



RESEARCH ARTICLE

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First documentation of the *Polygnathoides siluricus* conodont Zone (Ludfordian) in South America (Argentina) and the stratigraphic significance of the younger species of *Kockelella* (Conodonta)

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The coquinoid beds from the middle part of the Los Espejos Formation at the Poblete creek section (Talacasto Creek) yielded abundant conodonts. The genus *Kockelella* (Walliser) represents the most relevant biostratigraphical genus in this conodont fauna. The co-occurrence of *Kockelella maenniki* Serpagli and Corradini, *Kockelella variabilis ichnusae* Serpagli and Corradini, *K. variabilis* Walliser, *Kockelella ortus sardoa* (Serpagli & Corradini), and *Kockelella ortus absidata* (Barrick & Klapper) allow us to record for the first time the *Polygnathoides siluricus* Zone in South America, which suggests the Ludfordian Stage (late Ludlow). We also propose an accurate correlation of the Los Espejos Formation with the lower Ludfordian deposits from the Carnic Alps, Sardinia, Morocco, Czech Republic, Gotland, and North America.

KEYWORDS

biostratigraphy, conodonts, Ludlow, Precordillera, Silurian

1 | INTRODUCTION

The *Polygnathoides siluricus* Zone corresponds to the total range interval of *P. siluricus* Branson and Mehl (1933) and is one of the zones with widest distribution in the Silurian. It has been documented in all the continents, with the only exception of South America. In fact, the uncertain attribution to the *P. siluricus*–*Pedavis latialata* Zone of a sample collected by Hünicken and Sarmiento (1986) from the middle part of the Los Espejos Formation at Sierra de Talacasto cannot be confirmed, since a new interpretation of the conodont association listed and illustrated by these authors only allows suggesting a general late Silurian age for this stratigraphical interval. Recently, reworked fragments attributed to *P. siluricus* have been recovered from the upper part of the Los Espejos Formation in samples yielding an uppermost Silurian and lowermost Devonian conodont fauna (Garcías, 2016; Gómez, 2015; Mestre, Gómez, Garcías, Corradini, & Heredia, 2017).

The main goal of this contribution is to report a new Ludfordian conodont assemblage from the middle part of the Los Espejos Formation at the Poblete creek section, with special focus on describing and illustrating the different Ludfordian species of the genus *Kockelella*,

and especially the finding of *Kockelella maenniki*, allowing the accurate record of the *P. siluricus* Zone for the first time in South America.

1.1 | Previous studies on Silurian conodonts from South America

The studies on Silurian conodonts from South America, outside of the Precordillera regions, are very scarce. The early Wenlock conodont faunas from Bolivia (South America) were studied for the first time by Merino Rodo (1991), recording the *Ozarkodina sagitta rhenana* Zone (Jeppsson, 1997).

The first mention of Silurian conodonts from the Precordillera was carried out by Hünicken (1975), suggesting a Wenlock age in the Loma de Los Piojos section. Then, Hünicken and Sarmiento (1986) retrieved Ludlow conodont assemblages from the Los Espejos Formation that were referred to the *P. siluricus*–*P. latialata* Zone. Lehnert, Bergstrom, Benedetto, and Vaccari (1999) described a Llandovery conodont association from the La Chilca Formation at the Cerro del Fuerte, this association represents the *Distomodus kentuckyensis* Zone.

Later, Albanesi, Ortega, and Hünicken (2006) identified the *Kockelella variabilis variabilis* Zone for the first time in Silurian strata of the Precordillera, recording a Gorstian age (lower Ludlow) from the middle and upper part of the Los Espejos Formation in the Ancha creek section, near Talacasto Creek. Heredia, Mestre, and Milana (2007) defined the conodont biostratigraphy of the Los Espejos Formation at Cerro del Fuerte locality. In addition, Mestre (2009) documented a Pridolian conodont assemblage from the Tambolar Formation (Facies Pachaco). Subsequently, Heredia, Sarmiento, Mestre, and Rodríguez (2010) proposed the first biostratigraphical range chart of Silurian Precordilleran conodonts.

Recently, Gómez (2015) studied the conodont biostratigraphy of the Los Espejos Formation in the Ancha creek section. This author proposed a new biostratigraphical scheme from the Silurian of the Precordillera, identifying the probable *P. siluricus* Zone, the Lower *Oulodus elegans detortus* Zone, with the horizon of "*Ozarkodina eosteinhornensis* s.s. and the Upper *Oulodus elegans detortus* Zone; and proposing a Ludfordian–Pridoli interval for these deposits. Garcías (2016), in her unpublished contribution, documented the *P. siluricus*, *Oz. eosteinhornensis* s.l., *Oz. eosteinhornensis* s.s., *Oulodus elegans detortus*, and *Icriodus hesperius* zones in the Poblete creek section. The occurrence of the Lochkovian key conodont in the upper part of the Los Espejos Formation, established accurately the Silurian–Devonian boundary for the first time for South America (Mestre et al., 2017). Recent contributions such as Garcías (2016), Gómez (2015), Gómez, Garcías, Corradini, Mestre, and Heredia (2017), and Mestre et al. (2017) represent an important progress in the Silurian conodont biostratigraphical knowledge of South America.

2 | GEOLOGICAL SETTING

The Silurian deposits of the Precordillera are represented by the Tucunuco Group (Cuerda, 1965), which is composed of the La Chilca Formation (Hirnantian–Wenlock) and the Los Espejos Formation (Wenlock–lower Lochkovian); the contact between these units is a paraconformity. Also, the upper boundary of the Los Espejos Formation is identified by a paraconformity with the Talacasto Formation (Lower Devonian).

The La Chilca Formation is characterized by orthoconglomerates with clasts of chert at its base, which is called the "classic Silurian conglomerate" (Rolleri, 1947). The La Chilca Formation culminates with a level of oolitic sandstone followed by green shale of the Los Espejos Formation (Cuerda, 1969). The age of this unit extends from the Hirnantian to the late Llandovery–early Wenlock (Benedetto, 1995; García-Muro & Rubinstein, 2015; Lehnert et al., 1999; Pöthe de Baldis, 1987). This formation was interpreted as a typical shallow-water, storm-dominated sequence (Astini & Maretto, 1996; Astini & Piovano, 1992; Peralta, 1990), possibly related to a global sea-level change.

The Los Espejos Formation is composed of marine siliciclastic strata, comprising green shale, green to brown sandstone, and green siltstone (Astini & Piovano, 1992). The middle and upper parts of this unit bear abundant shelly fauna, conodonts, graptolites, and palynomorphs, which are present in coarse levels that pinch out laterally. This unit was deposited on middle to shallow platform settings

and in shoreface settings, with interstratified coarse deposits, which were associated with storm events (Astini & Maretto, 1996; Peralta, 1990; Rodríguez, Mestre, Sánchez, & Heredia, 2010). Brachiopods, trilobites, graptolites, tentaculitids, crinoids, conodonts, corals, gastropods, and trace fossils are common (Aceñolaza & Peralta, 1985; Baldis & Aceñolaza, 1978; Baldis, Peralta, & Uliarte, 1984; Brussa & Toro, 1989; Ciguel & Peralta, 1990; Cuerda, 1969; Sánchez, Waisfeld, & Benedetto, 1991).

