SPATIO-TEMPORAL DISTRIBUTION OF THE TITHONIAN VACA MUERTA FORMATION IN THE CENTRAL NEUQUÉN BASIN BASED ON AMMONITE BIOHORIZONS

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Introduction

The Tithonian rocks of the Neuquén Basin (Fig. 1A) are mostly included in the Vaca Muerta Formation (Leanza 1981). Their chronostratigraphic classification by ammonite zones, started by Burckhardt (1900), has advanced continuously by progressive subdivision of the sequences (Leanza 1981), currently including seven zones (Fig. 1B). This classification remains hard to time-correlate with the Tethyan standard because few common ammonites between the Andean and Tethyan domains are known.

The distribution of the Vaca Muerta Fm through the basin is rather well known at the stage level, but rather roughly at the zonal level (see Leanza & Hugo 1977, Leanza 1981, Leanza et al. 2011, Aguirre-Urreta et al. 2019, among others). The formation is currently mainly subdivided in the Portada Covunco and Pichi Moncol members (Parent et al. 2013, Garrido et al. 2018). In the central part of the basin intercalates the Middle Tithonian Los Catutos Mb (Leanza & Zeiss 1990), and in the western border of the basin occurs the latest Tithonian turbiditic Huncal Mb (Leanza et al. 2003).

Refination of the Andean ammonite-based chronostratigraphy has increased significantly in the last years by the identification of 16 Tithonian ammonite biohorizons (Leanza & Zeiss 1992, Parent et al. 2007, 2011, 2015, 2019a, Zeiss & Leanza 2010; see review in Parent 2022), most of which have been recognized throughout the basin. They consist of a bed or beds containing a fauna of ammonites within which no further stratigraphic differentiation can be discerned (see Gabilly 1971, Callomon 1995, Page 2017, Parent et al. 2015, Parent 2022). These biohorizons are rock-units, biostratigraphic in this case, representing time-planes, instants of time at geological scale. This property makes the biohorizons can be taken as fixed points in time for to translate the biostratigraphic distribution of fossils into a chronostratigraphic scale or classification.

In this paper we first present the updated succession of Andean Tithonian ammonite biohorizons and its record in selected localities of the Neuquén Basin. Taking the biohorizons as representations of time-planes, their succession is then taken as the time-reference grid for modelling the spatial and temporal distribution of the Vaca Muerta Formation with the highest resolution possible in stratigraphy.

Studied sections and procedure

The selected localities for this study meet the conditions that their rock succession and the associated ammonite fauna have been described in detail, on a bed-by-bed basis. These are situated more or less along the 70°W meridian (Fig. 1A):

(1) Picún Leufú (PL). The geology and stratigraphy of the area were described, among others, by Groeber (1952), Leanza (1973), Leanza & Hugo (1997), and more recently by Parent et al. (2011a).

(2) Transect Cerro Lotena-Cerro Granito (CL-CG). The geology and stratigraphy of this area were described by Weaver (1931), Suero (1951), Leanza (1980), and more recently by Parent & Garrido (2021) including new sections between Cerro Granito and Cerro Lotena.

(3) Transect Portada Covunco-Cerrito Caracoles (PC-CC). The first modern studies and descripton of the geology and ammonite fauna in the area were reported by Leanza & Zeiss (1990, 1992), Zeiss & Leanza (2010); later Parent et al. (2013, including the log-section referred below).

(4) Mallín Quemado (MQ). The geology and stratigraphy of the area were described, among others, by Leanza (1973), Garrido & Parent (2017), and Garrido et al. (2018).

(5) Pampa Tril (PT). The geology and stratigraphy of the area were described, among others, by Weaver (1931), Leanza & Hugo (1977), Spalletti et al. (1999) and Parent et al. (2015).

The modelling presented herein was obtained in two steps. We have first classified the studied sections in the different members of the Vaca Muerta Fm, according to lithology exclusively. Then, after lithostratigraphic correlation, according to the ammonites identified and taking the biohorizons as good approximations to time-planes, it was modelled the spatio-temporal distribution of the deposits at the highest level of resolution possible in stratigraphy. The chronostratigraphic framework and the succession of biohorizons are shown in Fig. 1B.

