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Biostratigraphic implications of *Kallidontus nodosus* Pyle and Barnes in the Ordovician of the Eastern Cordillera, Argentina

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ABSTRACT. A biostratigraphic reevaluation of the conodont faunas of the Acoite Formation at the La Ciénaga de Purmamarca, northwestern Argentina, is presented here to constrain its depositional age and improve its regional correlation. The new conodont assemblage, consisting of 636 elements, includes Balognathidae indet., *Drepanodus arcuatus*, *Drepanoistodus pitjanti*, *D.* cf. *andinus*, *D.* sp. A, *Gothodus andinus*, *Kallidontus nodosus, Paroistodus* sp., and *Zentagnathus argentinensis*. These species were obtained from the same beds sampled by previous authors, who attributed varying ages to the conodont assemblage. Of special importance is the record of *K. nodosus*, which allows for precise correlation of the lower levels of the *Gothodus andinus* Zone with the early Floian *Prioniodus elegans* Zone (Fl 1). This finding is consistent with the graptolite and trilobite data available at the La Ciénaga de Purmamarca, and it raises caution regarding the taxonomic determination of *Baltoniodus triangularis*, the index fossil for the Lower-Middle Ordovician Series boundary in other stratigraphic sections of the Acoite Formation along the Eastern Cordillera.

Keywords: Conodont, Biostratigraphy, Floian, Dapingian, Argentina.

RESUMEN. *Kallidontus nodosus* Pyle y Barnes en el Ordovícico de la Cordillera Oriental, Argentina: implicaciones bioestratigráficas. Este trabajo presenta una reevaluación bioestratigráfica de las faunas de conodontes de la Formación Acoite en La Ciénaga de Purmamarca, en el Noroeste de Argentina, a fin de ajustar su edad de depositación y mejorar su correlación regional. La nueva asociación de conodontes, compuesta por 636 elementos, incluye Balognathidae indet., *Drepanodus arcuatus*, *Drepanoistodus pitjanti*, *D.* cf. *andinus*, *D.* sp. A, *Gothodus andinus*, *Kallidontus nodosus, Paroistodus* sp. y *Zentagnathus argentinensis*. Este registro representa los mismos estratos muestreados por autores previos, quienes les atribuyeron edades variables a la asociación de conodontes. De especial importancia es el registro de *K. nodosus*, el cual permite una correlación precisa de los niveles inferiores de la zona de *Gothodus andinus* con la zona de *Prioniodus elegans* del Floiano temprano (Fl 1). Este hallazgo es consistente con los datos de graptolitos y trilobites de La Ciénaga de Purmamarca. Se sugiere precaución respecto a la determinación taxonómica de *Baltoniodus triangularis*, el fósil guía para el límite Ordovícico Inferior-Medio, en otras secciones estratigráficas de la Formación Acoite a lo largo de la Cordillera Oriental.

Palabras clave: Conodonte, Bioestratigrafía, Floiano, Dapingiano, Argentina.

1. Introduction

Ordovician faunas from the Eastern Cordillera in northwest Argentina exhibit endemism, which complicates precise biostratigraphic intercontinental correlations (*e.g.,* Waisfeld *et al.*, 2023). This is particularly evident in the case of conodonts, where the analysis of isolated, discontinuous outcrops and differing taxonomic approaches have led to conflicting biostratigraphic interpretations (*e.g.,* Carlorosi *et al*., 2017; Albanesi *et al*., 2021). These issues are especially compounded regarding *Baltoniodus triangularis* (Lindström, 1954), the index marker for the Lower-Middle Ordovician Series boundary (Wang *et al*., 2009) and earlier representatives of the Balognathidae family (*e.g.,* Sweet, 1988; Stouge and Bagnoli, 1999; Wang *et al*., 2003; Dzik, 2015). Controversies primarily concern the conodont records of the Acoite Formation in the La Ciénaga de Purmamarca, located around eight kilometers west of the town of Purmamarca in the Jujuy Province (Fig. 1). This study therefore aims to correct and refine the biostratigraphy of this area based on a new conodont assemblage from a succession tightly integrated with graptolite and trilobite data, providing a more precise biostratigraphic correlation of the Acoite Formation at both regional and global scales.

2. Geological setting

Early Paleozoic marine sedimentary successions are widely exposed in the southern part of the Central Andean basin of Argentina and Bolivia. These are collectively referred to as the Santa Victoria Group, comprising the Santa Rosita (Furongian-Tremadocian) and the Acoite (Floian, possibly upper Tremadocian-lower Dapingian) formations (Turner, 1960). In the Purmamarca area of northwestern Argentina, however, the intricate interplay of rapid lateral facies changes and widespread Cenozoic Andean deformation has resulted in a complex local stratigraphic nomenclature. This includes, in stratigraphically ascending order, the Purmamarca shales, Chañarcito limestones, Coquena shales, Cieneguillas shales, and Sepulturas limestones (Harrington and Leanza, 1957). This stratigraphic scheme has been extrapolated to other sectors of the basin with varying degrees of confidence, often relying on single fossil samples obtained from discontinuous outcrops. Currently, the use of Cieneguillas shales has become obsolete, as it is considered a lateral equivalent to the widely accepted Acoite Formation, and to avoid confusion with the Tremadocian Cieneguillas Formation of Bolivia (*e.g.,* Vaccari *et al.*, 2006; Toro *et al.*, 2017; Waisfeld *et al.*, 2023).

At the La Ciénaga de Purmamarca, the Acoite Formation is composed of >400 meters of dark grey shales, subordinate sandstones, calcarenites, and calcareous concretions (Toro *et al.*, 2017) (Fig. 1B, C). It developed in a relatively deep, low energy, largely dysaerobic, restricted foreland shelf ramp (Waisfeld and Asitini, 2003). The entire stratigraphic succession is strongly deformed, with both its lower and upper sections delimited by faults.

3. Previous biostratigraphic studies

The first reference to the age of the Ordovician outcrops at the La Ciénaga de Purmamarca was provided by Harrington (*in* Harrington and Leanza, 1957, p. 13). He attributed the Cieneguillas shales to the Arenigian based on the presence of *Thysanopyge argentina* Kayser (1898) and *Megalaspidella kayseri* Kobayashi (1937) and assigned the Sepulturas limestones to the Llanvirnian due to the presence of *Hoekaspis schlaginweiti* Harrington and Leanza (1942). A review of the material assigned to *H. schlaginweiti* from the La Ciénaga de Purmamarca by Harrington and Leanza (1957, p. 235), along with the revision of the trilobites housed at the Centro de Investigaciones en Ciencias de la Tierra (CICTERRA)-Universidad Nacional de Córdoba (N.E. Vaccari collection), however, suggests that this taxon may instead correspond to *Niobides armatus* Harrington and Leanza (1957). At its type locality, in the Santa Victoria area (Acoite Formation), *N. armatus* is associated with *T. argentina*. Aceñolaza (2003), on the other hand, pointed out the presence of *Pliomeridius sulcatus* Leanza and Baldis (1975) in the Sepulturas Formation (another name given to the Sepulturas limestones) at the La Ciénaga de Purmamarca, suggesting a late early Arenigian age. In our collection, the trilobite association is composed of *P. sulcatus*, *Thysanopyge clavijoi* Harrington and Leanza (1957), *N. armatus* and *Pytine wirayasqa* Vaccari *et al.* (2006), which are indicative of the Early Ordovician *Thysanopyge* fauna (stage slices Tr 3-Fl 2 *sensu* Bergström *et al.,* 2009).