2.1 | The Poblete creek section

The Poblete creek section represents a classical succession for the study of the Silurian–Devonian deposits from the Precordillera. There, the La Chilca and Los Espejos formations are well exposed. This creek is located about 18 km NW of Talacasto locality, at coordinates 31°00'06" S, 68°46'31" W (Figure 1).

The Los Espejos Formation begins with greenish burrowed mudstones and shales, containing thin bioclastic accumulations. In the middle part, the succession develops thin sandstone beds that include brachiopods such as *Harringtonina*, *Clarkeia*, and *Australina*, among others, associated with trilobites, nautiloids, ostracods, and crinoids. An ichnological association is characterized mainly by the *Nereites* Ichnofacies (Aceñolaza & Peralta, 1985). In the upper part, sandstone beds become thicker, showing shell-beds and hummocky cross-stratification (HCS) structures are associated to storm deposition. Also, trace fossils of the *Cruziana* Ichnofacies (Aceñolaza & Peralta, 1985; Astini & Maretto, 1996) have been identified. Synsedimentary deformation structures, such as slumps, ball and pillow, and load casts occur in the uppermost part of the section (Astini & Maretto, 1996).

Graptolites were described from the Los Espejos Formation: *Saetograptus argentinus* (Cuerda) occurs associated with shelly fauna from the middle part, while *Monograptus uncinatus* var. *notouncinatus* (Cuerda) occurs in the upper and uppermost part of the formation (Cuerda, 1969). The Los Espejos Formation was sampled for conodonts, with nine samples collected from the base to the top of this unit, (Figure 2).

3 | METHODS AND STUDIED MATERIAL

This study is focused on two samples (yp5 and yp7) collected from the middle part of the Los Espejos Formation in the Poblete creek section (Figure 2). The yp5 sample is represented by a 5-cm-thick light green coquinoid bed, located at 122 m above the base of the unit. Beside conodonts, the fauna is represented by tentaculitids, ostracods, poorly preserved graptolites, and abundant brachiopods of different sizes, densely packed and with orientation parallel to bedding.

The yp7 sample was collected at 161 m above the base of the Los Espejos Formation from a greenish grey sandstone bed, 10 cm thick, with 3 cm of coquina at its base. The fauna present in the coquinoid bed is composed of gastropods, tentaculitids, ostracods, and brachiopods. It should be noted that a third sample (yp6) barren of conodonts was collected at 150 m above the base of the Los Espejos Formation, between the two productive samples.

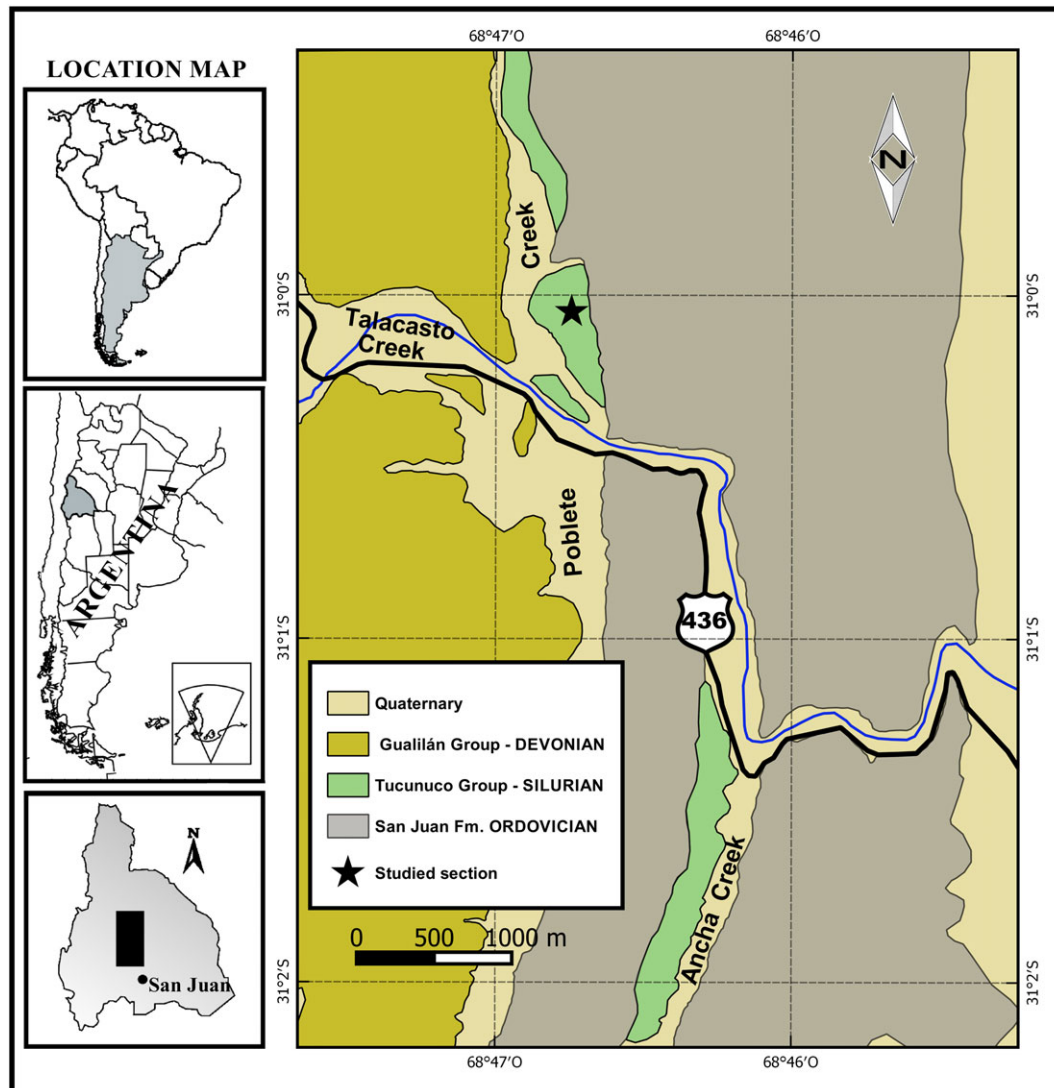


FIGURE 1 Location and geological map of the study area, Poblete creek, Central Precordillera, San Juan Province, Argentina [Colour figure can be viewed at wileyonlinelibrary.com]

Both productive samples weighed around 1.3 kg and were processed by conventional laboratory methods using formic acid (Stone, 1987) in the Micropalaeontology Lab, San Juan University (Argentina). A total of about 6,000 conodont elements were collected by hand-picking from the insoluble material. The conodont collection is stored in the INGEO, National University of San Juan, under the code INGEO-MP.

