# SILURIAN CONODONTS FROM THE RINCONADA FORMATION, ARGENTINE PRECORDILLERA

VOLDMAN, G. G.[1], ALONSO, J. L.[2], BANCHIG, A. L.[3] AND ALBANESI, G. L.[1]

[1]CICTERRA-CONICET, CIGEA, Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba, X5000JJC, Córdoba, Argentina. gvoldman@unc.edu.ar, guillermo.albanesi@unc.edu.ar

[2]Departamento de Geología, Universidad de Oviedo, c/ Arias de Velasco s/n, 33005 Oviedo, Spain. jlalonso@geol.uniovi.es

[3]Departamento de Geología, Universidad Nacional de San Juan, c/ Ignacio de La Rosa y Meglioli s/n, 5400, San Juan, Argentina. abanchig@yahoo.com.ar

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Corresponding author: Voldman, G.G.

**Abstract.** At the eastern margin of the Precordillera and close to the boundary with the Sierras Pampeanas, the Rinconada Formation displays extensional faults, boudinaged sequences and scarce slump folds whose age are not well constrained. It represents a stacking of "broken formations" intercalated with scarce debris flows. A calcareous iron-rich sample from the upper levels of the Rinconada Formation yielded 134 conodont elements including *Dapsilodus obliquicostatus*, *Decoriconus fragilis*, *Oulodus* sp., *Pseudooneotodus beckmanni*, *P. b. bicornis*, *Wurmiella excavata* along with ozarkodinids of the "*Oz.*" *bohemica* – "*Oz.*" *snajdri* lineage. The record of "*Oz.*" aff. *snajdri* suggests a late Homerian – early Gorstian (late Wenlock – early Ludlow) minimum depositional age for the upper debris flows of the Rinconada Formation. The studied conodont fauna improves the biostratigraphic correlation of the Rinconada melange to other successions in the Precordillera and the world as well as it provides clues on the tectonostratigraphic development of the SW Gondwanan foreland during the Silurian times.

**Keywords:** conodonts, biostratigraphy, Rinconada Formation, Silurian, Precordillera, Argentina.

**Resumen.** CONODONTES SILÚRICOS DE LA FORMACIÓN RINCONADA, PRECORDILLERA ARGENTINA. La Formación Rinconada, situada en el margen oriental de la Precordillera y próxima al límite con las Sierras Pampeanas, muestra fallas extensionales, así como pliegues y budines originados por deformación de sedimentos no litificados. Esta formación, cuya edad no ha sido bien precisada, está constituida por un apilamiento de "formaciones rotas" intercaladas con escasos flujos de detritos. Una muestra calcárea rica en hierro de los niveles superiores de la Formación Rinconada brindó 134 conodontes, incluyendo *Dapsilodus obliquicostatus*, *Decoriconus fragilis*, *Oulodus* sp., *Pseudooneotodus beckmanni*, *P. b. bicornis*, *Wurmiella excavata* y ozarkodínidos del linaje "*Oz*." *bohemica* – "*Oz*." *snajdri*. El registro de "*Oz*." aff. *snajdri* permite sugerir una edad mínima depositacional Homeriana tardía – Gorstiana temprana (Wenlock tardío – Ludlow temprano) para los flujos de detritos del tramo superior de la Formación Rinconada. La fauna de conodontes recuperada de la Formación Rinconada favorece la correlación estratigráfica con otras sucesiones sedimentarias de la Precordillera y del mundo, así como brinda claves sobre el desarrollo tectonoestratigráfico del antepaís del suroeste de Gondwana en tiempos silúricos.

**Palabras clave:** conodontes, bioestratigrafía, Formación Rinconada, Precordillera, Argentina.

**INTRODUCTION**

In the eastern margin of the Argentine Precordillera, the Rinconada melange (Amos, 1954; Gosen *et al*., 1995) accounts for a major rearrangement process in the early Palaeozoic basin nearby the boundary with Sierras Pampeanas. The genesis and age of this melange are controversial due to the inherent reworked character of its components but they are essential to decipher the interrelationship between both continental blocks during the building of southwestern Gondwana (*e.g.*, Gosen *et al*., 1995; Ramos *et al*., 1996; Rapela *et al*., 2016).

After a multidisciplinary study of the Rinconada Formation committed to decipher its geological significance, we conducted a systematic conodont sampling along with detailed structural and sedimentological analysis. We processed 46 rock samples (85 kg total weight) from carbonate-cemented sandstones, conglomerates and blocks included in the melange, which yielded Early Ordovician, Middle Ordovician (Voldman *et al*., 2015), and a unique Silurian conodont fauna that is subject of this contribution.

The Silurian conodont collection proceeds from a calcareous sandstone incorporated in a debris flow from the upper levels of the Rinconada Formation (Figures 1, 2). The preservation of the specimens is in general poor, probably related to the slumping forces that gave rise to the melange, but provided significant biostratigraphic information. In addition to the long-range simple cones *Decoriconus, Dapsilodus* and *Pseudooneotodus*, the conodont collection includes specimens of the genera *Oulodus*, "*Ozarkodina*" and *Wurmiella*, which suggests a late Silurian age for the upper levels of the Rinconada Formation. The purpose of the present contribution is to enhance the biostratigraphic correlation of the Rinconada Formation to other successions in the Precordillera and basins of the world, as well as shed light on the scarcely known Silurian conodont faunas from SW Gondwana.

**[Figure 1]**

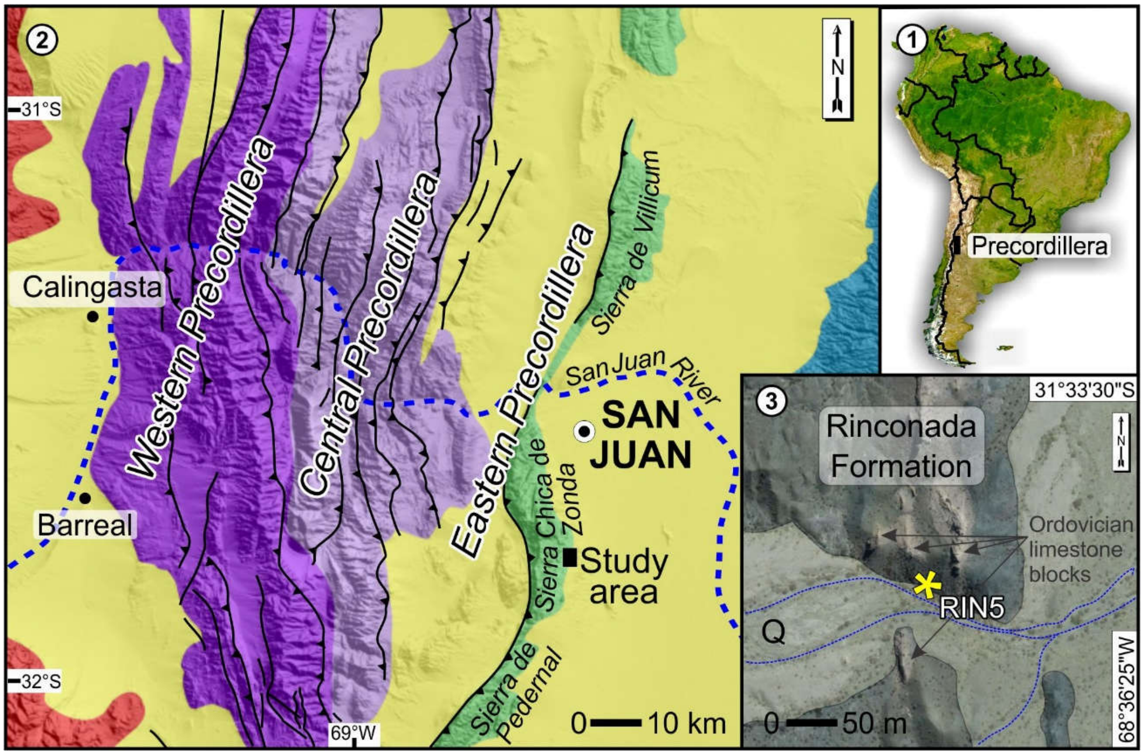


**Figure 1.1.** Geographic location of the Precordillera, Argentina; **2,** Location map of the Rinconada Formation study area, on the eastern flank of the Sierra Chica de Zonda, Eastern Precordillera; **3,** Geographic location of the fossiliferous sample RIN5, Rinconada Formation, San Juan Province.

