LITHOFACIES AND AGE OF THE QUINTUCO FORMATION (LOWER CRETACEOUS) IN THE MALLÍN QUEMADO AREA (SIERRA DE LA VACA MUERTA, NEUQUÉN BASIN, ARGENTINA). STRATIGRAPHIC AND DEPOSITIONAL IMPLICATIONS.

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Abstract: A detailed lithostratigraphic study of the Quintuco Fm in the Cerro Mallín Quemado area (Sierra de la Vaca Muerta) has provided the opportunity to review the conflictive diversity of interpretations proposed in the last 40 years for this unit. In the study area the Quintuco Fm shows a heterolithic succession about 80 m-thick. This succession is composed of interbedded sandy mudstones, wacky sandstones and fine to medium-grained sandstones in a coarsening-upwards arrangement. Thin coquiniferous levels occur interestratified towards the medium and upper parts of the stratigraphic column. The underlying offshore Vaca Muerta Fm-facies, developed under euxinic to anoxic conditions change gradually towards the dysoxic, storm waves-influenced conditions of the offshore transition zone of the Quintuco Fm-facies. Upwards the Quintuco Fm passes gradationally to shoreface sandy deposits of the Mulichinco Fm. The transition between both units is defined in a short section of the sedimentary column.

The Quintuco Fm can be clearly recognized, and differentiated from the contiguous units, following the lithologic characterization of the original definition. There are important discrepancies in its determination among the authors. The main source of these discrepancies has been the use of biostratigraphic, chronostratigraphic and/or sequence-stratigraphic criteria.

Once recognized the lithostratigraphic unit from the observed lithology in the section, the ammonites collected from there were studied in order to date these rocks and to establish regional time-correlation. These ammonites indicate the Quintuco Fm in the study area is Berriasian in age. This age was obtained from the chronostratigraphic zones estimated from the ammonite biostratigraphy of the studied section. Towards northern positions in the basin, e.g. Pampa Tril area, the age of the Quintuco Fm is early Valanginian. This pattern of the units becoming younger towards north reflects the shoreline progradation towards the basin.

Keywords: Neuquén Basin ▪ Quintuco Formation ▪ Berriasian ▪ Lithostratigraphy ▪ Chronostratigraphy.

Resumen.- ***Litofacies y edad de la Formación Quintuco (Cretácico Inferior) en el área de Mallín Quemado (Sierra de la Vaca Muerta, Cuenca Neuquina, Argentina). Implicancias estratigráficas y depositacionales.*** A partir de un estudio detallado de la litoestratigrafía de la Formación Quintuco en el área del Cerro Mallín Quemado (Sierra de la Vaca Muerta) se efectuó una revisión de las numerosas interpretaciones de esta unidad propuestas en los últimos 40 años. En el área estudiada la Formación Quintuco muestra una sucesión heterolítica de unos 80 m de espesor. La sucesión está compuesta por limolitas arenosas interestratificadas, areniscas grauvaquicas y areniscas de grano fino a mediano, con un arreglo de tamaño de grano creciente hacia arriba. Hacia las partes media y superior de la columna estratigráfica se presentan delgados niveles coquiníferos interestratificados. Las facies subyacentes de la Formación Vaca Muerta, que se han desarrollado bajo condiciones euxínicas a anóxicas, pasan hacia arriba gradualmente a condiciones disóxicas, influenciadas por olas de tormenta de la zona de transición correspondiente a las facies de la Formación Quintuco. Hacia arriba la Formación Quintuco pasa gradacionalmente a depósitos arenosos costeros correspondientes a la Formación Mulichinco. La transición entre estas dos últimas unidades está definida en un corto tramo de la columna sedimentaria.

La Formación Quintuco puede reconocerse claramente y diferenciarse de las unidades contiguas a partir de la caracterización litológica de la definición original. Existen importantes discrepancias entre los distintos autores acerca de su determinación. La principal fuente de estas discrepancias ha sido el uso de criterios bioestratigráficos, cronoestratigráficos y/o de estratigrafía secuencial.

Una vez reconocida la unidad litoestratigráfica a partir de la litología observada en la sección analizada, los amonites allí muestreados fueron estudiados con el objetivo de datar estas rocas y establecer correlaciones temporales regionales. Estos amonites indican que la Formación Quintuco es de edad Berriasiana. Esta edad fué obtenida a partir de las zonas cronoestratigráficas estimadas a partir de la bioestratigrafía de dichos amonites. Hacia posiciones del norte de la cuenca, e.g. Pampa Tril, la edad de la Formación Quintuco corresponde al Valanginiano temprano. Este patrón de las unidades siendo mas jóvenes hacia el norte refleja la progradación de la línea de costa hacia el interior de cuenca.

Palabras clave: Cuenca Neuquina ▪ Formación Quintuco ▪ Berriasiano ▪ Litoestratigrafía ▪ Cronoestratigrafía.

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INTRODUCTION

The Neuquén Basin, an ensialic marginal trough, developed during Triassic to Paleocene on southwestern South America. Along most part of the Jurassic and Cretaceous, a structural high (Huincul High, Fig. 1A) behaved intermittently as a positive topographic relief (subaerial and/or submarine) that divided asymmetrically the basin and strongly influenced the distribution of the depositional systems developed on both of its sides (de Ferrariis 1947, Marchese 1971, Ploszkiewicks et al. 1984).

From the beginning of the Tithonian (Late Jurassic) a sudden and widespread marine transgression was followed by a prolonged cycle of regression and somerization until the Early Valanginian (Groeber 1946). The corresponding succession is bounded by two maximum-flooding surfaces, which have been thoroughly characterized in subsurface on the basis of seismic-stratigraphic studies by Mitchum & Uliana (1985) and aptly described by Macellari (1988). This succession is recognized informally as "Lower Mendocian Cycle" (Ciclo Mendociano Inferior; Orchuela & Plozkiewicz 1984, Macellari 1988) or partially modified under the name "Lower Mendoza Group" (Grupo Mendoza Inferior; Leanza, 2009, Leanza et al. 2011, Arregui et al. 2011). In the north or the Neuquén Province, where our study area is located, the Lower Mendocian Cycle (sensu Macellari 1988) is composed of the Vaca Muerta, Quintuco and Mulichinco formations. These units represent a thick progradational succession that grades from basinal facies to shallow marine and continental deposits. The Quintuco Fm is one of the most differently interpreted lithostratigraphic units of the Neuquén Basin. In some cases it has been even neglected by many authors considering it as part of the Vaca Muerta Fm, or, guided by stratigraphic criteria other than strictly lithological, correlated with other very different surface or subsurface units.

The purpose of this paper is to report the results of the study of a section in Mallín Quemado (Puesto Báez) where we have recognized the Quintuco Fm, based on a detailed survey of the succession. The much debated lithostratigraphy, identity and age of this unit is reviewed. The ammonites collected allowed to establish the age of the formation in the study area and its regional time-correlation. It is shown that following the lithological criteria of the original definition by Weaver (1931), the Quintuco Fm consists of a well delimited unit, clearly distinguishable from the Vaca Muerta and Mulichinco formations, and of variable age depending on the domain of the basin.

THE QUINTUCO FORMATION LITHOSTRATIGRAPHIC PROBLEM

The Quintuco Fm was defined by Weaver (1931) from the type section in the Cerro Quintuco-Puerta Quintuco area (central point: 38°09'10"S, 70°23'10"W) as a marine succession composed predominantly by dark gray to black clayey shales, which continue gradationally over black shales of the Vaca Muerta Fm, and covered by thick sandy and conglomerate beds of the Mulichinco Fm.

Respect to the lithological similarity with the underlying bituminous black shale deposits of the Vaca Muerta Fm, Weaver (1931:55) stated: "*The black shales of the Quintuco Formation pass downward into similar shales of the upper Tithonien beds and usually upon a lithologic basis it is impossible to determine the line of demarcation. There are, however, well defined faunal distinctions which can be utilized in establishing the contact relations. These transitional beds are widely spread, and involve all of the northern two-thirds of Neuquen*". Unfortunately none of the ammonite species he considered characteristic of the basal portion of the Quintuco Fm was illustrated in his monograph.

This definition has originated confusion in the differentiation of the deposits of the Quintuco Fm from those of the Vaca Muerta Fm in the northern area of the depocentre of the Neuquén Basin. First, because of the apparent lithologic similarity between both units; secondly by the use of biostratigraphic criteria for defining a lithostratigraphic unit and thus the subsequent chronostratigraphic framing.

A third drawback originates from the lithostratigraphic correlation attempted by Weaver (1931) towards the meridional end of the basin (Picún Leufú sub-basin), where he assigned a succession of limestones, calcareous shales, and argilaceous limestones to the Quintuco Fm. The criterion followed by Weaver (1931) for this "lithostratigraphic" correlation would have been the stratigraphic superposition of these carbonate deposits over the shales of the Vaca Muerta Fm, but leaving aside the lithologic attributes. Later, Leanza (1973) established the Picún Leufú Fm for those deposits, demonstrating, beyond lithological differences, their asynchrony with respect to the fine-clastic succession that characterizes the Quintuco Fm in the centre of the basin.

The mixed litho-, bio-, and chronostratigraphic scheme of Weaver was, in some way followed by Herrero-Ducloux (1946: 263), indicating that the Quintuco Fm is found always overlying the Tithonian (sic), and that the boundary between them is hard to draw due to the lithologic similarity. Groeber (1946, 1952) pointed out that the lithostratigraphic subdivision proposed by Weaver (1931) for the Tithonian-Barremian succession of the Neuquén Basin (Mendoza Group) has only a restricted applicability, due to the gradational character of the succession and the lateral variation of facies of these deposits. Furthermore, he stated that the boundaries of their units oscillate considerably with respect to the "ammonite zones". However, even though Groeber (1946, 1952) noted this inconsistency, he applied the biostratigraphic concept (i.e. the ammonite content) for the "rapid field identification" of these lithostratigraphic units. Subsequent authors, until the end of the 1960s, continued adopting and applying these biostratigraphic criteria for the identification of the Quintuco Fm, assigning the unit to the Upper Tithonian (e.g. Stipanicic 1969).

