

Tithonian stratigraphy and ammonite fauna of the Vaca Muerta Formation in Mallín Quemado (Neuquén Basin, Argentina), with remarks on the Andean chronostratigraphy

Alberto C. GARRIDO¹, Horacio PARENT², Luciano BRAMBILLA³

Key words: ammonites, Tithonian, Mallín Quemado, Vaca Muerta Formation, chronostratigraphy, ammonite bio-horizons, Neuquén Basin.

Abstract. In the Cerro Mallín Quemado area (Sierra de la Vaca Muerta) the three members of the Vaca Muerta Formation (Portada Covunco, Los Catutos and Pichi Moncol) can be recognized, including the whole of the Tithonian rock-record. The ammonite fauna does not show significant differences with respect to that of the nearby locality Pampa Tril, but the record of faunal horizons is patchier. Eighteen species of ammonites were recorded through the studied sections, covering the whole of the Andean Tithonian. The current chronostratigraphic zonation of the Andean Tithonian is briefly discussed, updated and correlated with the most recent literature. From the current succession of ammonite bio-horizons previously defined in the basin, only three (*picunleufuense alpha*, *picunleufuense beta* and *falculatum*) were recognized definitely. Four other bio-horizons (*perlaevis*, *erinoides*, *internispinosum alpha* and *vetustum*) were recognized only tentatively, because the typical assemblages of morphotypes (morpho-species) were not clearly or completely recognized. The current regional time-correlation chart dated by the ammonite bio-horizons of the Neuquén Basin along a 70°W transect is updated with the results of the present study and additional information recently obtained from other localities.

INTRODUCTION

The Neuquén Basin (Fig. 1) developed during Triassic to Paleocene times in southwestern South America. Through most of the Jurassic and Cretaceous a structural high (Huincul High, Fig. 2A) behaved intermittently as a positive topographic relief (subaerial and/or submarine) that divided the basin asymmetrically and strongly influenced the deposi-

tional systems developed on both of its sides (de Ferrariis, 1947; Marchese, 1971; Ploszkiewicks *et al.*, 1984). From the beginning of the Tithonian a sudden and widespread marine transgression was followed by a prolonged cycle of regression and shallowing until the Early Valanginian (Groeber, 1946). The Tithonian-Valanginian outcrops of the Sierra de la Vaca Muerta (Fig. 2) are extensive but rather scattered and affected by tectonics and modern physiographic pro-

¹ Museo Provincial de Ciencias Naturales “Prof. Dr. J.A. Olsacher”, Dirección Provincial de Minería, Etcheluz y Ejército Argentino, 8340 Zapala, Neuquén, Argentina;
Departamento Geología y Petróleo, Facultad de Ingeniería, Universidad Nacional del Comahue, Buenos Aires 1400, 8300 Neuquén, Argentina;
albertocarlogarrido@gmail.com.

² Laboratorio de Paleontología, Instituto de Fisiografía y Geología, Facultad de Ingeniería, Universidad Nacional de Rosario, Pellegrini 250, 2000 Rosario, Argentina; parent@fceia.unr.edu.ar.

³ Facultad de Ciencias Exactas, Ingeniería y Agrimensura, Universidad Nacional de Rosario, Pellegrini 250, S2000BTP Rosario, Argentina;
lbrambilla@fbioyf.unr.edu.ar.



Fig. 1. Geographical map showing the Neuquén (or Neuquén-Mendoza) Basin (grey), with the study area Mallín Quemado (MQ) and other localities mentioned through the text. Modified from Parent *et al.* (2011a)

Locality names: PLB – Paso Los Bayos; ACP – Arroyo Cruz Piedra; RD: Río Diamante; AM – Arroyo de la Manga; CB – Cajón del Burro-Río Choicas; AP – Arroyo Paraguay; AA – Arroyo Alberjillo; BDF – Baños del Flaco; AC – Arroyo Cieneguita; RV – Rodeo Viejo; AD – Arroyo del Durazno; AL – Arroyo Loncoche; PM – Paso Montañés; CP – Casa Pincheira; MC – Molinos Colgados; BB – Bardas Blancas; AY – Arroyo del Yeso; MR – Mallín Redondo; PT – Pampa Tril; CM – Chacay Melehué; CDA – Cajón de Almanza; PQ – Puerta Quintuco; CA – Cañadón de los Alazanes; PC – Puerta Covunco; LC – Los Catutos; CG – Cerro Granito (La Amarga); CL – Cerro Lotena; PL – Puente Picún Leufú; CH – Charahuilla. Thick solid line – transect of localities considered in Fig. 17

cesses which usually mean that large parts of the successions in different localities are covered or not accessible. The geology and stratigraphy of the Sierra de la Vaca Muerta, including the Cerro Mallín Quemado and its environs (Fig. 2B), of interest here, have been studied by several authors, *e.g.* Burckhardt (1900b), Weaver (1931), Groeber (1952), Lambert (1956), Leanza (1973, 1975), Leanza, Hugo (1977, 2001), Spalletti *et al.* (2015), Olivo *et al.* (2016), Garrido and Parent (2017).

The Tithonian ammonite fauna of the Mallín Quemado area was previously poorly known. The type specimens of *Himalayites andinus* Leanza, 1975 came from a section about 3 km northwest of Cerro Mallín Quemado. Numerous stratigraphic studies have been published with the citation of many ammonite species (Weaver, 1931; Lambert, 1956; Leanza, 1973, 1975; Leanza, Hugo, 1977) but with no figures other than that of Leanza (1975), thus hampering comparisons other than nominally. This situation called for a detailed study of the succession of this important area which is intermediate between the already described successions of Portada Covunco (Leanza, Zeiss, 1990; Parent *et al.*, 2013), close to the Huincul High, and Pampa Tril (Spalletti *et al.*, 1999; Parent *et al.*, 2015) in the north (Fig. 1). The successions of these three localities provide a detailed coverage of the Vaca Muerta Formation through the eastern border of the basin north of the Huincul High. The stratigraphic knowledge of the successions of this transect will allow facies studies with high chronostratigraphic resolution, uniquely provided by the sequences of ammonite bio-horizons.

Following our programme of study of the ammonid fauna and stratigraphy of the Vaca Muerta Fm. throughout the Neuquén Basin, we have made a complete stratigraphic and palaeontological survey in the northwestern part of the Sierra de la Vaca Muerta. The purpose of this paper is to report the results of the study of the stratigraphy and the ammonoid fauna of the Vaca Muerta Fm. in the Mallín Quemado area (Fig. 2). This report is associated with a previous one (Garrido, Parent, 2017) dealing with the upper part of the local succession, including a revision of the Quintuco Fm. and its Berriasian ammonite fauna.

The following stratigraphic terminology is adopted herein: (a) biozone as a body of rock characterized by its fossil content, (b) chronostratigraphic zone as a sheet of rock (one or more strata) bounded by two time-planes, and (c) standard chronostratigraphic zone as a chronostratigraphic zone defined only by a time-plane marked by a faunal horizon at its base, belonging to a succession of standard zones without gaps or overlaps. These definitions and the corresponding nomenclature of the units are widely discussed by Callomon (1995, 2001). Abbreviations are used for Chronostratigraphic Zone, or Zone for short (Z.) and ammonite horizon or bio-horizon (Hz.).

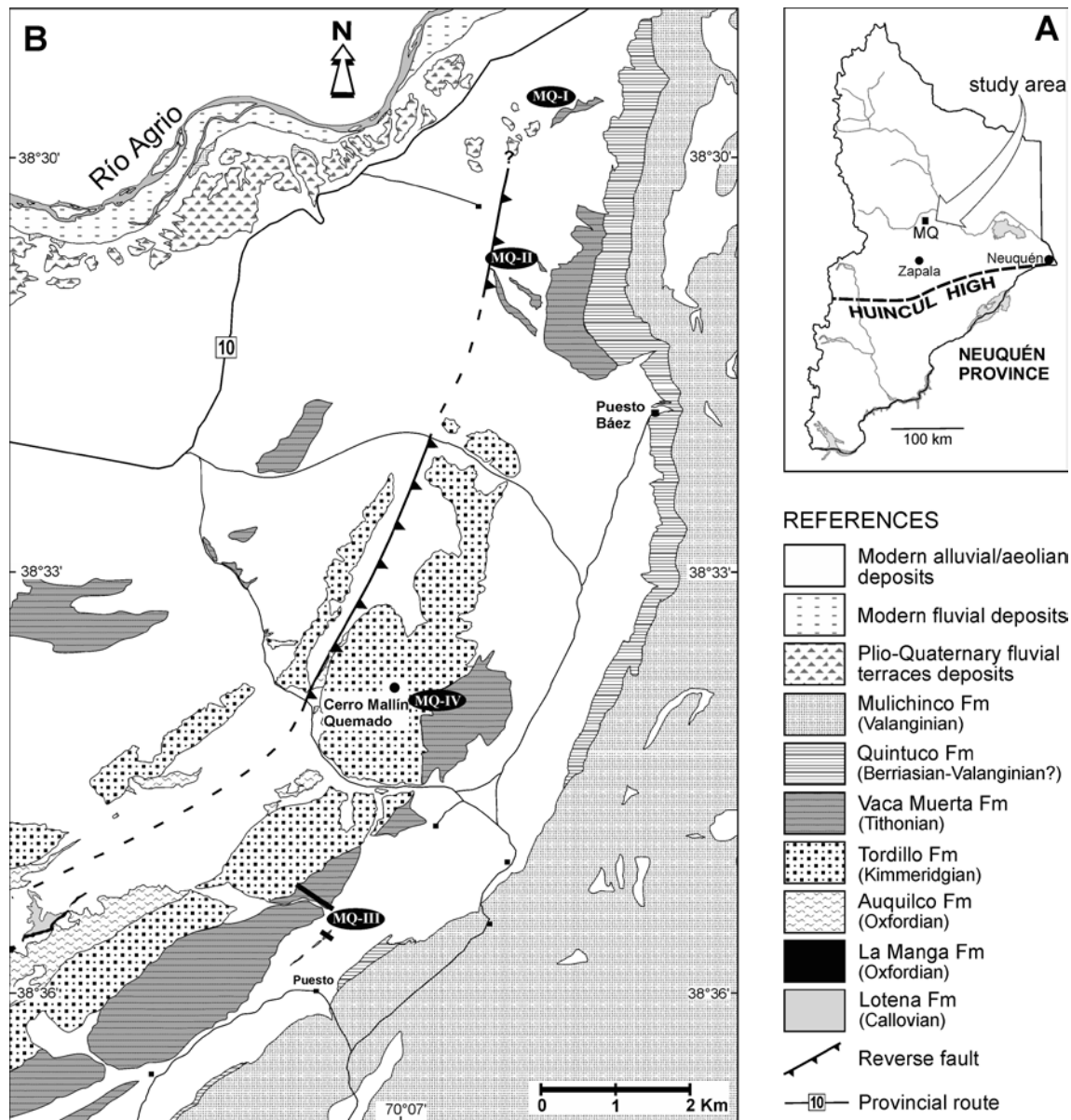


Fig. 2. A. Regional position of the study area, north of the Huincul High in the Neuquén Province; B. Geologic map of the study area Mallín Quemado (adapted from Garrido, Parent, 2017), indicating the position of the studied sections labelled as MQ-I – MQ-IV

GEOLOGIC SETTING OF THE STUDY AREA

The Sierra de la Vaca Muerta (SVM) is a north-south elongate range with low-relief, bounded by the Agrío River and the Covunco creek in their northern and southern extremes respectively. It extends between $38^{\circ}20'25''$ – $38^{\circ}47'40''$ south latitude and $69^{\circ}52'13''$ – $70^{\circ}18'03''$ west longitude (considering its major axes), covering about 900 km^2 . The SVM belongs to a pre-Andean deformation belt, inte-

grating the thrust front of the Agrío fold-and-thrust belt. Extensive outcrops of Jurassic and Cretaceous (Aalenian to Albian) deposits are exposed there, showing gradually younger sedimentary successions towards the north and east (Lambert, 1956; Leanza, Hugo, 2001). Palaeogeographically the SVM has a position close to the depocentre area of the basin.

