



# New Finding of Regular Echinoid Elements and Microfossils from the Pilmatué Member, Agrio Formation (Early Cretaceous), Neuquén Basin, Argentina

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**Abstract.** This contribution presents new findings of regular echinoid elements from Upper Valanginian claystones, marlstones, and mudstones recovered near the base of the Pilmatué Member, Agrio Formation, in the Puerta Curaco and Área 3000 sections, Province of Neuquén. The recovered material includes isolated elements of Aristotle’s lantern, spines, ambulacral and interambulacral plates obtained from washed residues of micropaleontological samples. Their taxonomy covers several possible regular echinoids included within the Acroechinoidea. Considering the tubercles, pore-pairs, type of plates, and ambulacral plating style, these fragments could be assigned to the “diademataceans”. The spines and the rotulae cannot be attributed to a specific taxon because they are found in several different regular echinoid clades. The morphology of the hemi-pyramids is common to different regulars; this fact coupled with their poor preservation prevents a confident assignment to a higher taxonomic level. Wedge-shaped teeth, typical of irregular echinoids, cannot be linked to any of the other recovered remains. These fossiliferous horizons also contain a rare to very abundant assemblage of benthic foraminifera dominated by *Epistomina loncochensis* Ballent, few ostracods, and resistant calcareous nannofossils. The presence of *E. loncochensis* indicates quiet marine environments and scarcity of oxygen in the water/bottom interface. Claystone composition of the level rich in echinoid remains suggests a detrital input from shallower environments by means of currents, explaining the disarticulation of the echinoids.

**Keywords:** Echinoids · Early Cretaceous · Late Valanginian · Agrio Formation Neuquén Basin · Argentina

## 1 Introduction

With the aim to improve the biostratigraphic framework of the Lower Cretaceous strata of the Agrío Formation, a micropaleontological study was carried out in the lower levels of the Pilmatué Member of two sections located in the Curaco area, within the central sector of Neuquén Basin. Initially, the benthic foraminifera were studied, which consists of a very low diverse and poorly preserved assemblage. An unexpected large number of echinoderm remains belonging to the Echinoidea and Holothuroidea were also recovered. The first ones have inspired this contribution, whose main objective is to present and illustrate this new record from the Neuquén Basin.

Echinoids are important organisms of current marine benthic communities living from the intertidal zone to 5000 m depth. They are characterized by having a test of high-Mg calcite made of individual elements that usually interlock to a lesser or greater extent to form the test (Kroh and Nebelsick 2010). The irregular echinoids are more likely to be preserved than the regulars because they live buried within the sediment (Kier 1977). Test construction and post-mortem conditions also play an important role (Kidwell and Baumiller 1990) along with sedimentary environments (Nebelsick et al. 2015).

The specimens studied by Rodríguez (2007) from the Agrío Formation include complete coronas of both regular and irregular echinoids. The following species were recovered from the Pilmatué Member: the irregular echinoids *Clypeopygus robinaldinus* d'Orbigny, *Pygopyrina gerthi* (Weaver), and *Coenholectypus planatus* Roemer var. *numismalis* (Gabb) as well as the presence of unidentifiable regular echinoids and their spines from Barda del Cerro Marucho locality. Rodríguez (2007) also reported the presence of the regular echinoids *Leptosalenia prestensis* (Desor), *Codechinus* sp. A, and the irregular echinoids *Pygorhynchus obovatus* L. Agassiz and *Coenholectypus planatus* Roemer var. *numismalis* (Gabb) from the younger Agua de la Mula Member.

Other records of echinoids from the Agrío Formation are limited to brief reports. These include the presence of spines from the basal beds of the Pilmatué Member, further north in Cuesta del Chihuido section, south of Mendoza Province (Ballent et al. 2006). There, the spines were collected from the same levels as *Epistomina loncochensis*, benthic foraminifera originally described as a widespread biostratigraphic marker species in the lower beds of the Agrío Formation (Sagasti and Ballent 2002).

## 2 Geological Setting

The analyzed material was recovered from the Lower Cretaceous marine deposits of the Pilmatué Member which belongs to the Agrío Formation which itself is part of the Mendoza Group. The Agrío Formation consists of three members: the Pilmatué, Avilé and Agua de la Mula Members (Leanza and Hugo 2001). Both the Pilmatué and Agua de la Mula Members are of marine origin and mainly composed of shales and sandy limestones (packstones and wackestones). Their deposition has been related to the Pacific Ocean transgressions. These members have been interpreted as siliciclastic-carbonate successions ranging from the offshore to shoreface and are influenced by wave movements of both fair weather and storm conditions (Spalletti et al. 2011).

The Avilé Member is non-marine sandstone that has been interpreted as a lowstand wedge produced by a rapid relative sea-level drop during mid-Hauterivian times (Legarreta and Gulisano 1989) and provides a conspicuous marker horizon separating the two marine members.

Ammonoids and calcareous nannofossils have provided a detailed biostratigraphy (Aguirre-Urreta and Rawson 1997, 2012; Aguirre-Urreta et al. 2005, 2007, 2017; Bown and Concheyro 2004; Concheyro et al. 2009). According to both groups, the age of the Agrio Formation is Upper Lower Valanginian to Lower Barremian and, in particular, the Pilmatué Member is assigned to the Lower Valanginian to Lower Hauterivian.