In the early 1970s, several authors proposed that due to the lithologic similarity of the the Vaca Muerta and Quintuco formations in the basin centre area, it could be considered as a single lithostratigraphic unit under the name Vaca Muerta-Quintuco Fm (Marchese 1971, Digregorio 1972) or simply Vaca Muerta Fm (emend., Leanza 1972). Leanza (1973) carried out a detailed litho- and biostatigraphic regional study on the deposits of the Lower Mendocian Cycle. This integrative work clarified several stratigraphic aspects, setting some concepts such as the heterochrony existing in the deposits equivalent to the Vaca

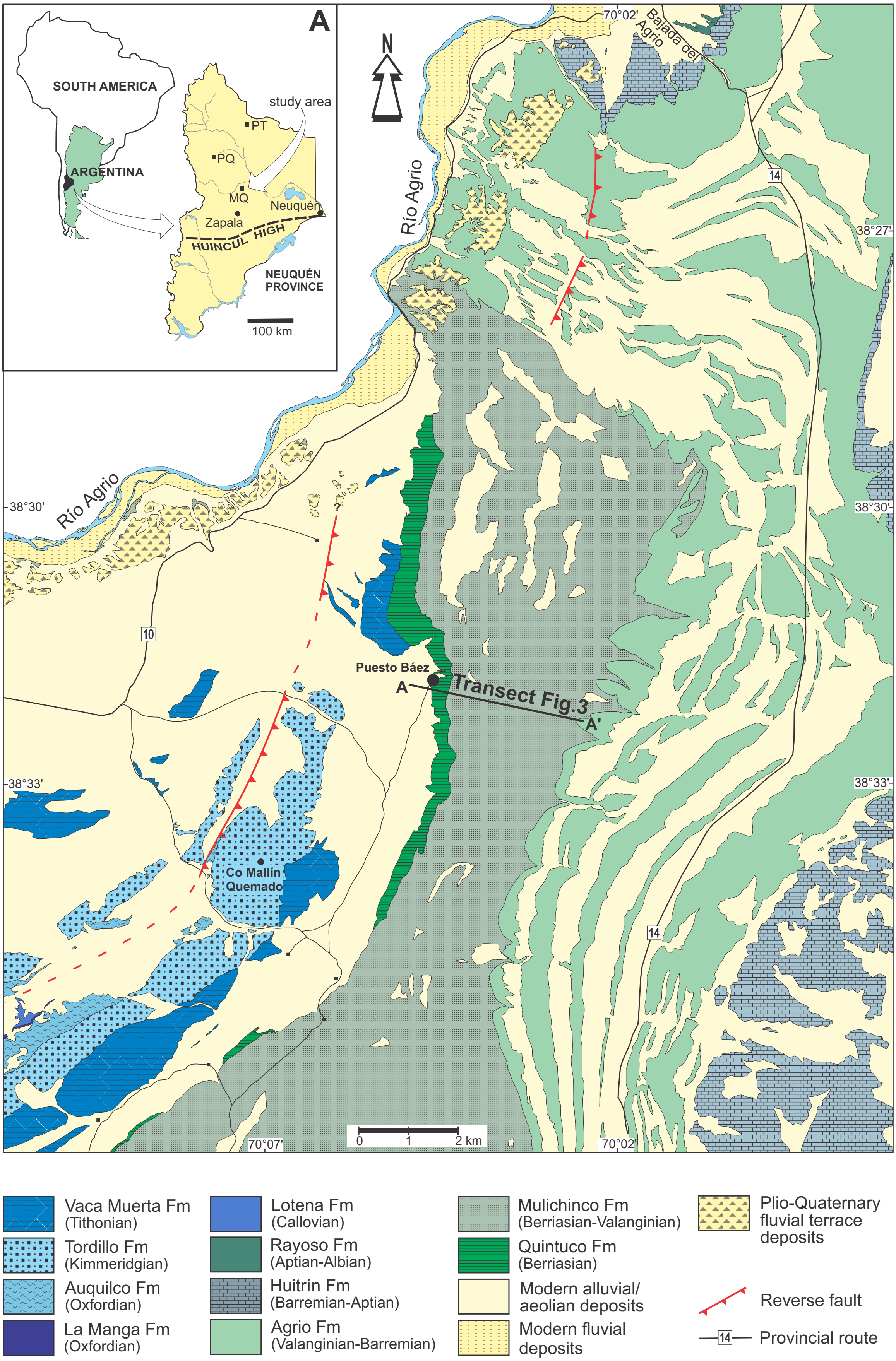


Figure 1. **A**: Location of the study area. MQ: Mallín Quemado (Sierra de la Vaca Muerta), PQ: Puerta Quintuco (type locality of the Quintuco Fm), PT: Pampa Tril. **B**: Geologic map of the study area in the Sierra de la Vaca Muerta.

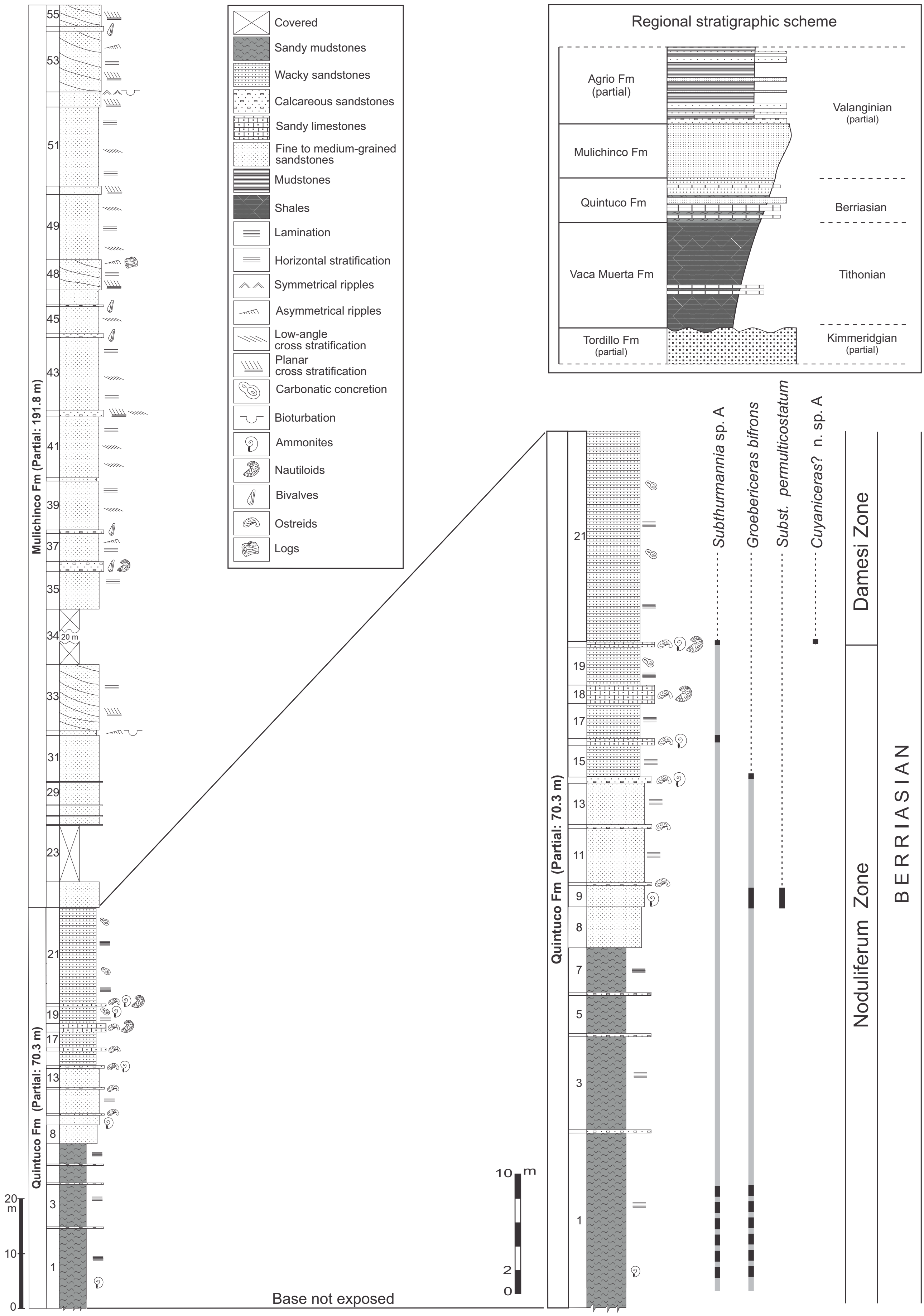
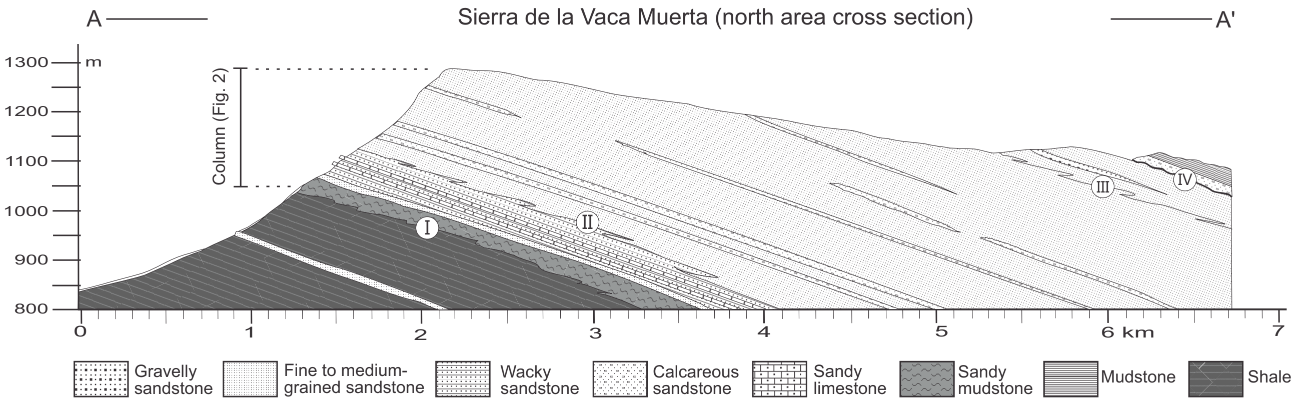


Figure 2. Stratigraphic column of Mallín Quemado area (Puesto Báez), with amplification (right) of the Quintuco Fm, indicating the succession of ammonites and chronostratigraphy. The upper-right inset summarizes the regional stratigraphic succession and position of the Quintuco Fm.



<table>
<tr><th>Weaver (1931)</th><th>Leanza (1973, 1975), Leanza & Hugo (2001)</th><th>Leanza (2009), Leanza et al. (2011)</th><th>Schwarz et al. (2011), Martínez & Olivo (2015), Olivo et al. (2016)</th><th>Legarreta & Villar (2015: fig. 5)</th><th colspan="2">This work</th></tr>
<tr><td>Agrio Fm. (partial)</td><td>Agrio Fm. (partial)</td><td>Agrio Fm. (partial)</td><td>Agrio Fm. (partial)</td><td rowspan="2">not represented</td><td colspan="2">Agrio Fm. (partial)</td></tr>
<tr><td rowspan="2">Mulichinco Fm.</td><td rowspan="2">Mulichinco Fm.</td><td>Mulichinco Fm.</td><td>Mulichinco Fm.</td><td rowspan="2">IV
Mulichinco Fm.</td><td>Upper section</td></tr>
<tr><td>Quintuco Fm.</td><td>Quintuco Fm.</td><td>?
Mulichinco Fm. (partial)</td><td>III
Lower section</td></tr>
<tr><td>Quintuco Fm.</td><td rowspan="2">Vaca Muerta Fm. (partial)</td><td rowspan="2">Vaca Muerta Fm. (partial)</td><td rowspan="2">?
Vaca Muerta Fm. (partial)</td><td>Quintuco Fm.</td><td colspan="2">II
Quintuco Fm.</td></tr>
<tr><td>Vaca Muerta Fm. (partial)</td><td>Vaca Muerta Fm. (partial)</td><td colspan="2">I
Vaca Muerta Fm. (partial)</td></tr>
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Figure 3. Cross-section of the north area of the Sierra de la Vaca Muerta through the transect A-A' in Fig. 1, with a comparison (table) of the different lithostratigraphic schemes proposed by other authors with that of the present report. Contact-surfaces I-IV indicated as explained in text.