## GEOLOGICAL SETTING

The Rinconada Formation is a melange located in the Eastern Precordillera, a west-verging imbricate thrust system developed in Silurian times (*e.g.*, Ramos *et al*., 1996). The Rinconada melange crops out along the eastern slopes of Sierra Chica de Zonda, Sierra de Pedernal (Fig. 1), and also in the Sierra de Villicum, where it has been named Mogotes Negros Formation (Cuerda, 1985; Benedetto *et al.,* 1992; Peralta, 1993). Its geological significance is controversial, being considered either as the result of tectonic (Keidel, 1938; Heim, 1948) or gravity-driven processes (Amos, 1954; Borrello, 1969; Harrington, 1971; Amos and Fernandez, 1977; Peralta, 1990; Gosen *et al.,* 1995).

First fossil findings from the Rinconada Formation were reported by Keidel (1938), who identified *Atrypina acutiplicata* (= *Harringtonina australis*) and *Monograptus* sp. at its type locality (La Rinconada). Amos and Fernández (1977) reported the brachiopod *Leptocoelia nunezi* (Early Devonian) from an equivalent sequence at Cerro Bola, to the south of the type section. Cuerda (1981) described from the upper levels of the Rinconada Formation a graptolitic association composed of *Climacograptus* cf. *minutus*, *Diplograptus* sp. and *Monograptus* sp., which referred to the Llandovery, supporting the early ideas of Keidel (1938) and Heim (1948), who postulated a Silurian age for all or at least parts of the Rinconada Formation. Benedetto and Franciosi (1998) suggested that the uppermost strata of the Rinconada Formation may be older than late Wenlock based on the record of the inarticulate brachiopod *Leangella* (*Leangella*) in the Sierra Chica de Zonda.

The age of the base of the Rinconada Formation is less constrained. For instance, Peralta and Uliarte (1986) recovered middle Darriwilian graptolites from the lower levels of the Rinconada Formation, which they interpreted as deposited over the San Juan Formation in transitional contact. Sarmiento *et al*. (1988) studied a conodont collection from correlative levels and supported a middle Darriwilian age for the top of the San Juan Formation and the base of the Rinconada Formation though the samples from the latter unit correspond to allochthonous blocks. Indeed, carbonate blocks of decametric size as well as limestone clasts incorporated in polymictic conglomerates yielded Early to Middle Ordovician conodont specimens as recognized in recent studies (Lehnert, 1995; Voldman *et al*., 2015).

In the Don Braulio section, situated on the eastern flank of Sierra de Villicum, the

Rinconada Formation overlies the Don Braulio Formation, which bears graptolites of Llandovery age (Peralta, 1986). Gosen *et al*. (1995) suggested that the Rinconada Formation is Silurian but did not discard an Ordovician age for parts within or at the base of the melange.

In the Rinconada locality (Sierra de Chica de Zonda), the melange is at least 2500 m-thick and overlies limestones of the San Juan Formation. It is composed mainly of sandstone-shale alternations, massive shales, conglomerates and limestone boulders up to km-scale in length. In most places, these lithostratigrahic units display ubiquitous extensional faults with variable extension values. There are also boudinaged sequences and scarce slump folds, which record deformation of not well-lithified sediments. Therefore, most of the Rinconada melange could be regarded as a stacking of "broken formations" s*ensu* Raymond (1984), intercalated with scarce debris flows that mainly occur in the upper part of the succession. The arrangement of the deposits suggests submarine mass-transport processes probably at the orogenic wedge front (for a review see Festa *et al*., 2016).

From the upper levels of the sedimentary succession comes the conodont sample RIN 5 (31°44'39.78"S, 68°36'35.72"W, Figures 1, 2), which is a lenticular reddish calcareous sandstone with iron oolites, similar to the fossiliferous samples studied by Benedetto and Franciosi (1998). Successively, the Rinconada Formation is covered through angular unconformities by Carboniferous and Neogene sedimentary rocks (Heim, 1948; Amos, 1954), which are involved in thrusting and folding related to the Andean orogeny.

**[Figure 2]**


**Figure 2.1.** Limestone blocks from the San Juan Formation embedded in debris flows from the upper levels of the Rinconada Formation, proximate to the Neogene unconformity (view to the north); **2.** Iron-rich calcareous level Rin5, which provided the first Silurian conodont fauna from the Rinconada Formation (for location see figure 1); **3.** Debris flow from the upper levels of the Rinconada Formation showing a cleavaged matrix with pelitic, siliceous and calcareous intraclasts. Hammer for scale is 33 cm long.

**METHODS**

The Silurian conodont collection consists of 134 elements (and tens of fragments) that were obtained after digestion of 4.25 kg of rock in 10% formic acid solution, following the standard acid etching techniques described by Stone (1987). The conodont elements appear frequently broken and show a conodont Colour Alteration Index (CAI) 3, which indicates burial palaeotemperatures ranging from 110–200 °C (Epstein *et al*., 1977). The abundant microfractures of the specimens inhibited ultrasonic cleaning, as test specimens resulted severely damaged. Conodont images were acquired with an Olympus LEXT OLS4000 confocal microscope at the LAMARX (Universidad de Córdoba) and with a Leica M205FA Microscope of the Servicios Científico-Técnicos (Universidad de Oviedo). The conodont elements are housed under repository code CORD-MP 50815 up to 50949 in the Museo de Paleontología, Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba, Argentina.

## SYSTEMATIC PALAEONTOLOGY

Class CONODONTA Pander, 1856

Order BELODELLIDA Sweet, 1988

Family DAPSILODONTIDAE Sweet, 1988

Genus ***Dapsilodus*** Cooper, 1976

***Type species.*** *Distacodus obliquicostatus* Branson and Mehl, 1933.

***Discussion.*** *Dapsilodus* has an apparatus composed of laterally compressed coniform elements characterized by distinctive chevron-shaped ornamentation adjacent to the anterior margin (Cooper, 1976; Barrick, 1977). It includes M elements (acodontiform) and a symmetry transition series. The Sa elements (modified distacodontiform) are symmetrical, have a long base, and a lateral costa on each side that may extend behind the posterior keel. The Sb elements (distacodiform) are slightly twisted whereas the Sc elements (distacodiform) are strongly twisted. The Sb-Sc elements in *Dapsilodus* are morphologically similar to their homologous of the Ordovician genus *Besselodus*. However, in the latter genus the distacodiform elements are straight, not twisted, and the M elements are oistodiform (*e.g.*, Nowlan *et al.*, 1988).

***Dapsilodus obliquicostatus*** (Branson and Mehl, 1933)

Figure 3.12

1933. *Distacodus obliquicostatus*. Branson and Mehl, p. 41, pl. 3, fig. 2.