4 | CONODONT DATA

The conodont association recovered from the studied samples includes: *Coryssognathus dubius* (Rhodes), *Dapsilodus obliquicostatus* (Branson and Mehl), *K. maenniki* (Serpagli and Corradini), *Kockelella ortus absidata* (Barrick & Klapper), *Kockelella ortus sardoa*, *Kockelella variabilis ichnusae* (Serpagli & Corradini), *K. v. variabilis* (Walliser), *Oulodus siluricus* (Branson & Mehl), *Oulodus sp.*, *Panderodus unicastatus* (Branson & Mehl), *Ps. beckmanni* (Bischoff & Sannemann), *Ps. bicornis* (Drygant), *Ps. bicornis contiguus* (Corradini), and *Wurmiella excavata*

(Branson & Mehl). The association can be attributed to the *P. siluricus* Zone because of the occurrence of *K. maenniki*, which occurs only in this Zone (Serpagli & Corradini, 1999).

The association is dominated by *Ps. beckmanni* (Bischoff & Sannemann), *Ps. bicornis* (Drygant), *Ps. bicornis contiguus* (Corradini), *P. unicastatus* (Branson & Mehl), *Oulodus sp.*, and *W. excavata* (Branson & Mehl). The important species for biostratigraphic assignment belong to the genus *Kockelella* that actually represents only 2.5% of the assemblage.

5 | SYSTEMATIC PALAEOLOGY

Systematic notes are limited to the genus *Kockelella*. The conventional orientational terms—anterior, posterior, and lateral—for the descriptions of the elements (see Purnell, Donoghue, & Aldridge, 2000) is followed in this paper. The suprageneric classification scheme proposed by Sweet (1988) is adopted.

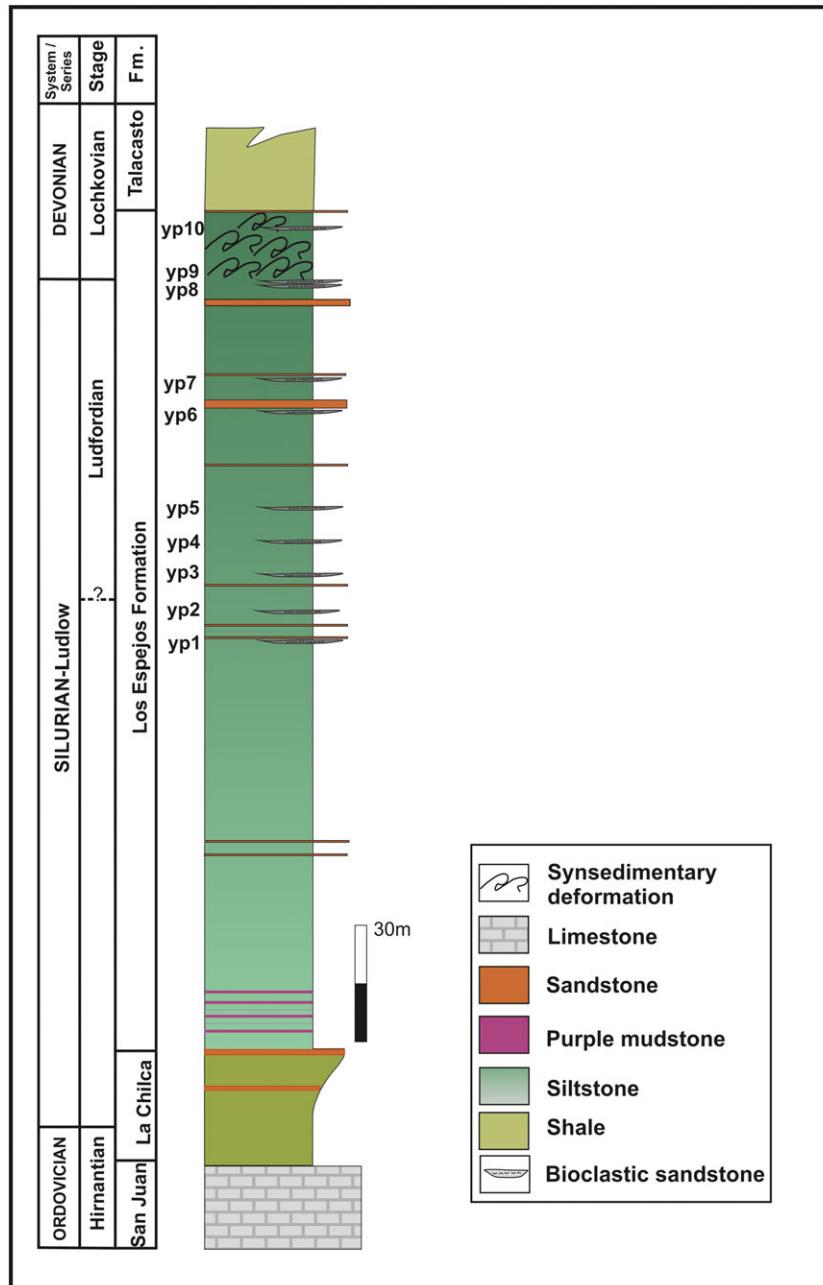


FIGURE 2 Stratigraphic column showing the Los Espejos Formation in the Poblete creek section. Numbers on the left side of the lithology column indicate conodont samples [Colour figure can be viewed at wileyonlinelibrary.com]

Class Conodonta Pander, 1856

Order Ozarkodina Dzik, 1976

Family Kockelellidae Klapper, 1981

Genus *Kockelella* Walliser, 1957

Type species: *Kockelella variabilis* Walliser, 1957

Remarks:

The genus *Kockelella* was defined by Walliser (1957), with the type species *K. variabilis*. Possible reconstruction of the apparatus of that species proposed by Walliser (1964) named it "Conodonten Apparat

G." Later, Barrick and Klapper (1976) amended the diagnosis of the genus in terms of multielement apparatus and provided a preliminary reconstruction of the apparatuses of some species. Serpagli and Corradini (1999) revised the genus and amended the diagnosis of the *K. v. variabilis* on the basis of an apparatus conformed by six elements (P1, P2, M, S0, S1, and S2). These authors suggested that some elements of the apparatus are the similar in several species of *Kockelella*, whereas only M elements can be distinguished.

We focus on the description of the P1 elements of the different species of *Kockelella*, because M elements are not present in our material, and P2, S0, S1, and S2 elements are apparently indistinguishable from the corresponding elements of *K. v. variabilis*, as already pointed out by Serpagli and Corradini (1999).

***Kockelella maenniki* Serpagli & Corradini, 1998**

Figure 3g–h; Figure 4c.

- 1998 *Kockelella manniki* n. sp. SERPAGLI and CORRADINI, p. 80–81, pl.1, fig 5. 6.
- 1999 *Kockelella maenniki* Serpagli and Corradini, SERPAGLI and CORRADINI, p. 284–286, pl. 3, figs, 1–12 (*cum syn.*).
- 2002 *Kockelella maenniki* Serpagli and Corradini, CORRADINI et al. fig 6. (a,b).
- 2006 *Kockelella maenniki* Serpagli and Corradini, VALENTINE et al. p. 228–229, fig 11n–o.
- 2009b *Kockelella maenniki* Serpagli and Corradini, CORRADINI et al. pl.1, fig. 13.
- 2009 *Kockelella maenniki* Serpagli and Corradini, CORRIGA et al. pl. 1, fig 1.
- 2009 *Kockelella maenniki* Serpagli and Corradini, FERRETTI et al. pl. 1, fig. 9.
- 2010 *Kockelella maenniki* Serpagli and Corradini, SLAVÍK et al. pl. 4, figs. C, O, N.
- 2012 *Kockelella maenniki* Serpagli and Corradini, MANDA et al. fig. 4a.
- 2016 *Kockelella maenniki* Serpagli and Corradini, GARCÍAS, pl.1, fig F, I.
- 2017 *Kockelella maenniki* Serpagli and Corradini, PERCIVAL and ZHEN, fig 4c–h.