The first ones to document conodonts from the Acoite Formation at the La Ciénaga de Purmamarca

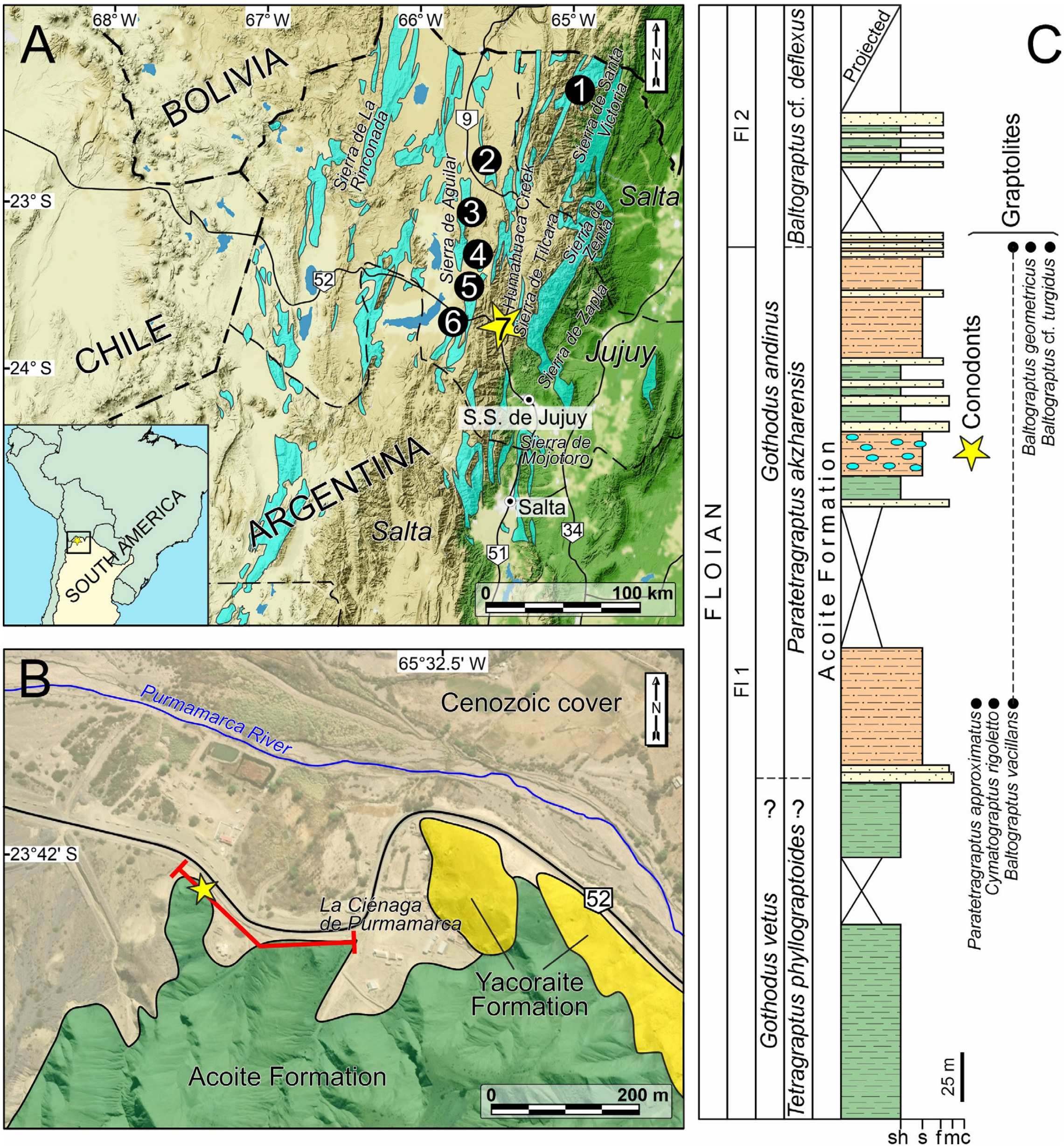

FIG. 1. **A.** Ordovician siliciclastic outcrops of the Central Andean basin of northwestern Argentina with location of classical stratigraphical sections involving Tremadocian-Floian deposits. **1**: Santa Victoria area (Chulpíos Creek), **2**: Espinazo del Diablo, **3**: El Aguilar, **4**: Cajas, **5**: Los Colorados-Chamarra, Aguas Blancas Creek, Alto de Lipán, **6**: Angosto del Moreno, and **7**: La Ciénaga de Purmamarca (map modified from Waisfeld *et al*., 2023). **B.** Simplified geological map of the La Ciénaga de Purmamarca study area, showing the location of the fossiliferous samples (yellow star) and of the measured stratigraphic section (red lines). **C.** Stratigraphic column of the Acoite Formation at the La Ciénaga de Purmarmarca, indicating the position of the fossiliferous conodont sample (yellow star) and previous graptolite records (black circles) (modified from Toro *et al*., 2017). Abbreviations, **sh**: shale, **s**: siltstone, **f**: fine-grained sandstone, **m**: medium-grained sandstone, and **c**: coarse-grained sandstone. In A, words in italics refer to geographic elements and province names.

were Rao *et al*. (1994). They referred the conodonts to the Billingenian Regional Stage (upper Latorpian) of the Oelandian Series of southern Sweden. The Billingenian Stage comprises the *Oepikodus evae, Trapezognathus diprion* and *Microzarkodina russica* conodont interval zones (Bagnoli and Stouge, 1997; Stouge *et al*., 2020), representing the upper part of the Floian Global Stage in Scandinavia and the East Baltic area (Goldman *et al.*, 2023; Nielsen *et al.*, 2023). Quoting Rao *et al.* (1994), the graptolites "*Didymograptus* (*s.l.*) aff. *demissus* (Törnquist, 1901), *D.* (*s.l.*) cf. *simulans* Elles and Wood (1901) and *D.* (*Corymbograptus*) aff. *vacillans* (Tullberg, 1880)" from the La Ciénaga de Purmamarca could represent an age equivalent to the *Tetragraptus phyllograptoides* Zone (Fl 1). However, the presence of *Baltograptus vacillans*, index species of the homonymous graptolite biozone in Scandinavia (Maletz, 2023), suggests a slightly younger age for the graptolite bearer levels (Ortega *et al.*, 2003). Based on a similar conodont assemblage, Rao (1999) established the *Baltoniodus crassulus andinus-Drepanoistodus pitjanti* Association Zone of early Arenigian age in the Espinazo del Diablo and Cajas sectors. Although Rao (1999) referred the conodont-bearing levels to the Sepulturas Formation, they correspond to the Acoite Formation instead, following the nomenclatural revision of Vaccari *et al*. (2006) and Toro *et al*. (2017).

