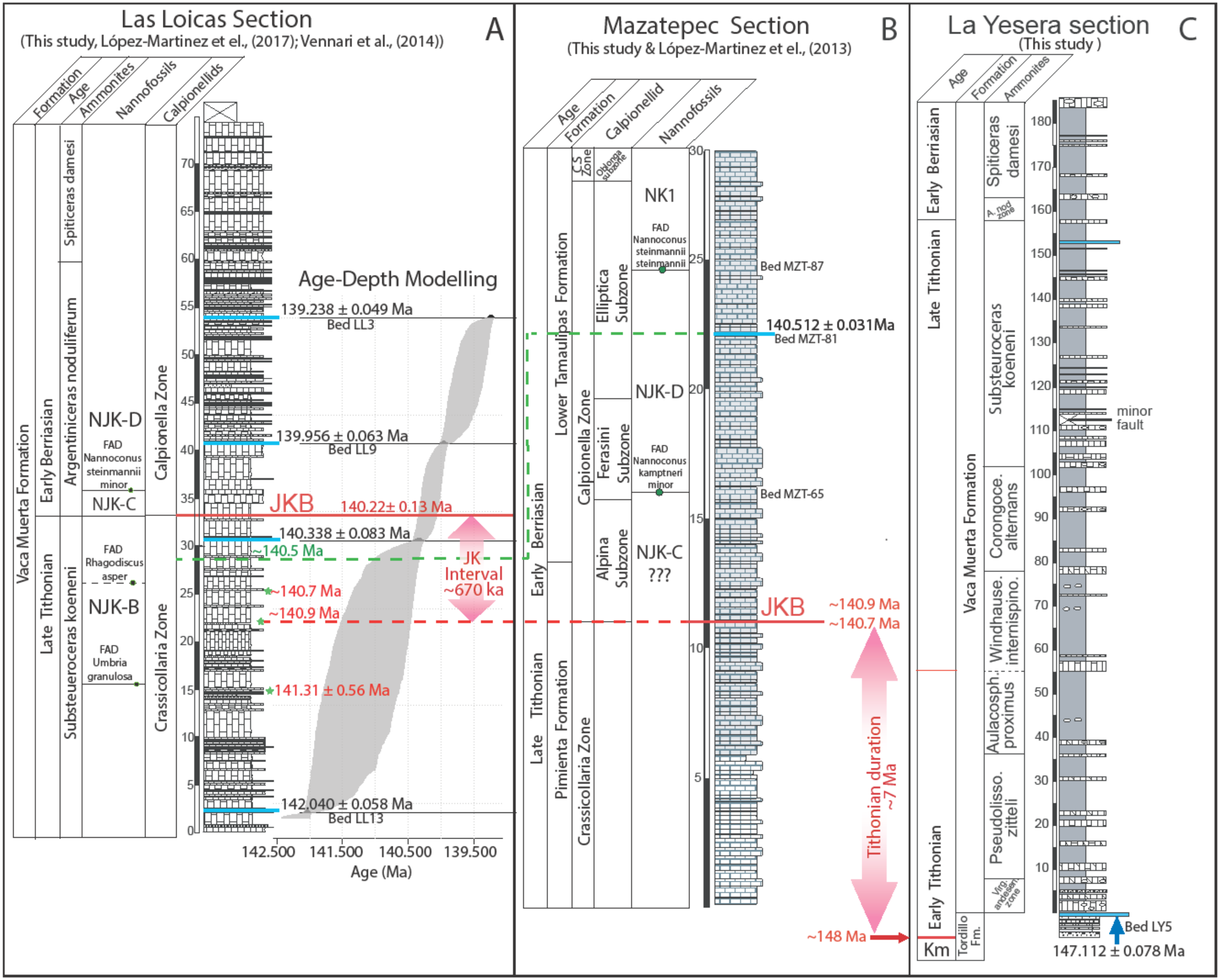

A
C. mexicana
B
C. mexicana
C
H. noeliae
D
H. geometricus
E
N. kamptneri minor
F
N. globulus
G
N. st. steinmannii
H
N. st. steinmannii
I
P. senaria
J
P. senaria
K
U. granulosa
L
E. primus
M
R. asper
N
R. asper
O
N. kamptneri minor
P
N. wintereri

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
JK Interval ~670 ka
~140.7 Ma
~140.9 Ma
141.31 ± 0.56 Ma
142.040 ± 0.058 Ma
Bed LL13
142.500
141.500
140.500
139.500
Age (Ma)
Mazatepec Section
(This study & López-Martinez et el., (2013)
B
Age
Formation
Calpionellid
Nannofossils
Berriasian
Early
Late Tithonian
Lower Tamaulipas Formation
Pimienta Formation
CS Zone
Oblonga subzone
Calpionella Zone
Elliptica Subzone
Ferasini Subzone
Alpina Subzone
Crassicollaria Zone
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
(This study)
C
Age
Formation
Ammonites
Early Berriasian
Late Tithonian
Early Tithonian
Km
Vaca Muerta Formation
Tordillo Fm.
Spiticeras damesi
A. nod zone
Substeuroceras koeneni
Corongoce. alternans
Windhause. internispino.
Aulacosph. proximus
Pseudolisso. zitteli
Virg. andesen zone
minor fault
Bed LY5
147.112 ± 0.078 Ma