Our study area is located at the northwestern end of the SVM, where Callovian to Valanginian deposits are exposed

(Fig. 2). The western structure of the SVM has been described as a large-scale, asymmetrical to overturned anticline plunging towards the north, eroded along its hinge zone (Lambert, 1956). Garrido and Parent (2017: fig. 1B) have recently described a low-angle reverse fault (back-thrust) that runs along the axis of this mega-structure, allowing the interpretation of it as a fault-propagation fold (partially shown in Fig. 2B).

STRATIGRAPHY AND SEDIMENTOLOGY

While the Sierra de la Vaca Muerta-Cerro Mallín Quemado area offers extensive outcrops of the Vaca Muerta Fm., these are mostly covered by Quaternary aeolian and alluvial deposits. This condition is generated by the easy erodability of the pelitic sediments of the Vaca Muerta Fm. compared to the wacky and sandy deposits of the under and overlying units (Tordillo and Quintuco-Mulichinco formations, respectively) (Fig. 2B). In this way the differential erosive processes generate large depressed areas along the deposits of the Vaca Muerta Fm. as reception areas for modern sediments. Thus, it is not possible to obtain a complete profile of this stratigraphic unit in this sector, leaving a large part of the middle section of the succession completely covered.

Through the nearly 16 km-long belt of outcrops of the Vaca Muerta Fm. with the Cerro Mallín Quemado in its middle part (Fig. 2B), called herein the Mallín Quemado area, four transects were surveyed for the present study (denoted as MQ-I to MQ-IV, see Fig. 2B). Only the successions exposed along the transects MQ-III and MQ-IV have yielded ammonites *in-situ*. The succession of the transect MQ-III (Fig. 3) is the more complete and has yielded the best preserved and more abundant ammonites, and is thus taken as the main section to which the information and discussion are referred to. The transect MQ-IV (Fig. 3) is also important, despite being hard to reach and exhibiting only the lowermost part of the Vaca Muerta Fm. resting on the Tordillo Fm., whereas upwards it is completely covered by modern sediments. This lowermost part of the Vaca Muerta Fm. belongs entirely to the Picunleufuense Zone. This short interval is very interesting in MQ-IV for it can be subdivided in at least 13 levels (levels MQ-IV-1-13) where well preserved adult macroconchs of *Indansites picunleufuense* and *Choiensisphinctes platyconus* can be collected in abundance – the limit is the time available to the collector.

The Vaca Muerta Fm. in transect MQ-III, although not observed up to its uppermost part (locally assigned to the Koeneni Z.) shows the three characteristic lithostratigraphic subdivisions, from below: the Portada Covunco, Los Catutos and Pichi Moncol (*pars*) members (Parent *et al.*, 2013). The stratigraphy and the scarce Berriasian ammonite fauna

of the Quintuco Fm. have already been described by Garrido, Parent (2017) from a section at Puesto Baez (Fig. 2B).

With respect to the sedimentological attributes of the Vaca Muerta Fm. in transect MQ-III, the deposits of the Portada Covunco Mb. show a monotonous succession of black shales and sandy shales, rich in organic matter with thin intercalations of calcareous lutite, laminated calcareous sandstones and wacky sandstones. This lithological association is a frequent feature of the lower deposits of the Vaca Muerta Fm., as can be seen in other sectors of the southern region of the basin (Parent *et al.*, 2011a, 2013). In the basal deposits exposed in transect MQ-IV, thick beds of laminated, fine-grained calcareous sandstones predominate (Fig. 3). Upwards in the succession of transect MQ-III carbonate facies dominate, consisting of marls and marly limestones with intercalations of black shales (Los Catutos Mb.), then culminating with a partial exposure of the Pichi Moncol Mb. represented by a domain of sandy shales showing variable contents of organic matter.

In general terms, these sediments were deposited in an offshore marine environment under restricted, low-oxygen conditions (Leanza *et al.*, 2011). The occurrence of sporadic storm events are recorded as thin, fine to medium-grained sandy levels characterized by the presence of tractive structures and isolated invertebrates (mainly bivalves) strongly reworked.

Leanza (1973) indicates a total thickness for the Vaca Muerta Fm. of 1150 m in the Cerro Mallín Quemado area. However, our measurements made in transect MQ-III indicate for this same unit an exposed thickness of 294 m, estimating a total thickness in the order of 550 m. Such differences are determined by the criteria used to define the upper limit of the unit (see Garrido, Parent, 2017: fig. 3).

THE AMMONITE FAUNA

The Tithonian ammonite succession in Mallín Quemado is rather poor in diversity and abundance (*cf.* Leanza, 1973, 1975). This is especially the case when it is compared with other localities where the ammonite faunas have been described from somewhat comparable palaeogeographical positions within the basin, *e.g.* Pampa Tril (Parent *et al.*, 2015), and also in northern positions like the Sierra Azul, Mendoza Province (Leanza, 1945) or Arroyo Cieneguita (Steuer, 1897; Parent *et al.*, 2011b). The majority of the species identified from our samples have already been described in the other papers cited above, so that it does not seem necessary to describe all of them in detail again. However, some of the species are represented by well preserved specimens or their local morphotypes show differences in adult size, morphology and/or stratigraphic position which means that they are

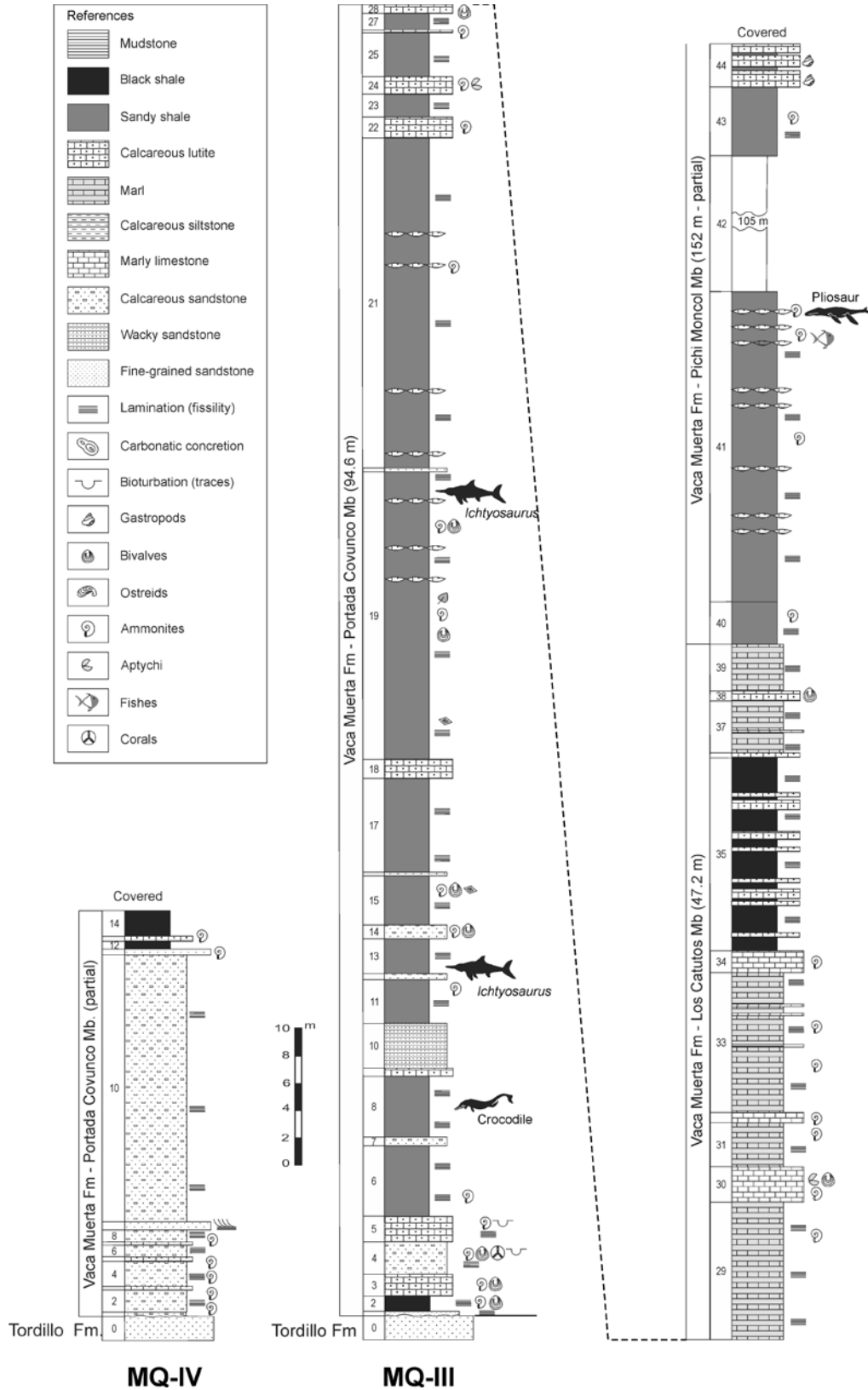


Fig. 3. Stratigraphic columns of the transects MQ-III and MQ-IV of the Mallín Quemado area indicated in the Figure 2

worth figuring and discussing briefly. All the specimens are in the collection of the Museo Provincial de Ciencias Naturales Prof. Olsacher, Zapala, Neuquén (MOZ-PI). The com-

plete list of species recorded in the studied sections, their systematic arrangement and their zonal chronostratigraphic range are given in Table 1.

Table 1
Systematic list of the ammonites recorded in the studied sections with indication of the local and regional zonal chronostratigraphic range

