Revista de la Asociación Geológica Argentina 75 (2): 175-187 (2018)

# Toward a multidisciplinary chronostratigraphic calibration of the Jurassic-Cretaceous transition in the Neuquén Basin

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## ABSTRACT

Detailed systematic studies have been carried out in the Vaca Muerta Formation in order to achieve an integrated multidisciplinary calibration of the Jurassic/Cretaceous transition in the Neuquén Basin. Although this unit has a very well-established ammonite biostratigraphy, the temporal distribution of biozones is yet a matter of hot debate. In this contribution we present the results of a well constrained integrated data from the Arroyo Loncoche section (southern Mendoza), where comprehensive cyclostratigraphic, paleomagnetic and biostratigraphic sampling/data allowed us to elaborate a very strong chronostratigraphic scheme for the Tithonian-Berriasian interval. The proposed stratigraphic calibration of the Tithonian-Berriasian Andean succession brings foward two key points: 1) The base of the Vaca Muerta Formation shows a polarities pattern which would only be compatible to the uppermost part of Hybonotum Zone (lowermost Lower Tithonian). 2) The position of the Jurassic - Cretaceous boundary is located within the lower third of the S. koeneni Zone.

**Keywords:** *Vaca Muerta Formation, Tithonian, Berriasian, chronostratigraphy*

## RESUMEN

*Calibración estratigráfica multidisciplinaria de la transición Jurásico-Cretácico en la Cuenca Neuquina*
Se realizaron estudios sistemáticos de detalle en la Formación Vaca Muerta con el fin de lograr una calibración multidisciplinaria integrada de la transición jurásico/cretácica en la Cuenca Neuquina. Aunque esta unidad se caracteriza por presentar una bioestratigrafía basada en amonites, la distribución temporal de las biozonas es todavía un tema de importante debate. En esta contribución se presentan los resultados integrados de la sección Arroyo Loncoche (sur de Mendoza), en donde exhaustivos estudios cicloestratigráficos, paleomagnéticos y bioestratigráficos han permitido elaborar un robusto esquema de correlación cronoestratigráfico para el intervalo Tithoniano-Berriasiano. La calibración estratigráfica propuesta para la sucesión tithoniano-berriasiana andina presenta dos puntos clave: 1) La base de la Formación Vaca Muerta muestra un patrón de polaridades que solo sería compatible con la parte superior de la Zona de Hybonotum (Tithoniano Inferior bajo). 2) La posición del límite Jurásico - Cretáceo está ubicada dentro del tercio inferior de la Zona de S. koeneni.

**Palabras clave:** *Formación Vaca Muerta, Tithoniano, Berriasiano, cronoestratigrafía*

## INTRODUCTION

The Vaca Muerta Formation is a thick rhythmic alternation of dark bituminous shales, marlstones, and limestones deposited as result of a rapid and widespread Paleo-Pacific Early Tithonian marine transgression in the Neuquén Basin. It is famous for its important oil and gas resources, as well as its abundant fossil content and temporal continuity along several hundred meters of section that comprise the Jurassic/

Cretaceous boundary (Leanza and Hugo 1977, Legarreta and Uliana 1991, Uliana y Legarreta 1993, Desjardins *et al*. 2016).

Jurassic-Cretaceous Andean biostratigraphy is well defined by ammonites (Leanza and Hugo 1977, Riccardi 2008, 2015) and to a lesser extent, by microfossils (Ballent *et al*. 2011). Andean ammonite zones are essentially based on the works of Leanza (1945) and Leanza (1980), with minor modifications. Such zones have high biostratigraphic resolution, even though their autochthony prevents a straightforward correlation with the Tethys and prompts the occurrence of different correlation schemes between Andean and Tethyan ammonite Zones (*e.g.* Leanza 1980, 1996, Riccardi 2008, 2015, Vennari *et al*. 2014).

The study of microfossils has advanced considerably since the first synthesis works of Musacchio (1978). An extremely detailed work that characterize the Jurassic – Cretaceous microfossils from outcrops and subsurface sediments is found in Ballent *et al*. (2011). Particularly, the studies of calcareous nannofossils (Bown and Ellison 1995, Scasso and Concheyro 1999, Bown and Concheyro 2004, Lescano and Concheyro 2009, 2014, Vennari *et al*. 2014), as well as other Tethyan calcareous microfossils, such as calpionellids, saccocomid microcrinoids and calcareous dinoflagellate cysts (Fernández Carmona *et al*. 1996, Fernández Carmona and Riccardi 1998, 1999, Kietzmann and Palma 2009, Kietzmann *et al*. 2011a, Kietzmann 2017, Ivanova and Kietzmann 2017).

The remarkable increase of faunal provinciality, as well as the uncertainties in the inter-regional correlation constitutes a major classic problem for the Tithonian-Berriasian across the world (*e.g.*, Ogg and Hinnov 2012). The definition of the base of the Cretaceous System is still controversial. Historically, at least three definitions are considered (Remane 1991, Wimbledon 2008, Grabowski 2011, Gradstein *et al*. 2012): 1) one is the base of the *Grandis* ammonite Zone defined in the *Colloque sur la Crétacé inferieur* (1963) that corresponds to the lower part of the *Calpionella* Zone, almost coinciding with the base of M18r Subchron. 2) The second is the base of the Jacobi ammonite Zone, defined in the *Colloque sur la limite Jurassique-Crétacé* (1973), which is often regarded as approximately equivalent to the base of the *Calpionella* Zone and correlated with the upper part of M19n.2n Subchron. 3) The last definition corresponds to the base of the *Occitanica* ammonite Zone, correlated with the middle part of the *Calpionella* Zone and the lower part of M17r Subchron (Hoedemaeker 1990). Recently, the Berriasian Working Group of the International Commission on Stratigraphy has defined the Jurassic/Cretaceous boundary at the base of the *Calpionella* Zone in the middle part of M19n.2n Subchron (*e.g.* Ogg *et al*. 2016, Wimbledon 2017).

In addition to this global problem, absolute ages coming from the Neuquén Basin are non-consistent with those of the geological time scales (Ogg and Hinnov 2012, Ogg *et al*. 2016). A TIMS age of ~139.5 Ma for the middle part of the *Argentiniceras noduliferum* ammonite Zone obtained by Vennari *et al*. (2014) led these authors to suggest a difference of c. 5 Ma with the present geologic time scale, based on oceanic basalts dating.

The aim of this work is to combine different methods in order to improve the reliability and accuracy of chronocorrelation in the Tithonian–Berriasian of the Neuquén Basin, using biostratigraphy (Kietzmann 2017, Ivanova and Kietzmann 2017), cyclostratigraphy (Kietzmann *et al*. 2011b, 2015) and magnetostratigraphy (Iglesia Llanos *et al*. 2017). We consider that the only way to resolve such discrepancies with absolute ages is in the first place, to build up a refined chronostratigraphic scheme that could allow a reliable correlation between the Andean and Tehyan realms.