1978. *Distacodus obliquicostatus* Branson and Mehl. Rexroad *et al*., p. 4, pl. 1, fig. 9.

1991. *Distacodus obliquicostatus* Branson and Mehl. McCracken, p. 78–79, pl. 4, figs. 11, 13–14, 16–28, 30–32, 35, 40. (*cum. syn.*).

1999. *Dapsilodus obliquicostatus* (Branson and Mehl). Lehnert *et al*., pl. 1, figs. 1–8.

1999. *Dapsilodus obliquicostatus* (Branson and Mehl). Cockle, p. 119, pl. 4, figs. 13–14, 17–19 (non 15–16).

2009. *Dapsilodus obliquicostatus* (Branson and Mehl). Mestre, p. 474, 476, figs. 3.12–3.15.

***Material.*** 3 Sa, 16 Sb, 16 Sc elements (CORD-MP 50815-50849).

***Discussion.*** The studied specimens display the typical oblique striations of the genus in the antero-basal margin. The base is broad and long, frequently extended to posterior. The basal cavity is deep and tapers gradually to the point of maximum curvature, with the apex centrally located. The anterior and posterior margins are keeled along the entire length of the elements. Soft lateral costae are present near midface. M elements were not recovered. *Dapsilodus obliquicostatus* is a widespread and long-ranging Silurian taxon that inhabited mainly off-shore to oceanic environments (*e.g.*, Aldridge and Jeppsson, 1984; Armstrong, 1990; McCracken, 1991; Zhang *et al*., 2006). Aldridge and Mabillard (1981) reported a strikingly high proportion of *D. obliquicostatus* in the furthest offshore localities across the Early Silurian shelf of the Wales Borderland area. It is also present in Silurian deposits of Australia (Cockle, 1999), Austria (Suttner, 2007), China (Lin, 1983), Czech Republic (Slavík, 2014), Greenland (Armstrong, 1990), Sweden (Bergström and Bergström, 1996; Dahlqvist and Bergström, 2005), Morocco (Benfrika *et al*., 2007; Corriga *et al*., 2014), North America (Cooper, 1976; McCracken, 1991), Russia (Zhang and Barnes, 2007; Kaljo *et al*., 2012), and Spain (Martín Algarra *et al.*, 2009), among other places.

**[Figure 3]**

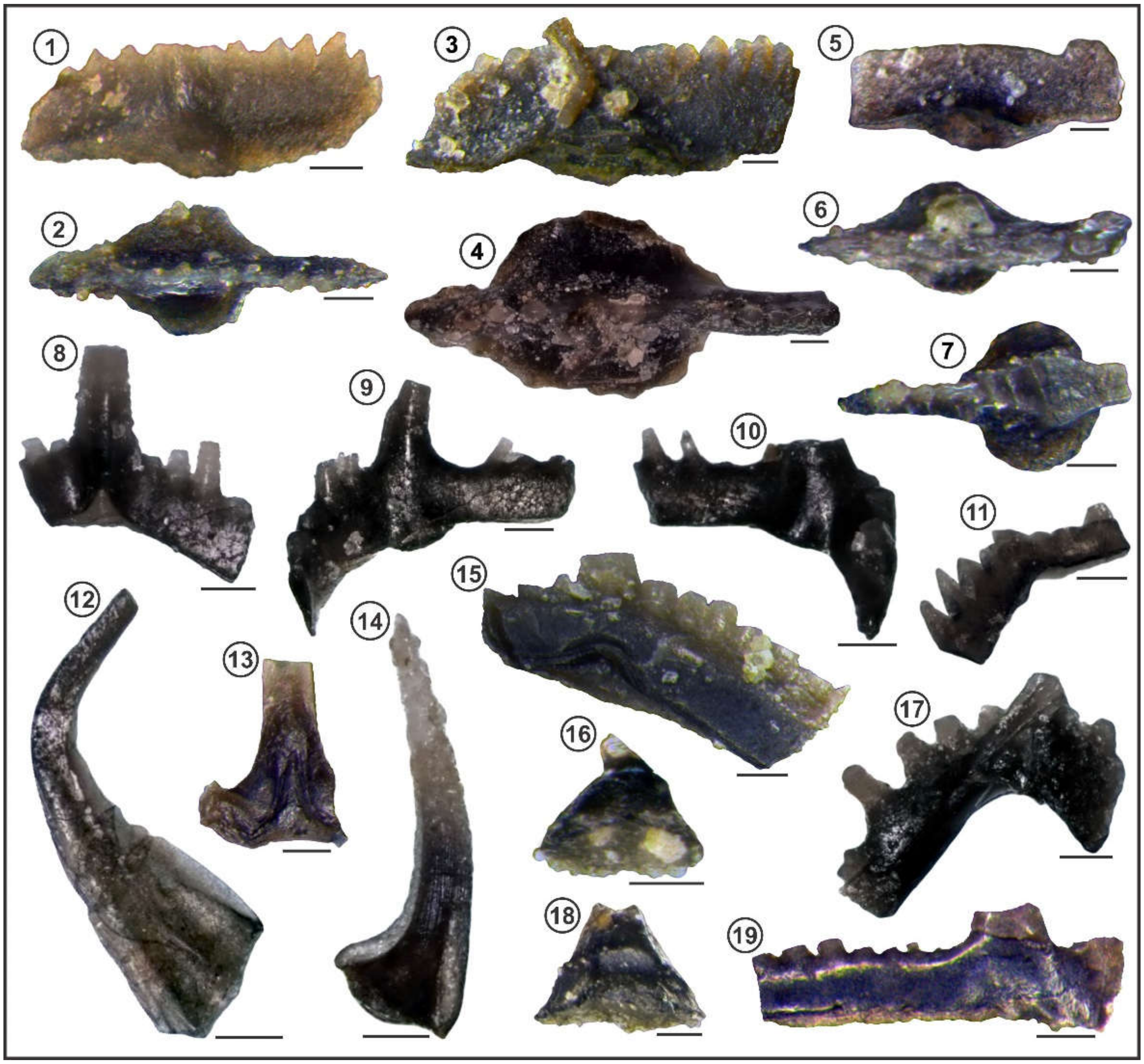


**Figure 3.** Silurian conodonts from the Rinconada Formation, sample RIN5, Precordillera Argentina. **1–4,** ***"Ozarkodina"*** aff. ***snajdri*** (Walliser), **1–2,** Pa element, lateral and oral view, CORD-MP 50913; **3–4,** Pa element, lateral and oral views, see attached coniform element on lateral side, CORD-MP 50914. **5–6,** ***"Ozarkodina"*** sp., Pa element, CORD-MP 50918, lateral and oral views. **7–8, 11,** undetermined "ozarkodinids", **7,** Pa element, CORD-MP 50941, oral view; **8,** Sa element, CORD-MP 50946, dorsal view; **11,** Pb element, CORD-MP50948, lateral view. **9–10, 17,** ***Oulodus*** sp., **9,** Sb element, CORD-MP 50920, lateral view; **10,** Sb element, CORD-MP 50922, lateral view; **17,** P element, CORD-

MP 50943, dorsal view. **12,** ***Dapsilodus obliquicostatus*** (Branson and Mehl), Sc element, CORD-MP 50815, lateral view. **13, 15, 19,** ***Wurmiella excavata*** (Branson and Mehl), **13,** Sa element, CORD-MP50921, dorsal (posterior) view; **15,** Pa element, CORD-MP 50919, lateral view; **19,** Sc element, CORD-MP 50923, lateral view. **14,** ***Decoriconus fragilis*** (Branson and Mehl, 1933), Sb element, CORD-MP 50850, lateral view. **16,** ***Pseudooneotodus beckmanni*** (Bischoff and Sannemann), P element, CORD-MP 50873, lateral view. **18,** ***Pseudooneotodus bicornis bicornis*** (Drygant), P element, CORD-MP 50870, lateral view. Scale bar: 0.1 mm.