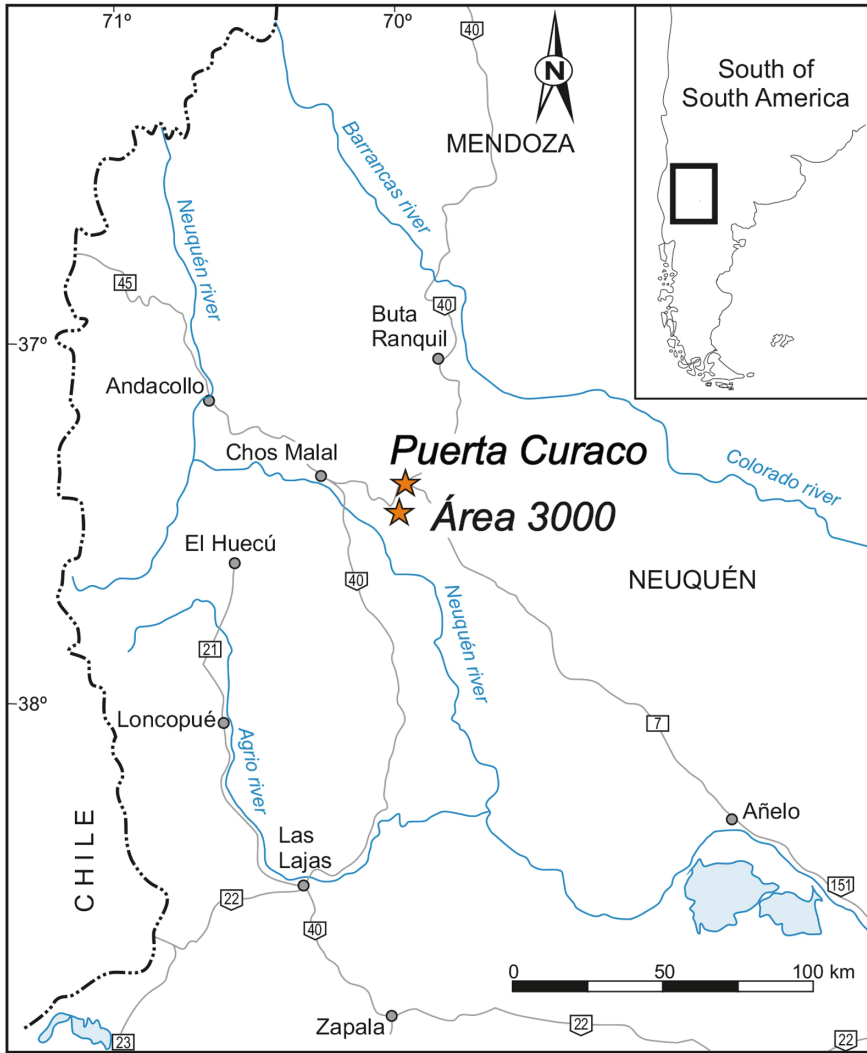
There are also few absolute ages, the first one obtained from the Pilmatué Member is a sensitive high resolution ion microprobe—SHRIMP U–Pb age of  $130.0 \pm 0.6$  or  $0.8$  Ma for the tuff layer that occurs at Mina San Eduardo section within beds belonging to the *Holcoptychites agrioensis* Subzone of the *Holcoptychites neuquensis* Zone (Schwarz et al. 2016). This dated tuff layer provides an estimated minimum age for the lower boundary of the Hauterivian in the Neuquén Basin. Recently, a new chemical abrasion isotope dilution thermal ionization mass spectrometry—CA-ID-TIMS U–Pb age of  $130.39 \pm 0.16$  Ma has been defined at the El Portón section, located further north of San Eduardo (Aguirre-Urreta et al. 2017), and was obtained from the same *Holcoptychites agrioensis* Subzone of the *Holcoptychites neuquensis* Zone. In addition, calcareous nannofossils from El Portón indicate the CC4A Zone (Roth 1983).

### 3 Materials and Methods

The remnants of echinoids studied herein were recovered from samples of the Pilmatué Member of the Agrio Formation and were collected at Puerta Curaco ( $37^{\circ} 22' 47''$  S,  $69^{\circ} 55' 45''$  W), and Área 3000 ( $37^{\circ} 25' 10''$  S,  $69^{\circ} 57' 4''$  W) sections, exposed at the center of the Neuquén Basin (Fig. 1). The Puerta Curaco log (ca 557 m thick) predominantly consists of marlstones and mudstones in the lower part and claystones and siltstones in the upper part (Fig. 2), similar to that of the Área 3000 log (ca 600 m thick).