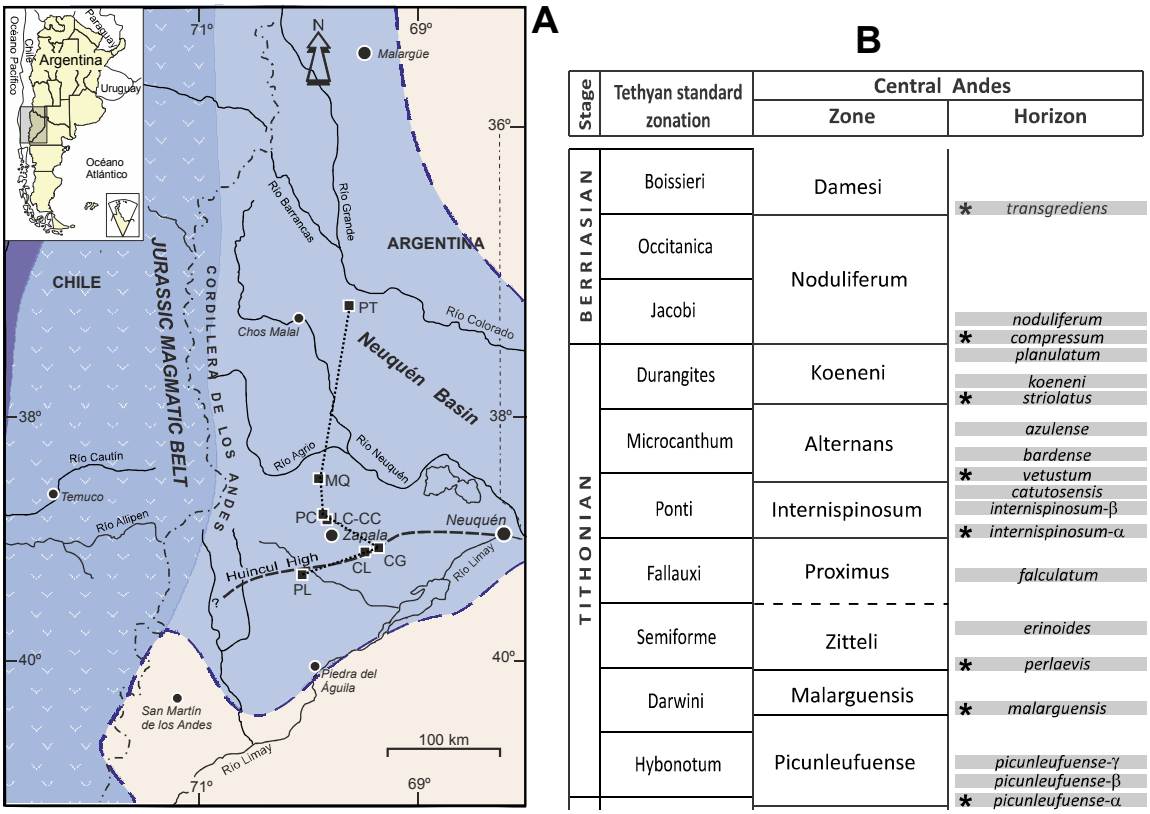

Figure 1. **A**: Localities of the Neuquén Basin studied for this paper. The broken line indicates the transect established. **B**: Succession of biohorizons currently defined for the basin and Andean the ammonite chronostratigraphic zonation time-correlated with the Primary Standard ammonite zonation of the Tethys (after Parent 2022). Asterisks indicating the horizons which are base of the corresponding standard zone.

Updated occurrence of biohorizons

According to the most recent results (see Parent 2022) some biohorizons can now be recognized in localities where they were not formerly. In some cases the recognition of a biohorizon can be not definite if the recorded assemblage is poorly preserved or the material available does not include a significant part of the guide-species. Often, the recognition of two or three of the guide-species represented by the typical morphotype associated in a single bed, may be enough for the recognition of a biohorizon.

The stratigraphic levels are indicated by its number with the code of the locality throughout the text, referred to the published reference log-section.

Picún Leufú. The *picunleufuense-alpha*, *picunleufuense-beta*, and *perlaevis* biohorizons were recorded and discussed in Parent et al. (2011a, 2019a, b). The *malarguensis* Hz., could be represented by the level PL-7f yielding *Choicensisphinctes windhauseni* (Weaver, 1931). Furthermore, recent collections have shown the occurrence of the *erinoides* Hz. represented by the level PL-12 yielding large specimens of *C. erinoides*, and *P. zitteli*. The interval Proximus-Koenini zones is recorded in this locality in the Picún Lufú Fm but the ammonite fauna is scarce and mostly poorly preserved and scattered in isolated horizons.