Muerta-Quintuco formations succession (or Vaca Muerta Fm, sensu Leanza 1972) that would become progressively younger from the edge to the centre of the basin. Most later studies were based on these latter concepts (e.g. Leanza 1975, 1981, Leanza & Hugo 1977, Leanza & Wiedmann 1989, Leanza et al. 1977).

The sequence stratigraphy-based studies developed by petroleum geologists from the 1980s, revived the Quintuco Fm within the Tithonian-Valanginian succession (e.g. Gulisano et al. 1984, Digregorio et al. 1984, Legarreta y Gulisano 1989, Uliana & Legarreta 1993, among others). However, in these studies the name Quintuco Fm is applied to a carbonate succession outcropping in the southern region of the basin (Picún Leufú Fm sensu Leanza 1973), as well as its equivalent subsurface deposits (Digregorio 1978, Mitchum & Uliana 1985, Orchuela & Plozkiewicz 1984, Carozzi et al. 1993, Olmos et al. 2002, Olmos y Sommerfeld 2005, among others). The usage of the name Quintuco Fm in the petroleum industry under this conception, creates a shortcoming in the true scope of its definition under strict lithostratigraphic terms; a point that has been recently discussed by Leanza et al. (2011) and Parent et al. (2013).

From the point of view of the sequence stratigraphy, the Quintuco Fm in the central area of the basin is bounded at its top by a surface of discontinuity called the Intravalanginian or Huncalican Unconformity. Following this criterion Leanza (2009) reintroduced the Quintuco Fm in the stratigraphic scheme of the basin centre, redefining it as a set of marine siliciclastic sedimentites (mostly psamitic) accumulated in nearshore areas during the late Berriasian-Valanginian.

In summary, the difficulties in the identification of the Quintuco Fm according to its original definition are mainly due to its subtle lithological differences with respect to the underlying deposits of the Vaca Muerta Fm and the misleading lithostratigraphic correlation between different areas of the basin proposed by Weaver (1931). In order to overcome these problems, different authors have attempted to place and/or redefine the Quintuco Fm on the basis of biostratigraphic, chronostratigraphic, or palaeoenvironmental criteria and, more recently, even from concepts of sequence stratigraphy. However, all these attempts are somewhat confusing, since the essential principle of independence of the different kinds of stratigraphic units was not taken in consideration.

GEOLOGICAL SETTING OF THE STUDY AREA

The Sierra de la Vaca Muerta (SVM) is a north-south elongate range, bounded by the Agrio river and the Covunco creek in their northern and southern extremes respectively. It extends between 38°20'25”-38°47'40” S latitude and 69°52'13”-70°18'03” W longitude (considering its major axes), covering about 900 km2.

The SVM belongs to a pre-andean deformation belt, integrating the thrust front of the Agrio fold-and-thrust belt. Extensive outcrops of Jurassic and Cretaceous (Aalenian to Albian) deposits are exposed there, showing gradually younger sedimentary successions towards north and east (Lambert 1956, Leanza & Hugo 2001). Palaeogeographically the SVM has a position close to the basin depocentre.

Our study area is located at the northwestern end of the SVM, in which Callovian to Albian deposits are exposed (Fig. 1B). The western structure of the SVM has been described as a large-scale, asymmetrical to overturned anticline plunging towards north, eroded along their hinge zone (Lambert 1956). During field-work for the present study it was observed a low-angle reverse fault (back-thrust) that runs along the axis of this mega-structure, allowing to interpret it as a fault-propagation fold (Fig. 1B).

Based on the descriptions of the SVM of Weaver (1931), a stratigraphic survey was conducted 5 km northeast of cerro Mallín Quemado. The stratigraphic column in Fig. 2 is based on observartions made in the site known as Puesto Baez (38°31'50.1"S, 70° 04'39.7"W; Fig. 1B). In this sector rather well exposed outcrops of the Quintuco and Mulichinco formations can be studied. In this point the Vaca Muerta Fm is covered by a thin carpet of modern alluvial/aeolian deposits, although laterally it is possible to observe its relationship with the Quintuco Fm (Fig. 1B).

In Fig. 2 the Quintuco Fm is shown with partial thickness of 70.3 m, and based on field observations it could inferred that its lower contact lies at not more than 12 m below the base of the stratigraphic column. The cross-section in Fig. 3 shows the stratigraphic relationships observed between the different units, their contact-surfaces are indicated by roman numerals. Contact-surfaces I-III are established at the shifts of predominant lithology within a gradational and continuous sedimentary succession. Laterally these contact-surfaces show an interfingering pattern, while in regional scale the deposits limited by them exhibit a prograding character from south to north. The contact-surface IV forms a well-defined boundary as a sharp contact, overlain by the transgressive marine deposits of the Agrio Formation.

Fig. 3 shows some of the different stratigraphic schemes proposed in previous studies in the area. In Leanza (2009), Leanza et al. (2011), Schwarz et al. (2011), and Olivo et al. (2016) the Quintuco Fm is approximately placed between the contact-surfaces II and III, being represented by a shallow marine to proximal deltaic dominant sandy succession. The contact-surface III is consigned by Olivo et al. (2016) as a first-order bounding surface, named by Leanza (2009) as the Huncalican unconformity (formerly Intravalaginian unconformity). Between the contact-surfaces III and IV occurs a reddish siliciclastic succession, attributed to fluvial deposits (Leanza 2009) or continental to marginal-marine at the top (Schwarz et al. 2011, Martínez & Olivo 2015), and assigned to the Mulichinco Fm. According to our observations, this later succession is interpreted as deposits of distributary channels and lacustrine bodies, developed under an upper delta plain environment. Above the contact-surface IV the Agrio Fm is developed, existing in this case a generalized consensus regarding the location of its basal contact.

As discussed above, the difference between these schemes with respect to the descriptions of Weaver (1931) arises mainly from the redefinition of the lithostratigraphic units on the basis of concepts of sequence stratigraphy. In this paper the identification of the Quintuco Fm and its underlying and overlying units has been made on the basis of the lithological descriptions provided by Weaver (1931) from this region. For the purpose of lithostratigraphic classification, only lithologic attributes have been considered and analyzed in lithofacial terms. The fossil content is analyzed independently of the other attributes, with the purpose to establish a temporal framework to the succession analyzed in this region after lithostratigraphic classification.

LITHOFACIES

Five lithofacies (F1-F5) were recognized in the Quintuco Fm deposits in the study area (Table 1). In outcrops they form a monotonous, dark coloured siliciclastic succession, gradationally from the black shales of the underlying Vaca Muerta Fm towards the sandy-dominated deposits of the Mulichinco Fm. The deposits of the Quintuco Fm are thus characterized as a hetrolithic, coarsening-upwards succession integrated by interbedded mudstones, wacky sandstones, calcareous sandstones, fine-grained sandstones, and thin intercalations of coquiniferous sandy limestones.

F1. Laminated sandy mudstones

Black to dark gray laminate sandy mudstone, with some massive interbedded horizons. The lamination is medium range (between 5 to 10 mm), producing a platy type parting (sensu Potter et al. 1980). However, in the weathered surface these sediments tend to break or disintegrate in the form of blocky structures. Only scarce ammonite fragments were collected from these levels. Deposits of F1 conform the first 30 m of the exposed section (Fig. 2), developed as a monotonous succession interrupted only by sporadic intercalation of thin horizons of calcareous sandstones (see facies F4). The laminated sandy mudstone facies gradationally overlies the black shales of the Vaca Muerta Fm, granting to the naked eye an aspect of similar appearance. However, the main distinction lies in the finer lamination (minor to 2 mm-thick) and the well-developed fissility of the Vaca Muerta Fm shale facies, which break as thin flagstone-like rocks.

Interpretation: This facies is attributed to pelitic particle settling from suspension to low flow regime under low oxygen water conditions. Massive intercalated beds can be related to the action of burrowing infauna (Byers 1974), or by reworking processes of the muddy substrate by combined flow currents during storm events (Brenchley et al. 1993).

F2. Wacky sandstones

Dark greenish gray, fine-grained sandstones with abundant pelitic matrix. These deposits are weakly lithified, forming extensive tabular bodies with sharp basal, non-erosive contact. Each individual body reaches 1.2 m in thickness,

Table 1. Summary of the lithofacies recognized from deposits of the Quintuco Fm in Mallín Quemado (Puesto Báez).

Code	Name	Sedimentological attributes	Geometry	Interpretation
F1	Laminated sandy mudstones	Black to dark gray sandy mudstones. Medium range lamination (5 to 10 mm). Platty type parting. Scarce ammonites.	Tabular. Pass gradationally from underlying black shales of the Vaca Muerta Fm.	Suspension deposits. Deposition from water column. Low oxygen water conditions.
F2	Wacky sandstones	Dark greenish gray, fine -grained wacky sandstones. Massive to faint lamination.	Tabular. Sharp basal contact.	Suspension deposits. Deposition from suspension clouds. Interaction of waning turbulent flow with bedload.
F3	Fine to medium-grained sandstones	Yellowish to greenish gray, fine to medium-grained quartzitic sandstones. Low content of muddy matrix (< 10%) Massive to laminated. Scarce ammonites.	Tabular. Sharp basal contact.	
F4	Calcareous sandstones	Greenish gray to yellowish gray, fine to medium-grained quartzitic sandstones. Monospecific, autochthonous oyster assemblage of *Aetostreon* cf. *latissimum*.	Tabular. Sharp basal contact.	Soft-bottom marine. Low sedimentation rate. High environmental stress conditions. Dysaerobic conditions.
F5	Coquiniferous sandy limestones	Dark ochre (gray in fresh surface), coquiniferous sandy limestones. Monospecific, autochthonous and parautochtonus oyster assemblage of *Aetostreon* cf. *latissimum*.	Tabular. Sharp basal contact.	Soft-bottom marine. Very low sedimentation rate High environmental stress conditions. Dysaerobic conditions. Strongly influenced by winnowing and storm waves reworking.

however tending to amalgamate and developing a monotonous succession of up to 18 m-thick. Internally, massive or faintly laminated. No bioturbation was observed. Occasionally there occur dark-coloured carbonate concretions, ranging 7-15 cm in diameter, without fossils. This facies is the second in order of abundance, mostly developed towards the top of the succession (Fig. 2).