Material:

4 P1 elements from sample yp5: INGEO-MP-5203(1-4)

Description:

The P1 elements from the Poblete creek are narrow and slightly curved. The platform is strongly asymmetrical and typically is more developed on the outer side of the element, where a simple long process bears sometimes one or two denticles. The blades are laterally compressed and thin; the anterior process is straight and bears from six to eight closely spaced denticles. The posterior process is arched downward and inward bearing three to five denticles. The cusp is proclined and slightly larger than the adjacent denticles.

Remarks:

In most of our material, the lateral process is directed anteriorly, bent, and bears strong denticles. It is difficult to assign small, juvenile specimens, where the lateral process is not fully developed.

Biostratigraphic distribution:

The species occurs only from the base to the upper part of the *P. siluricus* Zone but does not reach the top of the zone (Corradini et al., 2015; Serpagli & Corradini, 1999).

***Kockelella ortus absidata* Barrick & Klapper, 1976**

Figure 3i

- 1976 *Kockelella absidata* n.sp. BARRICK and KLAPPER, pp. 76–77, pl. 2, figs. 15–16.

- 1999 *Kockelella absidata absidata* Barrick and Klapper, SERPAGLI and CORRADINI, p. 277–279, pl.1, figs. 8–13 (*cum syn.*).
- 2003 *Kockelella absidata absidata* Barrick and Klapper, CORRADINI et al. pl. 1, fig. 9.
- 2003 *Kockelella ortus absidata* Barrick and Klapper, CALNER and JEPSSON, p. 197–199, fig. 15r, 17a–h.
- 2009b *Kockelella absidata absidata* Barrick and Klapper, CORRADINI et al. pl.1, fig. 16.
- 2009 *Kockelella absidata absidata* Barrick and Klapper, FERRETTI et al. pl.1, fig. 12.
- 2009 *Kockelella absidata absidata* Barrick and Klapper, PILLOLA et al. fig. 6d.
- 2010 *Kockelella absidata absidata* Barrick and Klapper, CORRADINI et al. fig. 3k.
- 2014 *Kockelella absidata absidata* Barrick and Klapper, CORRIGA et al. fig. 5D.
- 2014 *Kockelella ortus absidata* Barrick and Klapper, RADZEVICIUS et al. fig. 3A.
- 2014 *Kockelella ortus absidata* Barrick and Klapper, SLAVÍK, fig. 2V.
- 2016 *Kockelella absidata absidata* Barrick and Klapper, GARCÍAS pl. 1, fig. J.
- 2017 *Kockelella ortus absidata* Barrick and Klapper, SCHÖNLAUB et al. pl.2, fig. 18.

Material:

2 P1 elements from sample yp5: INGEO-MP-5204(1-2)

Description:

P1 element is stout and laterally compressed. The anterior process is straight and longer than the posterior process, bearing seven to ten denticles. The posterior process is short and slightly curved downward, bearing two to four denticles, sometimes partly fused. The cusp is slightly reclined and located on the posterior third of unit, is laterally compressed, and only slightly larger than the anterior denticles. The basal cavity is wide beneath the cusp, is slightly more developed on the outer side, and may bear one denticles beside the cusp (Figure 3i).

Remarks:

The P1 element of *K. o. absidata* has a narrow blade with anteriorly fused denticles. The anterior blade is usually higher than the posterior one and has the basal cavity with a “heart-shaped outline.”

Biostratigraphic distribution:

K. o. absidata is a long-ranging taxon from the upper part of the Homeric (*K. o. absidata* Zone) to the Ludfordian (*P. siluricus* Zone). Calner and Jeppsson (2003) introduced a *K. o. absidata* Zone in Gotland as a short interval from the entry of the species and the first occurrence of *Ctenognathodus murchisoni*, an endemic species documented only in Baltica. The definition of the *K. o. absidata* Zone was later modified by Cramer et al. (2011), as the interval from the FAD of