Cerro Lotena-Cerro Granito. Based on the very abundant and well preserved ammonite fauna collected from these localities (Parent & Garrido 2021), the following biohorizons of the interval Picunleufuense-Internispinosum zones have been recorded with certainty: *picunleufuense-alpha*, *malarguensis*, *perlaevis*, *erinoides*, *internispinosum-alpha*, *internispinosum-beta*, and *catutosensis*. The *picunleufuense-beta*, and *falculatum* biohorizons seem to be represented, but there the fauna remains to be described for definite recognition.

Portada Covunco-Cerrito Caracoles. The ammonite record in these sections is rather mediocre in most levels, especially in the Picún Leufú Formation. The ammonite fauna of the whole Vaca Muerta and Picún Leufú formations was described by Parent et al. (2013), and new material has become available from new collections of the last years. Taking all this in consideration it is possible the refinement of the interpretation of some parts of the ammonite sequence and the recognition of some biohorizons with more or less certainty.

The *picunleufuense-alpha* Hz. is well represented by the level PC-1 yielding the diagnostic transients (morphotypes of the phyletic succession) of the guide-species: *Indansites picunleufuense* transient alpha and *Choicensisphinctes platyconus* transient alpha (Parent, Garrido, Schweigert & Scherzinger, 2011a). The *picunleufuense-beta* Hz. seems to be represented by the level PC-2 yielding *I. picunleufuense* transient beta and *C. platyconus* transient beta.

Catutosphinctes windhauseni (Weaver, 1931) ranges through a short stratigraphic interval around the *malarguensis* Hz. in the localities where it has been recorded (Arroyo Cieneguita, Casa Pincheira, and CL-CG). This suggests the *malarguensis* Hz. is represented by the level PC-19 which yields *Cat.* cf. *windhauseni*, *P. zitteli* and *Sutneria* cf. *parabolistriatum* (Krantz, 1926).