Order Prioniodontida Donoghue *et al*., 2008

Suborder Ozarkodinida Donoghue *et al*., 2008

***Remarks.*** Murphy *et al*. (2004) provided a major taxonomical revision of late Silurian and Early Devonian ozarkodinids. They introduced *Wurmiella* to house taxa related to the "*excavata* Group", *Zieglerodina* to include the ozarkodinids of the "*remscheidensis* Group", and an informal genus ("Genus W") to contain the "*eosteinhornensis* stock*".* Their proposal was rejected by Suttner (2007, 2009), but adopted with some modifications by others (*e.g.*, Carls *et al*., 2007; Corriga and Corradini, 2009; Drygant and Szaniawski, 2012; Corriga *et al*., 2014; Jarochowska and Munnecke, 2015). Donoghue *et al*. (2008) verified the polyphyletic character of the multiple species assigned to *Ozarkodina*, and pointed out that "*Nicollidina* (= *Zieglerodina*) *remscheidensis* (Ziegler, 1960)" is closely related to the Frasnian polygnathid *Nicollidina brevis* Dzik (2002). On the other hand, "*Oz*." *bohemica* (Walliser, 1964), "*Oz*." *crispa*, "*Oz*." *sagitta rhenana* (Walliser, 1964), and "*Oz*." *s. sagitta* (Walliser, 1964), would conform a 'stem' group along with *Oz*." *snajdri* and "*Oz*." *parasnajdri* (Walliser, 1964), given the marked morphological differences of their Pa elements (*e.g.,* lack of anterior cockscomb, far posterior extension of basal lobes, fused denticles) when compared to *Ozarkodina* s.s. (*e.g.*, Slavík and Carls, 2012; Peavey, 2015).

***"Ozarkodina"*** aff. ***snajdri*** (Walliser, 1964)

Figures 3.1–3.4, 3.6, 4.1–4.4

***Material.*** 5 Pa elements (CORD-MP 50913-50917).

***Remarks.*** The Pa elements attributed to "*Ozarkodina*" aff. *snajdri* include transitional forms of the "*Oz.*" *bohemica–snajdri* group (Figs. 3.1–3.4, 4.1–4.4). They have denticles of subequal size, stout, fused except for discrete tips, and slightly tilted ventrally. Denticles located above the aboral cavity are completely fused so conform a crenulated ridge. The platform is spear-shaped, unornamented and weakly asymmetrical, with the halves on both sides of the blade slightly offset from each other. It extends approximately from the centre of the blade to just before its dorsal edge. The basal margin profile is stepped, with the anterior section slightly bowed. The anterior process has a steeply curved termination, with a distal denticle approximately half way up blade (Figs. 3.1, 3.3). The posterior process also reduces rapidly in size at its end. White matter concentrates at the tip of the denticles and gradually diffuses toward the blade whereas the basal cavity tip is not discernible due to the opaque aspect of the elements.

Helfrich (1975) introduced *Spathognathus tillmani* from the lower Wills Creek Formation, central Appalachian Mountains, to include specimens grossly similar to *S. sagitta bohemicus* and *S. snajdri*, but with a slightly longer blade and the basal platform more posteriorly located. Helfrich's illustrations of "*Oz. tillmani*" include Pa elements very similar to elements of this study, but differ in the more developed denticulation. "*Oz. tillmani*" was subsequently considered a *nomem dubium* because the systematics appeared on microfiche (Cooper, 1980) and regarded as a junior synonym of "*Oz.*" *bohemica* (Calner and Jeppson, 2003). Currently, “*Oz*.” *bohemica s.l.* encompass a group of forms with considerable variability, even within collections, that are frequently described as morphotypes or subspecies (Schönlaub in Kříž *et al*., 1993; Viira and Aldridge, 1998; Calner and Jeppson, 2003).

In particular, “*Oz.*” aff. *snajdri* is distinguished from typical representatives of “*Oz*.” *snajdri* by having a blade of more uniform height and a less expanded, more symmetrical, and centrally located basal cavity. Notwithstanding that, specimens attributed to “*Oz*.” *snajdri* with a relatively small basal cavity and a straight upper margin are included in the literature (*e.g.*, Miller, 1995; Viira and Aldridge, 1998). “*Oz.*” aff. *snajdri* also shows resemblance to *Oz. bohemica* morphotype 3 of Schönlaub and the coeval *Oz. bohemica longa* (Calner and Jeppsson, 2003; Slavík, 2014), but differ in the more centrally located basal expansion, the gently convex anterior and posterior edges, and the shorter blade length. On the other hand, *Oz. inflata* (Walliser, 1964) is distinct as it possesses the oral margin convex, lacks denticle fusion, and the basal lobes are more symmetrical. The transitional character of the “*Oz*.” *snajdri* lineage and the scarce number of specimens recovered from the Rinconada Formation inhibits a further refinement of the taxonomic designation. Eventually, more records of *“Oz.”* *tillmani* and of “*Oz.*” aff. *snajdri* would help determine if they are conspecific.

***“Ozarkodina”*** sp.

Figures 3.5–3.6, 4.5–4.6

***Material.*** 1 Pa element (CORD-MP 50918).

***Remarks.*** “*Ozarkodina*” sp. is characterized by having a small basal cavity relatively centrally located and the oral margin adenticulated. The basal cavity lips prolong up to the posterior tip of the blade, whereas they continue as a narrow groove towards the anterior edge. The anterior and posterior margins of the blade are fairly straight.

"*Ozarkodina*" sp. resembles "*Oz*." *parasnajdri* (Viira and Aldridge, 1998) in the adenticulated oral margin and in the basal cavity position, though it lacks the large basal cavity that characterizes the representatives of the "*Oz*." *snajdri–parasnajdri* group. It is also morphologically similar to "*Oz.*" *b. longa*, but it has the basal cavity more centrally located. Moreover, in "*Oz.*" *b. longa* the fused ridges of denticles occur mainly in mature to gerontic elements, thought they are more frequent in the younger populations (Calner and Jeppsson, 2003).

Genus ***Wurmiella*** Murphy *et al*., 2004

***Type species.*** *Ozarkodina excavata* subspecies *tuma* Murphy and Matti, 1983

***Wurmiella excavata*** (Branson and Mehl, 1933)

Figures 3.13, 3.15, 3.19, 4.8, 4.9

1933. *Prioniodus excavatus* Branson and Mehl, p. 45, pl. 3, figs. 7, 8.

2005. *Ozarkodina excavata* (Branson and Mehl). Bitter and Purnell, text-figs. 2–3, pl. 1–3.

2006. *Ozarkodina excavata excavata* (Branson and Mehl). Albanesi *et al*., pl. 5, figs. M-Y.

2009. *Wurmiella* cf. *excavata* Branson and Mehl. Mestre, p. 474, fig. 3: 4–6.

2016. *Wurmiella excavata* (Branson and Mehl 1933). Sullivan *et al*., fig. 4: 3–12.

2016. *Ozarkodina excavata* (Branson and Mehl). Mathieson *et al*., p. 624, 626, figs 20, 30W, X, 32L–Q (*cum. syn*.).