Based on the La Ciénaga de Purmamarca fauna described by Rao *et al*. (1994), Albanesi *et al.* (2008) established the *Gothodus* Zone for the Eastern Cordillera, replacing the equivalent *Oepikodus evae* Zone of Albanesi and Ortega (2002), which encompasses the middle to upper late Floian. Albanesi *et al.* (2014) reported a similar conodont association from the La Ciénaga de Purmamarca, in the Aguas Blancas Creek, near Altos de Lipán, which they ascribed to the late Floian. Toro *et al*. (2015), on the other hand, considered that the *Gothodus* Zone of northwestern Argentina begins at least in the early Floian *Paratetragraptus akzharensis* Zone, which aligns with the recently estimated early-to-middle Floian biostratigraphic range of the *Gothodus andinus* Zone in the Chulpíos Creek section (Voldman *et al*., 2017). Albanesi *et al.* (2021) referred the Aguas Blancas fossil assemblage to the early-middle Floian based on its associated graptolite records (upper *P. akzharensis* Zone, or possibly the lower *Baltograptus* cf. *B*. *deflexus* Zone), and suggested that the Aguas Blancas section is stratigraphically younger than the outcrops exposed at the La Ciénaga de Purmamarca.

Aceñolaza *et al.* (2008) described the index species *Trapezognathus diprion* (Lindström, 1954) from the La Ciénaga de Purmamarca. They suggested that part of the elements described as *T. argentinensis* Rao *et al.* (1994) from the La Ciénaga de Purmamarca and Espinazo del Diablo (Rao *et al*., 1994; Rao, 1999) should be assigned to *T. diprion*, while others could represent an undescribed species of the same genus. Aceñolaza *et al.* (2008) also reported from the same sample a fragmentary element of the index species *Oepikodus intermedius* Serpagli (1974) and assigned the assemblage to the late Early Ordovician.

Subsequent studies interpreted *T. argentinensis* as a mixture of other species and partly synonymized it with *T. diprion* (Carlorosi and Heredia, 2013) and with the index species for the base of the Dapingian, *Baltoniodus triangularis* (Carlorosi, 2013; Carlorosi *et al.*, 2013). Although *T. diprion* and *O. intermedius* coexist throughout most of the *O. evae* Zone, their last appearance does not reach the base of the Dapingian in the Huanghuachang section of South China (Wang *et al.*, 2009). Conversely, *O. intermedius* was documented in the lower Dapingian of the Argentine Precordillera (*e.g.,* Serpagli, 1974; Albanesi *et al.*, 1998; Mango and Albanesi, 2020), with a closely related species also recorded in North America (Stouge and Bagnoli, 1988). In addition, *O. evae* (Lindström, 1954) occurs in some offshore stratigraphic sections of Scandinavia within the *B. triangularis* Zone (*e.g.,* Rasmussen, 2001; Bergström and Löfgren, 2009; Stouge *et al*., 2020, and references therein). In summary of the conodont taxonomic analysis, the same specimens studied by Rao *et al.* (1994) and Rao (1999) from the La Ciénaga de Purmamarca and Espinazo del Diablo were referred to both the Floian and Dapingian ages (Carlorosi, 2013; Carlorosi and Heredia, 2013; Carlorosi *et al.*, 2013).

The graptolite records from the La Ciénaga de Purmamarca suggest an early to middle Floian age for the bearer levels. For instance, Toro and Vento (2013) recognized there early Floian levels after recording *Baltograptus vacillans* (Tullberg, 1880) and *P. akzharensis* (Tzaj, 1968). However, in the Cow Head Group of Newfoundland, Canada, the *P. akzharensis* Zone of Williams and Stevens (1988) correlates with the top of the *Prioniodus elegans* Zone, reaching the base of the *O. evae* Zone (cf. Stouge and Bagnoli, 1988; Johnston and Barnes, 1999) and possibly implying that age limits vary depending on the location. Some years later, Toro *et al.* (2017, 2024) and Navarro *et al.* (2019) updated the graptolite biostratigraphy at the La Ciénaga de Purmamarca and determined the *Tetragraptus phyllograptoides* (Fl 1), *P. akzharensis* (Fl 1) and the lower part of the *Baltograptus* cf. *deflexus* (Fl 2) biozones in tectonically truncated sedimentary packages in the Acoite Formation. These Floian graptolite biozones have also been recognized in the Aguas Blancas, El Aguilar, Angosto del Moreno, Cajas, and Los Colorados sectors in the western flank of the Eastern Cordillera, in the Cieneguillas section in Bolivia, as well as in the northern Santa Victoria area (Egenhoff *et al.*, 2004; Albanesi *et al.*, 2008, 2014; Toro and Maletz, 2008; Toro and Vento, 2013; Toro *et al.*, 2015; Voldman *et al.*, 2017), providing a good temporal constraint for the low-diversity conodont faunas along the Eastern Cordillera.

4. Material and methods

The La Ciénaga de Purmamarca is a classical locality for the study of the Ordovician of northwestern Argentina (Cecioni, 1953, 1965; Harrington and Leanza, 1957; Rao, 1994). In this contribution, the analyzed rock sample (geographical coordinates: 23°42' S, 65°32.7' W; Fig. 1B) is a phosphatized, highly fossiliferous matrix-supported calcareous coquina that includes conodonts, cnidarians, linguliform and rhynchonelliform brachiopods, hyoliths, mollusks (gastropods, bivalves, and cephalopods), as well as remnants of trilobites, ostracods and echinoderms. From this same bed, the raphiophorid trilobite *Pytine wirayasqa* Vaccari *et al.* (2006) was originally defined. 1,700 g of sample were fragmented and dissolved in buffered acetic acid following the standard conodont recovery techniques (Stone, 1987; Jeppsson *et al.*, 1999), obtaining 636 conodont elements (Table 1).

The conodont specimens are generally smaller than 500 µm, complete to moderately fragmented, and exhibit a Color Alteration Index (CAI; Epstein *et al.*, 1977) of 3, indicating burial temperatures of 110-200 °C. For the morphotype classification, the terminology of Sweet (in Clark *et al.*, 1981) was adopted, which includes P, M, and S elements and their subdivisions. Images of the microfossils were obtained with a MC170 HD camera attached to a Leica DM4500 petrographic microscope and with a ZEISS Sigma scanning electron microscope (CICTERRA and LAMARX, Universidad Nacional de Córdoba, Argentina). The systematic taxonomy of *Kallidontus nodosus* Pyle and Barnes (2002) and of *Zentagnathus argentinesis* (Rao *et al.*, 1994) is provided in the Appendix. The specimens are housed in the CICTERRA Institute under the repository code prefix CEGH-UNC.

5. Conodont biostratigraphy and implications

In the original conodont collection from the La Ciénaga de Purmamarca area, Rao *et al.* (1994) described >1,400 elements, consisting of *Baltoniodus crassulus andinus* Rao *et al.* (1994), *Cornuodus longibasis* (Lindström, 1954), *Drepanodus*? sp., *Drepanoistodus basiovalis* (Sergeeva, 1963), *Drepanoistodus pitjanti* Cooper (1981) (labelled as

TABLE 1. NUMERICAL DISTRIBUTION OF CONODONT SPECIES FROM THE LA CIÉNAGA DE PURMAMARCA, NW ARGENTINA.