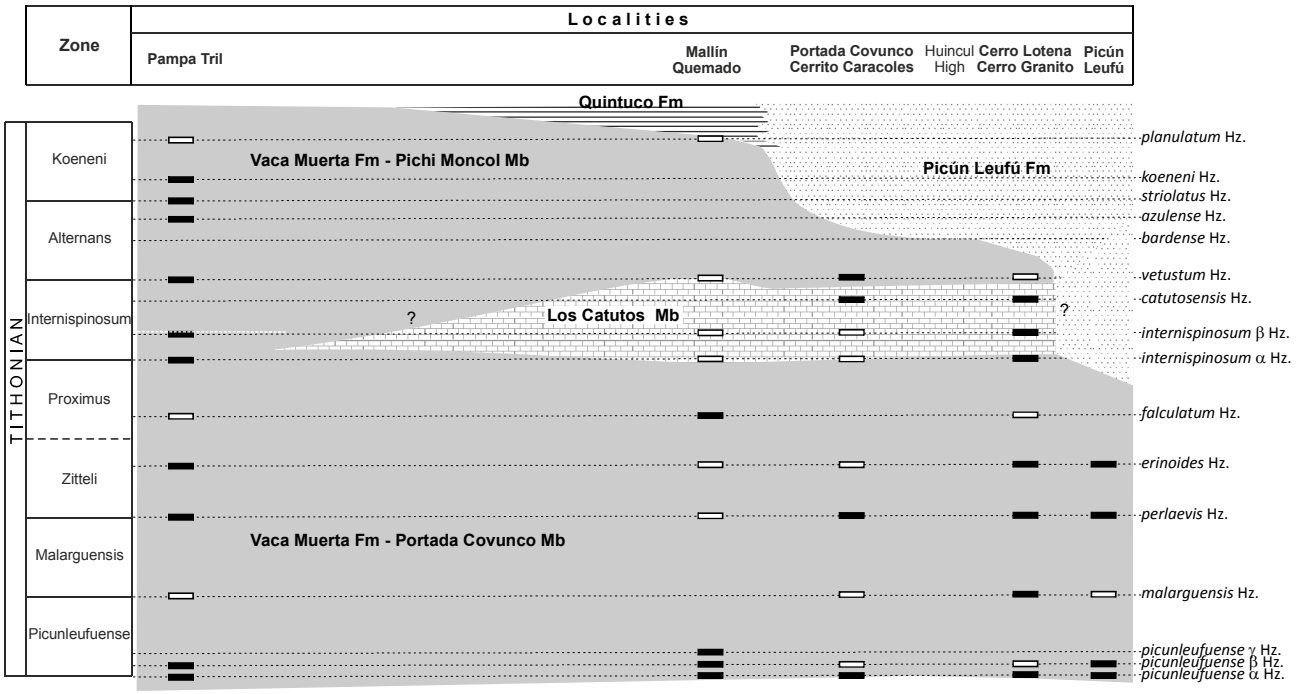

Figure 2. Spatio-temporal model for the distribution of the Tithonian deposits of the Vaca Muerta Fm along the studied transect. The model has been elaborated from described sections sampled bed-by-bed for ammonites and time-planes derived from the ammonite biohorizons recognized locally. The localities are positioned each other at approximate scaled distances. The broken white line in Pampa Tril indicates the boundary between the Portada Covunco and Pichi Moncol members. Lateral changes of the Los Catutos Mb towards Picún Leufú and Pampa Tril are approximate. The black rectangles indicate firm recognition of the biohorizon, the white ones provisional recognition (explained in the text).

The *perlaevis* Hz. is well reperesented by the level PC-27 yielding *Pseudolissoceras zitteli* (Burckhardt, 1903), *Pasottia andina* Parent, Schweigert, Scherzinger & Enay, 2008, and *C. erinoides* (Burckhardt, 1903) transient beta (sensu Parent & Garrido 2021); the index-species although not diagnostic occurs as impressions of microconchs.

The *erinoides* Hz. could likely be represented by the level PC-29 yielding *P. zitteli*, and *C. erinoides* transient gamma (sensu Parent & Garrido 2021), including large, involute suboxyconic macroconchs (= *Craspedites limits* Burckhardt, 1930).

The *internispinosum-alpha* Hz. seems to be represented by the level PC-71-72 yielding *Catutosphinctes rafaeli* Leanza & Zeiss, 1992, and poorly preserved specimens of *Windhauseniceras internispinosum* (Krantz, 1926) comparable with the earliest representatives of the species (e.g. Parent et al 2017: fig. 9B). The *internispinosum-beta* Hz. seems to be represented in the levels PC-78-80 yielding *W. internispinosum* transient beta, *Aspidoceras* cf. *euomphalum* Steuer, 1897 and *Catutosphinctes* cf. *araucanensis* (Leanza, 1980).

The *vetustum* Hz. is represented by the levels PC-140 and CC-33 where occur the following guide-species: *Blanfordiceras vetustum* (Steuer, 1897), *Corongoceras mendozanum* (Behrendsen, 1891), *Chigaroceras*? *gerthi* (Krantz, 1926), and *Steueria alternans* (Gerth, 1921).

Mallín Quemado. The biohorizons recognized in this locality have been discussed in Garrido et al. (2018). The *picunleufuense-gamma* Hz., defined from the section of Estancia María Juana (Parent et al. 2019b), is represented by the level MQ-IV-7.

Pampa Tril. The biohorizons recognized in this locality, as shown in Fig. 2, have been discussed in Parent et al. (2015, 2017).

Spatio-temporal distribution of the deposits of the Vaca Muerta Formation

The results of our study are summarized in Fig. 2. The key points to be discussed are the following.

Portada Covunco Mb. This is evenly represented all throughout the studied region, underlying the Los Catutos Mb from Picún Leufú up to about Puerta Curacó, ranging the chronostratigraphic interval Picunleufuense-Proximus zones, i.e. all the rocks below the *internispinosum-alpha* Hz. (standard base of the Internispinosum Zone). In Picún Leufú the uppermost part of the member belongs to the Proximus Zone, possibly the middle part, suggesting the Picún Leufú Fm ranges there from the upper Proximus Zone. In Pampa Tril the member ranges a little upwards, including the *internispinosum-beta* Hz. (white broken line in Fig. 2), above which the lithology is that characteristic of the Pichi Moncol Mb.

The ammonites from the base of the Portada Covunco Mb are mainly those of the *picunleufuense-alpha* Hz. (Parent et al. 2011a, 2015, 2019b, Vennari 2016, Garrido et al. 2018). However, we have collected ammonites from the few underlying levels in Picún Leufú, Mallín Quemado, and Pampa Tril.