## GEOLOGICAL SETTING

The Neuquén Basin was a retro-arc basin developed in Mesozoic times along the Pacific margin of South America (Fig. 1). Different tectonic regimes exerted a first-order control in basin development and sedimentary evolution (Legarreta and Uliana 1991, 1996): 1) Extension was established during Late Triassic-Early Jurassic, that prompted the formation of narrow, isolated depocentres controlled by large transcurrent fault systems filled mainly with continental deposits of the Precuyo Group (Manceda and Figueroa 1993, Vergani *et al*. 1995, Giambiagi *et al*. 2008). 2) Thermal subsidence with local tectonic events established in the Early Jurassic - Late Cretaceous was characterized by regional deposition of marine sequences, included in the Mendoza Group. The Vaca Muerta Formation (Early Tithonian - Early Valanginian) represents the most distal deposits (*e.g.*, Legarreta and Uliana 1991). 3) A compressive deformation regime was established during the Late Cretaceous, and continued throughout the Cenozoic, although alternating with extensional events (Ramos and Folguera 2005, Ramos 2010). This Andean deformation resulted in the development of a series of N-S-oriented fold and thrust belts (Aconcagua, Malargüe and Agrio fold and thrust belts) where extensive outcrops of the Mesozoic successions are exposed.

In the southern Mendoza area of the Neuquén Basin, the Lower Mendoza Subgroup (Leanza 2009) consists of aggradational sequences, with a maximum thickness of 500 m towards the center of the basin (Legarreta and Gulisano 1989). It includes continental deposits of the Tordillo Formation (Kimmeridgian-Early Tithonian?), basinal to middle carbonate ramp deposits of the Vaca Muerta Formation (Early Tithonian-Early Valanginian) and middle to inner ramp oyster-deposits of the Chachao Formation (Early Valanginian), which form a homoclinal carbonate ramp system (*e.g.* Carozzi *et al*. 1981, Mitchum and Uliana 1985, Kietzmann *et al*. 2014).

In this work, a detailed stratigraphic analysis of the Arroyo Loncoche section is presented. This corresponds to a classical Jurassic-Cretaceous section from the Neuquén Basin, where the Lower Mendoza Subgroup includes the Tordillo Formation (~150 m), the Vaca Muerta Formation (~280 m) and the Chachao Formation (~25 m). The biostratigraphy has also been derived from complementary outcrops (Tres Esquinas in the Atuel depocenter, and Río Seco de Tosca, and Río Seco del Altar in Sierra de la Cara Cura), as well as subsurface data (Fig. 1).

## METHODOLOGY

Several studies were carried out at the Arroyo Loncoche section including facies analysis, and sequence stratigraphy (Kietzmann *et al*. 2008, 2011b, 2014), cyclostratigraphy, magnetostratigraphy (Kietzmann *et al*. 2015, Iglesia Llanos *et al*. 2017) and calcareous microfossil biostratigraphy (Kietzmann 2017, Ivanova and Kietzmann 2017).

Biostratigraphy is based on ammonites, calcareous dinoflagellate cysts and calpionellids. Ammonites come from 80 levels that restrain the deposition of the Vaca Muerta Formation to the Early Tithonian – Late Berriasian (*Virgatosphinctes andesensis* to *Spiticeras damesi* Assemblage Zones; Leanza *et al*. 1977, Kietzmann *et al*. 2011b, 2014). In addition, a total of 85 thin-sections distributed along the whole formation were studied under a petrographic microscope for taxonomic identifications of calcareous dinoflagellate cysts and calpionellids (Kietzmann 2017, Ivanova and Kietzmann 2017).

Cyclostratigraphic analysis is based on the differentiation of dm-scale carbonate/ siliciclastic lithofacies couplets or elemen-

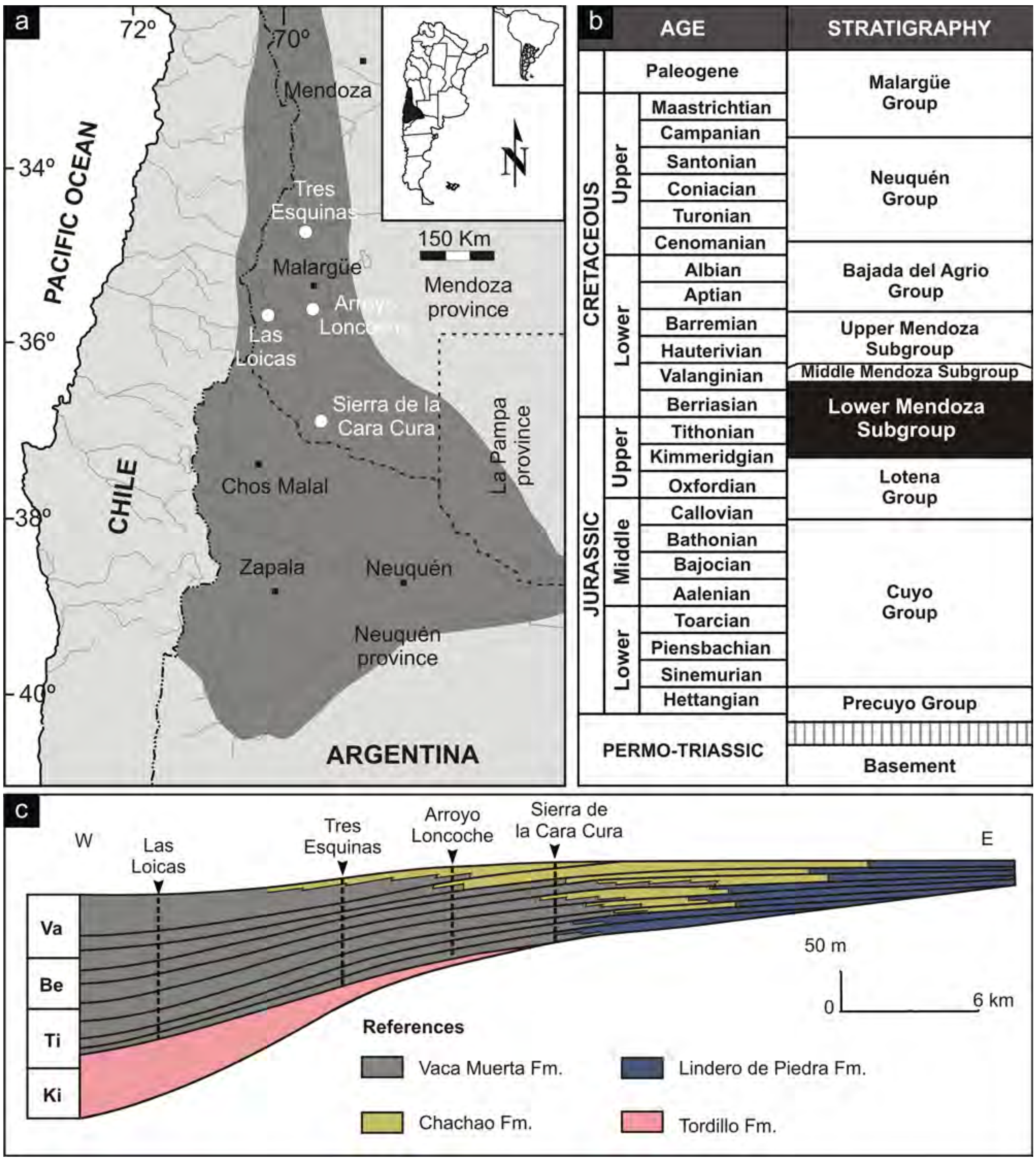


**Figure 1.** a) Sketch map of the Neuquén Basin with detail of the mentioned localities; b) Stratigraphic chart for the Neuquén Basin; c) Lithostratigraphic subdivision of the Lower Mendoza Subgroup in Southern Mendoza. Ki: Kimmeridgian, Ti: Tithonian, Be: Berriasian, Va: Valanginian.

tary cycles, and bundles and superbundles differentiated in the field. Lower frequencies are searched using spectral analysis with the software POWGRAF2 (Pardo-Igúzquiza and Rodríguez-Tovar, 2004) using Blackman-Tukey method. For further explanation, see Kietzmann *et al*. (2015).