Species / Morphotype	M	Pa	Pb	Sa	Sb	Sc	Sd	S	Total
Balognathidae indet.	-	-	1	-	-	-	-	-	1
Drepanodus arcuatus	2	2	1	2	3	0	0	0	10
Drepanoistodus pitjanti	13	0	0	12	25	19	7	1	77
Drepanoistodus cf. *andinus*	6	1	0	2	5	3	0	0	17
Drepanoistodus sp. A	3	1	0	2	1	1	0	2	10
Gothodus andinus	210	60	82	9	35	36	52	0	484
Kallidontus nodosus	-	1	1	-	-	-	-	-	2
Paroistodus sp.	-	-	-	-	-	-	-	3	3
Zentagnathus argentinensis	1	17	2	2	6	0	4	0	32
								Total	636

D. aff. *pitjanti* in the table and figure captions of Rao *et al.*, 1994), *Drepanoistodus* sp. 2, *Protopanderodus* sp. cf. *P.* n. sp. A McCracken (1989), *Trapezognathus argentinensis* Rao *et al.* (1994) and *Scandodus*? sp. The taxonomy of the species *Gothodus andinus* and *Zentagnathus argentinensis* were subsequently discussed in Voldman *et al*. (2013a, 2017). Note that Rasmussen *et al*. (2021) revised the genus *Drepanoistodus* and constrained *D. basiovalis* to a species with a first appearance in the Darriwilian. Accordingly, in the present collection this taxon was determined as *Drepanoistodus* sp. A.

The conodont sampling conducted in the present study allows for a biostratigraphic refinement of the original collection (Table 1). Based on its yield, faunal content, and field observations, our sample was obtained from the same beds from which the LC9 sample of Rao *et al.* (1994) was derived, sharing records of *G. andinus* (Fig. 2), *D. pitjanti* (Fig. 3A-F), *D.* sp. A (Fig. 3L-O), and *Z. argentinensis* (Fig. 4A-K). The species *Drepanodus*? sp. and *Drepanoistodus* sp. 2 of Rao *et al*. (1994) were assigned in the present contribution, respectively, to *Drepanodus arcuatus* Pander (1856) (Fig. 3R-T) and *Drepanoistodus* cf. *andinus* Voldman *et al.* (2013b) (Fig. 3G-K). It was not possible to recognize *Protopanderodus* sp. cf. *P.* n. sp. A McCracken (1989) and *Scandodus*? sp. in our collection, although *Paroistodus* sp. could indeed be identified (Fig. 3P-Q). The genus *Paroistodus*, in fact, occurs sporadically in the Early Ordovician of the Central Andean basin (*e.g.,* Voldman *et al.*, 2017; Albanesi *et al.*, 2021). Based on its faunal composition, the fossil assemblage described here corresponds to the Southwestern Gondwana Province, characterized by a mixture of endemic, Baltic, and Laurentian taxa (Zeballo and Albanesi, 2013a).

Notably, the new conodont sampling yielded *Kallidontus nodosus* (Fig. 4M-N), an index species of the Midcontinent Realm in the shallow-water platform facies of the northern Canadian Cordillera (Pyle and Barnes, 2002) (Fig. 5). Originally, *K. nodosus* was introduced from the Mount Sheffield Member of the Kechika Formation in northeastern British Columbia, where it was restricted to the *K. nodosus* Subzone of the upper *Acodus kechikaensis* Zone (Pyle and Barnes, 2002, 2003) (Fig. 5). The *K. nodosus* Subzone is approximately coeval with the lower half of the *Prioniodus elegans* Zone of Baltoscandia, extending from the first appearance of *K. nodosus* to the first appearance of *Oepikodus communis*, the nominate species of the overlying biozone (Pyle and Barnes, 2002, 2003) (Fig. 5). Other typical components of the *K. nodosus* Subzone in the Kechika Formation include *Acodus kechikaensis* Pyle and Barnes (2002), *A. neodeltatus* Pyle and Barnes (2002), *Drepanoistodus amoenus* (Lindström, 1954), *Drepanoistodus latus* Pyle and Barnes (2002), *Fahraeusodus marathonensis* (Bradshaw, 1969), *K. serratus* Pyle and Barnes (2002), *Oelandodus elongatus* van Wamel (1974), *Parapanderodus striatus* (Graves and Ellison, 1941), *Paroistodus parallelus* (Pander, 1856), *Scolopodus krummi* (Lehnert, 1995), and *Tropodus australis* (Serpagli, 1974).

In the Precordilleran scheme, the *Prioniodus elegans* Zone is well documented in the San Juan Formation, where it has been subdivided into the *Tropodus sweeti* and the *O. communis* subzones (Albanesi *et al.*, 1998; Albanesi and Ortega, 2016; Mango and Albanesi, 2020). These subzones approximately correlate with the upper part of the *Paratetragraptus approximatus* Zone and the *P. akzharensis* zones of the North America graptolite scheme (*e.g.,* Stouge and Bagnoli, 1988; Goldman *et al*., 2023; Maletz, 2023), respectively. Stratigraphically above, the base of the overlying *Oepikodus evae* Zone marks the base of the middle Floian (Fl 2) and partly correlates with the base of the *Baltograptus.* cf. *deflexus* Zone in the Eastern Cordillera (Bergström *et al*., 2009; Waisfeld *et al*., 2023) (Fig. 5).

Considering the stratigraphic position of the conodont sample, its composition, and the associated graptolite fauna (indicative of the *P. akzharensis* Zone), the presence of *K. nodosus* verifies an early Floian (Fl 1) age for the lower part of the *G. andinus* Zone in the study area (Fig. 5). The large difference in size of the two morphotypes of *K. nodosus* recovered (Fig. 4M, N), as well as the absence of reworked elements both in Rao's and in our collection (>2.000 elements in total), diminishes the possibility that *K. nododus* was reworked from older strata. An early Floian age for the lower levels of the *G. andinus* Zone aligns with the previous assessment of Voldman *et al.* (2017) and contradicts suggestions of a Dapingian age raised by others. In addition, the occurrence of *Erraticodon patu* Cooper (1981) in the upper portion of the Acoite Formation at the Chulpíos Creek and the Aguas Blancas sectors (Voldman *et al.*, 2017; Albanesi *et al.*, 2021) suggests a younger stratigraphical age for those levels, although still Floian, as indicated by the presence of graptolites characteristic of the lower *B.* cf. *deflexus* Zone.