The Los Catutos Mb. This is well represented from Cerro Lotena to Mallín Quemado, wedge-shaped, thinning northwards (cf. Rodriguez Blanco et al. 2020, Leanza 1973), then disappearing close to Pampa Tril where it is already not present (Parent et al. 2015). The base is rather isochronic, slightly older in Mallín Quemado and slightly younger in Los Catutos and a little further in Cerro Lotena. In Mallín Quemado it shows the maximum temporal span, including a level just below the *vetustum* Hz., the base of the Alternans Zone (Garrido et al. 2018). In Cerro Lotena-Cerro

Granito the Los Catutos Mb is well represented through most of the Internispinosum Zone, but not in the uppermost part.

Along the Picún Leufú River the Los Catutos Mb should occur in the northeasternmost outcrops, towards Cerro Lotena (see Rodriguez-Blanco et al. 2020). For instance, in the poor outcrops west of Barda Negra the member seems to be represented by a thin alternance of marls and limestones, probably not more than 3 m in thickness (see Parent et al. 2007). In our section, west of the bridge with the Road 40, above fine calcareous sandstones with *Catutosphinctes proximus* (Steuer, 1897), follow rocks of Internispinosum Zone age belonging to the Picún Leufú Fm. These are fine sandstones with ammonites and ostreids, and calcareous sandstones (cf. Rodriguez Blanco et al. 2020, Leanza 1973) with isolated coquinoid levels yielding bivalves, gastropods, corals, nautiloids, and ammonites (*Toulisphinctes* sp. and *Catutosphinctes* n. sp. B *in* Parent et al. 2013).

The Pichi Moncol Mb. This is almost confined to the north of the Huincul High, with just a small representation in the uppermost Internispinosum Zone and lower Alternans Zone of Cerro Lotena-Cerro Granito. The maximum temporal development is recorded in Pampa Tril, where it ranges from above the *internispinosum-beta* Hz. up to the *transgrediens* Hz. (Damesi Zone) of the Berriasian, and even reaching the Lower Valanginian Riveroi Zone (Parent et al. 2015, 2017).

In the area of Mallín de los Caballos-Mallín Quemado is recorded the lateral passage of the Vaca Muerta Fm into the Picún Leufú Fm during the Late Tithonian (Leanza 1973, Rodriguez-Blanco et al. 2020). The uppermost levels of the Vaca Muerta Fm in Mallín Quemado correspond to the *planulatum* Hz. of the uppermost Koeneni Zone. The Quintuco Fm, deposited during the Berriasian in this area (Garrido & Parent 2017), was described by Leanza (1973) as interdigitations (lenguas distales) of the Picún Leufú Fm into the Vaca Muerta Fm. However, these interdigitations are detritic and carbonatic, but the carbonate is non-primary since it was concentrated by late diagenesis.

Discussion and conclusion

The spatio-temporal distribution of the Vaca Muerta Fm in the Neuquén Basin has been modelled by several authors. The most comprehensive model seems to be that gradually elaborated by Leanza (1973), Leanza et al. (1977), Leanza & Hugo (1977), Leanza et al. (2011) and references therein, clearly summarized by Spalletti et al. (2000: table 1).

Our regional model (Fig. 2), composed from measured sections sampled by ammonites bed-by-bed and structured from the time-planes represented by ammonite biohorizons, is rather similar but some differences must be noted:

(1) We have considered all the members of the formation. Thus, the Portada Covunco Mb is separated from the Pichi Moncol Mb by the Los Catutos Mb from Cerro Lotena-Cerro Granito up to about Puerta Curacó. Northwards, from Puerta Curacó-Pampa Tril where the Los Catutos Mb cease to exist, the lithological change which differentiates the Portada Covunco Mb from the Pichi Moncol Mb occurs just above the *internispinosum-beta* Hz. In Picún Leufú the Portada Covunco Mb is directly overlaid by the Picún Leufú Fm from the upper Proximus Zone.

(2) The age of the base of the Vaca Muerta Fm in Portada Covunco and Cerro Lotena-Cerro Granito is established exactly by the *picunleufuense-alpha* Hz. (the base of the standard Picunleufuense Zone) but in Picún Leufú, Mallín Quemado, and Pampa Tril is older, probably not much but under study.

(3) There are small differences in the ages of the base and top of the Los Catutos Mb through the studied transect. Leanza & Zeiss (1990) indicate the base of this member in the type locality, Los Catutos, is Proximus Zone in age. Nevertheless, our results based on the described fauna indicate its age is slightly younger, as in Cerro Lotena, settled on the *internispinosum-alpha* Hz.

Other comparisons can be made from time-correlation at the level of the biohorizon. For example the extension of facial changes or the synchrony of other lithologic or sedimentologic types or their changes between localitites, regions, or even domains of the basin.

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