	Zonal chronostratigraphic range	
	Mallín Quemado area	Maximum in the Neuquén Basin
Superfamily Perisphinctoidea Steinmann, 1890		
Family Ataxioceratidae Buckman, 1921		
Subfamily Zapaliinae Parent <i>et al.</i>, 2017		
Genus <i>Indansites</i> Vennari, 2016		
<i>Indansites picunleufuense</i> Parent <i>et al.</i> , 2011	Picunleufuense	Picunleufuense
Genus <i>Choicensisphinctes</i> Leanza, 1980		
<i>Choicensisphinctes platyconus</i> Parent <i>et al.</i> , 2011	Picunleufuense	Picunleufuense
<i>Choicensisphinctes</i> cf. <i>burckhardti</i> (Douvillé, 1910)	Zitteli [incl. Mendozanus]	Picunleufuense? - Zitteli [incl. Mendoz.]
<i>Choicensisphinctes</i> cf. <i>erinoides</i> (Burckhardt, 1903)	Zitteli [incl. Mendozanus]	Zitteli [incl. Mendozanus]
Subfamily Torquatisphinctinae Tavera, 1985		
Genus <i>Catutosphinctes</i> Leanza & Zeiss, 1992		
<i>Catutosph.</i> n. sp. aff. <i>guenenakenensis</i> Parent <i>et al.</i> , 2011	Zitteli [incl. Mendozanus]	Zitteli [incl. Mendozanus]
<i>Catutosphinctes</i> sp. A	Zitteli [incl. Mendozanus]	not recorded
<i>Catutosphinctes</i> cf. <i>proximus</i> (Steuer, 1897)	Proximus	Proximus - Internispinosum
<i>Catutosphinctes rafaeli</i> Leanza & Zeiss, 1992	Internispinosum	Internispinosum
Genus <i>Mazatepites</i> Cantú-Chapa, 1967		
<i>Mazatepites arredondense</i> Cantú-Chapa, 1967	Proximus	Proximus - ?Internispinosum
Family Neocomitidae Salfeld, 1921		
Subfamily Berriasellinae Spath, 1922		
Genus <i>Blanfordiceras</i> Cossmann, 1907		
<i>Blanfordiceras</i> cf. <i>wallichi</i> (Gray, 1832)	Alternans	Alternans
Family Himalayitidae Spath, 1925		
Genus <i>Windhausenicerias</i> Leanza, 1945		
<i>Windhausenicerias internispinosum</i> (Krantz, 1926)	Internispinosum	Internispinosum
Genus <i>Corongoceras</i> Spath, 1925		
<i>Corongoceras</i> cf. <i>mendozanum</i> (Behrendsen, 1891)	Alternans	Alternans
Genus <i>Himalayites</i> Uhlig in Boehm, 1904		
<i>Himalayites</i> cf. <i>andinus</i> (Leanza, 1975)	Koeneni	Koeneni
Family Aspidoceratidae Zittel, 1895		
Subfamily Aspidoceratinae Zittel, 1895		
Genus <i>Aspidoceras</i> Zittel, 1868		
<i>Aspidoceras euomphalum</i> Steuer, 1897	Proximus - Internispinosum	Proximus - Internispinosum
Genus <i>Physodoceras</i> Hyatt, 1900		
<i>Physodoceras</i> sp. A (in Parent <i>et al.</i> , 2015)	Zitteli [incl. Mendozanus]	Zitteli [incl. Mendozanus] – Proximus
Genus <i>Pseudhimalayites</i> Spath, 1925		
<i>Pseudhimalayites subpretiosus</i> (Uhlig, 1878)	Proximus	Proximus - Internispinosum
Superfamily Haploceratoidea Zittel, 1884		
Family Lissoceratidae Douvillé, 1885		
Genus <i>Pseudolissoceras</i> Spath, 1925		
<i>Pseudolissoceras zitteli</i> (Burckhardt, 1903)	Zitteli [incl. Mendozanus]	Zitteli [incl. Mendozanus] -?lower Proximus
Family Oppeliidae Douvillé, 1890		
Subfamily Taramelliceratinae Spath, 1928		
Genus <i>Cieneguiticeras</i> Parent <i>et al.</i>, 2010		
<i>Cieneguiticeras perlaevis</i> (Steuer, 1897)	Zitteli [incl. Mendozanus]	Picunleufuense - Zitteli [incl. Mendozanus]

***Indansites picunleufuense* (Parent, Garrido, Schweigert, Scherzinger, 2011); Figs. 4–10A, B.** The genus *Indansites* Vennari, 2016 belongs to the subfamily Zapaliinae Parent, Schweigert, Scherzinger and Garrido, 2017. As in virtually the whole basin *I. picunleufuense* occurs from the basal beds of the Vaca Muerta Fm., and its earliest occurrences are in the form of at least two transients, named alpha and beta in Parent *et al.* (2011a). The transients are morphotypes in close succession interpreted as transitions in the phyletic evolution of the lineage; these transients usually differ in their mean morphology and/or sculpture and may also differ in adult size. The adult macroconchs of the transient beta differ from those of the transient alpha by their more densely and finely ribbed phragmocone and by having a short stage of widely spaced strengthened primary ribs not observed in transient alpha.

The lowermost record of the species in transect MQ-IV is the impression of an adult macroconch from level MQ-IV-1. This specimen (Fig. 4, plaster cast) has its adult rib-

bing somewhat different from that of the typical representatives of the transient alpha, having widely spaced primaries with several intercalatory ribs.

Well preserved adult macroconchs of transient beta from levels MQ-IV-5-7 are shown in Figs. 5-8. These specimens are identical to the most densely ribbed representatives of this transient in Picún Leufú (Parent *et al.*, 2011a: fig. 10), Pampa Tril (Parent *et al.*, 2015: fig. 11) and Casa Pincheira (Parent, 2003: fig. 6A), all from the *picunleufuense* beta Hz. of the Picunleufuense Zone.

In levels MQ-IV-11-13 (Fig. 9, 10A, B) the species is represented by specimens more or less similar to those of transient beta, but with delayed variocostation (Fig. 9) or with the bodychamber more strongly ribbed by primaries acutely raised on the lower flank, and irregularly bi- or trifurcated in bold secondaries (Fig. 10A). The significance of these differences cannot be assessed from the scarce material presently available. The specimen in Fig. 9 is similar to the holotype of *Indansites malarguensis* (Spath, 1931) and



Fig. 4. *Indansites picunleufuense* (Parent, Garrido, Schweigert, Scherzinger, 2011) transient beta?, plaster cast from the impression of an almost complete adult macroconch (MOZ-PI-5989/1), level MQ-IV-1, Picunleufuense Zone. Natural size ($\times 1$)



Fig. 5. *Indansites picunleufuense* (Parent, Garrido, Schweigert, Scherzinger, 2011) transient beta, almost complete adult macroconch (MOZ-PI-5989/1), level MQ-IV-5, *picunleufuense* beta Hz., Picunleufuense Zone. Natural size ($\times 1$), asterisk at last septum

its stratigraphic position seems comparable. The holotype of *I. malarguensis* consists of an apparently adult macroconch phragmocone, lacking at least the whole bodychamber (see Burckhardt, 1900a: pl. 24: 4 photograph of lateral view; Burckhardt, 1903: pl. 4: 2 drawing of the apertural view;

both refigured in Parent *et al.*, 2017a: fig. 2D). It differs from *I. picunleufuense* transient beta by its larger adult phragmocone, denser ribbing, and more frequent and marked constrictions.



Fig. 6. *Indansites picunleufuense* (Parent, Garrido, Schweigert, Scherzinger, 2011) transient beta, complete adult macroconch (MOZ-PI-5989/2), level MQ-IV-5, *picunleufuense* beta Hz., Picunleufuense Zone. Natural size ($\times 1$), asterisk at last septum

Choicensisphinctes platyconus Parent, Garrido, Schweigert & Scherzinger, 2011; Figs. 10C, 11. This species occurs in abundance in the interval levels MQ-III-1-6, the macroconch specimens representing the range of variation of the type series in the Picunleufuense Zone of Picún Leufú.

In level MQ-IV-5 there occur macroconchs which are closely similar to the representatives of the *picunleufuense* beta Hz. in Picún Leufú and Pampa Tril; others are identical to the variants from Arroyo Cieneguita described as *C. cf./aff. platyconus* in Parent *et al.* (2011b: fig. 6D, E), small adult macroconchs (females), platyconic, and rather invo-



Fig. 7. *Indansites picunleufuense* (Parent, Garrido, Schweigert, Scherzinger, 2011) transient beta, virtually complete adult macroconch (MOZ-PI-5990/3), level MQ-IV-7, *picunleufuense* beta Hz., Picunleufuense Zone. Natural size ($\times 1$), asterisk at last septum

lute. The last whorl of the phragmocone and the bodychamber have more or less strong primaries which divide into many finer secondaries in palmate style (cf. Fig. 11). The primaries give rise to several finer secondaries which tend to

fade-off towards the peristome. In the adult phragmocone and beginning of the bodychamber the ribbing is mostly fascipartite or palmate, with abundant polyschizotomic divisions (Fig. 11).

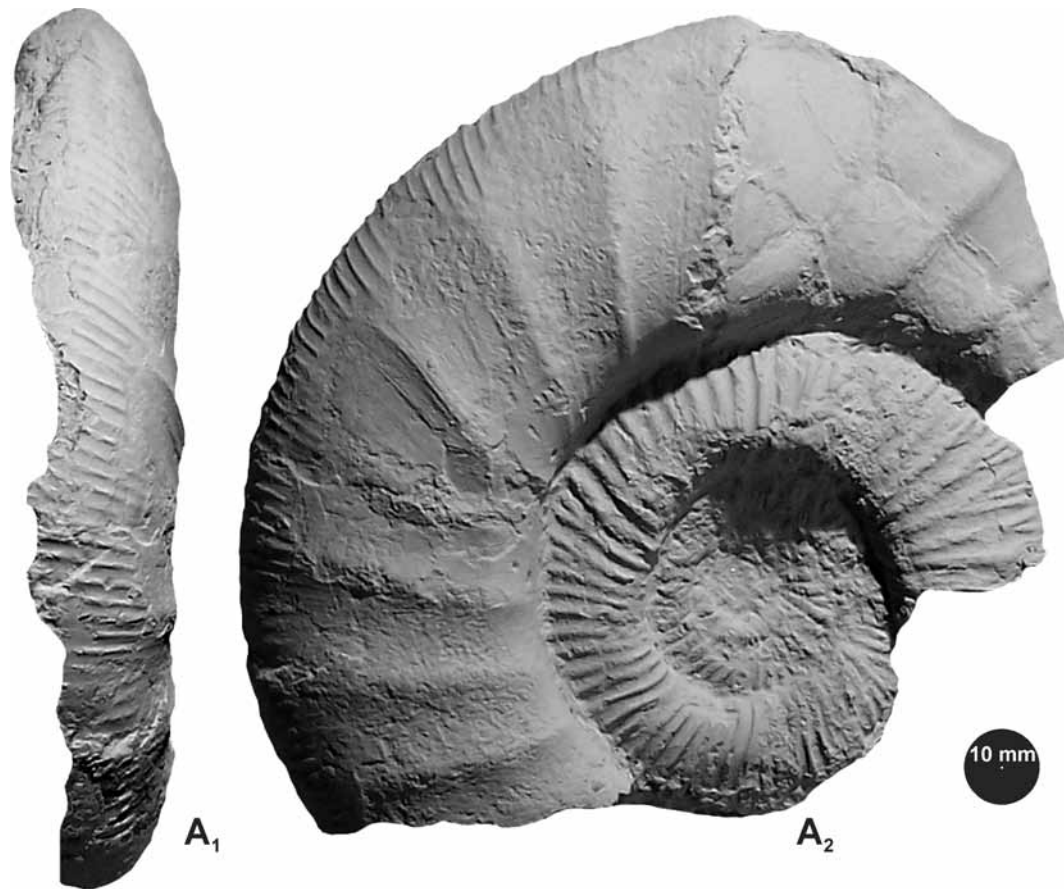


Fig. 8. *Indansites picunleufuense* (Parent, Garrido, Schweigert, Scherzinger, 2011) transient beta, adult macroconch (MOZ-PI-5990/2), last whorl is bodychamber, level MQ-IV-7, *picunleufuense* beta Hz., Picunleufuense Zone. Natural size ($\times 1$)

We take the opportunity to illustrate in Fig. 10B, C two macroconch phragmocones which show the respective diagnostic ribbing which differentiates the subadult-phragmocone stages of *Indansites* and *Choicensisphinctes* of the Picunleufuense Zone. These specimens, of similar size, represent the inner and middle whorls of adult macroconch phragmocones from the Picunleufuense Zone (level MQ-IV-12):

1. In *Indansites picunleufuense* (Fig. 10B) the whorls are compressed subrectangular, with a wide umbilicus. The ribbing consists of primaries evenly spaced, bifurcating on the upper half of the flank; the secondaries are slightly twisted backwards; there is rare trifurcation followed by an undivided primary.
2. *Choicensisphinctes platyconus* (Fig. 10C) is more narrowly umbilicate; the ribbing consists of densely spaced primaries, bifurcating on the upper half of the flank into finer secondaries forming a narrow angle; and there are frequent well marked, narrow, prosocline constrictions.

Catutosphinctes n. sp. aff. *guenenakenensis* Parent, Garrido, Schweigert & Scherzinger, 2011. Included here are several incomplete specimens comparable to the material figured in Parent *et al.* (2015: fig. 38B–E) from the Zitteli [incl. Mendozanus] Zone of Pampa Tril. This species is very similar to *C. guenenakenensis* from the Picunleufuense Z. of Picún Leufú, but it is more evolute and has more strongly constricted inner whorls. These moderate differences become significant considering their different stratigraphic positions, as *C. n. sp. aff. guenenakenensis* occurs well above the Picunleufuense Zone.