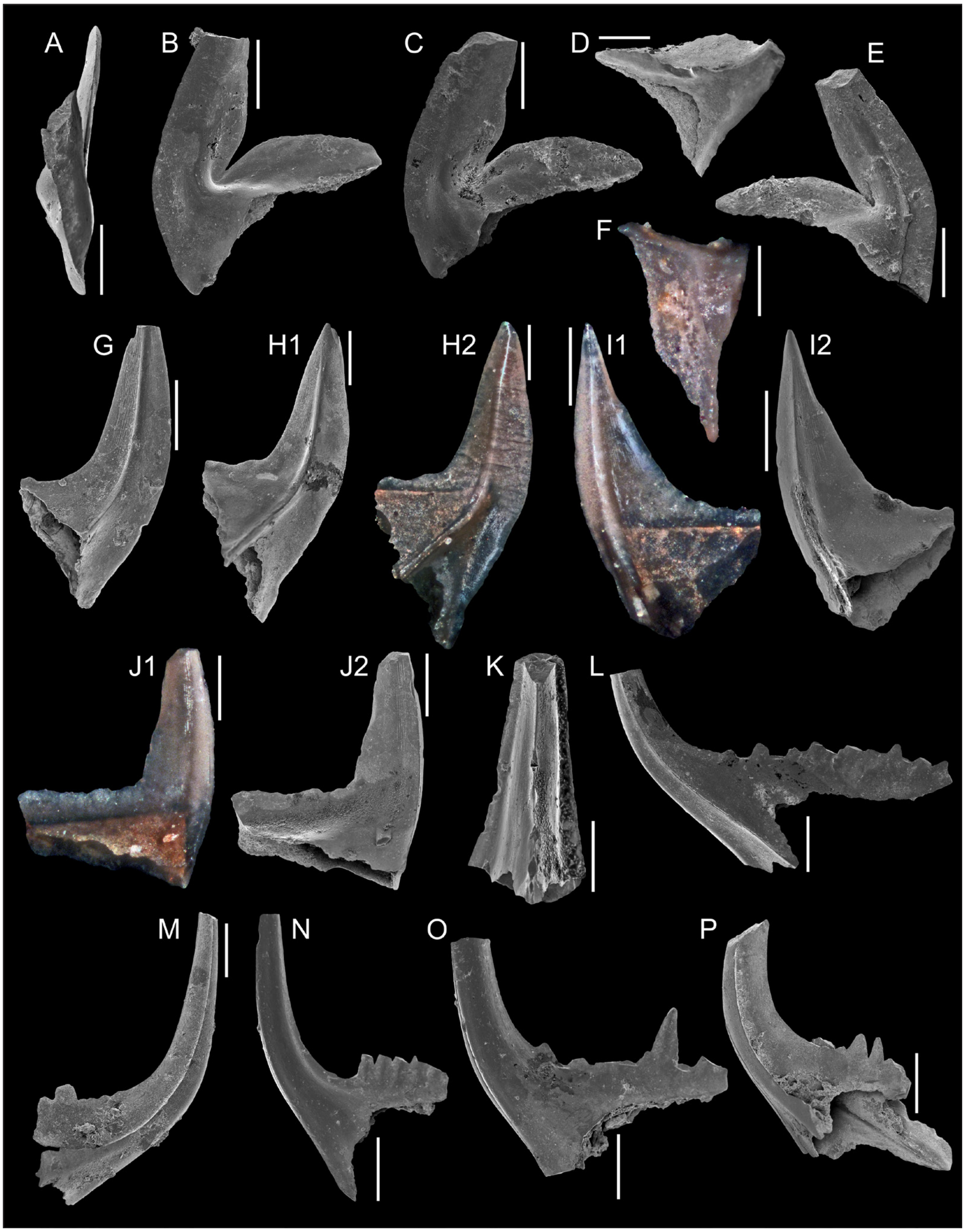

FIG. 2. SEM images (unless otherwise stated) of conodonts from the La Ciénaga de Purmamarca area. **A-P**. *Gothodus andinus* (Rao *et al*., 1994). **A.** M element, CEGH-UNC 27689; **B.** M element, CEGH-UNC 27690; **C.** M element, CEGH-UNC 27691; **D.** Pb element, CEGH-UNC 27692; **E.** M element, CEGH-UNC 27693; **F.** Pa element, CEGH-UNC 27694, optical image; **G.** Pb element, CEGH-UNC 27695; **H1-H2.** Pb element, CEGH-UNC 27696, H1: SEM image, H2: optical image; **I1-I2.** Pa element, CEGH-UNC 27697, I1: optical image, I2: SEM image; **J1-J2**, Pa element, CEGH-UNC 27698, J1: optical image, J2: SEM image; **K.** Sa element, CEGH-UNC 27699; **L.** Sb element, CEGH-UNC 27700; **M.** Sb element, CEGH-UNC 27701; **N.** Sc element, CEGH-UNC 27702; **O.** Sc element, CEGH-UNC 27703; **P.** Sd element, CEGH-UNC 27704. All scale bars are 100 µm.