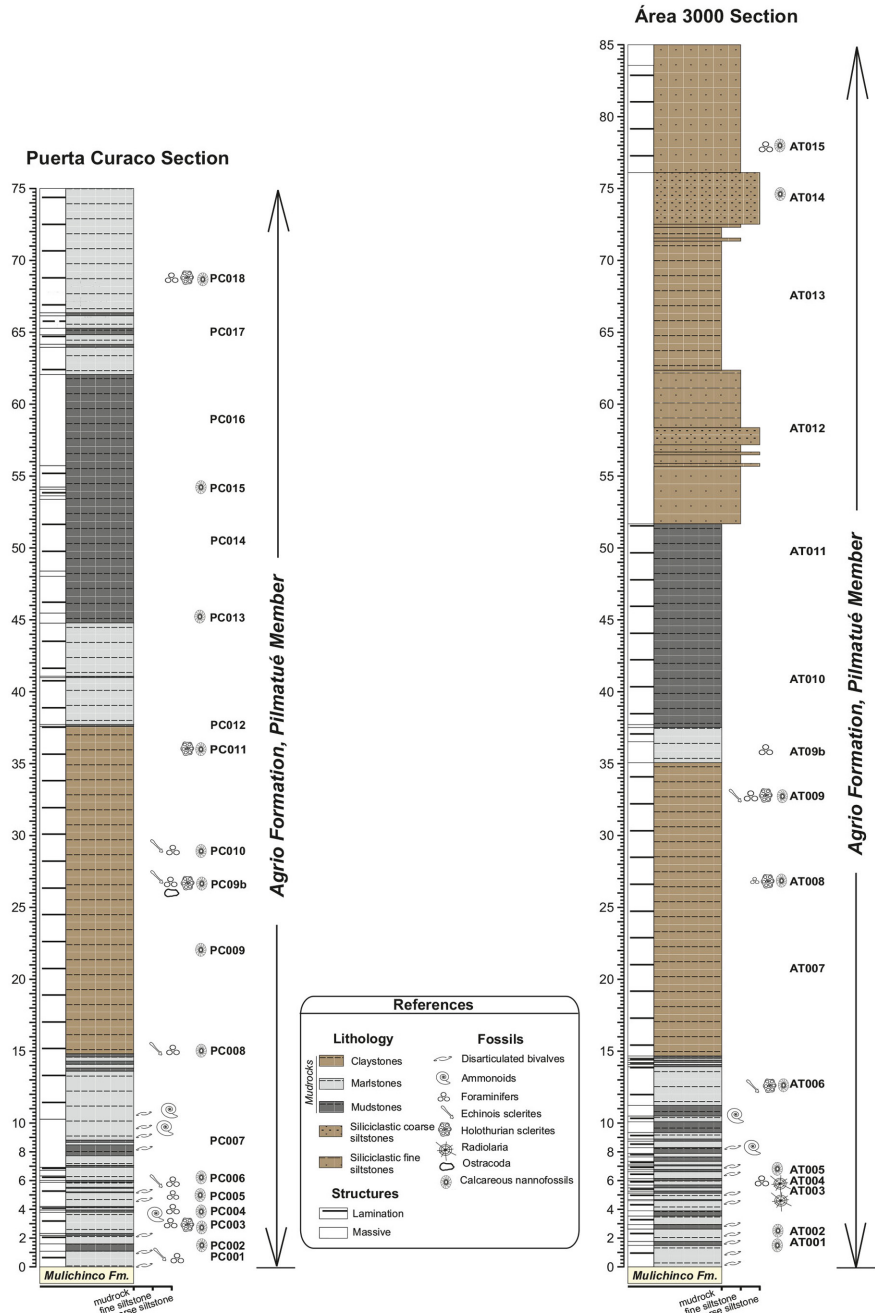
The lower part of these sections yielded dissociated echinoderm ossicles (echinoids, holothurians), foraminifera, few ostracods, and an impoverished assemblage of calcareous nannofossils. The most abundant echinoid remains of both sections come from claystones (samples PC009b and AT009 from the Puerta Curaco—PC, and Área 3000—AT sections) being Puerta Curaco more productive than Área 3000.

The studied samples were disaggregated using hydrogen peroxide solution (5%, 200 vols.), and the large residual fragments of non-disaggregated rock were treated using the repeated freezing-thawing technique (Hanna and Church 1928). Then, the disaggregated samples were washed over  $74 \mu$  and  $297 \mu$  sieves. The washed samples were dried, and the above-mentioned rests were picked under a Leica M165C stereoscopic microscope. The distribution of the different echinoid sclerites is given in Tables 1 and 2 along with the other benthic microfossils (holothurians spicules, foraminifera, and ostracoda). The abundance of all these microfossils is given in number of specimens and comes from approximately 40 g of washed sediment.



**Fig. 1.** Location map of the Puerta Curaco and Área 3000 sections in the north of Neuquén Province, Argentina

The distribution charts of calcareous nannofossils are given in Tables 3 and 4 and are based in a semiquantitative analysis, estimating specimens in two longitudinal transects of the slides. Selected specimens of echinoid sclerites are illustrated with photographs taken with Leica DFC295 camera. Specimens figured herein (Fig. 3) are housed in the micropaleontological collections of the Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires (Argentina), under the catalog numbers LM-FCEN 3756-3773. Calcareous nannofossils were recovered using smear slide technique (Edwards 1963; Bown and Young 1998). Cover slides were fixed with Norland Optical



**Fig. 2.** Stratigraphic logs of the lower levels outcropping at the Puerta Curaco and Área 3000 sections, Neuquén Province

**Table 1.** Stratigraphic distribution of the echinoid ossicles together with other microfossils remains (holothurian sclerites, foraminifers, ostracods, bivalve fragments, and fish teeth) at the lower levels of the Puerta Curaco section

PUERTA CURACO SECTION	ECHINOID OSSICLES						HOLOTHURIAN REMAINS	FORAMINIFERS			OSTRACOD	BIVALVE FRAGMENTS	FISH TEETH	
	Spine fragments	Fragments with tubercles	Rotulae	Hemi-pyramids	Fragments of teeth	Fragments of ambulacral plates		<i>Epistomina loncochensis</i> Ballent	<i>Saracenaria</i> sp.	<i>Lenticulina</i> sp. (juvenile)				<i>Lenticulina</i> sp.
PC018							2	1						
PC015														
PC013														
PC011							1		1					
PC010	28	2	1					33						
PC09b	117	116	83	47	29	10	308	310			2			
PC009														
PC008	1							1					2	
PC007														
PC006	1							12	1					
PC005								14				5		
PC004								12						
PC003							2	70						
PC002														
PC001	1							80						

Gray color indicates barren samples

Adhesive, and nannofossil identifications were carried out through a Leica DMLP petrographic microscope under 1000x magnification adding a gypsum plate. Calcareous nannofossils slides are housed in the Área Paleontología, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, under the catalog numbers BAFC-NP 4103-4123.