Catutosphinctes rafaeli Leanza & Zeiss, 1992; Fig. 12A. *C. rafaeli* is the type species of *Catutosphinctes* Leanza & Zeiss, 1992. Its holotype is a crushed and incomplete specimen apparently with the beginning of the adult? body-chamber, thus hard to compare as the maximum size and ribbing of its outer whorl are not preserved (Leanza, Zeiss, 1992: fig. 3). The stratigraphic position of the species in its type locality (El Ministerio, Los Catutos, Fig. 1) is in the



Fig. 9. *Indansites picunleufuense* (Parent, Garrido, Schweigert, Scherzinger, 2011), adult macroconch (MOZ-PI-5991) with beginning of bodychamber, level MQ-IV-11, Picunleufuense Zone. Natural size ($\times 1$), asterisk at last septum

lower part of the Internispinosum Zone (Leanza, Zeiss, 1992), and this is the case with our material.

The present specimen is a macroconch from level MQ-III-32, closely comparable with the holotype in terms of size and ribbing ontogeny. In the inner whorls the ribs are acute, bifurcating on the upper third of the flank with rare trifurcation, all secondaries crossing the venter unchanged. The ribbing of the bodychamber is more irregular with a few ribs

trifurcated from the mid-flank. The terminal portion of the bodychamber is not preserved.

Microconch specimens from other localities (Fig. 12B–D) are discussed below in terms of their biostratigraphic significance.

Mazatepites arredondense Cantú-Chapa, 1967. A single specimen from level MQ-III-21, an adult phragmocone

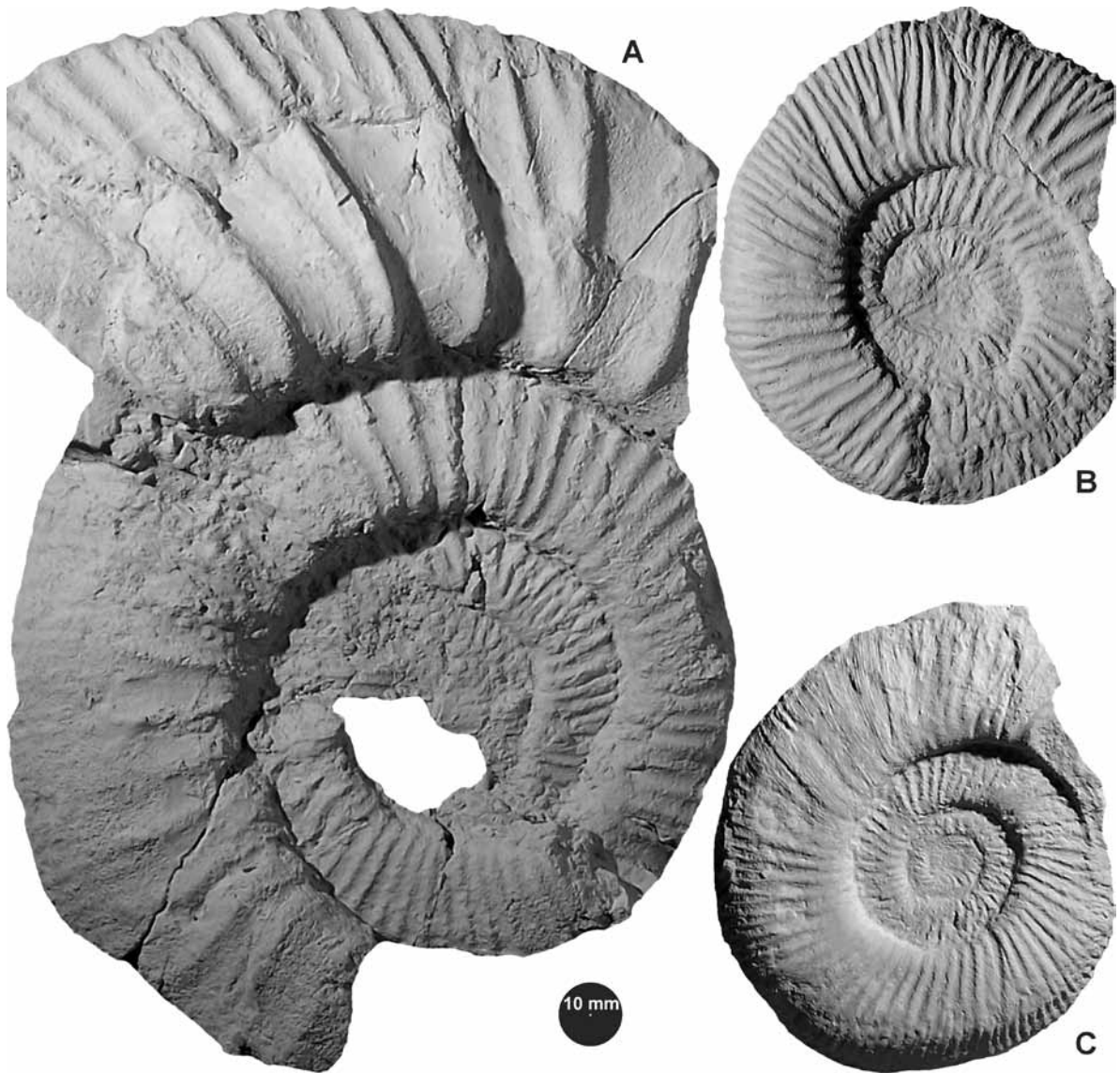


Fig. 10. A, B. *Indansites picunleufuense* (Parent, Garrido, Schweigert, Scherzinger, 2011), Picunleufuense Zone; **A.** Adult macroconch phragmocone with terminal portion of the bodychamber (MOZ-PI-6001/2), level MQ-IV-13; **B.** Phragmocone (MOZ-PI-6001/1), level MQ-IV-12; **C.** *Choicensiphinctes platyconus* Parent *et al.*, 2011b; phragmocone (MOZ-PI-5992/6), level MQ-IV-12, Picunleufuense Zone. All natural size ($\times 1$), asterisk at last septum

with the beginning of the bodychamber, possibly a macroconch. It is identical to the specimens from the *falculatum* Hz., Proximus Zone of Arroyo Cieneguita (Parent *et al.*, 2011b: fig. 22A, B).

***Blanfordiceras cf. wallichi* (Gray, 1832).** A single specimen closely comparable with that figured in Parent *et al.*

(2013: fig. 20D) from the level PC-154, upper Alternans Z. of Portada Covunco.

***Windhausenicerias internispinosum* (Krantz, 1926); Fig. 13A.** The figured specimen from level MQ-III-30 represents the lowermost occurrence of the species in the studied section. It shows tubercles on the uppermost flank con-

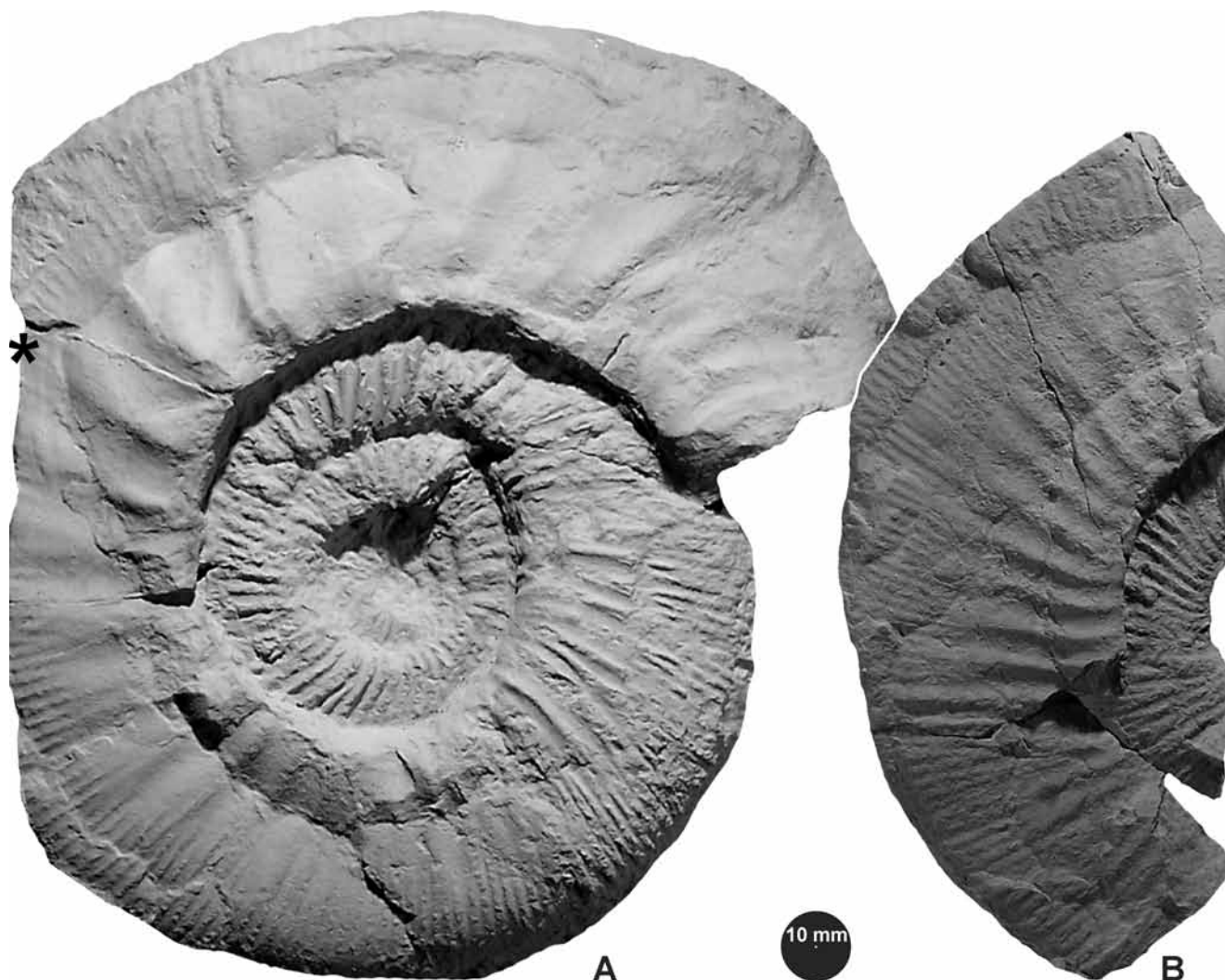


Fig. 11. *Choicensisphinctes platyconus* Parent, Garrido, Schweigert, Scherzinger, 2011; **A.** Almost complete adult macroconch (MOZ-PI-5989/3), level MQ-IV-5, *picunleufuense* beta Hz., Picunleufuense Zone; **B.** Portion of an adult macroconch phragmocone (MOZ-PI-5990/4), level MQ-IV-7, *picunleufuense* beta Hz., Picunleufuense Zone. All natural size ($\times 1$), asterisk at last septum

finned to the inner whorls (up to a size of about 25 mm shell diameter), suggesting it is a representative of the older of the transients distinguished within the species, transient alpha (see Parent *et al.*, 2015). Later representatives bear tubercles which extend up to the middle whorls (at a size about 60–70 mm shell diameter) following an evolutionary trend to develop tubercles towards the subadult whorls, and the macroconchs reaching larger adult sizes (see Parent *et al.*, 2007, 2015, 2017b). In this sense, adult macroconchs from level MQ-III-34 have a maximum observed diameter of the phragmocone not less than 400 mm, but the middle and inner whorls could not be observed. From level MQ-III-39 (top of the Internispinosum Zone) there was collected an incomplete microconch with tubercles up to the beginning of

the bodychamber, matching the specimen in Parent *et al.* (2007: fig. 9A).