Magnetostratigraphy derived from 56 sampling horizons or sites with an average site-distance of ~5 m. At each site, four oriented cores were obtained using a portable core drill, with at least two standard specimens, making a total of 8 specimens per site. Altogether, c. 450 specimens have been obtained and processed. Paleomagnetic treatment and analysis of specimens were performed using alternating fields (AF) and high temperatures (TH) demagnetizing methods. The AF method was carried out using a 2G demagnetizing device, whereas the TH with a Schoenstedt furnace. Residual magnetizations were measured in a 2G DC SQUID magnetometer (see Iglesia Llanos *et al*. 2017 for more details).

# CALCAREOUS MICROFOSSIL BIOSTRATIGRAPHY

Detailed micropaleontological studies in the southern Mendoza area of the Neuquén Basin reveal a relatively rich micropaleontological assemblage of 24 known species of calcareous dinoflagellate cysts, as well as levels with poor preserved 18 known species of calpionellids (Ivanova and Kietzmann 2017, Kietzmann 2017). Different bioevents of global importance are recognized that allowed to distinguish 6 calcareous dinoflagellate cyst zones and 2 calpionellid zones (Fig. 2).

## Calcareous dinoflagellate cysts

Calcareous dinocysts are important stratigraphic markers for the Upper Jurassic - Lower Cretaceous time interval in the Tethys. In the Vaca Muerta Formation, Ivanova and Kietzmann (2017) report the following dinocysts zones:

*Carpistomiosphaera tithonica Zone (Ivanova in: Lakova et al. 1999):* The establishment of this zone is defined by the presence of *Committosphaera pulla* (Fig. 3a), species that spans the Early Tithonian, and occurs in association with the index-species *Carpistomiosphaera tithonica*. The *C. tithonica* Zone spans the Kimmeridgian-Tithonian boundary interval (Ivanova in: Lakova *et al*. 1999, Reháková 2000a, b). This zone is recognized in the lower part of the *Virgatosphinctes andesensis* Zone.

*Parastomiosphaera malmica Zone* (*Nowak 1968)*: The base of this zone is defined at the first occurrence (FO) of the species *Parastomiosphaera malmica* (Fig. 3b) and its top at the FO of the species *Colomisphaera tenuis*. This zone corresponds to the Early Tithonian (Ivanova in: Lakova *et al*. 1999, Reháková 2000a, b). In the Vaca Muerta Formation, this zone is recognized in the upper part of the *Virgatosphinctes andesensis* and *Pseudolissoceras zitteli* Zones.

*Colomisphaera tenuis Zone (Řehánek 1992)*: The FO of the index-species *Colomisphaera tenuis* (Fig. 3c) marks the base of this zone in the Tethyan region and corresponds to the latest Early Tithonian (Ivanova in: Lakova *et al*. 1999). In the Vaca Muerta Formation, this zone is recognized for the moment within the *Aulacosphinctes proximus* and *Windhauseniceras internispinosum* Zones.

*Colomisphaera fortis/Stomiosphaerina proxima Zones (Řehánek 1992):* In the Tethyan realm, these correspond to two separate zones, but in the present study, it is not possible to separate one from each other. The lower boundary of *Colomisphaera fortis* Zone is defined by the FO of the index-species (Fig. 3d). The Fortis Zone coincides with the upper part of the calpionellids *Praetintinopsella* Zone and the lower *Crassicollaria* Zone (Late

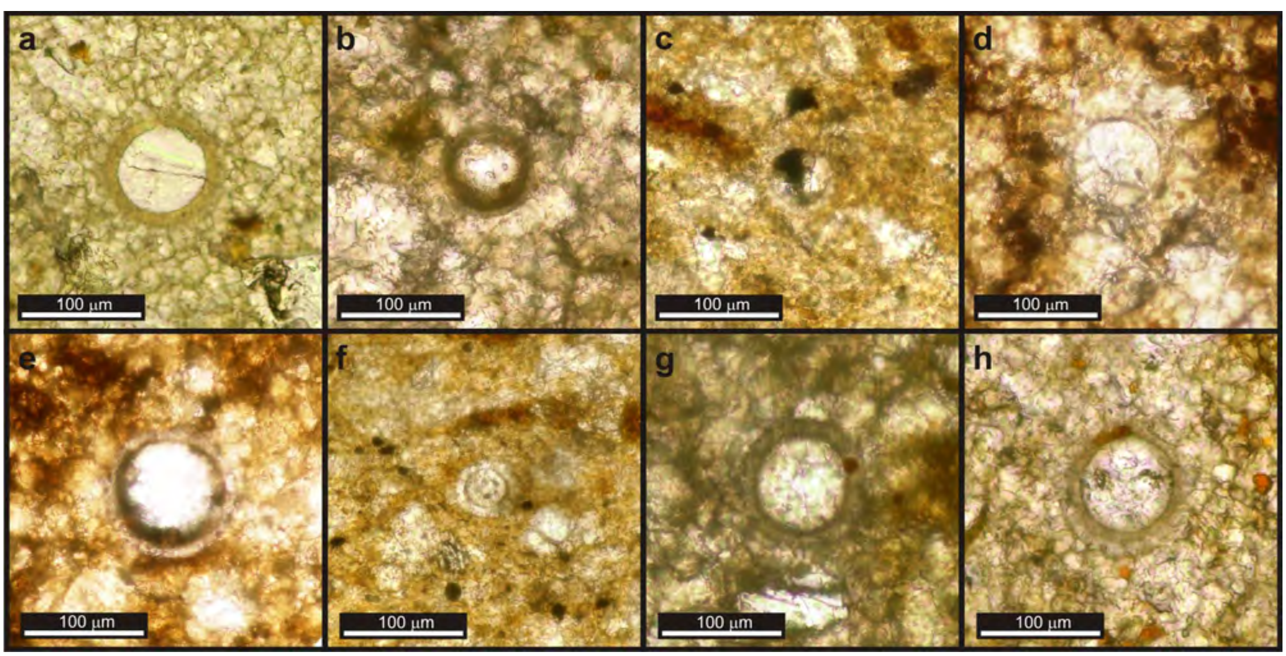


**Figure 2.** Calcareous dinocysts index-species from the Vaca Muerta Formation: a) *Committomiosphaera pulla* (Borza); b) *Parastomiosphaera malmica* Nowak; c) *Colomisphaera tenuis* (Nagy); d) *Colomisphaera fortis* Řehánek; e) *Stomiosphaerina proxima* Řehánek; f) *Stomiosphaera wanneri* Borza; g) *Colomisphaera conferta* Řehánek; h) *Carpistomiosphaera valanginiana* Borza.