**Table 2.** Stratigraphic distribution of the echinoid ossicles together with other microfossils remains (holothurian sclerites, foraminifers, Spumellaria radiolarians, and bivalve fragments) at the lower levels of the Área 3000 section

ÁREA 3000 SECTION	ECHINOID OSSICLES					HOLOTHURIAN REMAINS	FORAMINIFERS				SPUMELLARIA RADIOLARIANS	BIVALVE FRAGMENTS
	Spine fragments	Rotulae	Fragments with tubercles	Fragments of teeth	Hemi-pyramids		<i>Epistomina loncochensis</i> Ballent	<i>Astacolus ambanjabensis</i> (Espitalié and Sigal)	<i>Lenticulina</i> spp. (indet.)	<i>Vaginulinopsis</i> sp.		
AT015						7						
AT014												
AT013												
AT011												
AT09b								1	1			
AT009	21			2		24	4					
AT008						2		2				
AT007												
AT006	2	2	1	1	1	8		57				7
AT005												
AT004							4				8	
AT003											3	
AT002												
AT001												

Gray color indicates barren samples

## 4 Results

Echinoid remains include isolated and poorly preserved ossicles belonging to Aristotle's lantern including rotulae, hemi-pyramids, teeth, as well as spines, ambulacral and interambulacral plates. The spines, teeth, and hemi-pyramids are usually fragmented. The hemi-pyramids and plates show signs of dissolution and abrasion.

**Table 3.** Puerta Curaco section calcareous nannofossils range chart. Preservation of calcareous nannofossils: M, moderate; P, poor. Nannofossils abundance: A, abundant; C, common; F, frequent; R, rare

PUERTA CURACO SECTION	PRESERVATION	ABUNDANCE																	
		<i>Watznaueria barnesiae</i>	<i>Watznaueria fossacincta</i>	<i>Nannoconus steinmannii</i>	<i>Nannoconus</i> spp.	<i>Micrantholithus hoeschulzii</i>	<i>Calculites percentis</i>	<i>Nannoconus circularis</i>	<i>Micrantholithus obtusus</i>	<i>Eiffellithus striatus</i>	<i>Eiffellithus windii</i>	<i>Rhagodiscus asper</i>	<i>Watznaueria ovata</i>	<i>Nannoconus</i> cf. <i>N. bucheri</i>	<i>Retecapsa surirella</i>	<i>Rhagodiscus</i> sp.	<i>Zeughrabdotus embergeri</i>	<i>Watznaueria biporta</i>	<i>Cyclagelosphaera margerelii</i>
PC018	M	C	C	C		R			R		R					R		C	
PC015	P	C	C	C			R									R	R	C	
PC013	M	A	A	A	R	C	F	C	R		R					F		C	
PC011	P	F	F	F		F		F								F		F	F
PC010	P	R	R	R		R									R		R		
PC09b	M	C	C	C		F			R	R	R	R					R		
PC009	M	F	R	F		R	R					R				R	R	R	
PC008	M	F	F	F												F			
PC006	M	F	F	F	R	F		F	R	R	R	R	R	R					
PC005	P	R	R	R		R													
PC004	M	R	R	R		R													
PC003	P	F	F	F	R	R		R	R										
PC001																			

Gray color indicates barren samples

### 4.1 Echinoid Ossicles

#### 4.1.1 Fragments of Ambulacral Plates with Pore-Pairs

Figure 3 p, q.

*Material.* Puerta Curaco section: PC009b, 10 fragments. Área 3000 section: AT006, 1 fragment.

*Description.* Ambulacra apparently straight, plating trigeminate, ambulacral plates compounded in acrosaleniid style (two elements) bearing the primary tubercle, alternating with a simple element with secondaries only. Pore-pairs uniserially arranged, approximately equal-sized (partitioned isopores) forming oblique pore-pairs, with very narrow interporal partitions. Taking into account the attachment area breadth, pore size,



**Table 4.** Área 3000 section calcareous nannofossils range chart. Preservation of calcareous nannofossils: M, moderate; P, poor. Nannofossils abundance: A, abundant; C, common; F, frequent; R, rare; VR; very rare

AREA 3000 SECTION	PRESERVATION																		
	ABUNDANCE																		
		<i>Watznaueria barnesiae</i>	<i>Watznaueria fossacincta</i>	<i>Zeugrhabdotus embergeri</i>	<i>Micrantholithus hoschulzii</i>	<i>Micrantholithus obtusus</i>	<i>Retecapsa surirella</i>	<i>Cretarhabdus conicus</i>	<i>Watznaueria ovata</i>	<i>Watznaueria biporta</i>	Nannoconus cross-section	Nannoconus steinmannii	<i>Rhagodiscus asper</i>	Nannoconus cf. <i>N. bucheri</i>	<i>Eiffelithus windli</i>	<i>Crucellipsis cuvillieri</i>	<i>Eiffelithus striatus</i>	<i>Retecapsa angustiforata</i>	<i>Diazomatholithus lehmannii</i>
AT015	M	A	A	A			F		R										
AT014	M	A	A	A	F	R	R							R	R	R			
AT009	M	C	C	C	R	F	R	R	R	C	R	R	R	R					
AT008	M	R	R	R		R													
AT007																			
AT006	M	F	F	F			R												
AT005	M	R	R	R	R	R													
AT002	P	VR	VR	VR															
AT001	P	VR	VR	VR															

Gray color indicates barren samples

and interporal partition shape, the pores are classified as partitioned isopore type P2 of Smith (1978). The attachment area is asymmetric, being more developed toward the apical pole. No neural channels are observed in perradial pores. The stereom of many plate fragments show irregular struts and varying pore size and allow it to be classified as labyrinthic stereom (Smith 1980).

*Remarks.* Many of these features such as the acrosaleniid style, trigeminate ambulacral plating can be found in the “diademataceans”, and the families Acrosaleniidae, Emiratiidae, Hemicidaridae, and Pseudodiademataidae.

The recovered plates have been compared with the descriptions and pictures of these taxa from Smith and Kroh (2011) and assigned to the “diademataceans”. This group includes the orders Micropygoida, Aspidodiadematoidea, and Diadematoidea although the Micropygoida can be discarded because of the non-crenulate perforate tubercles.

