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Stratigraphical distribution of the Ordovician graptolite *Azygograptus* Nicholson & Lapworth in the Central Andean Basin (northwestern Argentina and southern Bolivia)

Distribution stratigraphique du graptolite ordovicien Azygograptus *Nicholson & Lapworth du Bassin andin central (Nord-Ouest de l'Argentine et Sud de la Bolivie)*

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ABSTRACT

We analyzed new occurrences of *Azygograptus lapworthi* from the Cordillera Oriental, Argentina. The bearer sandstones levels, corresponding to the Acoite Formation, are overlying the deposits, in which the *Didymograptellus bifidus* Biozone (Lower Ordovician, upper Floian, Fl3) was previously recognized, and are overlain by younger pelitic levels yielding *Xiphograptus lofuensis* (Middle Ordovician, early Dapingian, Dp2). Previous records from the Central Andean Basin are also reviewed in detail and accurately correlated, allowing us to conclude that the *Azygograptus lapworthi* Biozone corresponds to the Middle Ordovician (lower Dapingian, Dp1). This biostratigraphic framework documents that the transition between the Lower and Middle Ordovician deposits occurs in the uppermost levels of the Acoite Formation in the Argentine Cordillera Oriental. It is additionally integrated with up to date conodont records to establish a high-resolution regional correlation, with equivalent deposits from the Puna of northwestern Argentina and Cordillera Oriental of Bolivia, and to discuss new insights for global correlation.

RÉSUMÉ

Les dépôts de la formation d'Acoite ont révélé un enregistrement de *Azygograptus lapworthi* dans la cordillère orientale d'Argentine. Ces niveaux surplombent des dépôts déjà identifiés comme appartenant à la biozone à *Didymograptellus bifidus* (Ordovicien inférieur). Ils sont recouverts par des dépôts plus récents, incluant *Xiphograptus lofuensis* (Ordovicien moyen, Dapingien précoce). Les anciens registres du Bassin andin central sont, de plus, revus en détail et précisément corrélés régionalement, ce qui nous autorise à conclure que la biozone à *Azygograptus lapworthi* correspond à l'Ordovicien moyen (Dapingien, Dp1).

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Ce schéma biostratigraphique indique que la transition entre les dépôts de l'Ordovicien inférieur et moyen se déroule, dans la cordillère orientale d'Argentine, dans les niveaux les plus supérieurs de la formation d'Acoite. De plus, les registres récents de conodontes permettent d'établir une corrélation régionale à haute résolution avec les dépôts équivalents de la Puna, dans le Nord-Ouest de l'Argentine, et de la cordillère orientale de Bolivie, ainsi que de discuter de nouvelles propositions de corrélations globales.