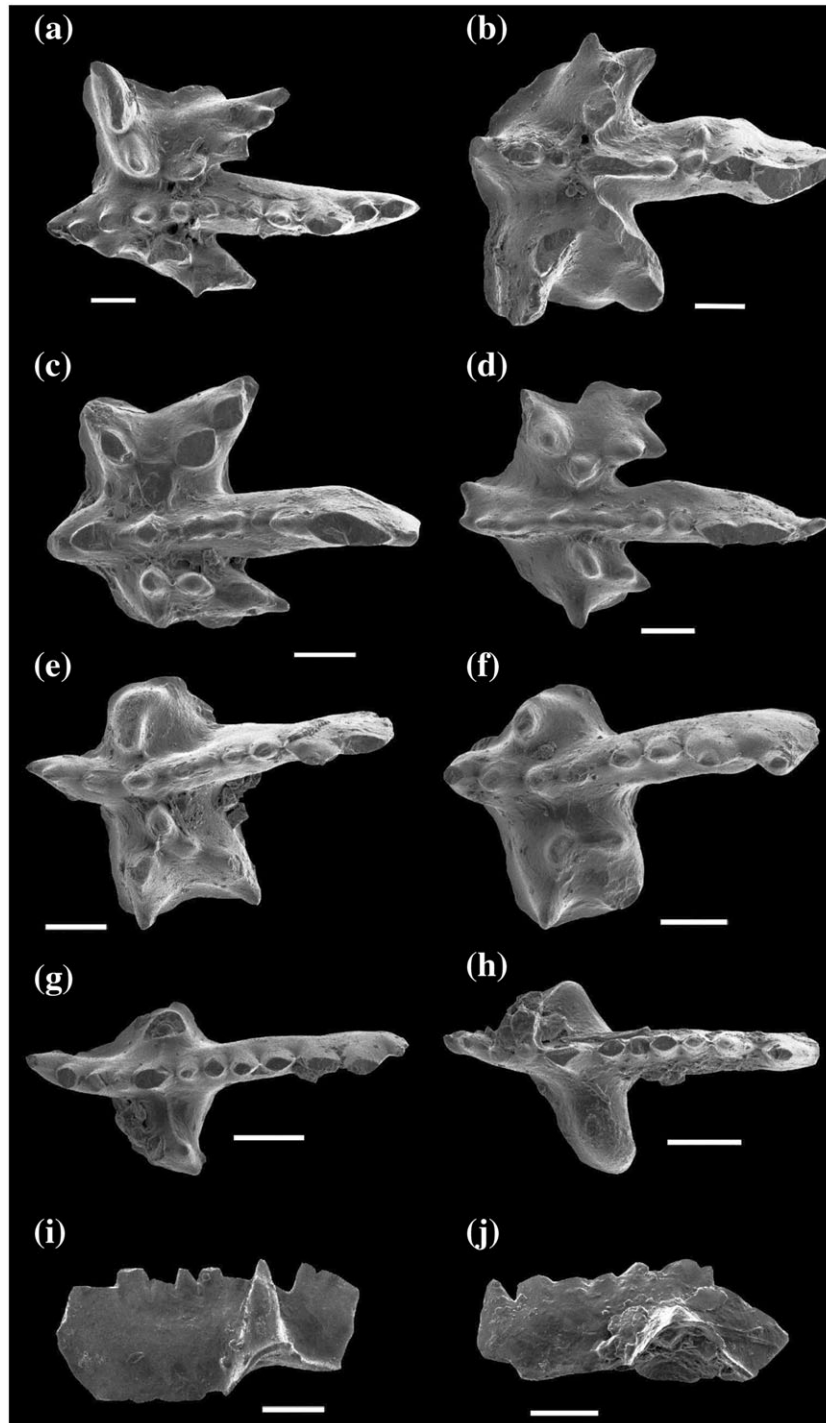


FIGURE 3 Microphotographs of selected conodonts at scanning electron microscope. Scale bar 0.1 mm. (a–d) *Kockelella variabilis variabilis*. All specimens from sample yp5 (*Polygnathoides siluricus* Zone). (a) INGEO-MP-5202 (1); upper view of P1 element; (b) INGEO-MP-5202 (2); upper view of P1 element; (c) INGEO-MP-5202 (3); upper view of P1 element; (d) INGEO-MP-5202 (4); upper view of P1 element. (e–f) *Kockelella variabilis ichnusae*. All specimens from sample yp5 (*P. siluricus* Zone). (e) INGEO-MP-5205 (1); upper view of P1 element; (f) INGEO-MP-5205 (2); upper view of P1 element. (g–h) *Kockelella maenniki*. All specimens from sample yp5 (*P. siluricus* Zone). (g) INGEO-MP-5203 (1); upper view of P1 element; (h) INGEO-MP-5203 (2); upper view of P1 element; (i) *Kockelella ortus absidata* (*P. siluricus* Zone). INGEO-MP-5204 (1), sample yp5; lateral view of P1 element; (j) *Kockelella ortus sardoa* (*P. siluricus* Zone). INGEO-MP-5208 (1), sample yp7; lateral view of P1 element

the index taxon to the FAD of *Kockelella crassa*. Thus the *K. o. absidata* Zone now includes the upper Homerian strata. At Gotland, *K. o. absidata* ranges only in the upper Homerian (Calner & Jeppsson, 2003), whereas elsewhere, occurs up to the *P. siluricus* Zone (e.g., Corradini et al., 2015;

Schönlaub, Corradini, Corriga, & Ferretti, 2017; Serpagli & Corradini, 1999; Slavík, 2014). The occurrence of *K. o. absidata* in Argentina together with *K. maenniki* confirms the long ranging of the species up to the *P. siluricus* Zone.

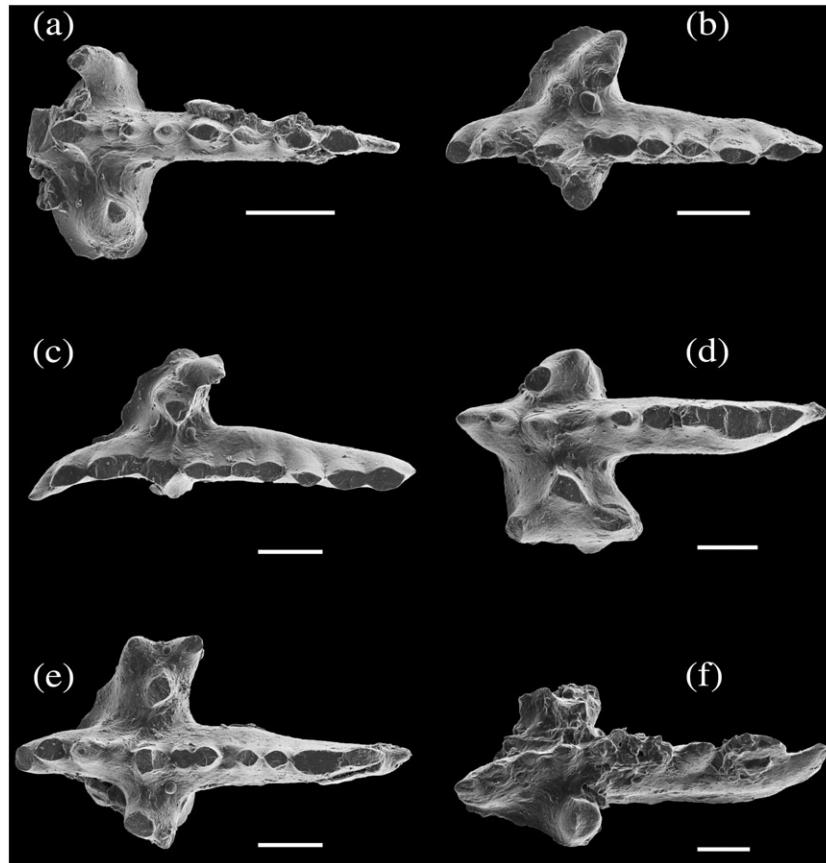


FIGURE 4 Microphotographs of selected conodonts at scanning electron microscope. Scale bar 0.1 mm. (a–b) *Kockelella variabilis variabilis*. All specimens from sample yp5 (*Polygnathoides siluricus* Zone). (a) INGEO-MP-5202 (5); upper view of P1 element; (b) INGEO-MP-5202 (6); upper view of P1 element; (c) *Kockelella maenniki* (*P. siluricus* Zone) INGEO-MP-5203 (3); sample yp5; upper view of P1 element; (d–e) *Kockelella variabilis ichnusae*. All specimens from sample yp5 (*P. siluricus* Zone). (d) INGEO-MP-5205 (3); upper view of P1 element; (e) INGEO-MP-5205 (4); upper view of P1 element; (f) *Kockelella variabilis variabilis*. (*P. siluricus* Zone) INGEO-MP-5228 (2), sample yp7; upper view of P1 element

Kockelella ortus sardoa Serpagli & Corradini, 1999

Figure 3j

1998 *Kockelella absidata sardoa* n.ssp. SERPAGLI and CORRADINI, p. 278–283, pl.1, figs. 1–7 (*cum syn.*).

2009 *Kockelella absidata sardoa* Serpagli and Corradini, CORRIGA et al. pl. 1, fig. 5.

2009 *Kockelella absidata sardoa* Serpagli and Corradini, FERRETTI et al. pl. 1, fig. 5.

2010 *Kockelella absidata sardoa* Serpagli and Corradini, BARRICK et al. fig. 4K.

2012 *Kockelella absidata sardoa* Serpagli and Corradini, MANDA et al. fig. 4c.