Echinoids belonging to the Aspidodiadematoidea have acrosaleniid ambulacral plating in triads at least adorally and with some elements united by tubercle overgrowth (Smith and Kroh 2011). Taking into account these features, these plates might be related to this taxon. Diadematoidea includes the family Heterodiademataidae and Diademataidae. The Heterodiademataidae are discarded because although this taxon has trigeminate ambulacral plates and uniserial pore-pairs, it has diademataid-style



◀ **Fig. 3.** Echinoid ossicles of the Pilmatué Member, Agrio Formation. **a–e** Hemi-pyramids: **a** on left-hand side: interpyramidal face wing with adaxial inner border showing comb-like indentations and striated attachment area of interpyramidal muscle; on right-hand side, abaxial face (LM-FCEN 3756); **b** interpyramidal face wing (LM-FCEN 3757); **c** detail of the interpyramidal face with a flat dorsal edge that seems to have a V-shape fossa (LM-FCEN 3758); **d** abaxial face (LM-FCEN 3756); **e** intrapyramidal face with suture face (LM-FCEN 3756). **f–g** Rotulae: **f** oral side with the abaxial condyles to the bottom and the adaxial condyles and grooves to the top, intermediate fossa in the middle (LM-FCEN 3759); **g** aboral side, large pored, abaxial head to bottom, adaxial head to top (LM-FCEN 3759). **h–i** Tooth: **h** cross section of a wedge-shaped tooth, abaxial edge to the top (LM-FCEN 3760); **i** lateral view with the oral chewing tip to the bottom and the abaxial edge to the right (LM-FCEN 3761). **j–n** Interambulacral fragments with primary tubercles perforate and crenulate (LM-FCEN 3762–3766). **m** Interambulacral plate with a primary and secondary tubercle perforate and crenulate and two small ones, being probably miliary granules (LM-FCEN 3765). **p–q** Ambulacral plates. **p** ambulacra plates compounded in acrosaleniid style and perradial suture on right (LM-FCEN 3767); **q** two plates with pore-pairs LM-FCEN 3768). **o, r, s, t, u, v** Spines (LM-FCEN 3769–3773). **o, r, s** cross section, with some wedges dichotomized (shown in **r, s**) (LM-FCEN 3769, 3770, 3771). **t–v** lateral view of the base and part of the shaft with ribs and no cortex (LM-FCEN 3772, 3773, 3771). Scale bar: 0.2 mm

compound plates. The Diadematidae have trigeminate ambulacral plates with an enlarged element and two smaller demiplates, and thus, the plates could potentially be assigned to this family. Thus, the ambulacral plates could belong either to the Aspidodiadematoida, or to the Diadematoida, particularly to the family Diadematidae.

#### 4.1.2 Fragments with Tubercles

Figure 3 j–n.

*Material.* Puerta Curaco section: PC009b, 116 fragments, PC010, 2 fragments. Área 3000 section: AT006, 1 fragment.

*Description.* Interambulacral plates with a large surface of the plate devoid of ornamentation. Primary and secondary tubercles of various sizes all perforate and crenulate with areolae not well defined and no scrobicular tubercles observed. Mamelons of the tubercles with a well-developed neck and a central perforation up to 1/3 of the mamelon diameter, platform broad, complete, and with a radially symmetrical development of crenulation that has more than ten nodes on the parapet. Scarce miliary granules.

*Remarks.* The interambulacral plates have been compared with the same taxa mentioned above for the ambulacral plates, and they match with the plates observed in “diademataceans”. The Aspidodiadematoida have interambulacral plates with a single large tubercle perforate and crenulate, while the Diadematoida have perforate and crenulate primary tubercles, without surrounding scrobiculae. The Heterodiadematidae are characterized by interambulacral plates with single primary tubercle and wide adradial and interradian granular zones, and tubercles with a small mamelon in proportion to the boss. The Diadematidae present interambulacral plates with multiple primary tubercles, or if there is only a single tubercle, these plates lack a wide adradial

and interradial granular zones. The observed material could perhaps belong to the Diademataeidae because of the scarce and scattered granules near the tubercle.

Some features exhibited in the following families allow them to be discarded with respect to the “diademataceans” (Kroh *pers. comm.* 2017). Members of the Acrosaleniidae have the areolae sharply delimited as the Emiratiidae, one or two large primary tubercles to each plate, and a dense secondary tuberculation. The Hemicidaridae are discarded because of a dense presence of secondary tubercles, the perforation of the mamelon is vertically elongate, the areolae are sunken and confluent, and the crenulation is different with respect to those described herein. The Pseudodiademataeidae are also discarded as they possess dense granulate plate surfaces (Smith and Kroh 2011).

### 4.1.3 Spines

Figure 3 o, r, s, t, u, v.

*Material.* Puerta Curaco section: PC001, 1 spine; PC006, 1 spine; PC008, 1 spine; PC009b, 117 spines; PC0010, 28 spines. Área 3000 section: AT006, 2 spines; AT009, 21 spines.

*Description.* Spine fragments of various sizes corresponding to primary and secondary tubercles. The bases of the spines are about as wide as the basal part of the shaft, which is straight, cylindrical, slender and with eight or more closely set, smooth longitudinal ribs, some of which dichotomize in cross section toward the base. The center of the spines seems to be hollow, but is filled with sediment. Spine articulation is by means of a restricted-pivot system.

*Remarks.* According to the above-mentioned characters especially the longitudinal ribs, these spines cannot be attributed to the “diademataceans” as these taxa have a verticillate surface, with the exception of the Micropygoida. Nevertheless, the spines described herein are probably hollow. The spines of the Aspidodiademataeidae possess a central lumen crossed by partitions and fine needle-like pillars and those of the Diademataeidae are fragile with a sparse trabecular meshwork filling the central lumen of the spines.