***Corongoceras* cf. *mendozanum* (Behrendsen, 1891); Fig. 13B–D.** The phragmocone of the present specimens from level MQ-III-41 is identical to those of the specimens from the lower Alternans Zone of Arroyo Cieneguita (Parent *et al.*, 2011b) and Pampa Tril (Parent *et al.*, 2015). However, one of the present specimens is an adult macroconch (Fig. 13D) whose bodychamber differs by being finely and densely ribbed by wiry primaries with few bifurcating. The last whorl of the phragmocone is compressed (width-to-height ratio 0.54 at 98 mm in diameter, with an umbilical width-to-diameter ratio of 0.41, and 14 primary ribs per half

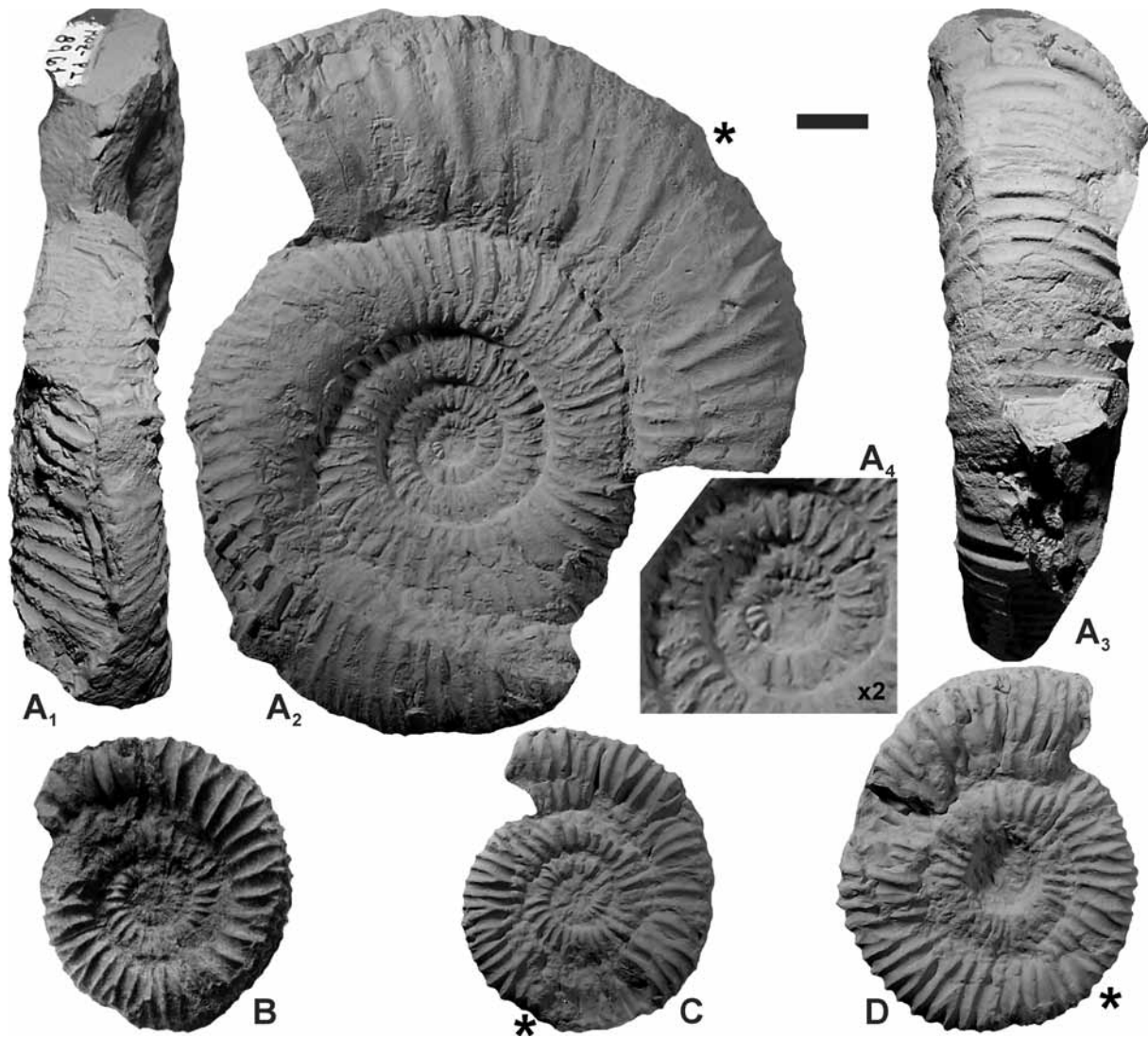


Fig. 12. **A.** *Catutosphinctes rafaeli* Leanza and Zeiss, 1992. Adult macroconch with incomplete bodychamber (MOZ-PI-8961), level MQ-III-32, Internispinosum Zone. **A₄**: inner whorls (×2); **B.** Lectotype of *Perisphinctes colubrinoides* Burckhardt, 1903; modified from Burckhardt (1900a: pl. 26: 4), an almost complete adult microconch from Cajón del Burro-Río Choicas; **C, D.** *Catutosphinctes rafaeli* Leanza and Zeiss, 1992; complete adult microconchs refigured from Parent and Cocca (2007: fig. 3A, B) after additional preparation; Internispinosum Zone of Portada Covunco.

All natural size (x1) except **A₄** (×2). Scale: 10 mm for **A₁–A₃**, 5 mm for **A₄**

whorl). The significance of the different ribbing on the adult bodychamber cannot be evaluated as only scarce material is available coming from a single stratigraphic horizon. A fragmentary but apparently comparable specimen has been reported from the lower part of the Internispinosum Zone in Pampa Tril (Parent *et al.*, 2015: fig. 77A).

In levels MQ-III-35-37 there occurs a very similar ammonite which differs in having fine and acute ribbing on the inner whorls, which then becomes stronger and uni- or bituberculate on the outer whorls (bodychamber?). Practically identical specimens occur in the lower Internispinosum Zone of Cerro Lotena.

Aspidoceras euomphalum Steuer, 1897. This species is typically abundant in the Internispinosum Zone throughout the Neuquén Basin, associated with *W. internispinosum* (see Leanza 1980, Parent *et al.*, 2007, 2011b), *Catutosphinctes araucanus* (Leanza, 1980), and *C. rafaeli*. In the interval of levels MQ-III-29-31 occur specimens matching the lectotype (Steuer, 1897: pl. 5: 1, 2, refigured in Parent *et al.*, 2007: fig. 8). These levels correspond to beds of the Los Catutos Mb. which are mostly Internispinosum Zone in age all throughout the Neuquén Basin (Leanza, Zeiss, 1990, 1992; Parent, Cocca, 2007; Parent *et al.*, 2013).

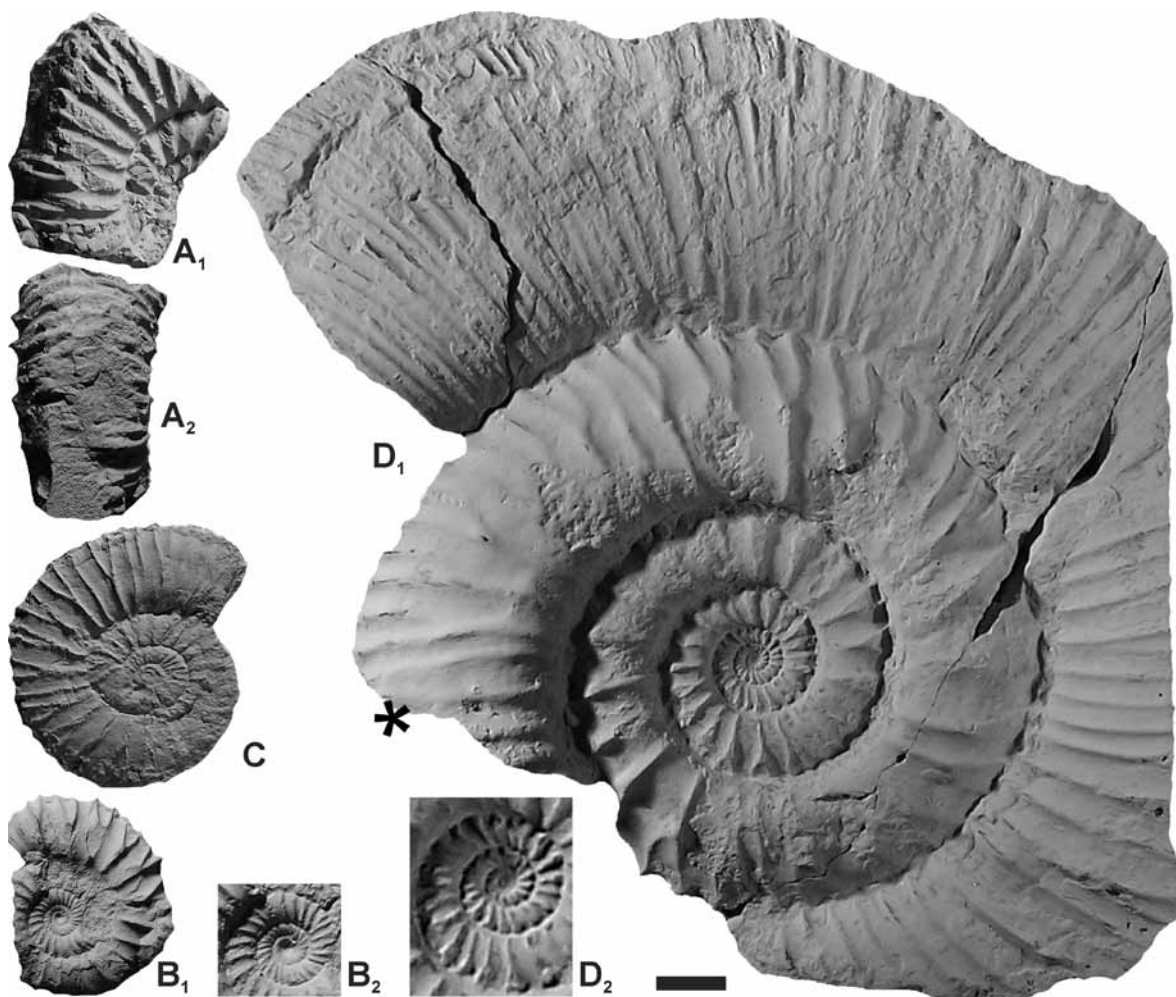


Fig. 13. **A.** *Windhauseniceras internispinosum* (Krantz, 1926), incomplete phragmocone (MOZ-PI-8960), level MQ-III-30, base of the Internispinosum Zone, **B–D.** *Corongoceras cf. mendozanum* (Behrendsen, 1891) from level MQ-III-41, Alternans Zone; **B.** Almost complete adult microconch (MOZ-PI-8967); **B₁,** Inner whorls enlarged ($\times 2$); **C.** Virtually complete adult microconch (MOZ-PI-8964); **D.** Complete adult macroconch (MOZ-PI-8932); **D₂,** Inner whorls enlarged ($\times 2$). All natural size otherwise indicated. Scale bar: 10 mm, except for for **B₁** and **D₁**: 5 mm

Physodoceras n. sp. A (in Parent *et al.*, 2011a, 2013, 2015). Included here are abundant phragmocones indistinguishable from the material of the Zitteli [incl. Mendozanus] Zone of Picún Leufú and Pampa Tril where they are relatively abundant too.

Pseudhimalayites subpretiosus (Uhlig, 1878), **Fig. 14.** Two adult macroconch phragmocones coming from levels MQ-III-21 (MOZ-PI-8928) and MQ-III-26 (Fig. 14). They match in shell-shape, sculpture and size the specimen from the *falculatum* Hz., Proximus Zone of Arroyo Cieneguita figured in Parent *et al.* (2011b: fig. 37B).