Interpretation: The development of mixed intermediate grain-size clastic deposits, the absence of bioturbation (unburrowed) and the poor or non-existent primary tractive structures, suggest low energy depositional conditions, non affected by the normal wave activity, and unfavourable conditions for the development of epibenthos and endobenthos.

F3. Fine to medium-grained sandstones

Fine to medium-grained quartzitic sandstones, yellowish to greenish gray in colour, showing a low content of muddy matrix (less than 10%). This facies is developed along extensive tabular bodies with planar sharp basal contact, internally massive or with horizontal stratification. Isolated ammonites and very scarce faint bioturbation have been observed. Thin levels of fossiliferous calcareous sandstones (see facies F4), and spherical to sub-spherical carbonate concretions interbedded with this facies can occur. These deposits appear towards the middle part of the succession, reaching 13.4 m in thickness.

Interpretation: The origin of the horizontal stratification is usually attributed to sandy deposition under upper flow regime conditions (Harms et al. 1982). In marine settings this facies type is mainly developed in beach areas by swash and backwash flows (Clifton 1981, Reineck & Wunderlich 1998). However, horizontal lamination in shoreface or deeper marine environments have been described by Reineck & Singh (1972) and Reineck & Wunderlich (1998) as "plane bed lamination from suspension", attributed to storm-sand layers deposits. According to Reineck & Singh (1972) laminate sand can be formed from suspension clouds, in still or slowly moving waters after a storm event. The high wave energy of the rough sea can transport sand in suspension from the coast towards the open sea, producing the deposition by decantation after decreasing wave energy.

F4. Calcareous sandstones

Fine to medium-grained quartzitic sandstones, greenish gray to yellowish gray in colour, with less than 10% of muddy matrix. These deposits are massive or structurless, forming tabular bodies, laterally wedged, with sharp planar basal contact. A moderate content of calcium carbonate cement confers greater resistance to erosion, forming prominent beds that stand out in the relief. These sandstone bodies commonly range 0.15 to 0.40 m in thickness, with a maximum of 0.7 m. This facies appears intercalated among deposits of F1 and F3, exhibiting a thickening upwards trend. The levels of calcareous sandstones associated with F3, contain shell concentrations of the oyster *Aetostreon* cf. *latissimum*. These shell concentrations form tabular bodies of densely packed valves in life position (small cup-shaped recliners, sensu Machalski 1998), conforming to a monospecific autochthonous assemblage (Kidwell et al. 1986). The shells are well preserved with no signals of abrasion, bioerosion or encrustations.

Interpretation: Facies F4 shows the same textural characteristics of the interbedded facies F3, so we consider a similar origin linked to storm-sand layers deposits. However, the carbonate cement seems to indicate a prolonged interruption in the sediment input afterwards the storm occurrence. This latter interpretation is consistent with the development of large oyster populations, suggesting a prolonged subaqueous exposure of the marine substrate. In the same way, according to Machalski (1998) the life position type of these soft-bottom oysters would imply a lower background sedimentation rate. The monospecific shell associations may reflect high environmental stress conditions (Hanna & Fürsich 2012), likely under the influence of a declining oxygen gradient (dysaerobic condition) (Wignall 1993). Likewise, the absence of encrustations or bioerosion marks on shells suggests conditions of lower biological productivity (Lescinsky et al. 2002).

F5. Coquiniferous sandy limestones

Ochre sandy limestones, showing medium to dark gray colour in fresh surface. These deposits form tabular beds of 0.4 m in average thickness, exceptionally reaching 1.65 m. This facies only appears at the upper part of the succession, interbedded into wacky sandstone levels (facies F2) and shares some general features with the fossiliferous calcareous sandstones (facies F4). The fossiliferous beds consist of shell accumulations of *A.* cf. *latissimum*, showing two types of concentrations. The first consists of monospecific autochthonous assemblages, typified by dense accumulations of oysters in life position. The valves are extensively distributed along tabular bodies, internally composed of several beds of skeletal accumulations. No signals of abrasion, bioerosion or encrustations have been observed in the valves. The second type is composed of lenticular or wedged bodies cutting through an erosive contact the concentrations of the first type. The oyster valves in these bodies are chaotically distributed, articulate and disarticulated forming monospecific parautochthonous assemblages (Kidwell et al. 1986). Likewise, no signals of bioerosion or encrustations have been observed in the valves. It should be noted that the deposits of facies F5 correspond to the so-called "lenguas distales de la Formación Picún Leufú" (distal tongues of the Picún Leufú Fm) described by Leanza (1973, 1975) from the area of the Cerro Mallín Quemado.

Interpretation: Similar conditions as for facies F4 are inferred, where the upwards increase in calcium carbonate contents and thickness of the oyster beds would indicate prolonged intervals with low sedimentation rate. The shell concentrations denote a mixed origin. The monospecific autochthonous assemblages indicate soft-bottom oyster colonization of a habitat free of predators, possibly regulated by environmental stress conditions. The monospecific parautochthonous assemblages denote catastrophic events where oyster populations were affected by storm waves producing the winnowing, reworking and partial disarticulation of the shells (Kidwell et al. 1986).

FACIES ASSOCIATION AND PALAEOENVIRONMENT

The facies association shows a domain of heterolitic, fine-grained siliciclastic marine deposits, mainly developed under the influence of sporadic storm waves. The dominant lithofacies (F1, F2-F3) show similar characteristics in the sedimentary bodies, mainly differing by the lithological change generated by the variation in their relationships of mud/sand contents. In general terms, the predominance of dark colours and the almost absence of bioturbation suggest low-oxygen marine conditions (Kauffman 1986, Myrow 1990, Potter et al. 2005). In this sense, monospecific shell-beds of facies F4 and F5 are consistent with environmental conditions of lower biological productivity. It is very likely that the environmental conditions were well tolerated by *A.* cf. *latissimum* but not by other organisms which could have predated them actively, thus enabling the proliferation into large populations.

Based on these features the succession of the Quintuco Fm is attributed to marine deposits developed in the offshore transition zone, defined as the area situated in the upper part of the inner shelf and limited by the fair-weather and the storm wave base (Shiip 1984). The offshore transition zone is characterized in lithofacial terms by Eide et al. (2015: 55) as a heterolithic succession comprising sandstone beds deposited by occasional storms, interbedded with mudstone deposited from suspension during fair-weather periods.

Sedimentological studies carried out on offshore-transition-zone environments, show that current coasts and ancient sedimentary successions have close analogies with the corresponding features of the Quintuco Fm deposits, strongly supporting the above interpretation. These are: (1) development of a coarsening-upward succession of heterolithic domain (Campbell 1971, Leckie et al. 1989, Johnson & Baldwin 1996, Eide et al. 2015); (2) development of extensive, markedly tabular sedimentary bodies (Eide et al. 2015), with thickening upward trends of the sandy beds (Leckie et al. 1989); (3) deposits characterized by poorly stratified beds, massive deposits, or presence of bedforms development under upper flow regime by storms (Shiip 1984, Greenwood & Mittler 1985, Leckie et al. 1989); (4) development of a dominant dark colour succession due to a high content of organic matter preserved under low-oxygen conditions (Shiip 1984).

In agreement with the original lithostratigraphic characterization of the Quintuco Fm by Weaver (1931), it is concluded that the apparent similarity of its deposits with those of the underlying Vaca Muerta Fm arises from the monotony that both successions exhibit in the outcrops. The gradational change makes hard to establish a clear boundary between these units, and in many cases it may be more or less arbitrary. However, according to the criterium adopted in a previous study (Parent et al. 2015), the boundary is established in the levels where the pelitic sediments lose the well-developed fissility characteristic of the black shales and sandy shales of the Vaca Muerta Fm (see facies F1). The loss of fissility in the shales would be linked to the gradual passage from euxinic-anoxic to dysoxic-oxic conditions. According to Moon & Hurst (1984), under very low oxygen conditions the presence of organic compounds acting as peptizing agent inhibit clay minerals flocculation, enabling their decantation and settling as single elements, thus favoring the development of marked fissility.

Summarizing, in general terms the succession Vaca Muerta-Quintuco formations indicates a gradual change in the sedimentary conditions, passing from euxinic to anoxic, as typical in the offshore zone (Vaca Muerta Fm facies), towards dysoxic conditions in shallower areas affected by storm waves typical of the offshore transition zone (Quintuco Fm facies).

THE AMMONITE FAUNA

Ammonites are scarce and poorly preserved in the studied section. Some few specimens could be collected from the Quintuco Fm. This material has provided the time-diagnostic elements in the the study area. In the upper part of the Vaca Muerta Fm a specimen of *Himalayites andinus* Leanza, 1975 was collected, indicating a level within the Upper Tithonian. The fossils are housed in the Museo Prof. Olsacher, Zapala (MOZ-PI). The ammonite succession and accessory fauna recorded (Fig. 2) is as follows (levels noted MQ-PB, Mallín Quemado area-Puesto Báez site), from below:

- Quintuco Fm
Level MQ-PB-1: *Groebericeras bifrons* (fragmentary macroconchs).
Level MQ-PB-9: *Substeueroceras permulticostatum* (Fig. 4) and *Groebericeras bifrons* (Fig. 5A-B).
Levels MQ-PB-10, 12: indeterminate ammonites and *Aetostreon* cf. *latissimum* (Lamarck).
Level MQ-PB-14: *Groebericeras bifrons* (1 large fragmentary macroconch) and oysters.
Level MQ-PB-16: *Subthurmannia* sp. A. and *A.* cf. *latissimum*.
Level MQ-PB-18: nautiloids and *A.* cf. *latissimum*.
Level MQ-PB-19: indeterminate ammonite.
Level MQ-PB-20: *Cuyaniceras*? n. sp. A (Fig. 5C), *Subthurmannia* sp. A, nautiloids, oysters and other bivalves.
- Mulichinco Fm
Level MQ-PB-36: nautiloids (MOZ-PI 8533, 8588) and *Panopea dupiniana* d'Orbigny (MOZ-PI 8534).
Level MQ-PB-38: *Anditrigonia lamberti* Levy (MOZ-PI 8536, 8539, 8528), *Pterotrigonia aliformis* (Parkinson) (MOZ-PI 8527), *Cucullaea gabrielis* Leymerie (MOZ-PI 8531), *Pinna robinaldina* d'Orbigny (MOZ-PI 8529), *P. dupiniana* (MOZ-PI 8526), *Aphrodina*? sp (MOZ-PI 8535), *A.* cf. *latissimum*.
Level MQ-PB-44: *Anditrigonia lamberti* (MOZ-PI 8532), *Lucina* sp., *P. dupiniana*.
Level MQ-PB-46, 54: *P. dupiniana*.