***Material.*** 17 Pa, 1 Pb, 1 Sa, 2 Sb, 1 Sc elements (CORD-MP 50919-50940).

***Discussion.*** *Wurmiella excavata* is frequently reported in many Silurian – Lower Devonian collections, yet there is a large uncertainty surrounding its type specimens (Murphy *et al*., 2004). In addition, it exhibits significant morphological variations through time probably associated with variations in diet (Jones and Purnell, 2007). Donoghue *et al*. (2008) suggested that *Wurmiella* may not be its appropriate taxonomic home, but awaits further phylogenetic evidence to establish it. The specimens from the Rinconada Formation fit well with respect to the typical material from the Bainbridge Limestone (Branson and Mehl 1933).

*Wurmiella excavata* is a very successful component of conodont communities, showing large resistance against palaeoenvironmental changes. It has a wide paleobiogeographic distribution, with records in the Carnic Alps (Walliser, 1964; Corradini *et al*., 2015), North America (Branson and Mehl, 1933; von Bitter and Purnell, 2005), Northern Australia (Simpson, 2000), Bohemia (Slavík *et al*., 2010), Central Iran (Männik *et al.*, 2013), as well as in the Los Espejos Formation (Albanesi *et al*., 2006) and the Tambolar Formation (Mestre, 2009) in the Precordillera.

**[Figure 4]**

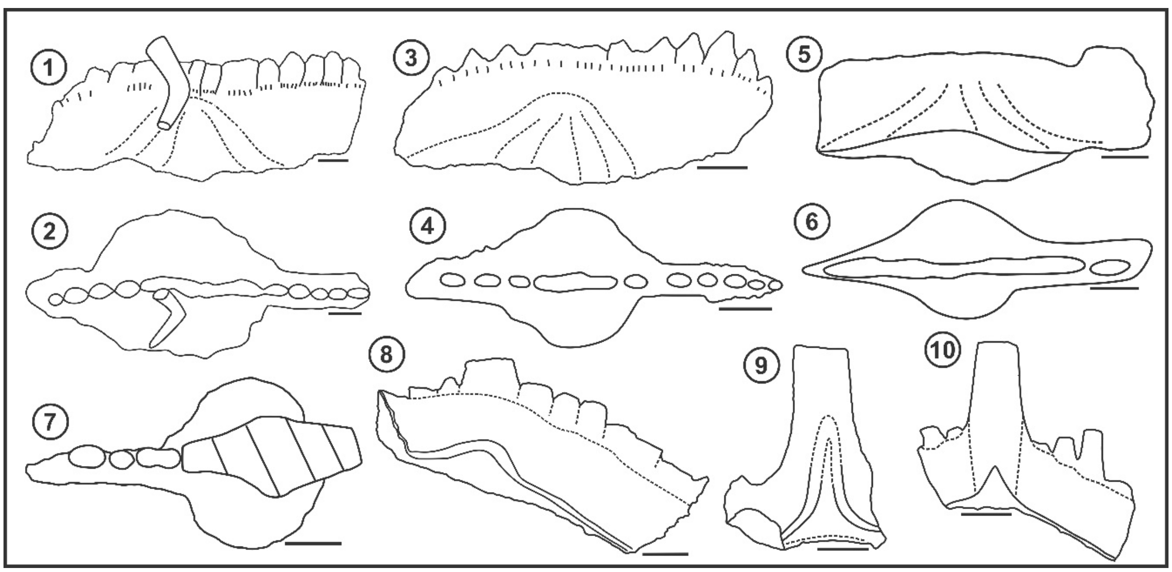


**Figure 4.** Line-art drawings of selected specimens from sample RIN5. **1–4, *"Ozarkodina"*** aff. ***snajdri***, **1–2,** Pa element, lateral and oral view, CORD-MP 50914; **3–4,** Pa element, lateral and oral views, see attached coniform element on lateral side, CORD-MP 50913. **5–6, *"Ozarkodina"*** sp., Pa element, CORD-MP 50918, lateral and oral views. **7,** undetermined "ozarkodinid", Pa element, CORD-MP 50941, oral view. **8–9, *Wurmiella* excavata** (Branson

and Mehl), **8,** Pa element, CORD-MP 50919, lateral view; **9,** Sa element, CORD-MP50921, dorsal (posterior) view. **10,** undetermined "ozarkodinid", Sa element, CORD-MP 50946, dorsal view. Scale bar: 0.1 mm.

Order Prioniodinina Donoghue *et al*., 2008

Family PRIONIODINIDAE Bassler, 1925

Genus ***Oulodus*** Branson and Mehl, 1933

***Type species.*** *Cordylodus serratus* Stauffer, 1930

***Oulodus*** sp.

Figures 3.9, 3.10, 3.17

***Material.*** 1 P, 2 Sb, 1 S (CORD-MP 50943-50945).

***Discussion.*** We follow here the diagnosis of *Oulodus* given by Sweet and Schönlaub (1975), which implies a conservative apparatus composition through the Middle Ordovician and Devonian. Slavík *et al*. (2010) adopted the genus name *Delotaxis* rather than *Oulodus* for the late Silurian-early Devonian taxa with digyrate apparatuses and five pairs of different elements. However, the upper Silurian species have seximembrate apparatuses, so belong to *Oulodus* (C. Corradini, written com.). Besides, Donoghue *et al*. (2008) observed that a definition of sexi- and septimembrate apparatus in Prioniodinina is meaningless due to the architectural stability of the apparatus within Ozarkodinida. Thus, the number of elements in the apparatus may reflect the subjective assessment of the morphological boundaries between element morphotypes.

The collection from the Rinconada Formation includes rather few fragmented elements that complicate the specific determination. These exhibit subcircular cusps and discrete denticles of similar height and round cross sections consistent with the morphological characteristics of *Oulodus*. The record of two Sb elements with the anterior process with different angles of curvature imply, eventually, the presence of two different species.

Order ?PROTOPANDERODONTIDA Sweet, 1988

Family ?PROTOPANDERODONTIDAE Lindström, 1970

Genus ***Decoriconus*** Cooper, 1975

***Type species.*** *Paltodus costulatus* Rexroad, 1967.

***Discussion.*** *Decoriconus* includes small, generally striated and laterally compressed coniform elements. The lineage can be traced back up to the Tremadocian with *D. peselephantis* (Lindström) and it extends up to the Devonian with *D. fragilis* (*e.g.*, Löfgren, 1998; Drygantand Szaniawski, 2012). Cusps and keels are albid whereas hyaline material surrounds the basal cavity. The abrupt transition between hyaline and albid material conforms a straight line that meets the anterior margin of the cusp at an angle of *ca.* 90º in Ordovician elements, which reduces to *ca*. 60º in the Silurian specimens (Löfgren, 1998).

***Decoriconus fragilis*** (Branson and Mehl, 1933)

Figure 3.14

1933. *Paltodus fragilis* Branson and Mehl, p. 43, pl. 3, fig. 6.

1978. *Decoriconus? fragilis* (Branson and Mehl). Rexroad *et al.*, p. 4, pl. 1, fig. 10.

1991. *Decoriconus fragilis* (Branson and Mehl). McCracken, p. 79–80, pl. 4, figs. 33, 39.

2002. *Decoriconus fragilis* (Branson and Mehl). Zhang and Barnes, p. 11–12, gs. 15.25–15.31.

2007. *Decoriconus fragilis* (Branson and Mehl). Zhang and Barnes, p. 505, figs. 9.10–9.15.