Pseudolissoceras zitteli (Burckhardt, 1903). Incomplete adult macroconchs, abundant juvenile macroconchs and scarce adult microconchs occur in concretions from levels MQ-III-11-12, 15 and 19. The shell morphology with smooth inner and outer whorls is typical of the species, as well as is the suture. The conspicuous septal suture line of *Pseudolissoceras* (Barthel, 1962: fig. 2; Leanza, 1980: fig. 3; Parent *et al.*, 2011b: fig. 39B₃) is an important feature enabling the differentiation of the species of this genus from the several other similarly smooth shells of haploceratoids and aspidoceratids which occur associated in these levels all through the basin, usually preserved as dozens,

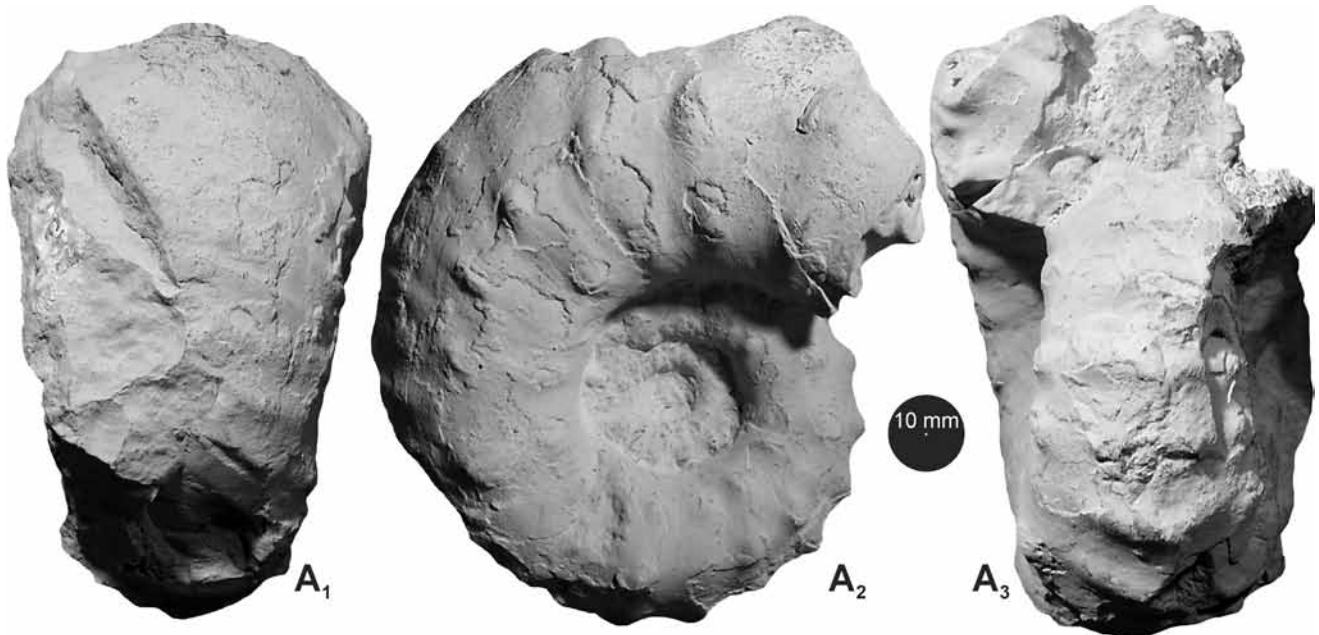


Fig. 14. *Pseudhimalayites subpretiosus* (Uhlig, 1878), incomplete macroconch phragmocone (MOZ-PI-8930), level MQ-III-26, Proximus Zone. Natural size ($\times 1$)

even hundreds, of similarly sized specimens within large calcareous concretions.

BIOSTRATIGRAPHIC CHRONOSTRATIGRAPHY AND TIME-CORRELATION

The chronostratigraphic scale for classification of the Andean Tithonian adopted in this paper (Fig. 15) is based on Leanza (1981), Parent *et al.* (2011a) and references therein (see Parent *et al.*, 2015 for details). The chronostratigraphic zonation of the studied sections based on the ammonite biostratigraphy was obtained in two steps, first by identification of ammonites known to occur within the zone, and second drawing the base of the zone. The base of each zone is determined by: (a) the basal bio-horizon if present (standard-zones), or (b) at the level with the first occurrence of the ammonites which are characteristic of the zone, *i.e.* one or more of the guide or characteristic species. This procedure, prompted in Parent (2006) and later established in Parent *et al.* (2013), provides a non-arbitrary criterion for zonation which was soon followed by other authors (*e.g.*, Vennari, 2016; Iglesia-Llanos *et al.*, 2017). The inherent low precision and instability of time-correlation based on non-standard chronostratigraphic zones, and/or first and last occurrences were already discussed in Parent *et al.* (2007: 20, 21), Garrido and Parent (2013: 37, 38), and Parent *et al.* (2015: 84, 85).

REMARKS ON THE CURRENT ZONATION

Most of the ammonite zones of the Andean Tithonian which were defined by Burckhardt (1900a, 1903), Windhausen (1918), Gerth (1925), Weaver (1931), Leanza (1945) and Groeber (1946) were defined as what today would be termed either a faunal horizon or a total-range-biozone. These units have been expanded or translated into chronostratigraphic zones by later authors but with little or no explanation (see the review by Leanza, 1981). Considering the most recent advances in the ammonite zonation of the Tithonian of the Neuquén Basin (Fig. 15), it is important to review the current status and to discuss some issues before presentation of the chronostratigraphic classification of the studied section.

1. Picunleufuense Zone (standard). This zone is defined by its base, a time-plane represented by the *picunleufuense alpha* Hz., and it extends up to the base of the Zitteli [incl. Mendozanus] Zone. Since this later zone has problems of definition (see below) and thus cannot be standardized yet (by fixation of its base by means of an ammonite bio-horizon), its lower boundary is variable in different localities and needs to be based on the criterion of recognition of the first ammonite(s) assignable to the zone. The *picunleufuense alpha* Hz. most usually corresponds to the lowermost levels at the base of the Vaca Muerta Fm. The characteristic species are: *I. picunleufuense*, *C. platyconus*, *C. guenenakenensis*, *Cieneguiti-*

Tethyan Primary Standard		Neuquén Basin					
		Parent <i>et al.</i> (2015) - this report		Zeiss and Leanza (2010)		Vennari (2016)	
Stage	Zone	Horizon	Zone	Zone	Subzone	Zone	Subzone
BERRIASIAN	Upper	Boissieri		Damesi			
	Middle	Occitanica	<i>transgrediens</i>				
	Lower	Jacobi	<i>noduliferum</i> <i>compressum</i>	Noduliferum			
TITHONIAN	Upper	Durangites	<i>planulatum</i> <i>koeneni</i> <i>striolatus</i>	Koeneni	Koeneni	Acutum Longaeva Vetustum Andinus	
		Microcanthum	<i>azulense</i> <i>bardense</i> <i>vetustum</i>	Alternans	Alternans	Inaequicostata Tapiai	
	Middle	Ponti	<i>catutosensis</i> "quinchoai" <i>internispinosum</i> α	Internispinosum	Internispinosum	Fascipartita Rafaeli	
		Fallauxi	<i>falculatum</i>	Proximus	Proximus	Steinmanni ?	
	Lower	Semiforme	<i>erinoides</i> <i>perlaevis</i>	Zitteli [Mendozanus]	Zitteli Mendozanus	Pseudoolithicum Choicensis	Zitteli
		Darwini	<i>malarguensis</i>			Malarguensis	Malarguensis
		Hybonotum	<i>picunleufuense</i> β <i>picunleufuense</i> α	Picunleufuense			Andesensis Primordialis
	KIMM.	Upper	Beckeri				

Fig. 15. Andean Tithonian-Berriasian chronostratigraphic zone scale (grey) adopted in this paper (based on Leanza A.F., 1945; Leanza H.A. 1981; Parent *et al.*, 2011a, 2015) correlated with those of Zeiss, Leanza (2010) and Vennari (2016) as explained in text. Time-correlation with the Tethyan Primary Standard scale after Parent *et al.* (2015)

ceras perlaevis (Steuer, 1897). Less commonly there occur aspidoceratids (*Aspidoceras* and *Physodoceras*).

- Zitteli [incl. Mendozanus] Zone. The Mendozanus Zone was defined by Burckhardt (1903: 106, as Zone des *Virgatites scythicus*), indicating that it underlies the Zitteli Zone defined in the same paper (Burckhardt, 1903: 107, as Zone der *Neumayria zitteli*). The index-species of this zone – „*V. scythicus* Vischniakoff” – was later renamed as *Virgatites mendozanus* Burckhardt, 1911. This species

has been revised (Parent *et al.*, 2011b, 2015, 2017b) and it was demonstrated that: (1) it is a synonym of *Choicensisphinctes erinoides* (Burckhardt, 1903) by being the corresponding microconch, and (2) the other nominal species of the guide assemblage (Burckhardt, 1903: 106; 1900a: pl. 25 1: 3–8) can be also considered synonyms of *C. erinoides*.

The Zitteli Zone, in current usage, is based on the total-range-biozone (lowermost to uppermost occurrence)

of *P. zitteli* (Leanza, 1981; see discussion in Parent *et al.*, 2011a). In this sense *P. zitteli* is the guide- and index-species, and so every bed or level yielding *P. zitteli* belongs to the Zitteli Zone. Under this definition the zone has different local time-ranges as the records of the guide-species depend on the extension of its living area, the preservation, and collection circumstances in different sections, thus this marker is unsuitable for precise time-correlation.

On the other hand, it has been recognized (*e.g.* Weaver, 1931; Parent *et al.*, 2011a, 2013, 2015) that the lowermost occurrences of *C. erinoides* (including the morpho-species cited above) are, all throughout the basin, in association with *P. zitteli*. Furthermore, the lowermost occurrence of *P. zitteli* in several localities is below the first of *C. erinoides*. In other words, since the Zitteli Zone is defined by the range of *P. zitteli*, the Mendozanus Zone is included in the Zitteli Zone. Thus, we use a Zitteli Zone as defined above, but named as Zitteli [incl. Mendozanus] Zone for denoting the overlapping or even inversion of these units in different localities.

3. Proximus Zone. Index-species: *Catutosphinctes proximus* (Steuer, 1897). This zone is defined as the time-rock interval bounded by two time planes represented by: (1) the basal by the last (or uppermost) occurrence of *P. zitteli*, and (2) the top, below the *internispinosum alpha* Hz. If this bio-horizon is not recorded, or not recognized, it must be considered the level below the first occurrence (or lowermost) of *W. internispinosum*, and/or any of the typical species of the zone. This non-standard Proximus Zone can have different ranges and time durations at every locality where it is recognized. Currently, there is a number of species more or less confined to the zone which can be considered for the recognition of the zone: *Platydiscus beresii* (Parent, Scherzinger, Schweigert, 2011), *M. arredondense*, *P. subpretiosus*, and *Aspidoceras* cf./aff. *quinchaoi* Zeiss & Leanza, 2010 (usually preserved as large bodychambers).

Identification of incomplete specimens of *Catutosphinctes* is usually difficult. *C. proximus* develops a variety of morphotypes, some of which hard to distinguish from *C. guenenakenensis* (Picunleufuense Zone) and *C. rafaeli* (Internispinosum Zone), especially comparing inner whorls or phragmocones. Thus, recognition of the zone on the basis of the index-species can be misleading, the only way to avoid misidentifications and so miscorrelations is to consider complete adult specimens as well as the association with other species known to occur in the zone.