***Substeueroceras permulticostatum* (Steuer, 1897), Fig. 4:** A large, almost complete adult macroconch (MOZ-PI 8909) from level MQ-PB-9. Compressed platycone with suboval whorl section in the inner whorls, passing to subrectangular with flat flanks and sharp umbilical shoulder from middle whorls. The umbilicus is relatively narrow in the inner whorls, becoming much wider from the last whorl of phragmocone, giving this species its salient aspect. The bodychamber is strongly uncoiled and about three-quarters whorl long. The ribbing consists of fine, slightly flexuous primary ribs which irregularly bi- or trifurcate around mid-flank, some divide from the umbilical shoulder in the adult phragmocone and bi- or trifurcate again on mid-flank; towards the peristome they become wider and more rounded. Secondary ribs reach the ventro-lateral shoulder evenly spaced, fading off besides a narrow ventral groove; this groove fades off from the beginning of the bodychamber and the ribs, slightly weaken, cross the venter uninterrupted. The maximum preserved diameter is c. 250 mm, with the last septum at 150 mm.

The shell-shape and sculpture clearly indicate the specimen belong to the genus *Substeueroceras*. The strongly evolute outer whorls, the flat flanks with sharp umbilical shoulder and the high rib density perfectly match with *S. permulticostatum* as described by Steuer (1897). This species differs from *Substeueroceras koeneni* (Steuer, 1897) by the more rectangular whorl section and the wider adult umbilicus. On the other hand, *S. koeneni* occurs in a lower stratigraphic position, most commonly in the Koeneni Zone of the uppermost Tithonian in the Andean sense. It is worth to note that incomplete specimens of *S. permulticostatum* could be confused with the stratigraphically older *S. koeneni*.

This species seems to be rare and it had been figured only by Steuer (1897), although some citations have been published, e.g. Gerth (1925) with discussion and used as index of a Berriasian Permulticostatum Zone (currently unused), and Leanza & Hugo (1977) for Mallín de los Caballos, Huncal and Cajón de Almanza. The specimen figured by Steuer (1897: pl. 23: 1) is the holotype by monotypy since it was the only one available to the author, coming from his level Loncoche-II of a section of Arroyo Loncoche, Mendoza Province. The ammonites cited by Steuer (1897: 19) from that level are, nominally: *Reineckeia koellikeri* (Oppel), *Odontoceras fasciatum* Steuer, and *Odontoceras subfasciatum* Steuer.

R. koellikeri is hard to interpret as part of this ensemble (set of fossils not horizoned or listed altogether with no specification of association; Parent et al. 2011) for it, nominally, should belong to the late Tithonian himalayitid genus *Micracanthoceras* (see Parent et al. 2011, Frau et al. 2016).

O. subfasciatum has been assigned to *Substeueroceras* by some authors (e.g. Vennari et al. 2012) and even considered as a synonym of *S. koeneni* by Verma & Westermann (1973). However, the sculpture composed by strong prosocline primary ribs divided on mid-flank in prorsiradiate secondaries, clearly differs

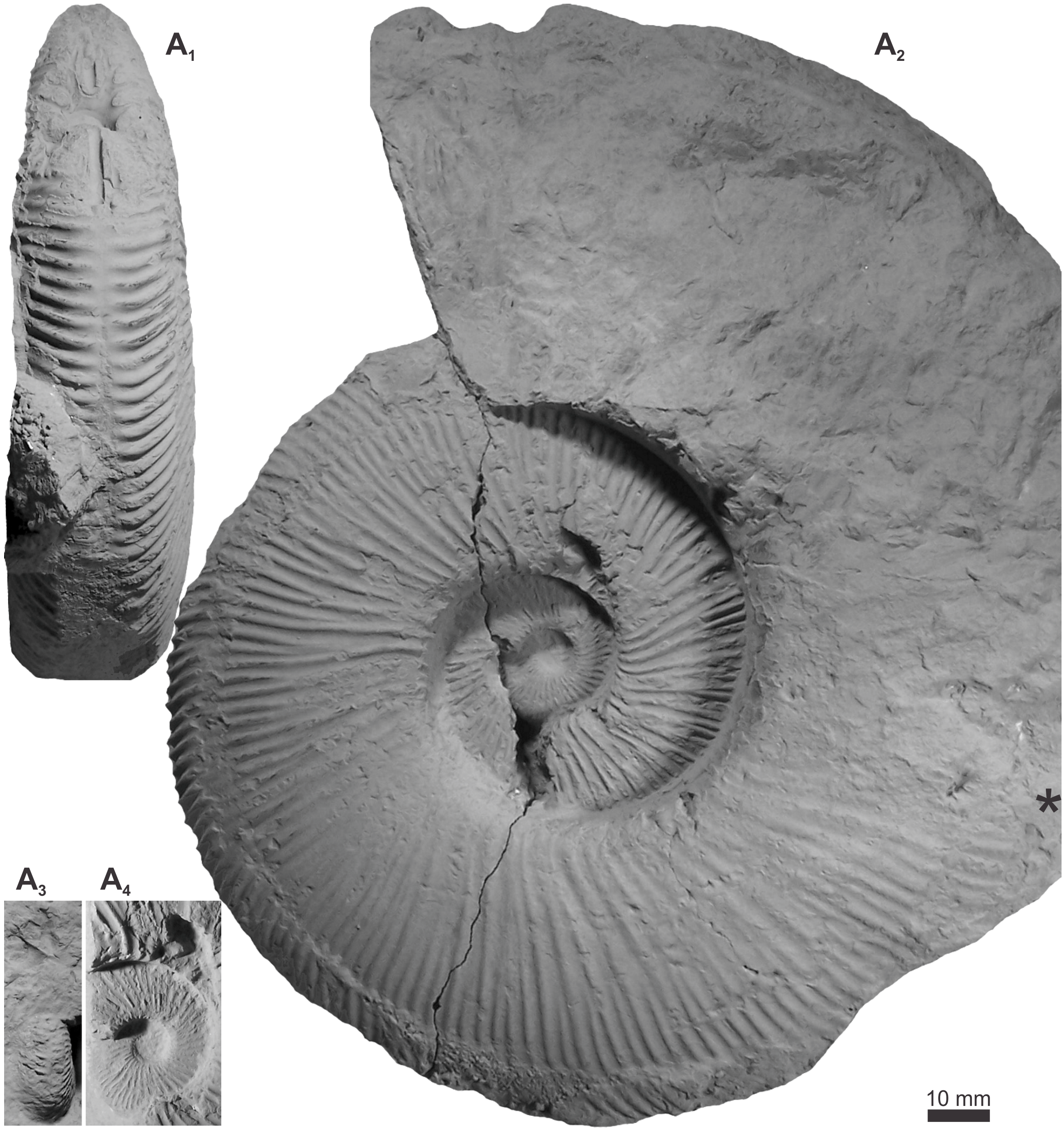

Figure 4. *Substeueroceras permulticostatum* (Steuer, 1897), complete adult macroconch (terminal-half of bodychamber removed), MOZ-PI-8909, Puesto Báez, level MQ-PB-09, Noduliferum Zone. $\mathbf{A_1}$: ventral view of the beginning of the last whorl of phragmocone; $\mathbf{A_2}$: lateral view, the asterisk indicates the last adult septum; $\mathbf{A_3}$-$\mathbf{A_4}$: ventral and lateral views of the inner whorls showing the rounded venter and the narrow umbilicus. – All natural size (x1).

from the diagnostic states of this character in *Substeueroceras* (e.g. Verma & Westermann 1973: 229). Steuer (1897: 44, 76) studied specimens from Arroyo Loncoche and Arroyo Cieneguita, but did not designate a type specimen, neither later by subsequent authors at our knowledge. We take the oportunity to designate the figured specimen from Arroyo Loncoche (Steuer 1897: pl. 19: 1-2) as the lectotype of *O. subfasciatum*.

O. fasciatum could be assigned to *Choicensisphinctes striolatus* (Steuer, 1897), since it is indistinguishable from specimens of the Koeneni Zone of Pampa Tril (Parent et al. 2015: fig. 32). Steuer (1897) studied specimens from Arroyo Loncoche and Arroyo Cieneguita, but did not designate a type specimen. We take the oportunity to designate the figured specimen from Arroyo Loncoche (Steuer 1897: pl. 18: 1-2) as the lectotype of *Odontoceras fasciatum*.

Groebericeras bifrons **Leanza, 1945; Fig. 5A-B:** several specimens loose from level MQ-PB-1 (MOZ-PI 8522), others well preserved from level MQ-PB-9 (MOZ-PI 8907-8908), a large fragmentary macroconch