2007. *Decoriconus fragilis* (Branson and Mehl). Suttner, p. 19–20, pl. 7, figs. 12–21 (*cum. syn.*).

2015. *Decoriconus fragilis* (Branson and Mehl). Jarochowska and Munnecke, fig. 7: O–S, fig. 8: M–Q.

***Material.*** 1 Sa, 18 Sb, 1 Sc elements (CORD-MP50850-50869).

***Discussion.*** Branson and Mehl (1933) defined *Paltodus fragilis* with specimens recovered from shales of the Bainbridge Formation in southeastern Missouri. Cooper (1976) reconstructed the oral apparatus of *D. fragilis* including acontiodontiform, paltodontiform and drepanodontiform elements. Barrick (1977) referred to them as Sa, Sb, and Sc elements, respectively, because they bear little resemblance to the shapes represented by the original genera, following the alphabetic locational scheme of Sweet and Schönlaub (1975). McCracken and Barnes (1981) included an Sc element in the apparatus reconstruction of *D. costulatus*, whose lack was previously attributed to a different apparatus composition. Based on this record, Zhang and Barnes (2002) suggested that *D. costulatus* is a junior synonym of *D. fragilis*.

According to the description of Barrick (1977), the Sa element is strongly compressed, nearly symmetrical and slightly twisted. The anterior margin is keeled and merges smoothly into the lateral faces. The posterior margin is also keeled but surrounded by a lateral groove on each side. The Sb element is asymmetrical, twisted inwardly and recurved near midheight. It has a moderately flaring base and sharp anterior and posterior keels. The latter is separated from the lateral faces by narrow grooves. The distinct Sc element is sharply incurved, with the anterior margin of the base extended as an anticusp of variable lengths.

The collection *D. fragilis* from the Rinconada Formation include Sa and Sb elements with well-developed keels on both anterior and posterior margins, even on the base, associated with relatively shallow grooves. In contrast, the recovered Sc element presents the anterior margin keeled and the posterior one subrounded, which is consistent with some previous reports (*e.g.*, Kleffner, 1987, fig. 6.20).

*Decoriconus fragilis* is common in outer shelf to basin environments, in some cases more than 100 m deep (*e.g.*, Aldridge and Mabillard, 1981; Aldridge and Jeppsson, 1984; Armstrong, 1990; Zhang and Barnes, 2002; Dahlqvist and Bergström, 2005). It is frequently the dominant species along with *D. obliquicostatus* and *Aspelundia* in the Silurian outer shelf and upper slope communities of Australia (Farrell, 2006), Austria (Suttner, 2007), Greenland (Armstrong, 1990), North America (McCracken, 1991; Zhang and Barnes, 2002), Russia (Zhang and Barnes, 2007) and Sweden (Bergström and Bergström, 1996).

Genus ***Pseudooneotodus*** Drygant, 1974

***Type species.*** *Oneotodus? beckmanni* Bischoff and Sannemann, 1958

***Discussion.*** *Pseudooneotodus* consists of short phosphatic cones arranged in an unimembrate apparatus, whose suprageneric classification is not clearly defined (see Corradini, 2008, for a recent discussion of the genus). It is made up of a lamellar cap underlain by a spherulitic basal tissue characteristic of conodonts (Sanson, 1996). The different species of *Pseudooneotodus* are classified according to the shape and number of apical tips and the outline of the basal margin.

*Pseudooneotodus* is widely distributed in Middle Ordovician to Lower Devonian rocks all over the world. In particular, Corradini (2008) observed that the occurrence of *Ps. beckmanni* and *Ps. bicornis* is very irregular, even in successive beds in the same section, suggesting that they were ecologically controlled to a higher degree than coeval conodont taxa. Both species are typical from open-marine, offshore shelf environments.

***Pseudooneotodus beckmanni*** (Bischoff and Sannemann, 1958)

Figure 3.16

1958. *Oneotodus? beckmanni* Bischoff and Sannemann, p. 98, pl. 15, figs. 22–25.

1988. *Pseudooneotodus beckmanni* (Bischoff and Sannemann). Hünicken and Sarmiento, p. 228, pl. 1, figs. 7a-b, pl. 3, figs. 10a-b.

2008. *Pseudooneotodus beckmanni* (Bischoff and Sannemann). Corradini, p. 142, pl. 1, figs. 1-7.

2011. *Pseudooneotodus beckmanni* (Bischoff and Sannemann). Sumrall *et al*., fig. 4: F.

2016. *Pseudooneotodus beckmanni* (Bischoff and Sannemann). Mathieson *et al*., p. 597–598, fig. 8: Q–S (*cum. syn.*).

***Material.*** 40 P elements (CORD-MP 50873-50912).

***Discussion.*** The squat, single apical, conical elements from the Rinconada Formation fit well with the described and illustrated specimens of *Ps. beckmanni* by Corradini (2008), who thoroughly analysed the species.

***Pseudooneotodus bicornis bicornis*** (Drygant, 1974)

Figure 3.18

1974. *Pseudooneotodus bicornis* Drygant, p. 67, pl. 2, figs 40–48.

2008. *Pseudooneotodus bicornis bicornis* (Drygant). Corradini, p. 144, 146, pl. 1, figs. 8–17.

2015. *Pseudooneotodus bicornis* Drygant, Jarochowska and Munnecke, fig. 7: J?

2016. *Pseudooneotodus bicornis* Drygant. Sullivan *et al*., fig. 4: 15–16.

***Material.*** 3 P elements (CORD-MP 50870-50872).

***Discussion.*** Corradini (2008) split *Pseudooneotodus bicornis* in two subspecies, *Ps. bicornis bicornis* and *Ps. bicornis contiguus*, based on the distance between the discrete tips. The studied material consists of squat cones with subtriangular basal outline. It exhibits two discrete tips in the apical part, separated by a depression, consistent with the diagnosis of *Ps. bicornis bicornis.* (Corradini, 2008).

**BIOSTRATIGRAPHY**

In the absence of index fossils, the coniform specimens recovered from the Rinconada Formation provide some general biostratigraphic information (Figure 5). For instance, *Ps. beckmanni* ranges from the Ordovician up to the Emsian, but starts to occur in large numbers in the Ludfordian, with two acme intervals during the Lochkovian and the Pragian, as observed in Sardinia and the Carnic Alps (Corradini, 2008). *Ps. bicornis bicornis* is more frequent during the upper Llandovery and Wenlock instead, uncommon in the Gorstian, and it re-appears in the Ludfordian, with its LAD in the Lower *Oulodus elegans detortus* Zone (Corradini, 2008). The species *D. obliquicostatus* extends for nearly the entire Silurian, while its LAD marks the lower boundary of the Upper *Oulodus e. detortus* Zone in Sardinia and the Carnic Alps (Corradini and Corriga, 2012). Conversely, *D. fragilis* transits across the terminal Ordovician mass extinction (Bergström *et al*., 2012), ranging up to middle Pragian in the Austrian Carnic Alps (Suttner, 2007).