The spines characterizing the Acrosaleniidae are solid, with a smooth cortex. Spines of the Emiratiidae are unknown except for those of *Tetragramma* and *Tiaromma* (subfamily Diplopodiinae) and those of *Allomma* (subfamily Emiratiinae). In the Hemicidaridae, the only spines known belong to *Cidaropsis* (Pseudocinarinae) and *Pseudocidaris* (Hemicidarinae). In the Pseudodiademataeidae, the only genera whose spines are known belong to *Pseudodiadema* and *Acrocidaris* (Smith and Kroh 2011). The spines described herein are, however, closely similar in their general morphology to the spines of *Schizechinus* (Toxopneustidae, Echinacea) (Kroh 2003).

The comparison of spines described herein with those of other families shows that the morphology of the former cannot be related to one specific taxon, because they possess characters that are present in several different regular echinoids.

### 4.1.4 Elements of the Aristotle’s Lantern

The non-cidaroid regular echinoids are characterized by gripping lanterns with strong hinge-joints, whereas the cidaroids possess socket joints (Märkel 1979). The jaw elements studied herein are compatible with those of non-cidaroid lanterns. Of the taxa

considered herein, the “diademataceans” possess aulodont lanterns, while the other families (Acrosaleniiidae, Emiratiidae, Hemicidaridae, and Pseudodiademataidae) have stirodont lanterns. Aulodont and stirodont lanterns have a short pyramidal suture, a more or less deep foramen magnum, and narrow epiphyses that do not meet. Aulodont lanterns possess grooved teeth, while stirodont lanterns possess keeled teeth.

### Hemi-pyramids

Figure 3 a–e.

*Material.* Puerta Curaco section: PC009b, 49 hemi-pyramids. Área 3000 section: AT006, 1 hemi-pyramid.

*Dimensions.* Interpyramidal length 0.074–0.156 cm, width 0.022–0.093 cm, abaxial face 0.021–0.073 cm.

*Description.* Hemi-pyramids isolated, not bounded together, rectangular on abaxial view, lateral wing (interpyramidal face) with a V-shaped apical edge and horizontal ridges forming a short comb-like fringe in the adaxial border. The oral tips of the hemi-pyramids are strongly curved axially. Intrapyraxial face with a short and narrow pyramidal suture. Processus superioris, supra alveolaris, foramen magnum, and epiphyses not observed.

*Remarks.* The presence of isolated hemi-pyramids, not bounded together, does not allow the observation of the foramen magnum. Nevertheless, it can be inferred by the short pyramidal suture, that a deep V-shaped foramen is present which is deeper than the lateral notches for epiphyses and seems to broaden upwards. The lack of epiphyses hinders the determination of either an aulodont, stirodont, or camarodont construction. The general morphology of the described hemi-pyramids is shared by several regular taxa. This, coupled with the lack of diagnostic characters does not allow a confident assignment to lower level taxa.

### Rotulae

Figure 3 f, g.

*Material.* Puerta Curaco section: PC009b, 85 rotulae; PC0010, 1 rotula. Área 3000 section: AT006, 2 rotulae.

*Dimensions.* Length 0.029–0.09 cm, width 0.016–0.038 cm, thickness 0.007–0.028 cm.

*Description.* Rectangular in outline, with parallel sides, dorso–ventrally flattened. Apical surface of the rotula with large pores, oral surface with a symmetrical arrangement of the articular areas that interact with the epiphyses. The abaxial condyle, the adaxial condyle and groove, and the intermediate fossa can be distinguished.

*Remarks.* Regarding the arrangement of the joints in non-cidaroids, the middle and inner joints are separated from one another by an area where the interior rotular muscle is attached, the middle tubercle of the epiphyses with the middle fossa of the rotula construct a sort of buffer, with the inner tubercle including the inner fossa representing gliding areas (Märkel 1979). The rotulae are highly similar to those of *Genocidaris*

*catenata* (Temnopleuridae, Echinacea) (Kroh 2003). Moreover, the rotulae described herein are also similar to those of *Paracentrotus lividus* (Parechinidae, Echinacea) (Candia Carnevali et al. 1991).

## Teeth

Figure 3 h, i.

*Material.* Puerta Curaco section: PC009b, 32 teeth. Área 3000 section: AT006, 1 tooth; AT009, 2 teeth.

*Dimensions.* In cross section, major axis is 0.038–0.046 cm, and minor axis is 0.018–0.025 cm.

*Description.* Isolated fragments of teeth, slightly abaxial curved and wedge-shape in cross section. Aboral end showing secondary plates.

*Remarks.* The cross section of the teeth somewhat resembles those of *Eodiadema*, an Early Jurassic paraphyletic or polyphyletic taxon, classified as a sister group to the Irregularia or between the Diadematidae and Pedinidae taking into account the different types of phylogenetic trees considered (Smith 1981, Kroh and Smith 2010; Thuy et al. 2011).

The teeth in *Eodiadema* are rhombic in cross section, whereas those described herein are more wedge-shaped in cross section; this type of macrostructure occurs in clypeasterid, fibularid, and astriclypeid lanterns in the Clypeasteroidea (Mani 2004).

## 4.2 Taxonomic Assignment of the Echinoid Ossicles

The diagnostic features that characterized the families of regular and irregular echinoids, such as the arrangement of the plates in the apical disk, the elements of the perignathic girdle, and the position of the periproct, among others, can only be observed and described in well-preserved complete specimens. Even if the material described in this paper consists of fragments of the test, spines, and several jaw elements, the described ossicles can be at least classified as non-cidaroid, regular echinoids.