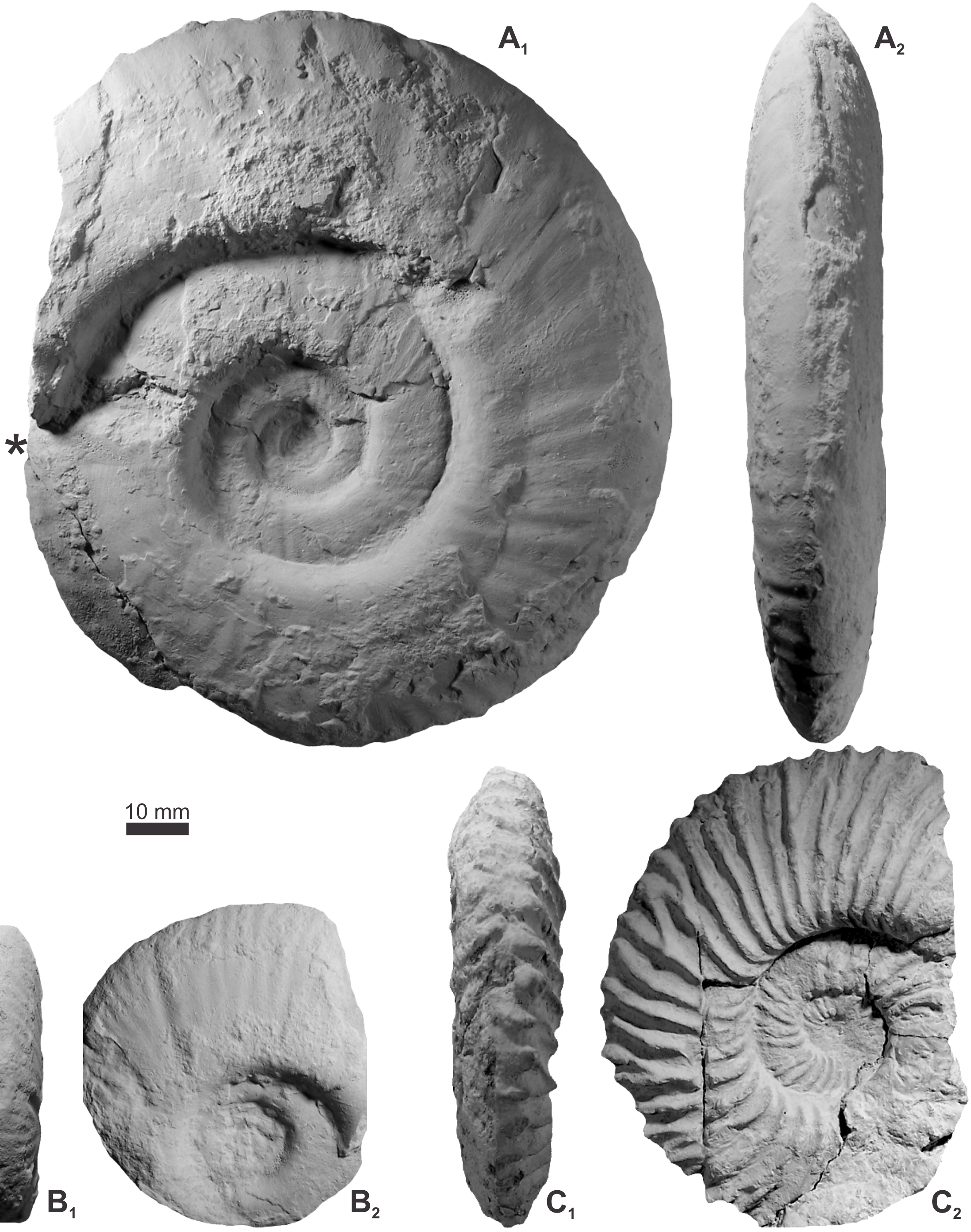

Figure 5. **A**-**B**: *Groebericeras bifrons* Leanza, 1945, Puesto Báez, level MQ-PB-09, Noduliferum Zone. **A**: virtually complete adult macroconch (MOZ-PI-8908), asterisk at the last adult septum. **B**: inner whorls (MOZ-PI-8907) of an involute variant. **C**: *Cuyaniceras*? n. sp. A, Puesto Báez, level MQ-PB-20, Noduliferum Zone; complete adult? phragmocone with beginning of the bodychamber (Col. E. Schwarz, MOZ-PI-8906/1). – All natural size (x1).

from level MQ-PB-14 (MOZ-PI 8520). The specimens in Fig. 5A-B are typical for the species, matching at comparable diameter with the lectotype and paralectotype (Leanza 1945: pl. 19: 1-2, pl. 18: 1, respectively). The best preserved specimen from level MQ-PB-14 is a complete adult macroconch with the last septum at 190 mm in diameter and maximum diameter at peristome estimated in 300 mm. The bodychamber is, at least, one whorl long.

G. bifrons has been consistently recorded in the Noduliferum Zone, above the last occurrences of *Substeueroceras koeneni* (Steuer, 1897) all throughout the Neuquén Basin north of the Huincul Arc (Leanza 1945, Leanza 1981, Aguirre-Urreta & Álvarez 1999,

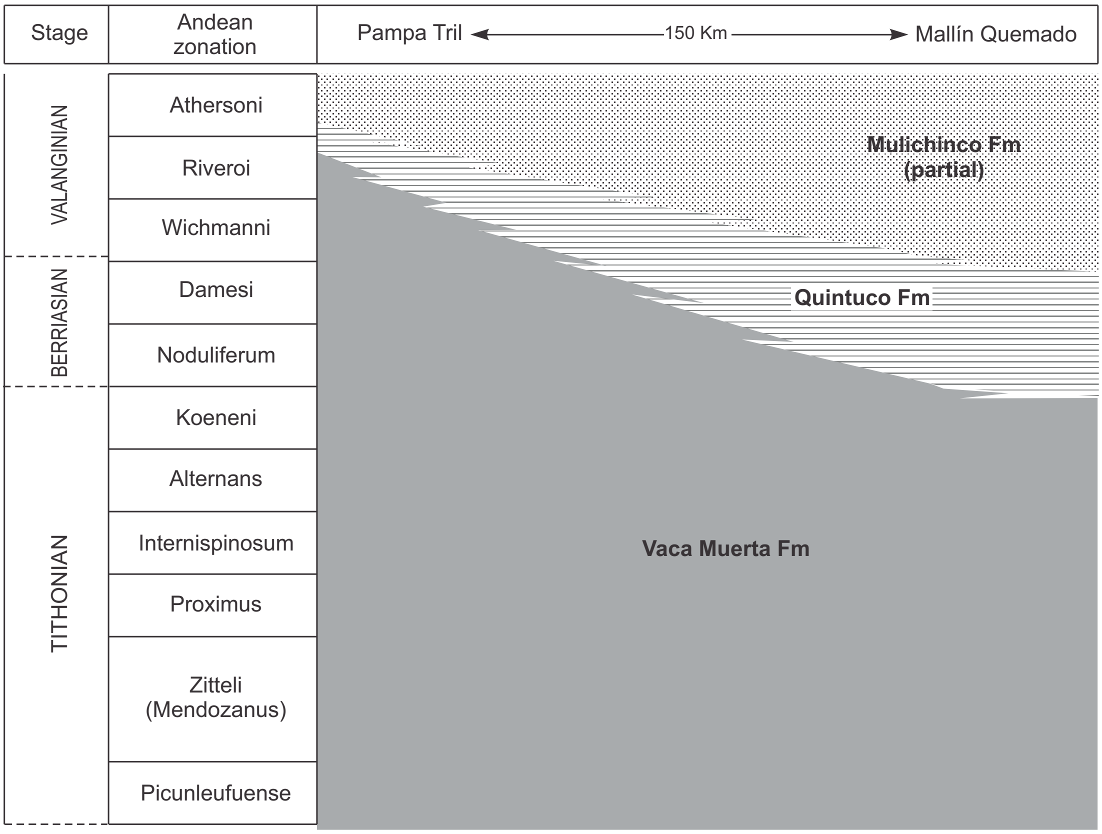

Figure 6. Age variations of the Vaca Muerta, Quintuco, and Mulichinco formations between Mallín Quemado (Sierra de la Vaca Muerta) and Pampa Tril (north, see Fig. 1A) according to the results of the present study. Chronostratigraphy and Andean zonation after Parent et al. (2011, 2015).

Parent et al. 2011, 2015). In Arroyo Cieneguita and Pampa Tril the records of *G. bifrons* are confined to the *compressum* Hz., which has been taken as the base of the Noduliferum standard Zone (Parent et al. 2015: 89).

***Cuyaniceras*? n. sp. A, Fig. 5C:** Two specimens from level MQ-PB-20, one rather complete, other fragmentary (MOZ-PI-8906/1-2). The best preserved is an adult phragmocone (incipiently uncoiled) with the beginning of the bodychamber. Compressed platycone, moderately involute with suboval to subrectangular whorl section. Inner whorls densely ribbed by acute prosocline primaries divided on the upper half of flank, some few from the umbilical shoulder. The last whorl is covered by sharp primaries born on the umbilical seam; they are mostly undivided, but some few bifurcate from a bulla on the upper half of the flank. All ribs reach the ventro-lateral shoulder, evenly spaced and forming a tubercle, then crossing the venter unchanged.

These specimens show superficial resemblance with *Neocosmoceras wichmanni* (Gerth, 1925), but this is trituberculate with more widely spaced, undivided primary ribs on the outer whorl (see lectotype refigured in Parent et al. 2015: fig. 60, a lappeted microconch).

The platyconic shell with acute ribbing irregularly bifurcated and forming ventro-lateral tubercles suggests the specimen could belong to the genus *Cuyaniceras*. However the known species of *Cuyaniceras* tend to have tabulated venter in the phragmocone what can not be observed in the present specimen. On the other hand in the present specimens the primary ribs are prosocline whereas in *Cuyaniceras* are flexuous.

The best resemblance seems to be with the ammonite from the Damesi Zone of Cerro Domuyo figured as *Neocosmoceras* aff. *perclarum* (Matheron) by Kietzmann & Vennari (2013: fig. 9e). Another very similar specimen comes from the bed l, upper Berriasian Damesi Zone, of Arroyo del Yeso (Fig. 1), figured by Leanza (1945: pl. 13: 5-6) as Palaeohoplitidae gen. et sp. indet. This specimen is a phragmocone with which the present specimen matches closely. The venter is tabulated, but in the present specimen is not well preserved, preventing a comparison at similar growth stages.

Cuyaniceras spreads a wide range of variation as observed in the several morphospecies described by Leanza (1945) from bed l of Arroyo del Yeso. The morphologic intergradation of these morphospecies was already discussed in Parent et al. (2011) in the sense that they likely represent the intraspecific variation of a single species. The bed l of Arroyo del Yeso was described as the *transgrediens* Hz. (Parent et al. 2011), and later proposed as the base for the Damesi standard Zone, approximately time-equivalent to the Boissieri Zone of the Upper Berriasian of the Tethys (Parent et al. 2015).

AGE OF THE QUINTUCO FORMATION

The stratigraphic distribution of the ammonites recorded in the studied section is indicated in Fig. 2. The chronostratigraphic assignation of the different levels is mainly based on the associations from levels MQ-PB-9 and 20.

The association of *G. bifrons* and *S. permulticostatum* (level MQ-PB-9) is described for the first time at our knowledge. *G. bifrons* has been widely recorded throughout the basin, confined within the Noduliferum Zone (Leanza 1945, Aguirre-Urreta & Álvarez 1999, Parent et al. 2011, 2015). *S. permulticostatum* was based on a specimen coming, apparently, from the Koeneni Zone (discussion above). Nevertheless, its stratigraphic range is now expanded on the basis of the present material which occurs above the lower occurrence of *G.* cf. *bifrons*. The base of the Noduliferum standard Zone is defined by the *compressum* Hz. (see Parent et al. 2015) where *G. bifrons* occurs associated with *Spiticeras fraternum* (Steuer, 1897) and *Krantziceras compressum* Parent et al., 2011. However, the association of level MQ-PB-09 is rather different and so, most likely, would belong to a different, upper horizon considering the occurrence of *G. bifrons* and *G.* cf. *bifrons* below. The lowermost part of the section (levels MQ-PB-1-8) could also belong to the Noduliferum Zone considering the occurrence of *G.* cf. *bifrons*.

The association of *Subthurmannia* sp. A with *Cuyaniceras*? n. sp. A (level MQ-PB-20) is loosely comparable with components of these genera of the *transgrediens* Hz. at the base of the standard Damesi Zone known in Pampa Tril (Parent et al. 2015) and Arroyo del Yeso (Leanza 1945) as discussed above. *Subthurmannia* has been abundantly recorded in Pampa Tril from a level of the upper Noduliferum through the Damesi Zone. Thus, the level MQ-PB-20 is assigned to the Damesi Zone, which base is traced at this level.

There is no much published information about the ammonite fauna and biostratigraphy of the study area. Leanza (1975) provided a log-section of outcrops close to our section, indicating the occurrence of *Spiticeras fraternum* (Steuer, 1897), *Cuyaniceras*, and *Hemispiticeras* cf. *steinmanni* (Steuer, 1897) in a stratigraphic position comparable or, perhaps, equivalent to our levels MQ-PB-18-20. The two first ammonites, if associated, indicate the Damesi Zone, for very similar ammonites occur associated in Arroyo del Yeso (Leanza 1945) and in Pampa Tril (Parent et al. 2015) in this chronostratigraphic zone, especially in the *transgrediens* Hz.