**[Figure 5]**

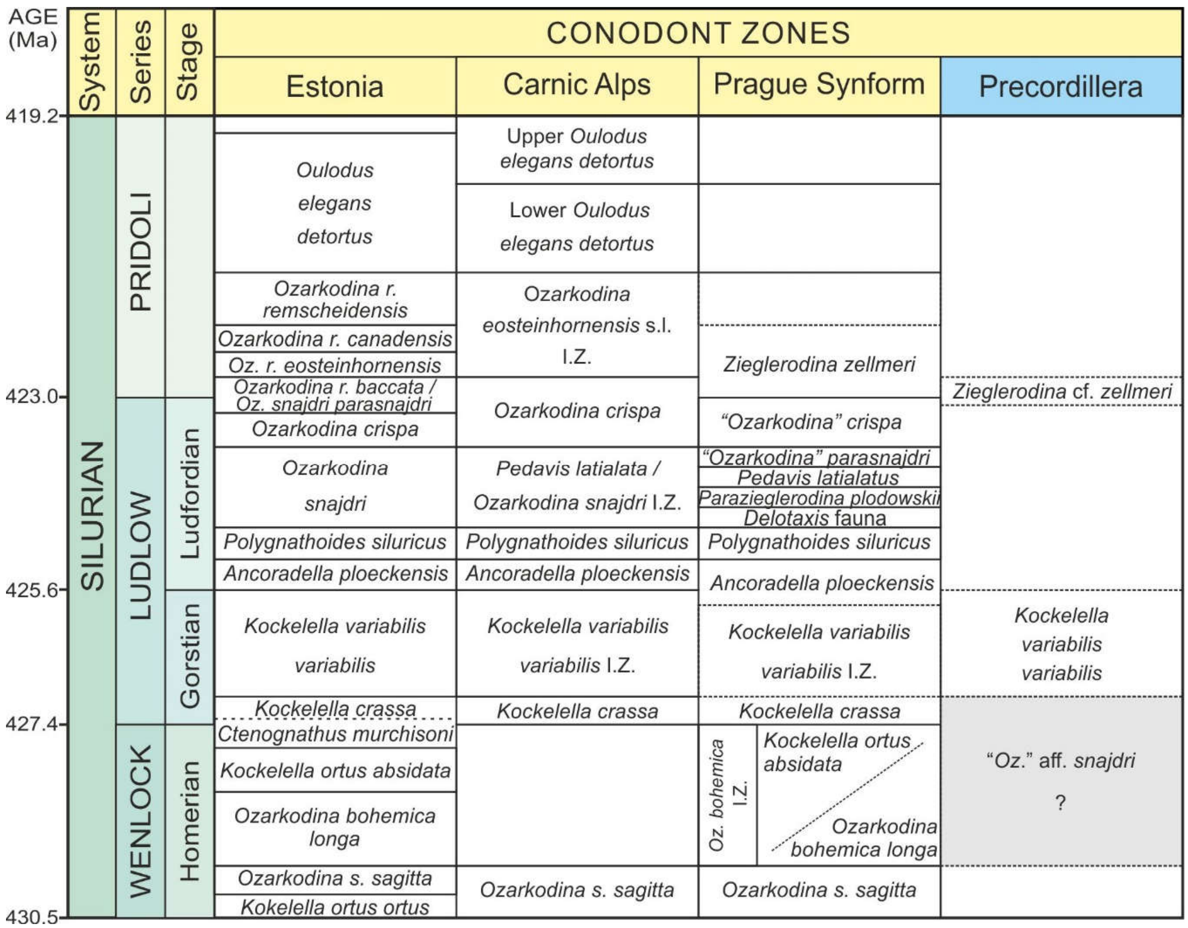


**Figure 5.** Comparison of late Wenlock – Pridoli conodont zones from Estonia (Männik, 2014), the Carnic Alps (Corradini *et al.*, 2015), the Prague Synform (Slavík and Carls, 2012; Slavík, 2014), and the Precordillera (this study in grey background), with previous conodont zones of Albanesi *et al.* (2006), Mestre (2009) and Sumrall *et al.* (2013).

The ramiform species *W. excavata* spans at least from the late Llandovery (*e.g.,* Cockle, 1999) up to the Emsian, with a wide paleobiogeographic distribution. It is frequently one of the dominant species in the "*Oz.*" *b. longa*, *P. siluricus*, "*Oz.*" *crispa* and "*Oz.*" *eosteinhornensis* zones (*e.g.*, Jeppsson, 1974; Mannik, 2007; Corriga and Corradini 2009; Fig. 5).

"*Oz.*" aff. *snajdri* offers a distinct morphology that serves us to improve the biostratigraphic information. Walliser (1964) included in his first Silurian biozonal scheme an *Oz. snajdri*-

horizon, which included in the upper part of the *P. siluricus* Zone. Subsequent studies from Gotland and Estonia recognized that "*Oz.*" *snajdri* appeared earlier in the Gorstian (early Ludlow) (Jeppsson *et al*. 1994; Viira and Aldridge, 1998; Jeppsson, 2005). "*Oz.*" *snajdri* becomes extinct in the Cellon Section of the Carnic Alps at the top of the "*Oz.*" *crispa* Zone (Corradini *et al.*, 2015), whereas at the Passo Volaia area of the Carnic Alps the LAD locates proximate to the base of the lower *O. e. detortus* Zone (Corradini and Corriga 2010; Corradini and Corriga, 2012).

The "*Oz*." *snajdri* Zone aka "*Oz*." *snajdri* Interval Zone involves the biostratigraphic interval between the LAD of *Polygnathoides siluricus* and the FAD of "*Oz*." *crispa* (*e.g.*, Corradini and Serpagli, 2009; Cramer *et al*. 2011; Slavík and Carls, 2012; Figure 5). According to Jeppsson *et al*. (2007), the base of the "*Oz*." *snajdri* Zone is marked by an abrupt major conodont faunal change associated to the improvement of the environmental conditions directly after the Lau event. The lower part of the "*Oz.*" *snajdri* Zone is characterized by the icriodontid *Pedavis latialata* (Walliser) and the upper part by "*Oz.*" *snajdri*. Corradini *et al*. (2015) renamed the "*Oz*." *snajdri* Interval Zone as *Pedavis latialata – Ozarkodina snajdri* Interval Zone for the Cellon Section, considering the two most characteristic species, which co-occur in a short stratigraphic interval.

Helfrich (1975) defined the *Spathognathus tillmani* Zone in the lower Wills Creek Formation from the Appalachians based on the occurrence of *S. tillmani* in association with *S. primus multidentatus* Helfrich, *Ozarkodina sinuosa* Helfrich, and *O. typica intermedia* Helfrich, and tentatively correlated it with the *Icriodus latialatus* Zone of Walliser (1964). Calner and Jeppsson (2003) regarded *Oz*. *tillmani* and *S. primus multidentatus* as synonyms of *Oz. bohemica* and of *Oz. confluens densidentata* (*S. primus densidentatus* Viira, 1982), respectively. Accordingly, "*Oz*." *tillmani* would be coeval with *Oz. b. longa*, which ranges from the base of the *Oz. b. longa* Zone and through the *C. murchisoni* Zone, though they are not necessarily conspecific (Calner and Jeppsson, 2003).

On the other hand, Viira and Einsnato (2003) noticed that the conodont fauna from the Wenlock–Ludlow transition of Saaremaa is comparable with the faunas described by Helfrich (1975) from the Mifflintown and Wills Creek formations, particularly for the species *Oz. bicornuta* and *Oz. tillmani*. Conodonts from the middle part of the Wills Creek Formation at Pinto, Maryland, merely indicate a Ludlow age (Harris *et al*, 1994). Successively, the upper part of the Wills Creek Formation and the overlying Tonolway Formation include the index fossil "*Oz*." *crispa*, which indicates a late Ludlow age (Helfrich, 1975).

Following previous studies, "*Oz.*" aff. *snajdri* would correspond to a transitional form of the "*Oz*." *bohemica* – "*Oz*." *snajdri* lineage. The record of "*Oz.*" aff. *snajdri* along with *W. excavata*, *Ps. beckmanni*, *Ps. bicornis bicornis* suggest a late Homerian – early Gorstian (late Wenlock – early Ludlow) minimum depositional age for the upper debris flows of the Rinconada melange.