Tithonian). The lower boundary of *Stomiosphaerina proxima* Zone is defined by the FO of *Stomiosphaerina proxima* (Fig. 3e). The zone is a relatively long-ranging from the latest Late Tithonian to the middle Late Berriasian (Ivanova in: Lakova *et al*. 1999). In the Vaca Muerta Formation this zone is recognized for the moment from the lower part of the *Corongoceras alternans* to the upper part of the *Argentiniceras noduliferum* Zones.

*Stomiosphaera wanneri Zone (Ivanova in: Lakova et al. 1999):* This zone is defined by the FO of the index-species *Stomiosphaera wanneri* (Fig. 3f) at the base and FO of *Colomisphaera conferta* at the top. The *Stomiosphaera wanneri* Zone corresponds to the latest Late Berriasian and Early Valanginian (Ivanova in: Lakova *et al*. 1999). However, due to the correction in the FO of the species *Colomisphaera conferta* (Fig. 3g) in the uppermost Berriasian (Grabowski *et al*. 2016), Ivanova and Kietzmann (2017) change the range of the zone to the latest Late Berriasian (except its very top). In the Vaca Muerta Formation this zone is recognized from the upper part of the *Argentiniceras noduliferum* to the upper part of *Spiticeras damesi* Zones.

*Colomisphaera conferta Zone (Ivanova in: Lakova et al. 1999):* This zone is defined as the interval between the FO of *Colomisphaera conferta* and the FOs of *Carpistomiosphaera valanginiana* (Fig. 3h) and/or *Colomisphaera vogleri* (Ivanova in: Lakova *et al*. 1999). The range of the zone is Late Berriasian - Early Valanginian (Grabowski *et al*. 2016). In the Vaca Muerta Formation this zone is recognized from the upper part of the *Spiticeras damesi* to the lower part of the *Neocomites wichmanni* Zones.

## Calpionellids

The distribution of calpionellid species allows recognizing two of the calpionellid standard zones: *Chitinoidella* and *Crassicollaria* Zones.

*Chitinoidella Zone (Enay and Geyssant 1975):* The base of the *Chitinoidella* Zone coincides with the first occurrence of chitinoidellids in the Vaca Muerta Formation at the middle part of the *Virgatosphinctes andesensis* Zone. The upper boundary is defined by the FO of hyaline calpionellids in the transition between the *Windhauseniceras internispinosum* and *Corongoceras alternans* Zones. This zone can be divided in two subzones. The lower one is characterized by *Borziella slovenica* and *Dobeniella* cf. *pinaraensis* (Fig. 4a-b), typical components of the *Longicollaria dobeni* Subzone. The upper one, corresponds to the *Chitinoidella boneti* Subzone, and coincides approximately with the *Windhauseniceras internispinosum* Zone. It contains *Chitinoidella boneti*, *Ch. hegarati* and *Ch. elongata* (Fig. 4c-e).

*Crassicollaria Zone (Alleman et al. 1971):* The base of this zone is represented by the FO Calpionellidae, including *Tintinnopsella carpthatica*, *Calpionella alpina, Crassicollaria intermedia, Cr. massutiniana,* and some chitinoidellids (Fig. 4f-j). It coincides approximately with the *Coro-*

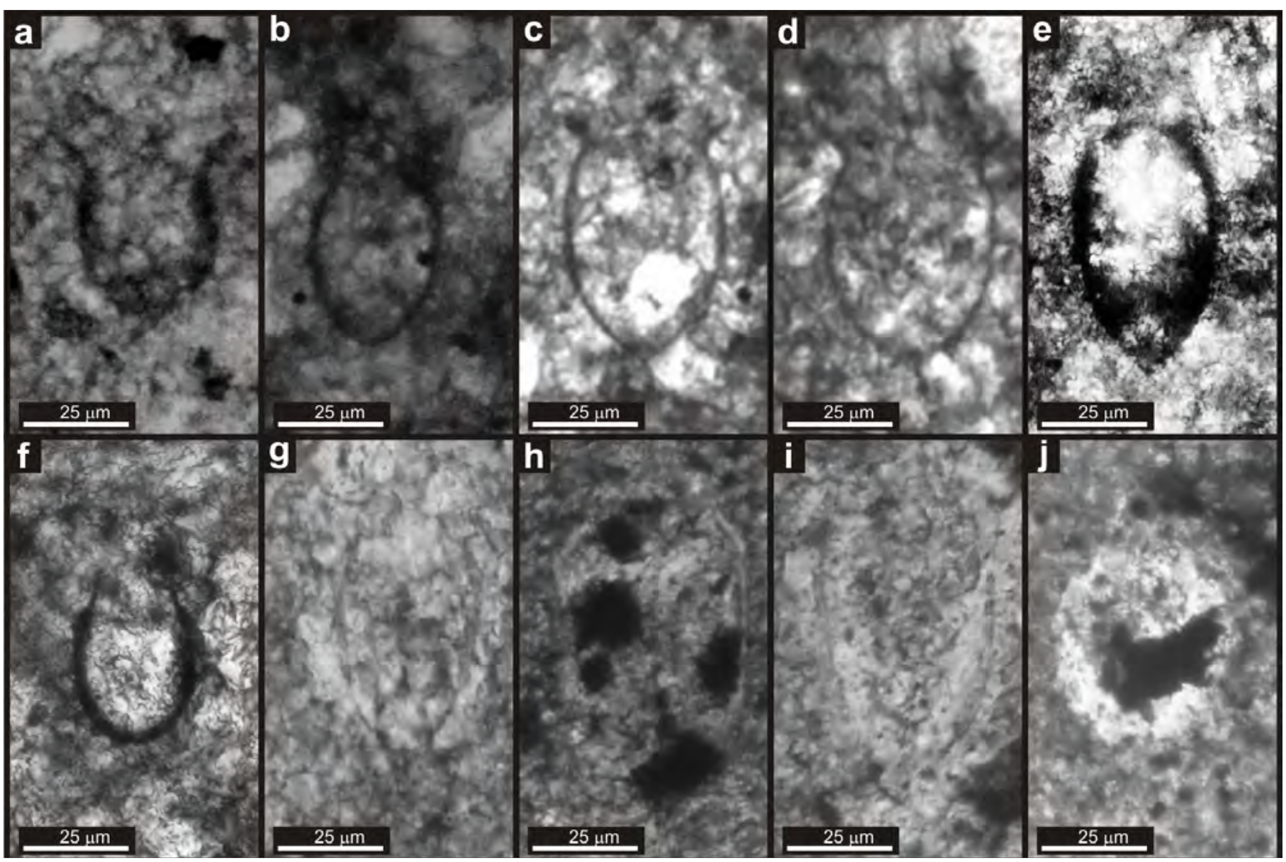


**Figure 3.** Chitinoidellids and calpionellids from the Vaca Muerta Formation: a) *Borziella slovenica* (Borza); b) *Dobeniella* cf. *pinaraensis* (Furazola Bermudez and Kreisel); c) *Chitinoidella boneti* Doben; d) *Chitinoidella hegarati* Sallouhi, Boughdiri, and Cordey; e) *Chitinoidella elongata* Pop; f) *Carpathella rumanica* Pop; g) *Crassicollaria intermedia* (Durand-Delga); h) *Crassicollaria massutiniana* (Colom); i) *Tintinnopsella carpathica* (Murgeanu and Filipescu); j) *Calpionella alpina* Lorenz.