According to Leanza (1981) the Proximus Zone corresponds to the Colubrinoïdes Zone proposed by Burckhardt (1900a, 1903, index: *Perisphinctes colubrinoïdes*

Burckhardt, 1903), renamed by Groeber (1946, 1952). However, *P. colubrinoïdes* was discussed by Parent *et al.* (2011b) concluding that the lectotype figured by Burckhardt (1900a: pl. 26: 4) would belong to the Internispinosum Zone. This conclusion is based on the fact that *P. colubrinoïdes* clearly represents the microconch of *Catutosphinctes rafaeli* (see Parent, Cocca, 2007: fig. 3A, B) by being identical in their inner whorls. However, the regular occurrence of simple ribs distinguishes this microconch from that of *C. proximus* which is consistently bifurcate. For comparison the lectotype and two of the specimens in Parent and Cocca (2007) from the Internispinosum Zone of Portada Covunco (Parent *et al.*, 2013: fig. 3, level PC-84) with additional preparation are refigured (Fig. 12B-D). This misinterpretation of *P. colubrinoïdes* and so the Colubrinoïdes Zone, which would be rather equivalent to the Internispinosum Zone, have passed unnoticed probably because (1) the Proximus Zone is poorly defined, and placed immediately below the Internispinosum Zone which has been interpreted everywhere from direct translation of the total-range-biozone of the species *W. internispinosum* into the Internispinosum Zone, and (2) by the superficial similarity between the phragmocones of both species.

4. Internispinosum Zone (standard). This zone is defined by its base, a time-plane represented by the *internispinosum alpha* Hz. (Parent *et al.*, 2015), and extends up to the recognition of ammonites assignable to the Alternans Zone.
5. Alternans Zone. This zone is usually recognized by most authors as the rock-interval between the last occurrence of *W. internispinosum* and the first of *Substeueroceras koeneni* (Steuer, 1897). Under these criteria it is obvious that each locality would have a different non-standard Alternans Zone, depending on the sampling and local representation of these species. In the localities where the zone is well developed like Pampa Tril (Parent *et al.*, 2015), Mallín Redondo (Leanza, 1945), Arroyo Cienequita (Parent *et al.*, 2011b), or Arroyo Durazno (Gerth, 1925), the characteristic species are: *Steueria alternans* (Gerth, 1921) with three macroconch-morphotypes: morph alternans, morph inaequicostata and morph spinulosa (Gerth, 1925; Parent *et al.*, 2011b), *Corongoceras mendozanum*, *Parodontoceras calistoides* (Behrendsen, 1891), *Pseudoparodontoceras dezai* Parent *et al.*, 2015, *Blanfordiceras vetustum* (Steuer, 1897), the earliest representatives of *Choicensisphinctes striolatus* (Steuer, 1897), *Krantziceras azulense* (Leanza, 1945), and *Catutosphinctes inflatus* (Leanza, 1945).

Parodontoceras calistoides is frequently assigned to the Koeneni Zone when the successions are poorly fossiliferous or poorly constrained stratigraphically, but it has been dem-

onstrated from abundant material that the typical representatives (those closer to the holotype) are confined to the Alternans Zone (see Parent *et al.*, 2011b, 2015). In the Koeneni Zone occurs a somewhat similar ammonite: *Thurmannia discoidalis* Gerth (1925: pl. 5: 3, holotype by monotypy). This ammonite seems to be a late transient of *P. calistoides* as discussed in Parent *et al.* (2011b), differing from the typical representatives of the Alternans Zone by being slightly more compressed and high-whorled, but showing the same sculpture ontogeny (up to what can be observed in the holotype) that characterizes the genus.

CORRELATION WITH OTHER AMMONITE-ZONE CHRONOSTRATIGRAPHIC SCALES

Zeiss and Leanza (2010) as well as Vennari (2016) have presented ammonite-zone scales with some differences with respect to that adopted in this paper as well as between them – especially for the Lower Tithonian. The correlation of these scales (Fig. 15) is discussed below, considering papers where, at least partially, the authors have presented the evidence in the form of described ammonites and log-sections.

In the zonation proposed by Zeiss and Leanza (2010: tab. 1) the Malarguensis Subzone could be correlated with the *malarguensis* Hz., assuming the authors referred to the bio-horizon of the holotype which is the only known specimen (Burckhardt, 1900a: pl. 24: 4) of *Indansites malarguensis*. This holotype has been assigned to the *malarguensis* Hz. (Parent *et al.*, 2011a) whose stratigraphic position is above the well-known and rich fauna of the Picunleufuense Zone (see Parent *et al.*, 2011a, 2015; Vennari, 2016). This Malarguensis Subzone seems to be rather equivalent to the Pseudolictor Zone of Groeber (1946) which was adopted by Leanza (1973) below a Choicensis Zone. The zonation of Groeber (1946) does not include a Mendozanus Zone. However, *Choicensisphinctes choicensis* (Burckhardt, 1903) belongs to the type assemblage of the Mendozanus Zone (see below).

The Rafaeli Subzone should correspond to the *rafaeli* Hz. of Leanza, Zeiss (1992), which then should be intercalated between the *internispinosum alpha* Hz. and the *quinchoai* Hz. (Fig. 15), but that horizon was apparently abandoned by the authors. The zones of other parts of the Tithonian seem to correlate with no differences from those adopted herein, leaving aside the subzones which were introduced without explanation.

Vennari (2016) has proposed a subdivision of the Lower Tithonian in subzones and biozones (sic), but in fact these units should be considered plain chronostratigraphic zones and subzones since in the end they are shown as partitions of the Tithonian stage in her text-fig. 19. The Andesensis Zone is based on the index-guide species *Virgatosphinctes ande-*

sensis (Douvillé, 1910). Leaving aside any consideration of the generic attribution, *V. andesensis* is based on a holotype with neither geographic nor stratigraphic provenance known (see Douvillé, 1910: 5), as already pointed out and discussed in Parent *et al.* (2011a). The presumption of Leanza (1980: 6) that the material collected by Recopé and described by Douvillé (1910) could come from the Cerro Lotena area, although taken as a confirmation of type locality by (Vennari, 2016: 101), is completely insufficient. Furthermore, the unknown locality of provenance makes it impossible to search for the type horizon in an indeterminate outcrop.

The Primordialis Subzone is certainly equivalent to the Picunleufuense Zone, nominally and chronostratigraphically. Nominally because the index-guide species *Pseudinvoluticeras primordialis* is a subjective synonym of *Choicensisphinctes platyconus*. This can be easily noted comparing the holotype of the former (Vennari, 2016: pl. 8: 1) with the exactly identical paratype-II of *C. platyconus* (Parent *et al.*, 2011a: 66, fig. 15A) from the *picunleufuense alpha* Hz., base of the Picunleufuense Zone. Chronostratigraphically because most of the ammonites or morphotypes assigned by Vennari (2016: 121) to this zone are well known to range more or less concurrently in the Picunleufuense Zone:

1. *Virgatosphinctes andesensis*, not time-diagnostic for *nomen dubium* (discussed above).
2. *Virgatosphinctes? densistriatus* (see natural-size refiguration of the holotype in Parent, 2003: fig. 3, and revision in Parent *et al.*, 2011a): the holotype corresponds to an early representative of *Choicensisphinctes* which compares well with Picunleufuense Zone specimens of *C. platyconus* (e.g. Parent *et al.*, 2011a: fig. 19A, B); nevertheless the holotype and all the specimens figured by Vennari (2016: pl. 5) are inner whorls which prevent any reliable species identification.
3. *Pseudinvoluticeras douvillei* (the holotype is not time-diagnostic for *nomen dubium* under identical issues as for “*V.*” *andesensis*; see above and Parent *et al.*, 2011a). On the other hand, the material figured by Vennari (2016: pl. 6: 4–8; 7: 1, 5–7) consists of ammonites which can be easily accommodated within the range of variation usually attributed to *C. platyconus*.
4. *Cieneguiticeras perlaevis*: a species which occurs from the lower Picunleufuense Zone upwards, see Parent *et al.* (2010, 2015).
5. *Physodoceras neoburgense*: in morphotypic terms this species ranges the interval Hybonotum-Semiforme zones in Europe (e.g. Kutek, Wierzbowski, 1986; Scherzinger, Schweigert, 1999; Schweigert *et al.*, 2002; Fözy *et al.*, 2011).

The Malarguensis Subzone of Vennari (2016) is here correlated with the *malarguensis* Hz. However, this correlation is tentative for all the macro- and microconchs figured

by Vennari (2016: pls. 1, 2) as *I. malarguensis* are indistinguishable from the Picunleufuense Zone representatives of *I. picunleufuense*. The holotype of *I. malarguensis* is just a macroconch? phragmocone showing similarities to the late representatives of *I. picunleufuense*, which have close relative stratigraphic positions and phyletic relationships (see above).

CHRONOSTRATIGRAPHY OF THE STUDIED SECTIONS

Under the criteria discussed above, the studied sections can be subdivided or classified with the current scheme as follows (Fig. 16):

Picunleufuense Zone (MQ-III-2-10 and MQ-IV-1-13). Clearly recognized from its base at the *picunleufuense* alpha Hz., the next bio-horizon *picunleufuense* beta Hz. and other levels above with specimens of later representatives of *I. picunleufuense*. The upper limit, in a non-standard form, is taken just below the first occurrence of *P. zitteli*.

Zitteli [incl. Mendozanus] Zone (MQ-III-11-19). In the present section the zone ranges from the first occurrence of *P. zitteli* up to the first level with ammonites characteristic of the Proximus Zone. The possible equivalence of level MQ-III-19 with the *erinooides* Hz. suggests there could be a gap between beds 19 and 20 with a magnitude larger than the usual between two contiguous beds, considering that other bio-horizons have been recognized in other sections (Cerro Lotena-Cerro Granito, to be published elsewhere), between this bio-horizon and the lower Proximus Zone. However, the ammonites of the lower part of the Proximus Zone are poorly known.

Proximus Zone (MQ-III-20-29). The index-species *C. proximus* has been revised from material coming from the type locality at Arroyo Cieneguita (Parent *et al.*, 2011b), collected from the type-horizon which has been detected with confidence. The species recorded in beds attributed to this zone are: *Catutosphinctes* cf. *proximus*, *Mazatepites arredondense*, *Pseudhimalayites subpretiosus*, and early representatives of *Aspidoceras euomphalum*. The occurrence of this latter species in level MQ-III-29 suggests this bed should be attributed to the Internispinosum Zone if the level MQ-III-30 is not exactly the *internispinosum* alpha Hz. (see below).

Internispinosum Zone (MQ-III-30-39). The ammonites recorded in this interval belong to the typical assemblage of the zone: *W. internispinosum* and *C. rafaelli*, plus *A. euomphalum*. The base of the zone is traced, following the criterion indicated above of first occurrence of a characteristic ammo-

nite, at level MQ-III-30 where the first specimen of *W. internispinosum* was recorded. This boundary with the underlying Proximus Zone could be moved downwards if indicated by future discovering of *W. internispinosum* in levels lower than the MQ-III-30. But in the present case it is possible that the base of the zone is well suited since the specimen of *W. internispinosum* in this level could likely belong to the transient alpha (see above), suggesting the *internispinosum* alpha Hz. which is the base of the standard Internispinosum Zone.

Alternans Zone (MQ-III-40-44). The species represented in these levels are *C. cf. mendozanum* and *B. cf. wallichii*. The diagnostic ammonite association of the Alternans Z. in the north of the Huincul High consists of *C. mendozanum*, *Parodontoceras calistoides* (Behrendsen, 1891) and *Steueria alternans* (Gerth, 1921). These two latter species are not present in our samples from the Mallín Quemado area. Under these constraints the interval of levels MQ-III-40-43 is assigned to the Alternans Z. by the combination of the following biostratigraphic features: (1) the position of the interval which overlies beds with ammonites of the Internispinosum Z., (2) the abundant occurrence of *C. cf. mendozanum*, and (3) the occurrence in level MQ-III-43 of a specimen assignable to *B. cf. wallichii* (in Parent *et al.*, 2013) that in Cerro Caracoles occurs in the Alternans Z., as well as similar forms in the same zone (specifically *vetustum* Hz.) in Pampa Tril (Parent *et al.*, 2015: fig. 58A). Level MQ-III-44 is included in the Alternans Zone tentatively, as no ammonites were found there.