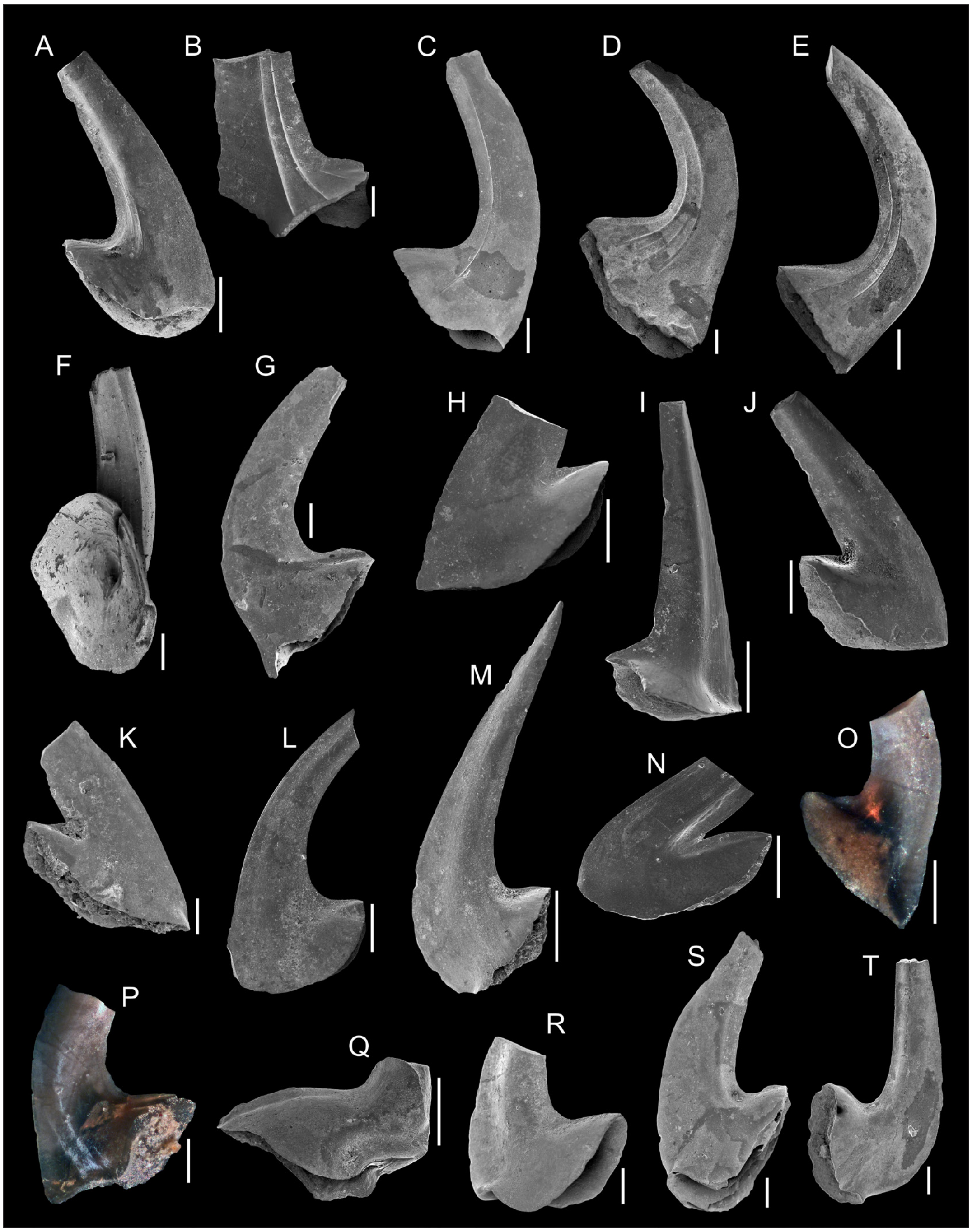

FIG. 3. SEM images (unless otherwise stated) of conodonts from the La Ciénaga de Purmamarca area. **A-F**. *Drepanoistodus pitjanti* Cooper (1981). **A.** M element, CEGH-UNC 27719; **B.** Sa element, CEGH-UNC 27720; **C.** Sc element, CEGH-UNC 27721; **D.** Sb element, CEGH-UNC 27722; **E.** Sd element, CEGH-UNC 27723; **F.** Sd element, CEGH-UNC 27724. **G-K.** *Drepanoistodus* cf. *andinus* Voldman *et al*. (2013b). **G.** Sb element, CEGH-UNC 27725; **H.** M element, CEGH-UNC 27726; **I.** Sa element, CEGH-UNC 27727; **J.** M element, CEGH-UNC 27728; **K.** M element, CEGH-UNC 27729. **L-O.** *Drepanoistodus* sp. A. **L.** Sc element, CEGH-UNC 27730; **M.** Sb element, CEGH-UNC 27731; **N.** M element, CEGH-UNC 27732; **O.** Pa element, CEGH-UNC 27733, optical image. **P-Q.** *Paroistodus* sp. **P.** S element, CEGH-UNC 27734, optical image; **Q.** S element, CEGH-UNC 27735. **R-T.** *Drepanodus arcuatus* Pander (1856). **R.** Pb element, CEGH-UNC 27736; **S.** Pa element, CEGH-UNC 27737; **T.** Pa element, CEGH-UNC 27764. All scale bars are 100 µm.

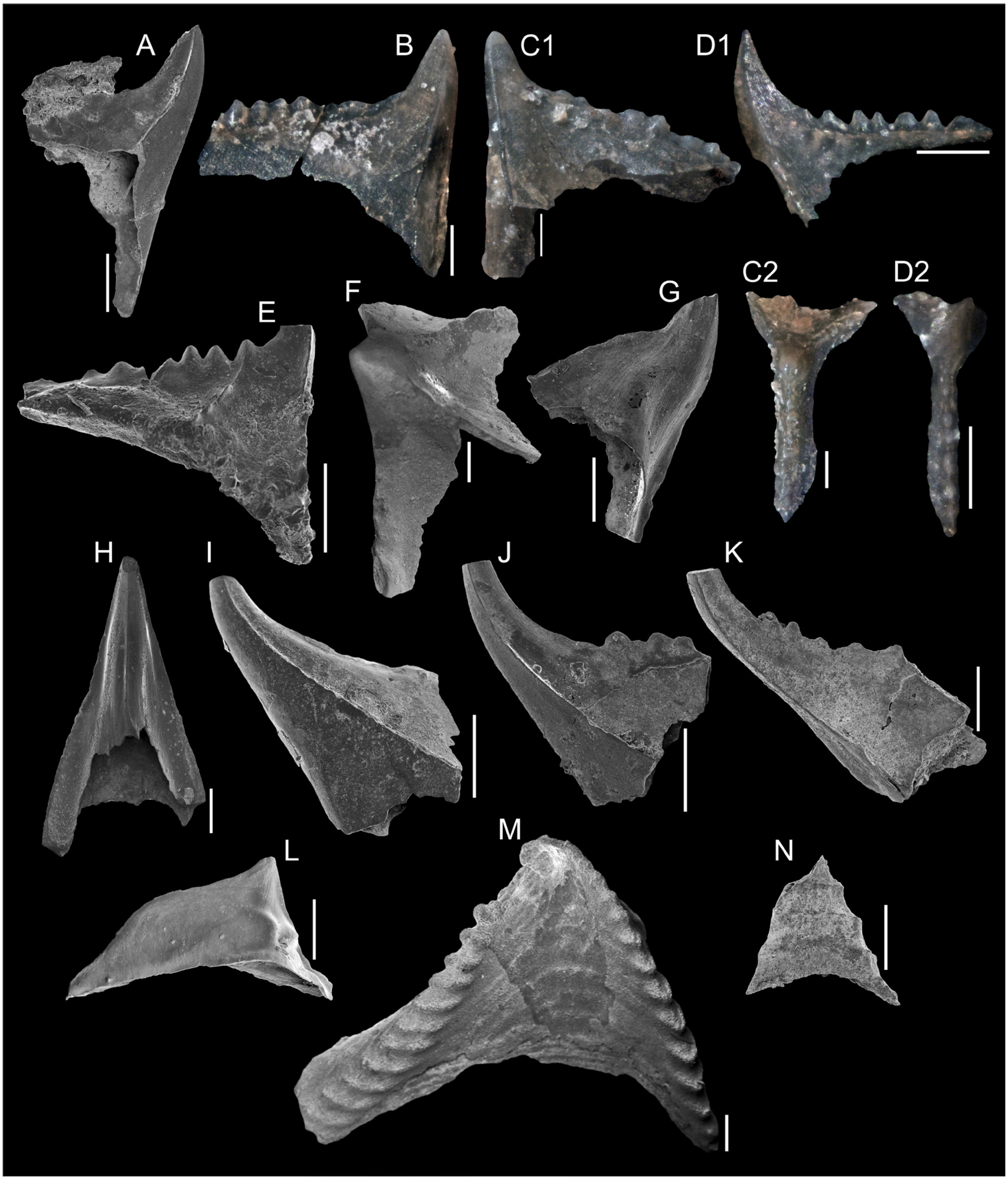

FIG. 4. SEM images (unless otherwise stated) of conodonts from the La Ciénaga de Purmamarca area. **A-K**. *Zentagnathus argentinensis* (Rao *et al.*, 1994). **A.** Pa element, CEGH-UNC 27705; **B.** Pa element, CEGH-UNC 27706, optical image; **C1-C2.** Pa element, CEGH-UNC 27707, optical images in lateral (C1) and upper view (C2); **D1-D2.** Pa element, CEGH-UNC 27708, optical images in lateral (D1) and upper view (D2); **E.** Pb element, CEGH-UNC 27709; **F.** Pb element, CEGH-UNC 27710; **G.** M element, CEGH-UNC 27711; **H.** Sa element, CEGH-UNC 27712; **I.** Sb element, CEGH-UNC 27713; **J.** Sb element, CEGH-UNC 27714; **K.** Sd element, CEGH-UNC 27715. **L.** Balognathidae indet., Pb element (basal filling?), CEGH-UNC 27716. **M-N.** *Kallidontus nodosus* Pyle and Barnes (2002), **M.** Pb element, CEGH-UNC 27717; **N.** Pa element, CEGH-UNC 27718. All scale bars are 100 µm.