**TECTONOSTRATIGAPHIC IMPLICATIONS**

Silurian deposits of the Precordillera show considerable local and regional variation in thickness and lithology (*e.g.*, Astini and Maretto, 1996; Peralta, 2006, 2007). In the Central Precordillera, the Silurian deposits are widely represented in the La Chilca and Los Espejos Formation of the Tucunuco Group (Cuerda, 1965, 1969), and its lateral equivalent, the Tambolar Formation, which crops out to the south in the Pachaco – San Juan River area (Heim, 1952). Further south and west, Silurian strata are less biostratigraphically constrained. The La Chilca Formation presents in the lower part conodonts from the *Distomodus kentuckyensis* Zone (Llandovery, Lehnert *et al.*, 1999), whereas the upper levels include graptolite and acritarch associations assigned to the late Llandovery – early Wenlock

(Kerlleñevich and Cuerda, 1986; Pöthe de Baldis, 1987; Albanesi *et al.*, 2006). The Los Espejos Formation paraconformably overlies the La Chilca Formation through a ferruginous-rich basal conglomerate of regional extension. It is succeeded by green sandstone and siltstone packages arranged in a thickening-upward sequence whose thickness ranges between 25 m to 510 m (Cuerda, 1969; Benedetto *et al*., 1992; Astini and Piovano, 1992). The middle-upper parts of the Los Espejos Formation include in the Jáchal area monospecific associations of *Saetograptus argentinus* (Cuerda) and *Monograptus uncinatus notouninatus* Cuerda, both indicating a Ludlow age (Cuerda, 1969, 1971), and contain conodonts from the *Kokelella v. variabilis* Zone (Gorstian) in the Cerro del Fuerte and the Talacasto areas (Albanesi *et al*., 2006; Sumrall *et al*., 2013). García-Muro and Rubinstein (2015) proposed that the middle-upper part of the La Chilca Formation is Wenlock and that the Los Espejos Formation is Wenlock (?), Ludlow to Pridoli, based on palynomorph assemblages and miospore biozones.

The iron-rich basal conglomerate, the lithologic contrast and the fossiliferous content suggest the presence of a hiatus between the La Chilca and the Los Espejos formations, involving the late Llandovery – early Wenlock up to the early Ludlow (Peralta, 1993; Astini and Maretto, 1996).

According to the new conodont fauna from the Rinconada Formation, the hiatus in the Central Precordillera is broadly contemporaneous with destabilization of the eastern Precordilleran platform, accompanying the west-verging thrusting of the Famatinean basement (*e.g.*, Ramos *et al*., 1996; Mulcahy *et al*., 2011),

**CONCLUSIONS**

We analyse here the first Silurian conodont fauna from the Rinconada Formation, proximate to the eastern boundary of the Precordillera. It proceeds from a debris flow from the upper levels of the melange, close to the Neogene disconformity. The conodont association includes the long-ranging species *Dapsilodus obliquicostatus*, *Decoriconus fragilis*, *Pseudooneotodus beckmanni*, *P. b. bicornis*, *Wurmiella excavata* along with ozarkodinids of the "*Oz*." *bohemica* – "*Oz*." *snajdri* lineage. The transitional character of "*Oz*." aff. *snajdri* provides a minimum depositional age for the upper debris flows of the Rinconada Formation, probably within the late Homerian – early Gorstian stages. Therefore, the deposition of the upper levels of the Rinconada melange is possibly coeval with the hiatus involved between the La Chilca and Los Espejos formations in the Central Precordillera, and the Silurian deformation in the evolving inner Gondwanan foreland.

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## EPIGRAPHS

**Figure 1.1.** Geographic location of the Precordillera, Argentina; **2,** Location map of the Rinconada Formation study area, on the eastern flank of the Sierra Chica de Zonda, Eastern Precordillera; **3,** Geographic location of the fossiliferous sample RIN5, Rinconada Formation, San Juan Province.

**Figure 2.1.** Limestone blocks from the San Juan Formation embedded in debris flows from the upper levels of the Rinconada Formation, proximate to the Neogene unconformity

(view to the north); **2.** Iron-rich calcareous level Rin5, which provided the first Silurian conodont fauna from the Rinconada Formation (for location see figure 1); **3.** Debris flow from the upper levels of the Rinconada Formation showing a cleavaged matrix with pelitic, siliceous and calcareous intraclasts. Hammer for scale is 33 cm long.

**Figure 3.** Silurian conodonts from the Rinconada Formation, sample RIN5, Precordillera Argentina. **1–4,** ***"Ozarkodina"*** aff. ***snajdri*** (Walliser), **1–2,** Pa element, lateral and oral view, CORD-MP 50913; **3–4,** Pa element, lateral and oral views, see attached coniform element on lateral side, CORD-MP 50914. **5–6,** ***"Ozarkodina"*** sp., Pa element, CORD-MP 50918, lateral and oral views. **7–8, 11,** undetermined "ozarkodinids", **7,** Pa element, CORD-MP 50941, oral view; **8,** Sa element, CORD-MP 50946, dorsal view; **11,** Pb element, CORD-MP50948, lateral view. **9–10, 17,** ***Oulodus*** sp., **9,** Sb element, CORD-MP 50920, lateral view; **10,** Sb element, CORD-MP 50922, lateral view; **17,** P element, CORD-MP 50943, dorsal view. **12,** ***Dapsilodus obliquicostatus*** (Branson and Mehl), Sc element, CORD-MP 50815, lateral view. **13, 15, 19,** ***Wurmiella excavata*** (Branson and Mehl), **13,** Sa element, CORD-MP50921, dorsal (posterior) view; **15,** Pa element, CORD-MP 50919, lateral view; **19,** Sc element, CORD-MP 50923, lateral view. **14,** ***Decoriconus fragilis*** (Branson and Mehl, 1933), Sb element, CORD-MP 50850, lateral view. **16,** ***Pseudooneotodus beckmanni*** (Bischoff and Sannemann), P element, CORD-MP 50873, lateral view. **18,** ***Pseudooneotodus bicornis bicornis*** (Drygant), P element, CORD-MP 50870, lateral view. Scale bar: 0.1 mm.

**Figure 4.** Line-art drawings of selected specimens from sample RIN5. **1–4,** ***"Ozarkodina"*** aff. ***snajdri***, **1–2,** Pa element, lateral and oral view, CORD-MP 50914; **3–4,** Pa element,

lateral and oral views, see attached coniform element on lateral side, CORD-MP 50913. **5–6, *“Ozarkodina”*** sp., Pa element, CORD-MP 50918, lateral and oral views. **7,** undetermined "ozarkodinid”, Pa element, CORD-MP 50941, oral view. **8–9, *Wurmiella* excavata** (Branson and Mehl), **8,** Pa element, CORD-MP 50919, lateral view; **9,** Sa element, CORD-MP50921, dorsal (posterior) view. **10,** undetermined "ozarkodinid”, Sa element, CORD-MP 50946, dorsal view. Scale bar: 0.1 mm.

**Figure 5.** Comparison of late Wenlock – Pridoli conodont zones from Estonia (Männik, 2014), the Carnic Alps (Corradini *et al.*, 2015), the Prague Synform (Slavík and Carls, 2012; Slavík, 2014), and the Precordillera (this study in grey background), with previous conodont zones of Albanesi *et al.* (2006), Mestre (2009) and Sumrall *et al.* (2013).