Koeneni Zone. In section MQ-I and in that of Puesto Báez (Garrido, Parent, 2017), we have collected a specimen of *Himalayites* cf. *andinus* Leanza, 1975 which is known to occur in the Upper Tithonian Koeneni Zone. In the upper part of the Vaca Muerta Fm. occurs a thin level with abundant but crushed ammonites which can be assigned to *Substeuero-ceras koeneni* – *S. permulticostatum* (MOZ-PI-5998/1-10) indicating the uppermost levels of the zone as constrained by the records of the next levels. Indeed, in the topmost levels of the formation occur abundant gastropods, bivalves and *Krantziceras* cf. *compressum* (MOZ-PI-5999/1-5). This latter species strongly suggests the *compressum* Hz., the base of the Noduliferum standard Zone.

REGIONAL TIME-CORRELATION

Time-correlation with sections of other localities can be much refined with respect to zonation by means of the recognition and comparison of successions of ammonite bio-horizons. This correlation is much finer and more precise than that obtained considering only the ammonite zones,

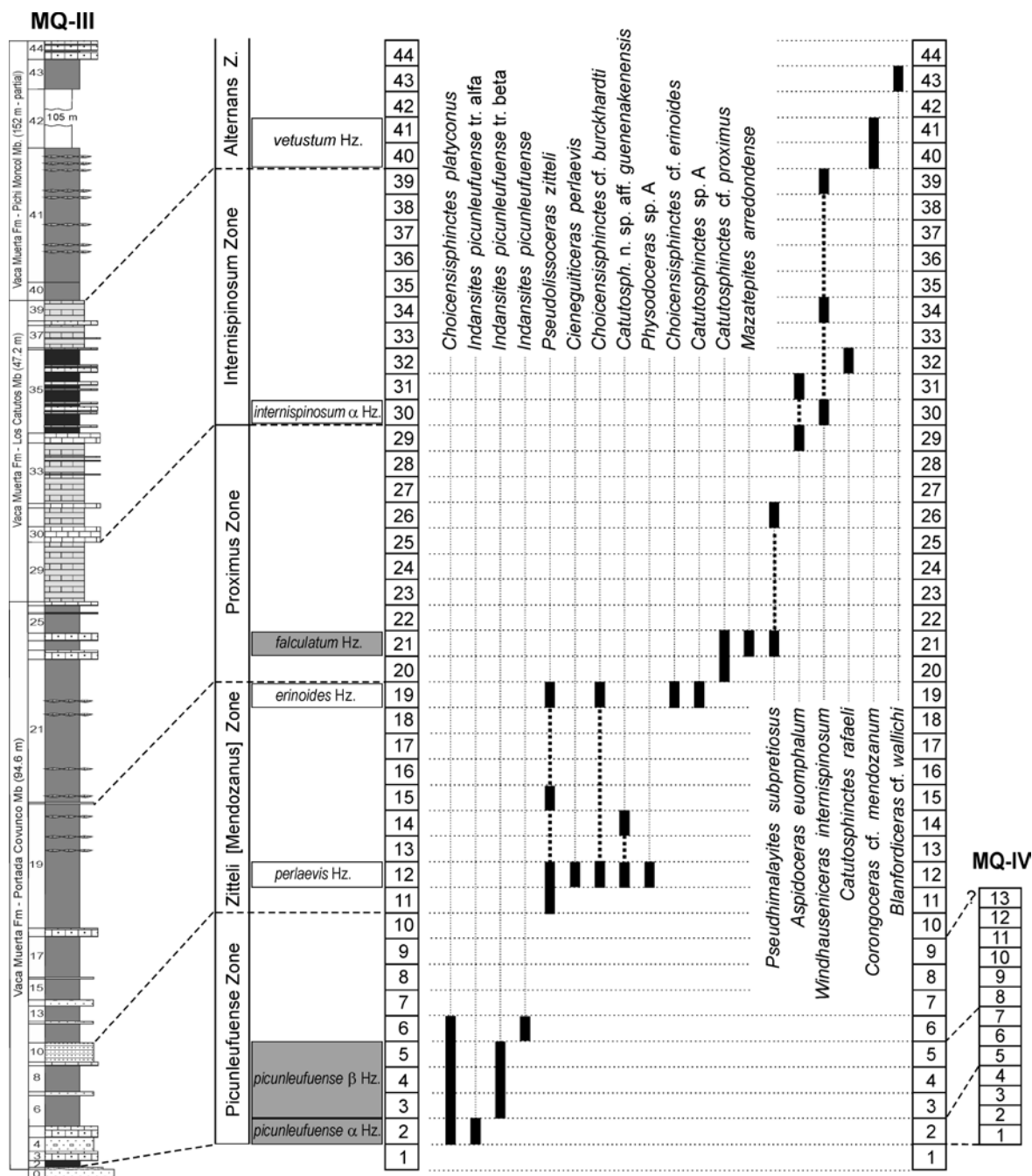


Fig. 16. Stratigraphic distribution of the ammonite fauna referred to the columnar section of transect MQ-III (Fig. 3), shown at left, and the base of section of transect MQ-IV. Chronostratigraphic ammonite zonation as explained in text (see Fig. 15)

since the bio-horizon succession provides higher resolution. Limitations to this procedure of refinement are imposed by the fact that the whole succession of bio-horizons is not complete at any locality.

Efforts to elaborate the successions of ammonite bio-horizons for the Upper Jurassic and Lower Cretaceous of the Neuquén Basin have been done in last years (see reviews in

Parent *et al.*, 2015 for the Tithonian, and Parent, Garrido, 2015 for the Callovian-Oxfordian), resulting in the definition of 15 ammonite bio-horizons for the Andean Tithonian (see Fig. 15). The regional time-correlation through different parts of the basin is shown in the chart of Fig. 17. The localities considered (see Fig. 1) have been selected through a transect of outcrops along the 70°W meridian which have

been deeply studied in a series of papers starting with Groeber (1946). The time-correlation chart shows only the levels which can be considered synchronous by the recognition of bio-horizons across the different localities indicated. However, usually there are other levels between any pair of horizons recognized locally, and although these levels cannot be

accurately correlated they can be approximated by interpolation between adjacent bio-horizons.

The chart in Fig. 17 is further refined by the present results with respect to that presented in Parent *et al.* (2015: fig. 86), and can be used for tracing time-planes for fine time-correlation across the Neuquén Basin.

Stage	Zone	Horizon	PL	CC-PC	MQ	PT	MR	AY	CP	AD	AC	
BERRIASIAN	Damesi	<i>transgrediens</i>			MQ-PB 20	PT-65	1771	* i	G-6		AC-20	
	Noduliferum	<i>noduliferum</i>				PT-61		* h				
		<i>compressum</i>			MQ-PB 09	PT-60	1768					* AC-19
TITHONIAN	Koeneni	<i>planulatum</i>				PT-58				* DU-49		
		<i>koeneni</i>				* PT-54						
		<i>striolatus</i>				PT-51-52		f	G-10	G-31h	* AC-17	
	Alternans	<i>azulense</i>				* PT-40		d		DU-37-41		
		<i>bardense</i>		CC-32-33				* 1762			G-31g	
		<i>vetustum</i>		PC-140	MQ-III 40-41	PT-36		c	G-11	DU-32-35	* AC-15	
Internispinosum	<i>catutosensis</i>		* Z-W									
	"quinchoai"		* y									
	<i>internispinosum</i> α		PC-71	MQ-III-30	* PT-19		a ₂				AC-9	
Proximus	<i>falculatum</i>			MQ-III-21						* AC-7		
Zitteli [Mendozanus]	<i>erinoides</i>	PL-12			MQ-III-19	PT-12					* AC-5	
	<i>perlaevis</i>	* PL-9	PC-27		MQ-III-12	PT-10c					AC-4	
	<i>malarguense</i>					PT-10b			* M-6		AC-2	
	[unnamed]	PL-7a-b	PC-4-6						G-14			
Picunleufuense	<i>picunleufuense</i> β	* PL-6			MQ-III-3-5	PT-10a			G-15			
	<i>picunleufuense</i> α	* PL-5	PC-1-3		MQ-III-2	PT-2-6					AC-1	
KIMM.												

Fig. 17. Regional time-correlation chart for selected localities (transect in Fig. 1, along the 70°W meridian) based on the ammonite bio-horizons currently defined through the Neuquén Basin (see Parent *et al.*, 2015)

Firm recognition of bio-horizons indicated with grey boxes, tentative with white boxes. The asterisk indicates the type locality/section of the corresponding bio-horizon. Between contiguous bio-horizons there usually exists one or more additional levels, some of them with ammonites - the number of bio-horizons is to be expanded every time a new one is differentiated in any local succession. The height of the boxes of each zone does not indicate time-duration neither content of horizons, they are sized for convenience of design. Broken lines indicate approximate correlation or non-standard zones; full lines for standard zones. Level numbers indicated into the boxes taken from the source of the information: Picún Leufú (PL): Parent *et al.* (2011a); Cerrito Caracoles-Portada Covunco (CC-PC): Leanza, Zeiss (1992) and Parent *et al.* (2013); Mallín Quemado (MQ): present report and Garrido, Parent (2017); Pampa Tril (PT): Parent *et al.* (2015, 2017b); Mallín Redondo (MR) and Arroyo del Yeso (AY): Leanza (1945); Casa Pincheira (CP): Gerth (1925), Parent (2003), Parent *et al.* (2011a); Arroyo Durazno (AD): the sequence of bio-horizons described by Parent *et al.* (2011b) from the sequence of Gerth (1925) are confirmed and expanded by results of the resampling by Vennari *et al.* (2012) and Vennari, Aguirre-Urreta (2017); Arroyo Cieneguita (AC): Parent *et al.* (2011b)

CONCLUSION

The Vaca Muerta Fm. in the Mallín Quemado area displays its three members: Portada Covunco, Los Catutos and Pichi Moncol, composed of sediments deposited in an offshore environment under restricted, low-oxygen conditions. The ammonite succession recorded is much less complete than that of Pampa Tril, with ammonite levels more scattered, except in the Picunleufuense Zone. On the other hand, the succession is somewhat more complete than that of the transect Portada Covunco-Cerrito Caracoles, an area which, significantly, is closer to the Huincul High, and most likely a shallower area. The ammonoid fauna in the study area is mostly composed of species well known from other localities north of the Huincul High. However, some show slight differences which could represent local infra-subspecific variants, or transients corresponding to stratigraphic horizons not recorded in other localities, either by faunal gaps or collection failure.

The fauna of the Picunleufuense Zone is very homogeneous all throughout the Neuquén Basin as also recorded in the present sections of Mallín Quemado. The Zitteli [incl. *Mendozanus*] Zone is well represented by species characteristic and mostly confined to the zone. In the Proximus Zone the ammonites are rather concentrated in two or three horizons, and are typical of the zone as represented in other parts of the basin, e.g. Arroyo Cieneguita and Pampa Tril. In the Internispinosum Zone the species *W. internispinosum* is well represented through several levels by typical specimens as recorded from Pampa Tril and towards the southern end of the basin, mainly in the Picún Leufú sub-basin. This distribution is the same as the geographic development of the Los Catutos Mb. on the eastern side of the basin. The Alternans Zone is recognized by the occurrence of abundant material of *C. cf. mendozanum* and *B. cf. wallichi*. The Koeneni Zone is well developed as a thick facies of black shales (see Leanza, 1975; Garrido, Parent, 2017).

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