2016 *Kockelella ortus sardoa* Serpagli and Corradini, CORRADINI et al. pl. 3, fig.11.

Material:

1 P1 element from sample yp7: INGEO-MP-5208(1)

Description:

The species is characterized by a narrow laterally compressed and densely denticulated blade. The posterior process is shorter than

the anterior and arched downward. The basal cavity has a typical heart-like shape and tapers gradually towards the posterior end of the element.

Remarks:

The shape of the basal cavities allows to distinguish between *K. o. sardoa* and *K. o. absidata*; furthermore, the latter has a stouter appearance. The species has an important biostratigraphic value, because the first occurrence of the species can be utilized for recognizing the base of the *Ancoradella ploeckensis* Zone when the index species is missing (Schönlaub et al., 2017).

Biostratigraphic distribution:

From the base of the *A. ploeckensis* Zone to within the *P. siluricus* Zone (Serpagli & Corradini, 1999).

Kockelella variabilis ichnusae Serpagli & Corradini, 1998

Figure 3e–f; Figure 4d–e.

1998 *Kockelella variabilis ichnusae* n.ssp. SERPAGLI and CORRADINI, pp. 80–82, pl.1, figs. 1a–c, 2.

1999 *Kockelella variabilis ichnusae* Serpagli and Corradini, SERPAGLI and CORRADINI, p. 293–294, pl. 4, figs. 1–7 (*cum syn.*).

- 2003 *Kockelella variabilis ichnusae* Serpagli and Corradini, CORRADINI et al. pl. 1, fig. 14.
- 2006 *Kockelella variabilis variabilis* Walliser, ALBANESI et al. p. 9, fig. 6T (only).
- 2009 *Kockelella variabilis ichnusae* Serpagli and Corradini, CORRIGA et al. pl. 1, fig. 3.
- 2009a *Kockelella variabilis ichnusae* Serpagli and Corradini, CORRADINI et al. pl. 1, fig. 14.
- 2009b *Kockelella variabilis ichnusae* Serpagli and Corradini, CORRADINI et al. pl. 1, fig. 14.
- 2009 *Kockelella variabilis ichnusae* Serpagli and Corradini, FERRETTI et al. pl. 1, fig. 13.
- 2009 *Kockelella variabilis ichnusae* Serpagli and Corradini, PILLOLA et al. fig. 6 (f).
- 2010 *Kockelella variabilis ichnusae?* Serpagli and Corradini, BARRICK et al. fig. 4Q (only).
- 2010 *Kockelella variabilis ichnusae* Serpagli and Corradini, SLAVÍK et al. pl. 4, figs. A-E, D, K, M.
- 2014 *Kockelella variabilis ichnusae* Serpagli and Corradini, CORRIGA et al. fig. 5 A
- 2016 *Kockelella variabilis ichnusae* Serpagli and Corradini, GARCÍAS, pl.1, fig. D, E.
- 2016 *Kockelella variabilis ichnusae* Serpagli and Corradini, WANG, p. 170–171, pl. S-5, fig. 6.
- 2017 *Kockelella variabilis ichnusae* Serpagli and Corradini, SCHÖNLAUB et al. pl.2, fig. 8.
- 2017 *Kockelella variabilis ichnusae* Serpagli and Corradini, SLAVIK, fig. 5.12, 5.15.

Material: P1 elements from sample yp5: INGEO-MP-5205(1-9)

Description: The P1 element of *K. v. ichnusae* is strong and stout. The short posterior process is arched downward and gently deflected. The anterior blade is relatively thick, long, and straight, and carries four to six denticles. The denticles close to the cusp are fused. The element has a wide asymmetrical platform bordered by a rim. The platform is short and rounded and bears a short process made of one or two denticles aligned perpendicularly to the blade; the outer side of the platform is large and bears a better developed lateral process that has two branches with three to six discrete or closely spaced denticles.

Remarks:

The diagnostic features in adult specimens of *K. v. ichnusae* are well developed, but only a few of these features are present in the juvenile specimens, which are apparently indistinguishable from those of *K. v. variabilis*. The specimens of *K. v. ichnusae* from our collection are similar to the original collection by Serpagli and Corradini (1999), except for a generally shorter anterior process that bears four to six strong denticles. In Argentina, the only specimens of this species already illustrated is that figured by Albanesi et al. (2006, figure 6T) as *K. v. variabilis*.

Biostratigraphic distribution:

From the upper part of the *K. v. variabilis* Interval Zone to within the *P. siluricus* Zone (Corradini et al., 2015).

Kockelella variabilis variabilis Walliser, 1957

(Figure 3, a-d; Figure 4, a-b,f)

- 1957 *Kockelella variabilis* n.sp. WALLISER, p. 35, pl. 1, fig. 3–10.
- 1976 *Kockelella variabilis* Walliser; BARRICK and KLAPPER, p. 77–78, pl. 3, figs. 12–17 (*cum syn.*).
- 1995 *Kockelella variabilis* Walliser; SIMPSON and TALENT, p. 137–138, pl. 6, figs. 8–17 (*cum syn.*).
- 1999 *Kockelella variabilis variabilis* Walliser; SERPAGLI and CORRADINI, p. 288–293, pl. 5, figs. 1–13, pl. 6, figs. 1–9, pl. 6, figs. 1–7 (*cum syn.*).
- 2001 *Kockelella variabilis variabilis* Walliser, CORRADINI et al. pl.1, fig. 15.
- 2003 *Kockelella variabilis variabilis* Walliser, CORRADINI et al. pl. 1, fig. 12.
- 2006 *Kockelella variabilis variabilis* Walliser, ALBANESI et al. p. 9, fig. 6. K-S, U (only).
- 2009 *Kockelella variabilis variabilis* Walliser, CORRIGA et al. pl. 2, fig. 11.
- 2009a *Kockelella variabilis variabilis* Walliser, CORRADINI et al. pl. 1, fig. 13.
- 2009 *Kockelella variabilis variabilis* Walliser, PILLOLA et al. fig. 6 (e).
- 2009 *Kockelella variabilis variabilis* Walliser, FERRETTI et al. pl.1, fig. 15.
- 2010 *Kockelella variabilis variabilis* Walliser, BARRICK et al. fig. 4 T-V.
- 2010 *Kockelella variabilis variabilis* Walliser, SLAVÍK et al. pl. 4, figs. B, J, L, V.
- 2010 *Kockelella variabilis variabilis* Walliser, CORRADINI et al. fig. 3 (j).
- 2014 *Kockelella variabilis variabilis* Walliser, CORRIGA et al. p. 194–196, fig. 5B, C.
- 2016 *Kockelella variabilis variabilis* Walliser, FERRETTI et al. fig. 5 (B).
- 2016 *Kockelella variabilis variabilis* Walliser, GARCÍAS, pl. 1, fig. A–C, G–H.
- 2017 *Kockelella variabilis variabilis* Walliser, SCHÖNLAUB et al. pl.2, fig. 10.
- 2017 *Kockelella variabilis variabilis* Walliser, SLAVIK, fig. 5.13.
- 2017 *Kockelella variabilis* Walliser, SPIRIDONOV et al. fig. 4K, L, P, Q.