*ngoceras alternans* Zone, but its upper boundary has not been identified yet in the Arroyo Loncoche section. In the subsurface this boundary was identified by the last occurrence of *Calpionella elliptalpina* at the upper part of the *Corongoceras alternans* Zone (Kietzmann 2013 in Gonzalez Tomassini *et al*. 2015), however, the acme of C. *alpina* has not been recognized in the studied sections.

## CYCLO- AND MAGNETO-STRATIGRAPHIC SCALES

In order to anchor these scales to the geological time scale of the International Commission on Stratigraphy, we followed the criterion chosen in Kietzmann *et al*. (2015) that uses the base of the *Windhauseni- ceras internispinosum* Zone as primary datum (equivalent to the base of *Microcanthum* Standard Zone).

### Cyclostratigraphy

The Vaca Muerta Formation has decimeter-scale rhythmicity, showing a well-ordered hierarchy of cycles within the Milankovitch frequency band (Scasso *et al*. 2005, Kietzmann *et al*. 2011b, 2015). Elementary cycles have a relatively regular

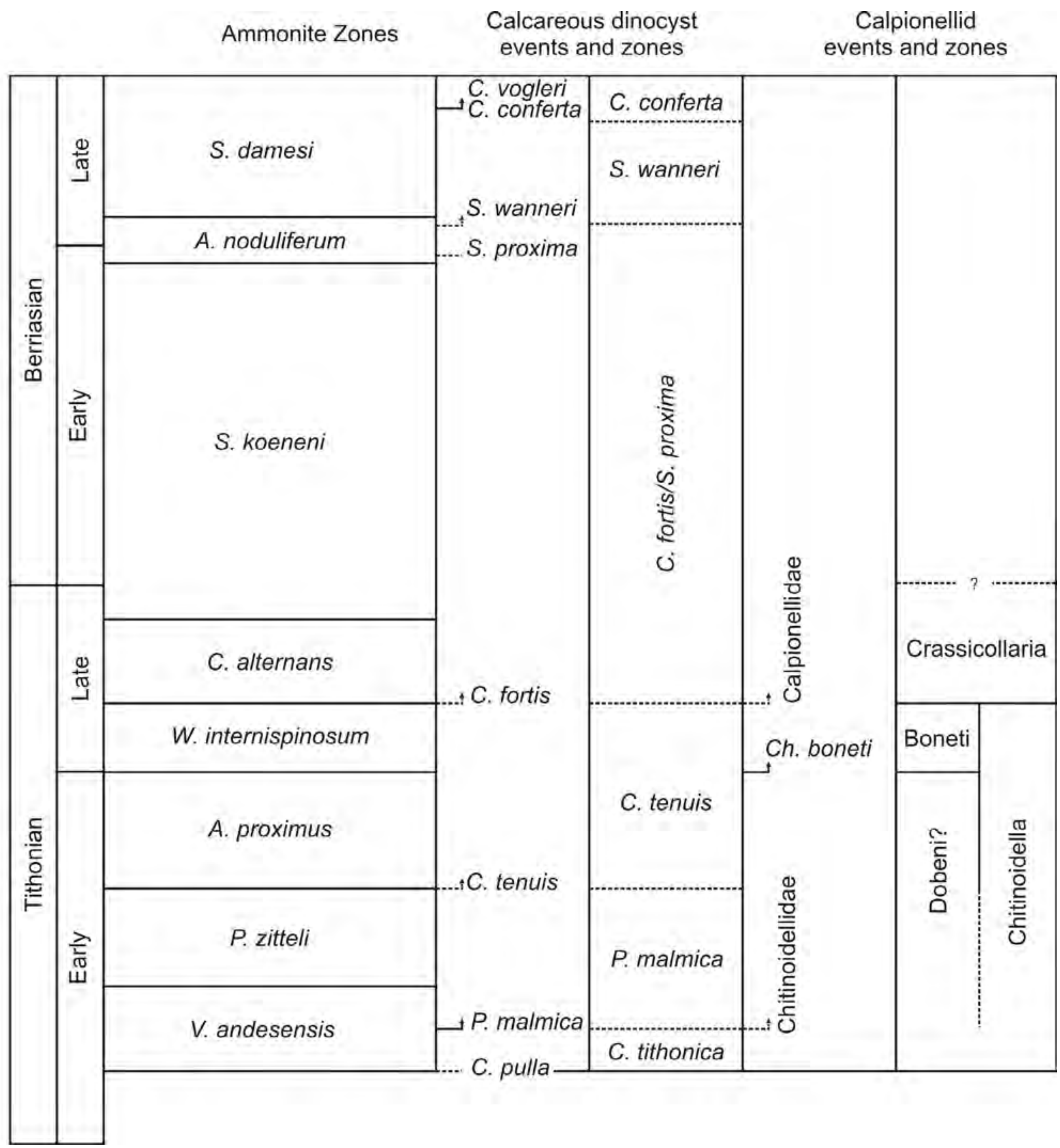


**Figure 4.** Summary of calcareous dinocyst and calpionellid events and zones identified so far in the southern Mendoza area of the Neuquén Basin (based in Kietzmann 2017 and Ivanova and Kietzmann 2017).

thickness in the order of 20 to 40 cm, so that they can be regarded as temporarily equivalent units. Three types of elementary cycles are recognized, which consists of two hemicycles of similar thickness: limestone/marlstone, marlstone/marlstone and marlstone/shale (Kietzmann *et al*. 2011b, 2015). Elementary cycles are grouped into sets of 4-5 elementary cycles (bundles), and these are grouped into sets of 4-5 bundles (superbundles). Such stacking pattern is used by different authors as diagnostic criteria to identify the influence of orbital forcing (*e.g.*, Goldhammer *et al*. 1990, Schwarzacher 1993, Anderson 2004, Strasser *et al*. 2004). The 5:1 ratio (5 elementary cycles per bundles) is commonly attributed to high frequency eccentricity (95 ky and 125 ky), while the 4:1 ratio (4 bundles per superbundles) as low frequency eccentricity (410 ky).

The Arroyo Loncoche section involves 487 elementary cycles, which are grouped in 98 bundles and 24 superbundles (Kietzmann *et al*. 2018). In this section, ammonite data point to a duration of about 10 myr on the basis of the time scale of Gradstein *et al*. (2004, 2012) and Ogg *et al*. (2016), so that the elementary cycle would have a periodicity attributable to the precessional cycle (~21 ky). Spectral analysis of time series constructed from thickness of elementary cycles show a peak above the 95% confidence level, and two peaks above the 99% confidence level (Fig. 4). The first one has a periodicity of 410 ky, which is consistent with the low-frequency eccentricity cycle. The other two peaks have periodicities of 118 ky and 91 ky. These periodicities can be also attributed to the high-frequency eccentricity cycle. Using high and low frequency eccentricity cycles, we built a floating astronomical scale for the Lower Tithonian-Upper Berriasian of the Neuquén Basin, which allowed estimating minimum durations of ammonite zones (Fig. 5).