Considering that each element (ambulacral and interambulacral plates, spines, hemi-pyramids, rotulae, teeth) is only represented by a unique morphotype and that almost all the material is derived from the same bed, the assumption that all the recovered remnants ultimately belong to a single taxon, could possibly be made. In fact, only the ambulacral and interambulacral plates can be related to one group of the “diademataceans”, while the rest of the ossicles cannot be assigned with confidence to any single lower order taxonomic group.

Although in some cases, morphological features of a spine enable a designation to a specific taxon, in the described material, the spines cannot be assigned with confidence to any specific taxa. The main features which characterize them are found in primary and secondary spines of non-cidaroid regular echinoids from basal to more derived taxa. The spines described herein are similar to *?Schizechinus* sp. (Toxopneustidae) illustrated by Kroh (2003), but this family is discarded as it has ambulacral plates following the echinoid style, and imperforate and non-crenulate tubercles. This,

coupled with the strong intraspecific variability shown by the primary spines related to the position on the coronae does not allow a closer classification of the material.

The same is true for the hemi-pyramids studied herein, because their morphological features are observed in many regular echinoid taxa. The short pyramidal suture in the studied material allows the cidaroid type to be discarded. Besides, the lack of epiphyses and associated teeth prevents an accurate classification to either an aulodont, stirodont, or camarodont pyramid type.

The rotulae studied herein matches in every detail the rotulae of non-cidaroid echinoids that belongs to a hinge-joint gripping lantern. Our rotulae are similar to those found in *?Genocidaris catenata* (Family Temnopleuridae) illustrated by Kroh (2003), but this family is discarded because it has imperforate primary tubercles, with or without crenulation, and the compound ambulacral plates in the echinoid style. The studied rotulae are also similar to those of *Paracentrotus lividus* (Family Parechinidae) described by Candia Carnevali et al. (1991), but this family is discarded because it has interambulacral plates with a dense number of subequal tubercles. More accurate assignments are difficult due to the poor fossil record of rotulae in general.

The cross section of the teeth is wedge-shaped and resembles the one found in the irregular Clypeasteroida, but this echinoid taxon appears in the Eocene; this would lead us to consider the possibility that this feature has appeared previously in some taxon during the Cretaceous.

### 4.3 Micropaleontological Assemblages

The micropaleontological content of the Puerta Curaco and Área 3000 sections show an extremely low richness of calcareous benthic foraminifers. The first section also provided only a single species of the ostracod *Sondagella colchesterensis* Valicenti and Stephens.

The Puerta Curaco section has a lower percentage of barren samples than the Área 3000 section (28% vs. 63%) and also has a greater abundance of specimens (537 specimens vs. 71 specimens, respectively). The productive samples vary from rare to frequent, with the exception of samples PC009b of the Puerta Curaco and AT006 of the Área 3000 with very abundant to abundant foraminiferal tests, respectively.

The assemblages recovered from both sections are quite different. While the lower levels of the Puerta Curaco record an abundant and nearly monotypic fauna composed by more than 99% of *Epistomina loncochensis* Ballent with accessory species belonging to the order Lagenida (Family Vaginulinidae), the lower productive levels of the Área 3000 provide some Spumellaria radiolarians followed by abundant vaginulinids and rare specimens of *Epistomina loncochensis*.

The echinoid remains were recovered in some levels with *Epistomina loncochensis* and/or lagenids, mainly in the samples PC009b, AT006, and AT009.

In the Área 3000 section, a high amount of Lagenida with abundant *Astacolus ambanjabensis* (Espitalié and Sigal) was recovered (sample AT006) representing another monotypic foraminiferal level.

All foraminiferal tests are poorly preserved. Specimens belonging to Lagenida and Robertinida are damaged and have infillings of sediment and framboidal pyrite, but, as was expected by its originally aragonitic composition, the genus *Epistomina* (Order

Robertinida) showed stronger signs of dissolution and recrystallization than those of the lagenids. Some samples contain blackened epistominid tests that, along with the dark claystone rich in organic matter and some traces of pyrite, suggests oxygen-deficient environments.

#### 4.4 Biostratigraphy

Twenty-two levels of the Pilmatué Member of the Agrío Formation from the Puerta Curaco and Área 3000 sections were examined for calcareous nannofossils. Only 20 were fossiliferous. The recovered nannoflora was scarce and poorly preserved, being only frequent in specific levels.

The nannoflora is composed by 23 species of the genera: *Calculites*, *Cretarhabdus*, *Cruciellipsis*, *Cyclagelosphaera*, *Diazomatholithus*, *Eiffellithus*, *Micrantholithus*, *Nannoconus*, *Retecapsa*, *Rhagodiscus*, *Watznaueria*, and *Zeugrhabdotus*. In both sections, the reliable calcareous nannofossils included the presence of *Eiffellithus windii*, *Eiffellithus striatus*, and also *Nannoconus circularis* in Puerta Curaco.

Up to now, the first and last occurrences (FO and LO) of genera *Eiffellithus* and *Nannoconus* were consistent global markers recorded in numerous sections in the Neuquén Basin and have been correlated with ammonite zones (Aguirre-Urreta et al. 2005, 2017; Concheyro et al. 2009; Lescano and Concheyro 2014).

At Puerta Curaco, the presence of *Nannoconus circularis*, *Eiffellithus windii* together with *Eiffellithus striatus* (Table 3) was recognized. All of them could be associated in the CC4A Zone, considering the Mediterranean zonation of the Tethys (Sissingh 1977, modified by Applegate and Bergen 1988) and other studies with nannofossils performed in the Neuquén Basin (Aguirre-Urreta et al. 2017). As nannoflora was identified together with fragments of the ammonite *Decliveites crassicosatus*, an Upper Valanginian age is suggested for this section. At Área 3000, the presence of *Eiffellithus windii* together with *Eiffellithus striatus* (Table 4) was recognized as also recorded at the Puerta Curaco section. For this reason, the nannoflora is included in the CC4A Zone.