Material:

73 P1 elements from sample yp5: INGEO-MP-5202(1-73) and 2 from sample yp7: INGEO-MP-5228 (1-2)

Description:

The P1 element is characterized by branched lateral processes included on a thick platform. The blade of P1 element is strong; the anterior process is thick, long, and straight, but usually slightly inner arched at the extremity. The anterior process bears from four to eight basally fused denticles, which increase its size distally to the cusp; in a few specimens, the blade ends with one or two short and small denticles. The posterior process is short and inner bent; in some adult specimens, the posterior process is represented by only one denticle fused with the cusp and included in the platform (Figure 3b), and other adult specimens show a distally bifurcate posterior process (Figure 3D). Bifurcated lateral processes are present on both sides of the blade, to which are connected by a narrow ridge. In adult specimens, the lateral processes protrude out from the platform. The outer lateral process is always more developed than the inner lateral process. The basal cavity is wide and deep, occupying the whole inferior part of the element, and extends as a groove under the anterior process.

Remarks:

Serpagli and Corradini (1999) demonstrated the series of morphologic changes of P1 elements of *K. v. variabilis*, from juvenile, with faint lateral processes, to intermediate forms, to adult specimens, with well-developed lateral processes on both sides of the blade. In our material, elements of different ontogenetic stage are present, like the *K. v. variabilis* specimens recovered by Albanesi et al. (2006) from the Quebrada Ancha section. Also, similar morphological variability from adult elements is observed on those from Sardinia and Bohemia (Serpagli & Corradini, 1999; Slavík, Kríž, & Carls, 2010), although some specimens from the Precordillera have a short and more laterally curved posterior process. One specimen (Figure 3d) shows an incipient

branching of the posterior process. All S, M, and few P elements conform to the description provided by Serpagli and Corradini (1998).

Biostratigraphic distribution:

From the *K. crassa* Zone to the lower part of the *P. siluricus* Zone (Corriga, Corradini, & Walliser, 2014).

6 | DISCUSSION AND CORRELATION

The study of the association recovered from the middle part of the Los Espejos Formation is assigned the *P. siluricus* Zone due to the occurrence of *K. maenniki* that is exclusive of this zone (Corradini et al., 2015; Serpagli & Corradini, 1999). The co-occurrence with other species of *Kockelella* permits to propose the lower part of the biozone (Figure 5).

The *P. siluricus* Zone is one of the best studied conodont biozones in the entire Silurian and is universally used in biostratigraphy. The success of this biozone is mainly due to easy identification of the conodont marker whose biostratigraphical importance has never been disputed. The species *P. siluricus* has a global distribution (for a summary of geographical occurrences and references, see Corradini & Corriga, 2018).

The *P. siluricus* Zone has been introduced by Walliser (1964) in the first biozonation scheme of the Silurian, as the total range interval of the conodont species *P. siluricus*. In all the more recent zonal schemes, the *P. siluricus* Zone always possess the same definition with the lower and upper boundaries defined by the First Appearance Datum and by the Last Appearance Datum of the species, respectively (e.g., Aldridge & Schönlaub, 1989; Corradini et al., 2015; Corradini & Corriga, 2012; Corradini & Serpagli, 1999; Cramer et al., 2011; Jeppsson, Eriksson, & Calner, 2006).

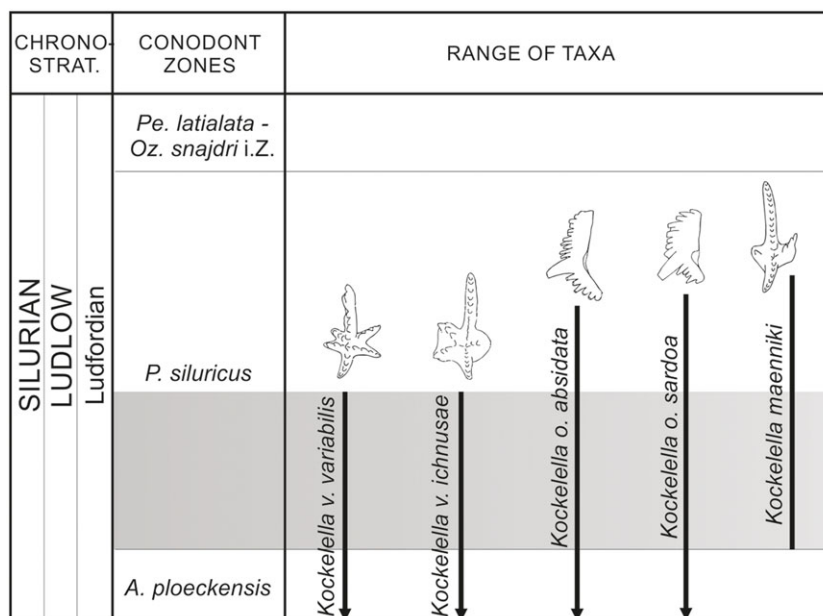


FIGURE 5 Range of the species of *Kockelella* within the *Polygnathoides siluricus* Zone (grey shade indicates the range in the Precordillera). Conodont zones after Corradini, Corriga, Männik, and Schönlaub (2015); sketch drawings of taxa of *Kockelella* after Serpagli and Corradini (1999) [Colour figure can be viewed at wileyonlinelibrary.com]

In general, most of the *P. siluricus* Zone represents a time interval with thriving conodont faunas characterized by high taxonomic diversity and high intra-specific variability. Also, beside "normal" conodonts, elements with anomalous morphologies, like branched processes, are relatively common (Corradini, Olivieri, & Serpagli, 1995; Corrigan, Corradini, & Ferretti, 2009; Corrigan et al., 2014; Slavík et al., 2010). Corradini et al. (1995) interpreted these anomalous elements as "evolutionary experiments" during a high nutrient supply P-episode (Jeppsson, 1993). In the upper part of the zone, the conodont abundance and diversity dropped at the onset of the "Lau Event" (Jeppsson, 1993; Jeppsson et al., 2012; Jeppsson & Aldridge, 2000; Slavík et al., 2010), a low magnitude mid-Ludfordian mass extinction.

The Ludfordian species of *Kockelella* are widely recorded and studied in different regions around the world and show their last occurrence at various levels within the *P. siluricus* Zone. *K. v. variabilis* was once supposed to have become extinct in the uppermost part of the *A. ploeckensis* Zone (Barrick & Klapper, 1976; Serpagli & Corradini, 1999) but has been recently documented in the lower part of the *P. siluricus* Zone (e.g., Corradini et al., 2015; Corrigan et al., 2014; Slavík et al., 2010). The other species of *Kockelella* present at Poblete creek section occur in the *P. siluricus* Zone, even if their last occurrences are documented at different stratigraphic levels within this biozone.