### Magnetostratigraphy

Virtual Geomagnetic Poles (VGP) were calculated from site mean directions, yielding 11 reverse and 10 normal polarity zones (Fig. 5). One interval at c. 30 m from the base bears no polarity, were a Cenozoic sill was intruded.

Based on the correlation between ammonite zones from the Andean and Tethys Regions, these polarities were calibrated according to the last Geomagnetic Polarity Time Scale (GPTS) compiled by Ogg and Hinnov (2012). Results show a good correlation between both magnetostratigraphic scales.

From base to top, the *Virgatosphinctes andesensis* Zone comprises a set of reverse, normal, reverse and normal polarities, which we interpret to span the M22r.2r to M22n Subchrons in the GPTS. The following *Pseudolissoceras zitteli* Zone bears normal, reverse and normal polarities that would correspond to M22n to the base of M21n Subchrons. *Aulacosphinctes proximus* Zone comprises a set of normal and reverse polarities that are correlated with M21n to M20r Subchrons. The *Windhauseniceras internispinosum* Zone bears only normal polarity that is correlated with the M20n.2n Subchron. Above, the *Corongoceras alternans* Zone includes normal, reverse, normal, reverse and normal polarities which are interpreted to correspond to the upper M20n.2n to M19n Subchrons. The *Substeueroceras koeneni* Zone comprises normal, reverse, normal, reverse, normal, reverse, normal and reverse polarities that are correlated with M19n to M16r Subchrons. Further above, the *Argentiniceras noduliferum* Zone includes a dominant reverse with a minor opposite polarity, which is correlated with M16r Subchron. Finally, the *Spiticeras damesi* Zone comprises reverse, normal and reverse polarities that are interpreted to correspond to M16r to M15r Subchrons. Therefore, deposition of the Vaca Muerta Formation in the locality of Arroyo Loncoche took place during M22r.2r to M15r Subchrons.

## TOWARDS A MULTIDISCIPLINARY CHRONOSTRATIGRAPHIC CALIBRATION

At the base of the Vaca Muerta Formation, the *Virgatosphinctes andesensis* Zone shows a minimum duration of 0.81 myr, and comprises the M22r.2r to M22n Subchrons in the GPTS. The pattern of polarities isolated in this interval rather correlates to the uppermost *Hybonotum* and lowermost *Darwini* Standard Zones. The presence of the *Carpistomiosphaera tithonica* calcareous dinoflagellate Zone also supports this correlation (Lakova *et al*. 1999, Reháková 2000).

The *Pseudolissoceras zittelli* Zone shows a minimum duration of ~0.61 myr, and spans the M22n to M21n Subchrons (upper *Darwini* to lower *Fallauxi* Standard Zones). This zone also contains calcispheres of the *Parastomiosphaera malmica* calcareous dinoflagellate Zone, and includes the FO of *Polycostella beckmannii* (see Kietzmann *et al*. 2011b) which occur at the upper M22n Subchron (Casellato 2010).

The *Aulacosphinctes proximus* Zone shows a minimum duration of ~0.61 myr, and comprises the M21n and M20r Subchrons (upper Fallauxi to Ponti Standard Zones). Also contains the L. *dobeni* Subzone of the *Chitinoidella* Zone and the *Colomisphaera tenuis* calcareous dinoflagellate Zone.

The *Windhauseniceras internispinosum* Zone has a minimum duration of ~1.21 myr, and bears only the M20n Subchron, which is consistent with the correlation to the *Microcanthum* Standard Zone (Zeiss and Leanza 2010, Riccardi 2015). Also contains the Ch. *boneti* Subzone of the *Chitinoidella* Zone and the *Colomisphaera tenuis* and *Colomisphaera fortis* calcareous dinoflagellate Zones, supporting its early Late Tithonian age.

The *Corongoceras alternans* Zone has a minimum duration of (~1.21 myr), and comprises the M20n to M19n2 Subchrons (upper *Microcanthum* Standard Zone and lower part of the *"Durangites"* Standard Zone). It correlates with the *Crassicollaria* calpionellid Zone and the *Colomisphaera fortis/Stomiosphaerina proxima* calcareous dinoflagellate Zones.

The *Substeueroceras koeneni* Zone would have a minimum duration of ~2.43 myr, comprises the M19n2 to the lowermost part of M16r Subchrons (upper part of *"Durangites"* to *Occitanica* Standard Zones). This zone contains the *Stomiosphaerina proxima* calcareous dinoflagellate Zone, as well as elements of the *Calpionella* Zone (Kietzmann 2013 in González Tomassini *et al*. 2015).Taking into account the two latest proposals of the Jurassic/Cretaceous boundary, these time-lines at Arroyo Loncoche are placed within the