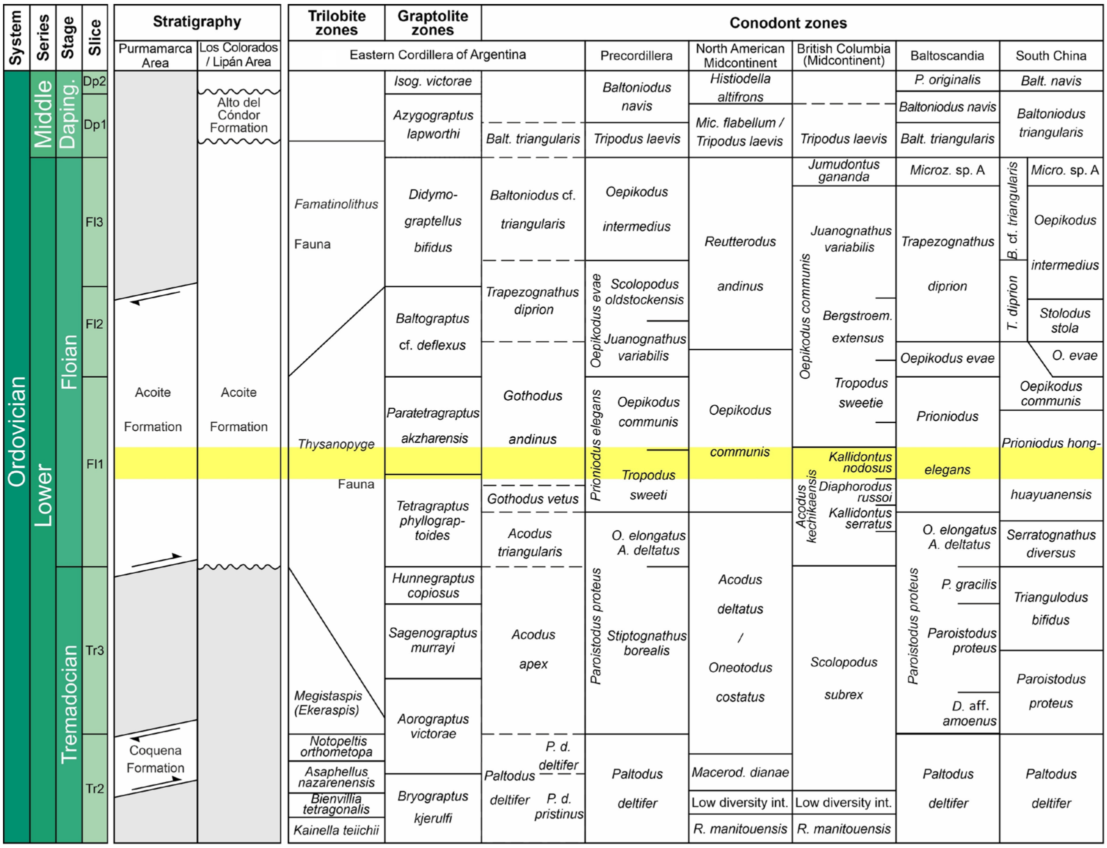

FIG. 5. Early-Middle Ordovician biostratigraphic scheme highlighting in pale yellow the approximate age of the conodont fauna from the Acoite Formation exposed at the La Ciénaga de Purmamarca and described in this work. Additional columns indicate its regional and global correlation (figure adapted from Ross *et al.*, 1997; Bagnoli and Stouge, 1997; Pyle and Barnes, 2002; Li *et al.*, 2010; Albanesi and Ortega, 2016; Voldman *et al.*, 2017; Goldman *et al.*, 2023; Waisfeld *et al.*, 2023).

The early Floian age of the endemic species *G. andinus* and *Z. argentinensis* at the La Ciénaga de Purmamarca provides an additional temporal constraint for the early evolution of prioniodontid conodonts (*e.g.,* Sweet, 1988; Stouge and Bagnoli, 1999; Dzik, 2015; Stouge *et al.*, 2020; Zhen *et al.*, 2023). In the Chulpíos Creek, *Gothodus vetus* Voldman *et al.* (2017), which exhibits rudimentary denticulation, evolved directly from an adentate species, likely *Acodus triangularis* (Ding in Wang, 1993), and was subsequently replaced by *G. andinus*. Voldman *et al.* (2017) noted a parallel evolution between *G. vetus* and *Prioniodus? transitans* (McTavish, 1973) from the Emanuel Formation in Australia, although they interpreted a slightly younger age for the former, as it succeeds *A. triangularis* in the stratigraphic column. Along with *Prioniodus antiquus* Zhen *et al.* (2023) and *P. gilberti* Stouge and Bagnoli (1988), all these forms share the development of short and rudimentary denticles in septimembrate apparatuses around the Tremadocian-Floian boundary (Zhen *et al.*, 2023).

The appearance of *Zentagnathus* in the early Floian places it among the oldest balognathids. In agreement, Heward *et al.* (2019) considered that the balognathids from the Middle Shale Member of the Amdeh Formation from the Sultanate of Oman, Arabian margin of Gondwana, are no older than early Floian. Zhen *et al.* (2023) suggested that the appearance and evolution of *Prioniodus* represented a significant adaptive strategy for conodont animals, enabling them to occupy and thrive in the increasingly diverse environments and complex food webs during the Great Ordovician Biodiversification Event (*e.g.,* Goldman *et al.*, 2020; Moreno *et al.,* 2024). The current record of *K. nodosus* in the *G. andinus* Zone at the La Ciénaga de Purmamarca marks a significant step towards refining the temporal framework of conodonts in the Early Ordovician of the Eastern Cordillera of Southwest Gondwana.

6. Conclusions

The new conodont assemblage from the Acoite Formation at the La Ciénaga de Purmamarca, northwestern Argentina, provides refined constraints on its depositional age and enhances regional and global correlation. The assemblage comprises Balognathidae indet., *Drepanodus arcuatus*, *Drepanoistodus pitjanti*, *D.* cf. *andinus*, *D.* sp. *A*, *Gothodus andinus*, *Kallidontus nodosus*, *Paroistodus* sp., and *Zentagnathus argentinensis*. The presence of *K. nodosus* allows for a precise correlation of the lower *Gothodus andinus* Zone with the early Floian *Prioniodus elegans* Zone (Fl 1). These new findings highlight the need for caution in the identification of *Baltoniodus triangularis*, the index fossil for the Lower-Middle Ordovician Series boundary, both in the La Ciénaga de Purmamarca and other sectors along the Eastern Cordillera.

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Appendix

Systematic Paleontology

Class Conodonta Pander (1856)
Order Panderodontida Sweet (1988)
Family Fryxellodontidae Miller (1980)
Genus *Kallidontus* Pyle and Barnes (2002)

Type species: *Kallidontus serratus* Pyle and Barnes (2002)

Referred species: *Kallidontus corbatoi* (Serpagli, 1974), *Kallidontus? lofgreni* (Stouge and Bagnoli, 1988), *K. gondwanicus* Zeballo and Albanesi (2013b), *K. princeps* Pyle and Barnes (2002), *K. nodosus* Pyle and Barnes (2002).

Remarks: Many platform conodont elements with transverse ridges and node-like denticles first appeared in the Early Ordovician (*e.g.,* Bergström, 1983; Dzik, 1983; Löfgren, 1985; Bagnoli *et al.*, 1988). However, their fossil record is relatively sparse and most specimens are fragmentary, complicating efforts to reconstruct taxonomic relationships. The genus *Kallidontus* is characterized by large, antero-posteriorly compressed Pb platform elements, with variable denticulation and ridge development (Pyle and Barnes, 2002). The first representative of the *Kallidontus* lineage is *K. gondwanicus* Zeballo and Albanesi (2013b), which occurs in the *Paltodus deltifer* Zone (Tr2) of the underlying Coquena Formation and the Santa Rosita Formation of the Santa Victoria Group, Eastern Cordillera, Argentina, and the Tiñú Formation of Oaxaca, Mexico (Zeballo and Albanesi, 2013b; Voldman *et al.*, 2013b). During the upper Tremadocian-lower Floian interval, the lineage is progressively succeeded by *K. princeps* Pyle and Barnes (2002), *K. serratus* Pyle and Barnes (2002), and *K. nodosus* Pyle and Barnes (2002).