In conclusion, the minimum chronostratigraphic range (age) of the Quintuco Fm in the study area can be rather safely assumed as Noduliferum-Damesi zones, that is the Berriasian in the Andean scale. Nevertheless, as the thick uppermost level MQ-PB-21 of the Quintuco Fm (Fig. 2) has not yielded ammonites, it can not be excluded the possibility that it could be already Valanginian.

DISCUSSION AND CONCLUSION

A lithostratigraphic unit is a body of rock characterized by its lithology and bounded in space (vertically and horizontally) by lithological discontinuities (Callomon 1985, Miall 2016: 313). Formation is the essential unit and its recognition in the field fulfils one of the primary purposes of the lithostratigraphy which is the construction of geological maps. Comparison of lithologies of different sections –lithostratigraphic correlation– is another main purpose of lithostratigraphic classification. Two lithostratigraphic units may be separated by non-sequences and, it is worth to consider that their boundaries may be, and most usually are, more or less diachronic in different localities. The fossil contents and the conjugated time (age of the rocks) are not considered in their definition.

These simple statements are widely accepted but, for different reasons not always followed in the practice, what has made of the Quintuco Fm (Weaver 1931) a number of different "hybrid" units with different lithologies and/or bounded by lithological discontinuities, discontinuity surfaces (non-sequences), or unconformities (observed or inferred), its definition changed, and its recognition usually depending on the "characteristic ammonites" (biostratigraphy) or the "age of these rocks" (chronostratigraphy). This latter distinction is emphasized because of the reason that the occurrence of, for example, the ammonite *Substeueroceras koeneni* indicates the *Koeneni* Biozone (a biostratigraphic unit: rocks characterized by their fossils), but does not accurately imply by itself (and much less in isolation), as currently assumed, an age in the interval indicated by the Koeneni Zone (a chronostratigraphic unit: rocks characterized by their age, bounded by time-planes).

The gradual transition and the close lithologic similarity between the locally thick and tectonically perturbed deposits of the Vaca Muerta and Quintuco formations, in the basin centre, have hampered their field recognition. Nevertheless, Leanza (1973, 1975) and Leanza & Hugo (1977) have studied the different ages of these successions through the basin. Although in the 80s an accurate framework of the Lower Mendocian Cycle was available (Mitchum & Uliana 1985, Macellari 1988), later studies based on the sequence stratigraphy model of Gulisano et al. (1984) changed the meaning of the Quintuco and Mulichinco formations, by moving their boundaries disregarding the lithologic features of the original definition.

From the lithological features indicated by Weaver (1931), and described in detail above for the study area (see Fig. 2), the Quintuco Fm can be clearly recognized and differentiated –from the underlying and overlying units– all throughout the Sierra de la Vaca Muerta. The offshore Vaca Muerta Fm-facies, developed under euxinic-anoxic conditions change gradually towards the dysoxic, storm waves-influenced conditions of the offshore transition zone which characterize the Quintuco Fm-facies.

Although the Quintuco-Mulichinco formations boundary is clear because of their strong lithologic contrast, the passage is gradational. The sand-bodies of the Mulichinco Fm become predominant in the succession, indicating transition towards a shoreface environment. Independently of minor sea level changes which could be recognized, the succession shows a clear upwards trend of somerization, as indicated by the development of a deltaic environment towards the middle and upper parts of the succession.

We have not observed any discontinuity surface which could indicate a significant temporal gap in the succession Vaca Muerta-Mulichinco formations in the study area. This observation agrees with the conclusion by Medina et al. (2016) obtained in the Cerro Salado area, located about 30 km north of the section studied here.

The age of the Quintuco Fm in the study area is Berriasian (Noduliferum to Damesi zones), and could range up into the early Valanginian (Figs. 2, 6). Towards northern positions of the basin, e.g. Pampa Tril area (Parent et al. 2015), the age is early Valanginian (Fig. 6). This pattern of the units becoming younger towards north reflects the shoreline progradation towards the basin.

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REFERENCES

Aguirre-Urreta M.B. & Alvarez P.P., 1999. The Berriasian genus *Groebericeras* in Argentina and the problem of its age. – *Scripta Geologica, special issue* **3**: 15-29.

Arregui C., Carbone O. & Leanza H., 2011. Contexto tectosedimentario. *In*: H. Leanza, C. Arregui, O. Carbone, J.C. Danielli & J. Vallés (*eds*.): Relatorio del 18º Congreso Geológico Argentino. Geología y Recursos Naturales de la Provincia del Neuquén: 29-36.

Brenchley P.J., Pickerill R.K. & Stromberg S.G., 1993. The role of wave reworking on the architecture of storm sandstone facies, Bell Island Group (Lower Ordovician), eastern Newfoundland. – *Sedimentology* **40**: 359-382.

Byers C.W., 1974. Shale fissility: relation to bioturbation. – *Sedimentology* **21**: 479-484.

Callomon J.H., 1985. Biostratigraphy, chronostratigraphy and all that –again. *In*: A. Zeiss & O. Michelsen (eds.): International Symposium on Jurassic Stratigraphy, Erlangen. Geological Survey of Denmark, Copenhagen.

Campbell C.V., 1971. Depositional model-Upper Cretaceous Gallup beach shoreline, Ship Rock Area, Northwestwern New Mexico. – *Journal of Sedimentary Petrology* **41**: 395-409.

Carozzi A.V., Orchuela I.A. & Rodríguez-Schelotto M.L., 1993. Depositional models of the Lower Cretaceous Quintuco-Loma Montosa Formation, Neuquén Basin, Argentina. – *Journal of Petroleum Geology* **16**: 421-450.

Clifton E.W., 1981. Progradational sequences in Miocene shoreline deposits, Southeastern Caliente Range, California. – *Journal of Sedimentary Petrology* **51**: 165-184.

De Ferrariis C., 1947. Edad del arco o Dorsal antigua del Neuquén oriental de acuerdo con la estratigrafía de la zona inmediata. – *Revista de la Asociación Geológica Argentina* **2**: 256-283.

Digregorio J.H., 1972. Neuquén. *In*: A.F. Leanza (*ed*.): Geología Regional Argentina. – *Centenario Academia Nacional de Ciencias*: 439-506.

Digregorio J.H., 1978. Estratigrafía de las acumulaciones mesozoicas. – *Séptimo Congreso Geológico Argentino*. Relatorio: Geología y Recursos Naturales del Neuquén: 37-65.

Digregorio J.H., Gulisano G.A., Guitérrez Pleimling A.R. & Minniti S.A., 1984. Esquema de la evolución geodinámica de la Cuenca Neuquina y sus implicancias paleogeográficas. – *Actas del Noveno Congreso Geológico Argentino* **2**: 147-162.

Eide C.H., Howell J.A. & Buckley S.J., 2015. Sedimentology and reservoir properties of tabular and erosive offshore transition deposits in wave-dominated, shallow-marine strata: Book Cliffs, USA. – *Petroleum Geoscience* **21**: 55-73.

Frau C., Bulot L.G., Wimbledon W.A.P. & Ifrim C., 2016. Upper Tithonian ammonites (Himalayitidae Spath, 1925 and Neocomitidae Salfeld, 1921) from Charens (Drôme, France). – *Geologica Carpathica* **67**: 543-559.

Gerth E., 1925. La fauna necocomiana de la Cordillera Argentina en la parte meridional de la Provincia de Mendoza. – *Actas de la Academia Nacional de Ciencias de la República Argentina* **9**: 57-132.

Greenwood B. & Mittler P.R., 1985. Vertical sequence and lateral transition in the facies of a barred nearshore environment. – *Journal of SedimentaryPetrology* **55**: 336-375.

Groeber P., 1946. Observaciones geológicas a lo largo del meridiano 70. 1 Hoja Chos Malal. – *Revista de la Sociedad Geológica Argentina* **1**: 177-208.

Groeber P., 1952. Ándico. *In*: P. Groeber, P. N. Stipanicic and A.R.G. Mingramm (*eds*.): Mesozoico. Geografía de la República Argentina. – *Sociedad Argentina de Estudios Geográficos*, Tomo **2**, primera parte: 349-536.

Gulisano C.A., Gutiérrez Pleimling A.R. & Digregorio R.E., 1984. Análisis estratigráfico del intervalo Tihoniano-Valanginiano (formaciones Vaca Muerta, Quintuco y Mulichinco) en el suroeste de la provincia del Neuquén. – *Noveno Congreso Geológico Argentino* **1**: 221-235.

Hannaa W.A. & Fürsich F.T., 2012. Palaeoecology and environmental significance of benthic associations from Cenomanian-Turonian of eastern Sinai, Egypt. – *Beringeria* **42**: 93-138.

Harms, J.C., Southard J.B. & Walker R.G., 1982. Structures and Sequences in Clastic Rocks. – *Society of Economic Paleontologists and Mineralogists, Short Course* **9**: 1-349.

Herrero Ducloux A., 1946. Contribución al conocimiento geológico del Neuquén extraandino. – *Boletín de Informaciones Petroleras* **23(226)**: 245-281.

Johnson H.D. & Baldwin C.T., 1996. Shallow clastic seas. *In*: H.G. Reading (*ed*.): Sedimentary Environments: processes, facies and stratigraphy, Chapter 7: 236-286. Blackwell Scientific Publications.

Kauffman E.G., 1986. High-resolution event stratigraphy: regional and global Cretaceous bio-events. *In*: O.H. Walliser (*ed*.): Global Bio-Events: A Critical Approach. – *Proceedings of the First International Meeting of the IGCP Project 216*: Global Biological Events in Earth History, p. 279-335. Springer-Verlag.

Kidwell S.M., Fürsich F.T. & Aigner T., 1986. Conceptual framework for the analysis and classification of fossil concentrations. – *Palaios* **1**: 228-238.

Kietzmann D. & Vennari V.V., 2013. Sedimentología y estratigrafía de la Formación Vaca Muerta (Tithoniano-Berriasiano) en el área del Cerro Domuyo, norte de Neuquén. – *Andean Geology* **40**: 41-65.

Lambert L.R., 1956. Descripción Geológica de la Hoja 35b Zapala. – *Boletín de la Dirección Nacional de Minería* **83**: 1-94.

Leanza A.F., 1945. Ammonites del Jurásico superior y del Cretáceo inferior de la Sierra Azul, en la parte meridional de la provincia de Mendoza. – *Anales del Museo de La Plata, nueva serie, Paleontología* **1**: 1-99.

Leanza H.A., 1972. *Acantholissonia*, nuevo género de ammonites del Valanginiano de Neuquén, Rep. Argentina y su posición estratigráfica. – *Revista de la Asociación Geológica Argentina* **27**: 63-70.