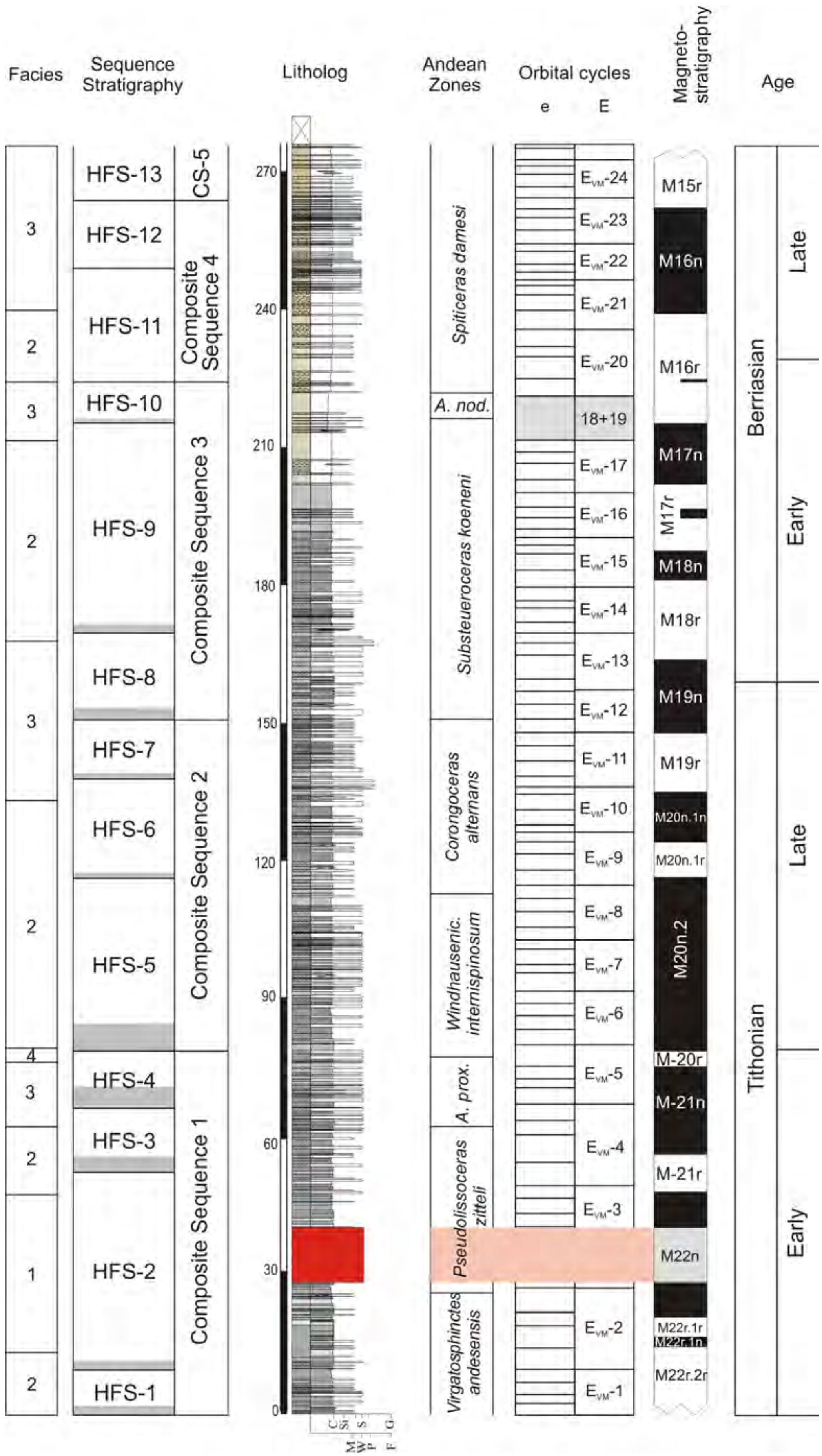


**Figure 5.** Cyclostratigraphic and magnetostratigraphic scales for the Arroyo Loncoche section (modified from Iglesia Llanos *et al.* 2017). From left to right are indicated: facies associations (1: distal outer ramp to basin. 2: bioclastic outer ramp. 3: bioclastic middle ramp to proximal outer ramp. 4: Oyster autoparabiostrome dominated middle ramp), depositional sequences, sedimentary log and ammonite zones (after Kietzmann *et al.* 2014), orbital cycles (Kietzmann *et al.* (2015, 2018) and magnetostratigraphic interpretation (Iglesia Llanos *et al.* 2017). Grey-shaded bars in depositional sequences are possible stratigraphic intervals where there may be condensation and omission of orbital cycles. Red/pink rectangles marks the Cenozoic sill bearing no polarity in the magnetostratigraphic scale

lower third of the *Substeueroceras koeneni* Zone.

Further above, the *Argentiniceras noduliferum* Zone shows a minimum duration of ~0.81 myr, and includes a dominant reverse, which is correlated with M16r Subchron (upper *Occitanica* to lower *Boissieri* Standard Zones). This zone contains the *Stomiosphaerina proxima* and *Stomiosphaera wanneri* calcareous dinoflagellate Zones being consistent with a Late Berriasian age.

Finally, the *Spiticeras damesi* Zone would have a minimum duration of ~1.62 myr and spans the M16r to M15r Subcrons (*Boissieri* Standard Zone), and includes the *Stomiosphaera wanneri* and lower *Colomisphaera conferta* calcareous dinoflagellate Zones, of Late Berriasian age.

## DISCUSSION

The calibration of the Tithonian - Berriasian obtained from the combination of different disciplines shows good consistency with the ammonite primary scheme proposed by Riccardi (2015). In this regard, these new data would draw the attention on the fact that there may be small shifts in the correlation of the basal intervals where biostratigraphic data are not conclusive for their correlation.

According to ammonite biostratigraphic proposals, the *Virgatosphinctes andesensis* Zone is equivalent to the *Darwini* and *Semiforme* Tethyan Zones (Riccardi 2015, Vennari 2016), both of which bear a single normal polarity (Subchron M22n). Yet, the polarities pattern isolated in this interval rather correlates to the uppermost *Hybonotum* and lowermost *Darwini* Zones, which is supported, on the other hand, by the presence of the *Carpistomiosphaera tithonica* calcareous dinoflagellate Zone. The correlation of the lower *Virgatosphinctes andesensis* Zone with the *Hybonotum* Standard Zone was previously proposed by Zeiss and Leanza (2010). These authors divided the *Virgatosphinctes andesensis* Zone into a lower *"Lithacoceras" malarguense* Subzone and an upper *Choicensisphinctes choicensis* Subzone, which were referred respectively to the *Hybonotum* and Darwini Zones (Fig. 6). Riccardi (2015) provides an extensive discussion about the correlation of the *Virgatosphinctes andesensiss* Zone, concluding that it correlates most likely with the *Semiforme* Zone. However, he does not discard the correlation with the *Mazapilites* beds of Mexico (Zeiss and Leanza 2010), a genus that ranges from the *Hybonotum* to the *Semiforme* Zones. Vennari (2016), on the other hand, proposed to rename the *Virgatosphinctes andesensis* Zone by *Virgatosphinctes andesensis* Zone, and divided two consecutive subzones *(Pseudinvoluticeras primordialis* and *Indansites malarguensis* Subzones), which were partially correlated with *Darwini* and *Semiforme* Zones. She correlated the P. *primordialis* Subzone with the *Darwini* Zone, as no typical elements of the *Hybonotum* Zone were determined. Nevertheless, she also reported the presence of *Schaireria neoburgensis* a species that spans the *Hybonotum* to *Semiforme* Zones.

The *Pseudolissoceras zitteli* Andean Zone is also largely discussed in Riccardi (2015), indicating that although it contains ammonites with ranges within the *Darwini, Semiforme* and *Fallauxi* Zones, its most likely equivalence would be the *Semiforme* and lower *Fallauxi* Zones. New magnetostratigraphic data from Iglesia Llanos *et al*. (2017) indicate the upper M22 to lower M21 Chrons, which are equivalent to the upper *Darwini* to lower *Fallauxi* Standard Zones. Ammonite data do not oppose this chronostratigraphic position. Also, the presence of the *Parastomiosphaera malmica* Zone (Ivanova and Kietzmann 2017), as well as the FO of *Polycostella beckmannii* in the middle part of the P. *zitteli* Zone (Kietzmann *et al*. 2011b), is very consistent with our magnetostratigraphic data.

The following *Aulacosphinctes proximus, Windhauseniceras internispinosum, Corongoceras alternans, Substeueroceras koeneni, Argentiniceras noduliferum,* and *Spiticeras damesi* ammonite Zones do correlate very well with the Tethyan Zones in Riccardi (2015), as well as the new cyclostratigraphic (Kietzmann *et al*. 2015), magneostratigraphic (Iglesia Llanos *et al*. 2017) and biostratigraphic data (Kietzmann 2017, Ivanova and Kietzmann 2017) (Fig. 6). This correlation was earlier proposed by Leanza (1996) on the basis of ammonite content, and also widely discussed in Riccardi (2015). Calpionellid reported by Kietzmann (2017) within the A. *proximus, W. internispinosum* and C. *alternans* fully support their correlation with the *Fallauxi* to *"Durangites"* Zones, since the presence of the *Chitinoidella* Zone (with the *L. dobeni?* and *Ch. boneti* Subzones) was identified for the A. *proximus* and *W. internispinosum* Zones, respectively, and the *Crassicollaria* Zone was identified for the C. *alternans* Zone. Magnetostratigraphic data indicates that the Jurassic - Cretaceous boundary would be restricted to the lower part of the *S. koeneni* Zone (M19n.2n Subchron), as proposed by Leanza (1996).