Based on surface ornamentation, Stouge and Bagnoli (1988) reclassified *Fryxellodontus*? *corbatoi* Serpagli (1974) as *Polonodus*? *corbatoi* and described *Polonodus*? *lofgreni* Stouge and Bagnoli (1988) from the *P. elegans* Zone of Newfoundland. Subsequently, these species were assigned to *Polonodus* (*e.g.,* Lehnert, 1995; Albanesi, 1998), and later to *Kallidontus* without formal taxonomic discussion (*e.g.,* Mango and Albanesi, 2020; Rueda and Albanesi, 2023). It remains possible that *Kallidontus* is in turn a junior subjective synonym of the obscure genus *Nericodus*, described from the *Paroistodus proteus* Zone of Sweden (Lindström, 1954; Miller, 1980; Dzik, 1983, 2024).

Kallidontus nodosus Pyle and Barnes (2002)
Fig. 4M-N

2002. *Kallidontus nodosus* n. sp. Pyle and Barnes, pp. 53-54, pl. 8, figs. 1-15.

2003. *Kallidontus nodosus* Pyle and Barnes, fig. 10: 12-14.

Material: 2 elements.

Remarks. The specimens at hand closely resemble the holotype of *K. nodosus* from British Columbia by its shape and the presence well-developed transverse ridges. In contrast, the transverse ridges are weakly developed in *K. serratus* Pyle and Barnes (2002) and barely visible in *K. princeps* Pyle and Barnes (2002). The holotype of *K. lofgreni* (Stouge and Bagnoli, 1988, pl. 11, fig. 1) from the lower Floian of Newfoundland also shows some resemblance to *K. nodosus.* However, *K. lofgreni* is more antero-posteriorly compressed and presents surface reticulation, while the paratypes may exhibit subtle radial ridges (Stouge and Bagnoli, 1988, pl. 11, fig. 3) not observed in *K. nodosus*. The discovery of additional specimens would certainly help clarify whether *K. nodosus* and *K. lofgreni* are distinct species or simply variations of a single species.

Order Prioniodontida Dzik (1976)
Family Balognathidae Hass (1959)
Genus ***Zentagnathus*** Voldman and Albanesi (in Voldman *et al.*, 2017)

Type species: *Trapezognathus? primitivus* Voldman *et al.* (2013a)

Referred species: *Z. argentinensis* (Rao *et al.*, 1994), *Z. gertrudisae* Albanesi *et al*. (2023).

Remarks: Voldman *et al.* (2013a) emended the diagnosis of *Trapezognathus argentinensis* after studying specimens from the Sierra de Zenta, although with doubts on its generic assignment. This issue became clear after the analysis of an extensive conodont collection from the Chulpíos Creek, in the Santa Victoria area, and the definition of the endemic genus *Zentagnathus* (Voldman *et al.*, 2017). *Zentagnathus* is distinguished from *Trapezognathus* and early species of *Baltoniodus* by presenting a tertiopedate M element in their septimembrate apparatus (cf. Bagnoli and Stouge, 1997; Heward *et al.*, 2019). Currently, it includes *Z. argentinensis* and *Z. primitivus*, both species distinguished by their degree of denticulation, from highly rudimentary to well-developed, and the more advanced, Darriwilian *Zentagnathus gertrudisae* Albanesi *et al.* (2023).

Zentagnathus argentinensis (Rao *et al.*, 1994)
Fig. 4A-K

1994. *Trapezognathus argentinensis* n. sp. Rao *et al.*, pp. 73, 75, pl. 3, figs. 7-12, 14, pl. 7, figs. 1-8.
?2003. *Lenodus* sp. Bultynck and Sarmiento, p. 266, pl.2, figs. 12-13 (only).
2008. *Trapezognathus diprion* (Lindström); Aceñolaza *et al.*, pp. 151-153, fig. 4B.
2011. *Trapezognathus diprion* (Lindström); Carlorosi, fig. 4C-D.
2013a. *Trapezognathus? argentinensis* Rao *et al.*; Voldman *et al.*, pp. 126-127, figs. 2.15-2.21.
2017. *Zentagnathus argentinensis* (Rao *et al.*); Voldman *et al.*, pp. 409, 411, figs. 6C-E, J, M-N.
2017. *Baltoniodus* sp. Voldman *et al.*, fig. 6: G-H.
2017. *Baltoniodus triangularis* (Lindström); Carlorosi *et al.*, figs. 2A, B.
2021. *Zentagnathus argentinensis* (Rao *et al.*); Albanesi *et al.*, p. 492, figs. 6Q-Y

Material. 32 elements.

Remarks: Pa elements of *Z. argentinensis* may resemble Pa elements of *G. andinus*, particularly when dealing with broken specimens, although the former are generally more denticulated and the basal cavity is slightly deeper. *Z. argentinensis* may look like *B. triangularis* (Lindström); however, its Pb element is diagnostic, as well as its non-geniculate M element, characteristic of the genus (Voldman *et al.*, 2013a, 2017). Moreover, S-elements in *Z. argentinensis* present a less pronounced length/with ratio compared to those of *B. triangularis*, which are more acicular and more denticulated (Bagnoli and Stouge, 1997; Bergström and Löfgren, 2009).

Conversely, Carlorosi (2013) and Carlorosi *et al.* (2013) partly considered *Z. argentinensis* from the La Ciénaga de Purmamarca as a junior synonym of *B. triangularis* and included elements of *G. andinus* (Rao *et al.*, 1994, pl. 3, fig. 2) under the same systematics. Alternatively, Carlorosi and Heredia (2013) partly synonymized *Z. argentinensis* from both the La Ciénaga de Purmamarca (Rao *et al.*, 1994, pl. 3, figs. 7, 14) and Sierra de Cajas (Rao, 1999, pl. 9, fig. 6) areas with *Trapezognathus diprion*, and interpreted the sedimentary sequence as Floian, in agreement with Aceñolaza *et al.* (2008).

Ultimately, Carlorosi *et al.* (2018, 2023) incorrectly incorporated specimens of *Z. argentinensis* from Sierra de Zenta, including a paratype from Purmamarca Rao´s collection illustrated by Voldman *et al.* (2013b), into the synonymy of *B. triangularis*. Voldman *et al.* (2013b) diagnosed some specimens (fig. 2: 5-6) as *B.* cf. *triangularis*, although their revision suggested that they possibly represent basal fillings of *Z. argentinensis.* Carlorosi *et al.* (2018, 2023) also included *Zentagnathus primitivus* from the Chulpíos Creek as a junior synonym of *B. triangularis*, although the cited figure corresponded to *Baltoniodus* sp. instead (Voldman *et al.*, 2017). Reexamination and comparison of *Baltoniodus* sp. with the new collection from the La Ciénaga de Purmamarca suggests it rather falls within the range of shape variability of *Z. argentinensis*, as juvenile specimens tend to exhibit sharper denticles than gerontic specimens (Voldman *et al.*, 2013a). The Pb elements of *Z. argentinensis* are more comparable to those of *Baltoniodus tetrachotomus* Li and Wang *in* Li *et al.* (2004) (=*Baltoniodus tetrastichus* Li *in* Wang *et al.*, 2003) from the lower Dawan Formation, Hubei Province, southern China, although the latter occurred later in time, in the lower *O. evae* Zone, but also before the base of the Dapingian.