The recovered calcareous nannofossils exhibited clear Tethyan affinities, including some cosmopolitan species, and others with a bipolar distribution. Therefore, the nannoflora identified herein would suggest the existence of marine connections with the Tethyan Realm and even part of northwestern Europe during the late Valanginian.

## 5 Paleoenvironmental Inferences

The echinoid skeletal elements found are generally isolated ossicles and occur scattered in marlstones, mudstones, and claystones. They are always accompanied by the foraminifer *Epistomina loncochensis*, sometimes by lagenids, calcareous nannofossils and sclerites of holothuroidea, and only in one sample by the ostracod *Sondagella colchesterensis* Valicenti and Stephens. Articulated echinoid skeletal elements have not been observed in the field, not even in the sample PC009b, which is the richest fossiliferous horizon.



Among the echinoid remains, the fragments of spines are the most numerous skeletal ossicles, followed by rotulae, hemi-pyramids, teeth, and fragments of test plates. Leaving aside the spines which are very abundant in any echinoid and which may be overestimated since they can be derived from fragmented spines, it is remarkable that the rotulae/spines ratio is very high (0.9) and also the rotulae/hemi-pyramids ratio is greater than 0.5 (1.88). Thus, the echinoid elements recovered could be strongly controlled by the resistance or robustness of the type of skeletal element. Also, the almost total absence of articulated skeletal parts (except for rare fragments formed by few ambulacral or interambulacral plates) would suggest a pre-depositional fragmentation of the coronae. Usually, the signs of fragmentation, dissolution, and abrasion are common among the skeletal elements, and with exception of dissolution, they are interpreted to have resulted from the high energy and transport mechanisms of the shallow water environment in which they occurred.

Regular echinoids which belong to the vagile epifauna usually live on rocky and sand substrates and often hidden among rocks, but also are found in muddy substrates (Mancosu and Nebelsick 2017). Regular echinoid tests are quite resistant, but because of being exposed to scavengers and currents after death, they have a poor fossil record compared to the irregulars that live within the sediment (see discussions in Kier 1977, 1982; Kidwell and Baumiller 1990; Mancosu and Nebelsick 2017). Paleoecological studies on echinoids are often based on complete coronae of echinoids, but also spines can provide clues with respect to the substrate type on which echinoids lived.

The monotypic foraminiferal assemblage of *Epistomina loncochensis* from this basal interval of the Agrio Formation as reported by Sagasti and Ballent (2002) from claystones, marlstones, and mudstones reflects an outer neritic ramp environment. They interpreted *Epistomina loncochensis* as an opportunistic species with the ability to cope with ephemeral dysaerobic to quasi-anaerobic conditions near the sediment–water interface attributed to the transgressive event. Toward higher stratigraphic levels, the echinoid ossicles and the epistominid foraminifera disappear, but the presence of scarce vaginulids are still recorded. According to Koutsoukos and Hart (1990), the lenticular, biconvex, planispirally coiled, smooth, or little-ornamented test and compressed shape of the coiled vaginulinids (*Astacolus*, *Lenticulina*, *Planularia*, *Saracenaria*) indicate they were epifaunal to shallow infaunal active deposit feeders and probably were rapid burrowers adapted to variable bottom conditions.

The fact that almost all echinoid elements were obtained from soft sediments containing *Epistomina loncochensis* (which indicates low oxygen conditions) may reflect their allochthonous nature, because echinoids are unknown in modern environments with depleted oxygen.

## 6 Concluding Remarks

The present work pointed out the presence of non-cidaroid regular echinoids belonging to the “diademataceans,” recovered from Upper Valanginian sediments of the Pilmatué Member, Agrio Formation. They have been found in fine sediments associated with quiet marine environments. The almost total absence of articulated skeletal parts, the ratios between the types of elements found and the signs of fragmentation, dissolution,

and abrasion are interpreted as the result of a high energy and transport. Besides, the associated low oxygen tolerant foraminifera fauna would reflect their allochthonous nature.

Findings of the opportunistic benthic foraminifera *Epistomina loncochensis* in the sections could be a response to variations in food and/or light supply, oxygen, salinity, etc. The lagenids could indicate some improvement of environmental conditions at the water/substrate interface. Anyway, the scarcity and the monospecific assemblage of lagenids in our sections would also indicate the persistence of the low oxygen content.

Finally, the consistent presence of nannoflora in both sections allowed to establish an Upper Valanginian age for this noteworthy deposit of regular echinoderm ossicles.

## 7 Supplementary Information About Nannoflora

Calcareous nannofossils species listed in alphabetical order

*Calculites percenis* Jeremiah

*Cretarhabdus conicus* Bramlette and Martini

*Crucellipsis cuvillieri* (Manivit) Thierstein

*Cyclagelosphaera margerelii* Noël

*Diazomatholithus lehmannii* Noël

*Eiffellithus striatus* (Black) Applegate and Bergen

*Eiffellithus windii* Applegate and Bergen

*Micrantholithus hoschulzii* (Reinhardt) Thierstein

*Micrantholithus obtusus* Stradner

*Nannoconus* cf. *N. bucheri* Brönnimann

*Nannoconus circularis* Deres and Achéritéguy

*Nannoconus* cross section

*Nannoconus* spp.

*Nannoconus steinmannii* (Kamptner) Deres and Achéritéguy

*Retecapsa angustiforata* Black

*Retecapsa surirella* (Deflandre and Fert) Grün in Grün and Allemann

*Rhagodiscus asper* (Stradner) Reinhardt

*Rhagodiscus* sp.

*Watznaueria barnesiae* (Black) Perch-Nielsen

*Watznaueria biporta* Bukry

*Watznaueria fossacincta* (Black) Bown

*Watznaueria ovata* Bukry

*Zeugrhabdotus embergeri* (Noël) Perch-Nielsen

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