Important nannofossil bioevents were reported by Vennari *et al*. (2014) at Las Loicas section, including the FOs of N. *wintereri* (M19r Subchron, see Grabowski *et al*. 2017, Wimbledon 2017), and N. *kamptneri* minor and *N. steinmannii steinmannii* (M19nSubchron, see Grabowski *et al*. 2017, Wimbledon 2017) in the uppermost S. *koeneni* Zone. However, new data from Vennari *et al*. (2017) locate the FOs of N. *kamptneri* minor and *N. steinmannii steinmannii* at the basal part of the S. *koeneni* Zone in Sierra de la Cara Cura section, which are also very consistent with the M19 Chron at the base of the S. *koeneni* Zone.

According to magnetostratigraphic, cyclostratigraphic and biostratigraphic data the resulted calibration of ammonite zones is similar to the biostratigraphic proposal of Leanza (1996) and Riccardi (2015).

## CONCLUSIONS

Data provided by magnetostratigraphy allowed us to calibrate the Tithonian – Berriasian in the Neuquén Basin with unprecedented precision. This was achieved from the combination of magnetostratigraphy with cyclostratigraphy, that where complemented with calpionellid and calcareous dinocyst biostratigraphy. The latter convey similar distributions than those proposed in Leanza (1996), Zeiss and Leanza (2010), and Riccardi (2015).

The resultant cyclo and magnetostratigraphic scales suggest that the deposition of the Vaca Muerta Formation in the local-

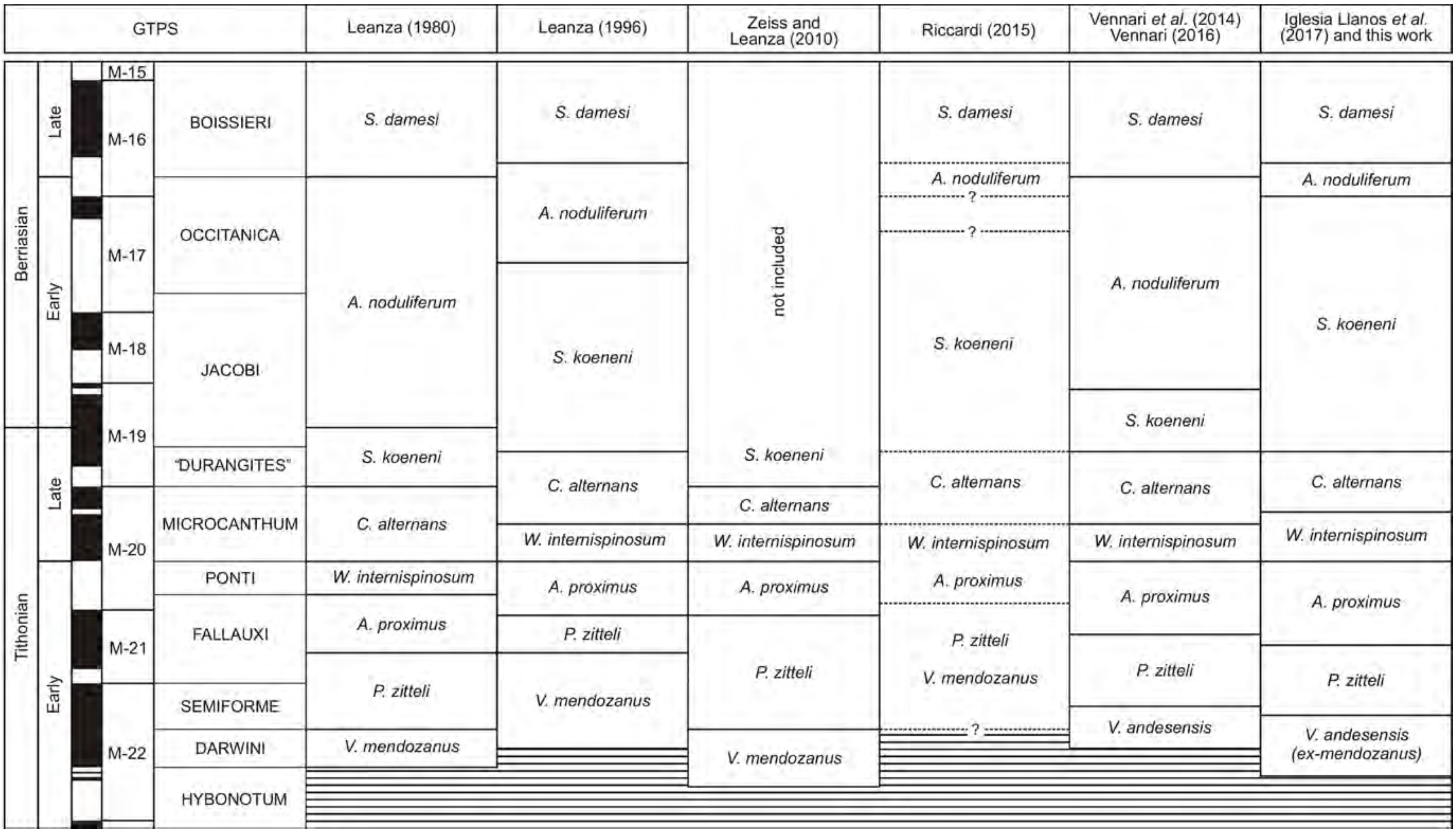


**Figure 6.** Comparision of different correlation proposals between Andean and Tethyan ammonite zones. Correlations from Leanza (1980, 1996), Zeiss and Leanza (2010), Vennari *et al.* (2014)/Vennari (2016) and Riccardi (2015) are based on ammonite and nannofossil biostratigraphic information. Correlation from Iglesia Llanos *et al.* (2017)/this work is based on magnetostratigraphic and calcareous microfossils biostratigraphy. Note the high similarities between the correlations obtained independently by Leanza (1996), Riccardi (2015) and Iglesia Llanos *et al.* (2017).

ity of Arroyo Loncoche took place during Chrons M22 to M16 in a minimum time of 10.13 myr (4.86 for the Tithonian and 5.27 for the Berriasian).

The proposed stratigraphic calibration of the Tithonian-Berriasian Andean succession brings foward two key points: 1) The base of the Vaca Muerta Formation (*V. andesensis* Zone) shows a polarities pattern which would only be compatible to the uppermost part of *Hybonotum* Zone. This correlation is consistent with the *C. tithonica* calcareous dinocysts Zone. 2) The position of the Jurassic - Cretaceous boundary within the lower third of the S. *koeneni* Zone is in very good agreement with the biostratigraphic proposal of Leanza (1996) and Riccardi (2015).

## ACKNOWLEDGMENTS

This research has been done under the framework of the PICT-2015-0206 and PICT-2016-3762 projects supported by the Agencia Nacional de Promoción Científica y Tecnológica, and UBACyT 20020150200218BA project supported by the University of Buenos Aires. We are especially grateful to Dr. Alberto Riccardi (Universidad Nacional de La Plata y Museo, Argentina) for ammonites and ammonite zones identification, as well as the discussion of Tithonian–Valanginian biostratigraphy. We especially appreciate the review and editorial work of Héctor Leanza.

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Recibido: 15 de diciembre, 2017
Aceptado: 7 de mayo, 2018