Leanza H.A., 1973. Estudio sobre los cambios faciales de los estratos limítrofes jurásico-cretácicos entre Loncopué y Picún Leufú provincia de Neuquén, República Argentina. – *Revista de la Asociación Geológica Argentina* **28**: 97-131.

Leanza H.A., 1975. *Himalayites andinus* n. sp. (Ammonitina) del Tithoniano superior de Neuquén, Argentina. – *Actas del Primer Congreso Argentino de Paleontología y Estratigrafía* **1**: 581-588.

Leanza H.A., 1981. The Jurassic-Cretaceous boundary beds in West Central Argentina and their ammonite zones. – *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* **161**: 62-92.

Leanza H.A., 2009. Las principales discordancias del Mesozoico de la Cuenca Neuquina según observaciones de superficie. – *Revista del Museo Argentino de Ciencias Naturales, Nueva Serie* **11**: 145-184.

Leanza H.A. & Hugo C.A., 1977. Sucesión de ammonites y edad de la Formación Vaca Muerta y sincrónicas entre los paralelos 35º y 40º l.s, Cuenca Neuquina-Mendocina. – *Revista de la Asociación Geológica Argentina* **32**: 248-264.

Leanza H.A. & Wiedmann J., 1989. Nuevos amonites del Berriasiano/Valanginiano (Cretácico Inferior) de Neuquén, Argentina. *In*: J. Wiedmann (*ed*.): Cretaceous of the Western Tethys. Proceedings Third International Cretaceous Symposium, Tübingen (1987), 793-810. Stuttgart.

Leanza H.A., Marchese H.G. & Riggi J.C., 1977. Estratigrafía del Grupo Mendoza con especial referencia a la Formación Vaca Muerta entre los paralelos 35° y 40° l.s., Cuenca Neuquina-Mendocina. – *Revista de la Asociación Geológica Argentina* **32**: 190-208.

Leanza H.A. & Hugo C.A., 2001. Hoja Geológica 3969-I - Zapala, provincia del Neuquén. – *Boletín del Instituto de Geología y Recursos Naturales, SEGEMAR* **275**: 1-128.

Leanza H.A., Sattler F., Martínez S. & Carbone O., 2011. La Formación Vaca Muerta y equivalentes (Jurásico Tardío-Cretácico Temprano) en la Cuenca Neuquina. *In*: H. Leanza, C. Arregui, O. Carbone, J.C. Danielli & J. Vallés (*eds*.): *Relatorio del 18º Congreso Geológico Argentino*. Geología y Recursos Naturales de la Provincia del Neuquén: 113-129.

Leckie D.A. & Krystinik L.F., 1989. Is there evidence for geostrophic currents preserved in the sedimentary record of inner to middle-shelf deposits? – *Journal of Sedimentary Petrology* **59**: 862-870.

Legarreta L. & Gulisano C.A., 1989. Análisis estratigráfico secuencial de la Cuenca Neuquina (Triásico superior - Terciario inferior). *In*: G. Chebli & L. Spalletti (*eds*.): Cuencas Sedimentarias Argentinas. Décimo Congreso Geológico Argentino. – *Serie Correlación Geológica* **6**: 221-243.

Legarreta L. & Villar H.J., 2015. The Vaca Muerta Formation (Late Jurassic - Early Cretaceous), Neuquén Basin, Argentina: Sequences, facies and source rock characteristics. - Unconventional Resources Technology Conference 2015: 1-15. [DOI: 10.15530/urtec-2015-2170906].

Lescinsky H.L., Edinger E. & Risk M., 2002. Mollusc shell encrustation and bioerosion rates in a modern epeiric sea: Taphonomy experiments in the Java Sea, Indonesia. – *Palaios* **17**: 171-191.

Macellari C.E., 1988. Cretaceous paleogeography and depositional cycles of western South America. – *Journal of South American Earth Sciences* **1**: 373-418.

Machalsky M., 1998. Oyster life positions and shell beds from the Upper Jurassic of Poland. – *Acta Palaeontologica Polonica* **43**: 609-634.

Marchese H., 1971. Litoestratigrafía y variaciones faciales de las sedimentitas mesozoicas de la Cuenca Neuquina, Provincia del Neuquén, República Argentina. – *Revista de la Asociación Geológica Argentina* **26**: 343-410.

Martínez L.C.A. & Olivo M.S., 2015. *Tempskya* in the Valanginian of South America (Mulichinco Formation, Neuquén Basin, Argentina) - Systematics, palaeoclimatology and paleoecology. – *Review of Palaeobotany and Palynology* **219**: 116-131.

Medina R., Scasso R.A. & Medina F.A., 2016. Geología y estratigrafía de los bancos fosfáticos del Cretácico Inferior en el área del cerro Salado, Cuenca Neuquina, Argentina. – *Revista de la Asociación Geológica Argentina* **73**: 520-537.

Miall A.D., 2016. Stratigraphy: A Modern Synthesis. Springer, Heidelbert, 454 p.

Mitchum R.M. & Uliana M.A., 1985. Sesmic stratigraphy of carbonate depositional sequences, Upper Jurassic-Lower Cretaceous, Neuquén Basin, Argentina. *In*: B.R. Berg & D.G. Woolverton (*eds*.): Seismic stratigraphy, II. An integrated approach to hydrocarbon analysis. – *American Association of Petroleum Geologists Memoir* **39**: 255-274.

Moon C.F. & Hurst C.W., 1984. Fabrics of muds and shales: an overview. *In*: D.A.V. Stow & D.J.W. Piper (*eds*.): Fine-grained Sediments: Deep-Water Processes and Facies. Blackwell Scientific. Oxford, 588 p.

Myrrow M., 1990. A new graph for understanding colors of mudrocks and shales. – *Journal of Geological Education* **38**: 16-20.

Olivo M.S., Schwarz E. & Veiga G.D., 2016. Modelo de acumulación y evolución secuencial del intervalo cuspidal de la Formación Quintuco en su área tipo: implicancias para las reconstrucciones paleogeográficas del margen austral de la Cuenca Neuquina durante el Valanginiano. – *Andean Geology* **43**: 215-239.

Olmos M. & Sommerfeld V., 2005. Trampas características de la Formación Quintuco en la región de la Plataforma nororiental de la Cuenca Neuquina. *In*: E. Kozlowski, G. Vergani & A. Boll (*eds*.): Las trampas de hidrocarburos en las Cuencas Productivas de Argentina. – *Actas del Sexto Congreso de Exploración y Desarrollo de Hidrocarburos* (Mar del Plata): 225-237.

Olmos M., Maretto H., Lasalle D., Carbone O. & Naides C., 2002. Los reservorios de la Formación Quintuco. *In*: M. Schiuma, G. Hinterwimmer & G. Vergani (*eds*.): Rocas Reservorios de las cuencas productivas argentinas. – *Actas del Quinto Congreso de Exploración y Desarrollo de Hidrocarburos* (Mar del Plata): 359-382.

Orchuela I.A. & Ploszkiewicz V., 1984. La Cuenca Neuquina. – *Relatorio del Noveno Congreso Geológico Argentino*: 163-188.

Parent H., Scherzinger A. & Schweigert G., 2011. The Tithonian-Berriasian ammonite fauna and stratigraphy of Arroyo Cieneguita, Mendoza, Argentina. – *Boletín del Instituto de Fisiografía y Geología* **79-81**: 21-94.

Parent H., Garrido A.C., Schweigert G. & Scherzinger A., 2013. The Tithonian stratigraphy and ammonite fauna of the transect Portada Covunco-Cerrito Caracoles (Neuquén Basin, Argentina). – *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen* **269**: 1-50.

Parent H., Garrido A.C., Scherzinger A., Schweigert G. & Fözy I., 2015. The Tithonian-Lower Valanginian stratigraphy and ammonite fauna of the Vaca Muerta Formation in Pampa Tril, Neuquén Basin, Argentina. – *Boletín del Instituto de Fisiografía y Geología* **86**: 1-96.

Ploszkiewics J.V., OrchuelaI.A., Vaillard J.C. & Viñes R.F., 1984. Compresión y desplazamiento lateral en la zona de la falla Huincul, estructuras asociadas, provincia del Neuquén. – *Actas del Noveno Congreso Geológico Argentino* **2**: 163-169.

Potter P.E., Maynard J.B. & Pryor W.A., 1980. Sedimentology of Shale. Springer-Verlag. New York, 339 p.

Potter P.E., Maynard J.B. & Depetris P.J., 2005. Mud and Mudstones. Introduction and Overview. Springer-Verlag. New York, 249 p.

Reineck H. & Sing I., 1972. Genesis of laminated sand and graded rhythmites in storm-sand layers of shelf mud. – *Sedimentology* **18**: 123-128.

Reineck H. & Wunderlich F., 1998. Lamination and laminated rhytmites in water-laid sands. – *Senckenbergiana maritime* **28**: 227-235.

Shiip R.C., 1984. Bedforms and depositional sedimentary structures of a barred nearshore system, eastern Long Island, New York. – *Marine Geology* **60**: 235-259.

Schwarz E., Spalletti L.A. & Veiga G.D., 2011. La Formación Mulichinco (Cretácico Temprano) en la Cuenca Neuquina. *In*: H. Leanza, C. Arregui, O. Carbone, J.C. Danielli & J. Vallés (*eds*.): Relatorio del 18º Congreso Geológico Argentino. Geología y Recursos Naturales de la Provincia del Neuquén: 131-144.

Steuer A., 1897. Argentinische Jura-Ablagerungen. Ein Beitrag zur Kenntnis der Geologie und Paläontologie der argentinischen Anden. – *Palaeontologische Abhandlungen (N.F. 3)* **7**: 129-222.

Stipanicic P.N., 1969. El avance en los conocimientos del Jurásico argentino a partir del esquema de Groeber. – *Revista de la Asociación Geológica Argentina* **24**: 367-388.

Uliana M.A. & Legarreta L., 1993. Hidrocarbons habitat in a Triassic-to-Cretaceous sub-andean setting: Neuquén Basin, Argentina. – *Journal of Petroleum Geology* **16**: 397-420.

Vennari V.V., Álvarez P.P. & Aguirre-Urreta M.B., 2012. A new species of *Andiceras* Krantz (Cephalopoda: Ammonoidea) from the Late Jurassic-Early Cretaceous of the Neuquén Basin, Mendoza, Argentina. Systematics and biostratigraphy. – *Andean Geology* **39**: 92-105.

Verma H.M. & Westermann G.E.G., 1973. The Tithonian (Jurassic) Ammonite Fauna and Stratigraphy of Sierra Catorce, San Luis Potosi, Mexico. – *Bulletin of American Paleontology* **63/277**: 107-320.

Weaver C., 1931. Paleontology of the Jurassic and Cretaceous of west central Argentina. – *Memoir University of Washington* **1**: 1-469.

Wignall P.B., 1993. Distinguishing between oxygen and substrate control in fossil benthic assemblages. – *Journal of the Geological Society London* **150**: 193-196.