The Cellon section, located in the Carnic Alps, is probably the most famous Silurian section of the world and reference section for many Silurian studies. Recently, Corradini et al. (2015) recognized that various species of the genus *Kockelella* have different last occurrences: *K. v. variabilis* and *K. v. ichnusae* occur only in the lower part of the *P. siluricus* Zone, *K. o. sardoa* reaches its upper part, while *K. o. absidata* and *K. maenniki* are present up to the top of this biozone (Figure 6). However, in the Cellon section at the top of the *P. siluricus* Zone, a hardground is present, suggesting a short hiatus between the Cardiola and the Alticola formations. This is confirmed by the occurrence of *P. latialata* (Walliser) in the lowermost bed of the Alticola Formation at Cellon, whereas in other sections in the area (e.g., Rauchkofel Boden: Schönlaub et al., 2017; Cuestalta: Corradini, unpublished data) the basal beds of this unit still belong to the *P. siluricus* Zone.

In Sardinia, the *K. v. variabilis* is not documented from the *P. siluricus* Zone (Corrigan et al., 2009), whereas *K. v. ichnusae* occurs

in the lowermost beds of this zone in the Silius Section (Corradini, Ferretti, Corrigan, & Serpagli, 2009a; Serpagli, Corradini, & Ferretti, 1998). On the other hand, in the last section, *K. o. sardoa* occurs up to the central part of the zone, and *K. maenniki* slightly higher, whereas in the nearby Genna Ciuerciu section (Corradini, Ferretti, Corrigan, & Serpagli, 2009b; Corradini, Ferretti, Serpagli, & Barca, 1998), these taxa have a contemporaneous last occurrence, about 2 m below the top of the *P. siluricus* Zone. Recently, Corrigan et al. (2014) recorded *K. v. variabilis* and *K. v. ichnusae* only in the lower part of the *P. siluricus* Zone in Morocco, whereas *K. maenniki* is not documented up to now in this region (Figure 6).

The subspecies *K. v. variabilis*, *K. v. ichnusae*, and *K. maenniki* are present in the lower and central part of the *P. siluricus* Zone and have their simultaneous last occurrence about 2 m below the top of the biozone from Pozary Quarry section, Czech Republic (Slavík et al., 2010). Furthermore, *K. a. sardoa* is documented in the central part of the *P. siluricus* Zone at Všeradice (Manda et al., 2012; Figure 6).

In the *P. siluricus* Zone from the Goldap core (NE Poland; Männik & Małkowski, 1998), the subspecies of *K. maenniki*, *K. v. variabilis*, and *K. v. ichnusae* were documented (Serpagli & Corradini, 1999). However, the precise stratigraphical distributions of these taxa are not available. Spiridonov et al. (2017) reported *K. variabilis* (subspecies not distinct) and *K. o. absidata* up to about 2 m below the last occurrence of *P. siluricus* in western Lithuania, also, have been recorded the last occurrences of *K. ortus*, *K. aff. Maenniki*, and *K. cf. variabilis* within the *P. siluricus* Zone at Botvide 1 section, Gotland (Jeppsson, Calner, & Eriksson, 2005), and *K. aff. o. sardoa* is recovered from the upper part of the biozone (Jeppsson et al., 2012).

The species of *Kockelella* in the *P. siluricus* Zone are documented in several sections from North America (Figure 6). Rexroad and Craig (1971) figured specimens now attributed to *K. v. ichnusae* from the Bainbridge Formation in Missouri. Subsequently, elements very similar to *K. maenniki* were figured from the *P. siluricus* Zone of the Roberts Mountains (Nevada) by Klapper and Murphy (1975), together with *K. v. variabilis*. Uyeno (1981) documented *K. variabilis* in the same sample yielding *P. siluricus* from the Canadian Arctic. Recently, Barrick, Klapper, Kleffner, and Karlsson (2010) reported the presence of *K. variabilis* from the lower part of this biozone in Oklahoma and claimed that *K. maenniki* was absent (Figure 6).

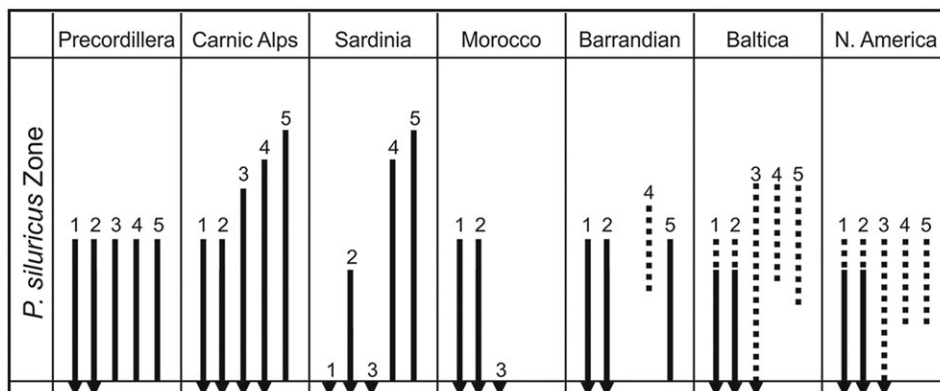


FIGURE 6 Tentative correlation chart of the occurrence of the species of *Kockelella* within the *P. siluricus* Zone. For discussion and references, see the text. Dotted lines indicate uncertain range. 1 = *Kockelella variabilis variabilis*; 2 = *Kockelella variabilis ichnusae*; 3 = *Kockelella ortus absidata*; 4 = *Kockelella ortus sardoa*; 5 = *Kockelella maenniki*

Precise biostratigraphical data on the occurrence of the species of *Kockelella* in Australia are not available. However, Jeppsson et al. (2012) referred that *K. v. variabilis* is not present in the upper part of the *P. siluricus* Zone in the Broken river area, and *K. maenniki* is sporadically documented from the lower and central part of the zone (e.g., Jeppsson et al., 2007; Percival & Zhen, 2017; Valentine, Cole, & Simpson, 2006).

After the analysis of all these biostratigraphical data, it is evident that the genus *Kockelella* became extinct within the *P. siluricus* Zone and does not reach the upper part of the zone. This extinction level is coincident with the beginning of the Lau Event, as suggested by a positive peak of $\delta^{18}\text{O}$ in Silus section (Corradini et al., 2009a) and Cellon (Jeppsson et al., 2012). The local last occurrences of the various species of *Kockelella* may be slightly different, but at first approximation, it looks that the taxa with a wide platform (*K. v. variabilis* and *K. v. ichnusae*) became extinct before those with a small platform (*K. maenniki*, *K. a. absidata*, and *K. a. sardoa*).

7 | CONCLUSIONS

In the present contribution, the Silurian conodonts *K. v. ichnusae*, *K. o. absidata*, *K. o. sardoa*, and *K. maenniki* are documented for the first time in Argentina, allowing the recognition of the *P. siluricus* Zone for the first time in South America. More precisely, the presence of *K. v. variabilis*, and *K. v. ichnusae*, in co-occurrence with *K. maenniki*, suggests that the studied strata may belong to the lower part of the zone, assigning the middle Ludfordian age for the middle part of Los Espejos Formation from the Central Precordillera. This finding allows an accurate correlation of the Los Espejos Formation with coeval strata from the Carnic Alps, Sardinia, Morocco, Czech Republic, Baltica, and North America.

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