1. Introduction

GRAPTOLITES is one of the most important groups to define global stages and correlations of the Lower Paleozoic sequences. They are largely distributed in the thick Ordovician successions of the Central Andean Basin, mainly in the Cordillera Oriental and Puna of northwestern Argentina and southern Bolivia. From the earliest reports of Kayser (1897) and Wood (1906) that mentioned "didymograptids" graptolites coming from Portezuelo, Cordillera Oriental of Argentina, and "Llanvirn pendent didymograptids, phyllograptids, diplograptids, and glossograptids" from Cule, northern Bolivia, respectively; the knowledge concerning the graptolites from the Central Andean Basin was significantly improved. The Lower Ordovician graptolite biostratigraphic framework for this region was based on records from numerous stratigraphic sections exposed mainly in the Cordillera Oriental of Argentina and Bolivia. Toro (1994, 1997) proposed for the first time a comprehensive biostratigraphic framework composed by four graptolite biozones for the Floian deposits of the Acoite Formation, exposed in the Cordillera Oriental of northwestern Argentina. The biostratigraphic succession included the *Tetragraptus phyllograptoides*, *T. akzharensis*, "*Baltograptus deflexus*" (= *Baltograptus* cf. *B. deflexus*, *sensu* Toro et al., 2015) and *Didymograptellus bifidus* biozones. It was earlier established at Los Colorados area and soon after correlated with equivalent successions located in the Cajas and Aguilar ranges, along the western flank of the Cordillera Oriental. Later on, this biostratigraphic scheme was documented at the Santa Victoria area, along the eastern flank of the Cordillera Oriental and expanded through four additional Tremadocian biozones: *Bryograptus kjerulfi*, *Aorograptus victoriae, Araneograptus murrayi*, and *Hunnegraptus copiosus* (Giuliano et al., 2013; Toro, 1999a, 1999b; Toro and Maletz, 2007; Toro et al., 2015). More recently, Albanesi and Ortega (2016) summarized a graptolite biostratigraphic framework for the Ordovician System of northwestern Argentina, including the biozones previously proposed by diverse authors. They referred the *Azygograptus eivionicus* Biozone (*sensu* Brussa et al., 2008) to the lower Dapingian (Dp1?), based on the records of the nominal taxa in the Huaytiquina area, western Puna (Monteros et al., 1996) and the Muñayoc section, in the Quichagua range, northeastern Puna (Martínez et al., 1999). On the other hand, Egenhoff et al. (2004) proposed a Lower Ordovician graptolite biozonation based on the records coming from a number of stratigraphic sections located in the Tarija, Potosí, and Chuquisaca Provinces, in southern Bolivia. The authors described the *Rhabdinopora flabelliformis*, *Adelograptus* sp., *Aorograptus victoriae*, *Araneograptus murrayi*, *Hunnegraptus copiosus*, *Tetragraptus phyllograptoides*, *Expansograptus protobalticus*, *E. holmi*, *Baltograptus minutus*, *Azygograptus lapworthi*, and *Isograptus victoriae* local biozones. They provided an international correlation with the Lower–Middle Ordovician biostratigraphic frameworks of Scandinavia and eastern North America (Egenhoff et al., 2004: figure 7), but they did not correlate these biozones with those previously proposed in northwestern Argentina. After that, Toro et al. (2015) established a regional correlation between the biostratigraphic schemes for Argentina and Bolivia, but did not include additional precisions about the Dapingian (Middle Ordovician) and younger graptolite biozones.

In recent years, more than a hundred of different taxa were identified, including some new species, and most of the problematic taxa have been systematically reviewed applying modern criteria of classification (Egenhoff et al., 2004; Toro and Brussa, 2003; Toro and Maletz, 2007, 2008, 2018, among others); moreover, a number of scientific publications including taxonomical revisions of new graptolite taxa and the results of a PhD thesis (Toro, 2017; Toro and Maletz, 2018; Toro and Vento, 2013; Vento, 2013, among others) allowed one to complete the Ordovician biostratigraphical scheme for the Central Andean Basin, which was also included in numerous compilations and correlations with other fossils, like conodonts and palynomorphs (Albanesi and Ortega, 2016; de la Puente and Rubinstein, 2013, and references therein). However, as happens worldwide, the previous records of the *Azygograptus* species in the Central Andean Basin are still scarcely known, their biostratigraphic ranges are difficult to correlate regionally and globally; moreover, the transition from the Lower to Middle Ordovician biostratigraphic units remained imprecisely defined, including gaps and confusing correlations.

The aim of this paper is to analyze the *Azygograptus* species previously recorded from South America, which come from two sections at the Cordillera Oriental of Argentina, two sections in the Puna region of Argentina, and one section from the Cordillera Oriental of Bolivia (Fig. 1B), to conclude on whether they correspond to *A. lapworthi*. By assessing the stratigraphic ranges of the key species, and discussing the stratigraphic relationship with the associated conodont records, we aim to establish a high-resolution regional correlation of the *Azygograptus lapworthi* Biozone and propose a more comprehensive biostratigraphic framework for the Central Andean Basin.

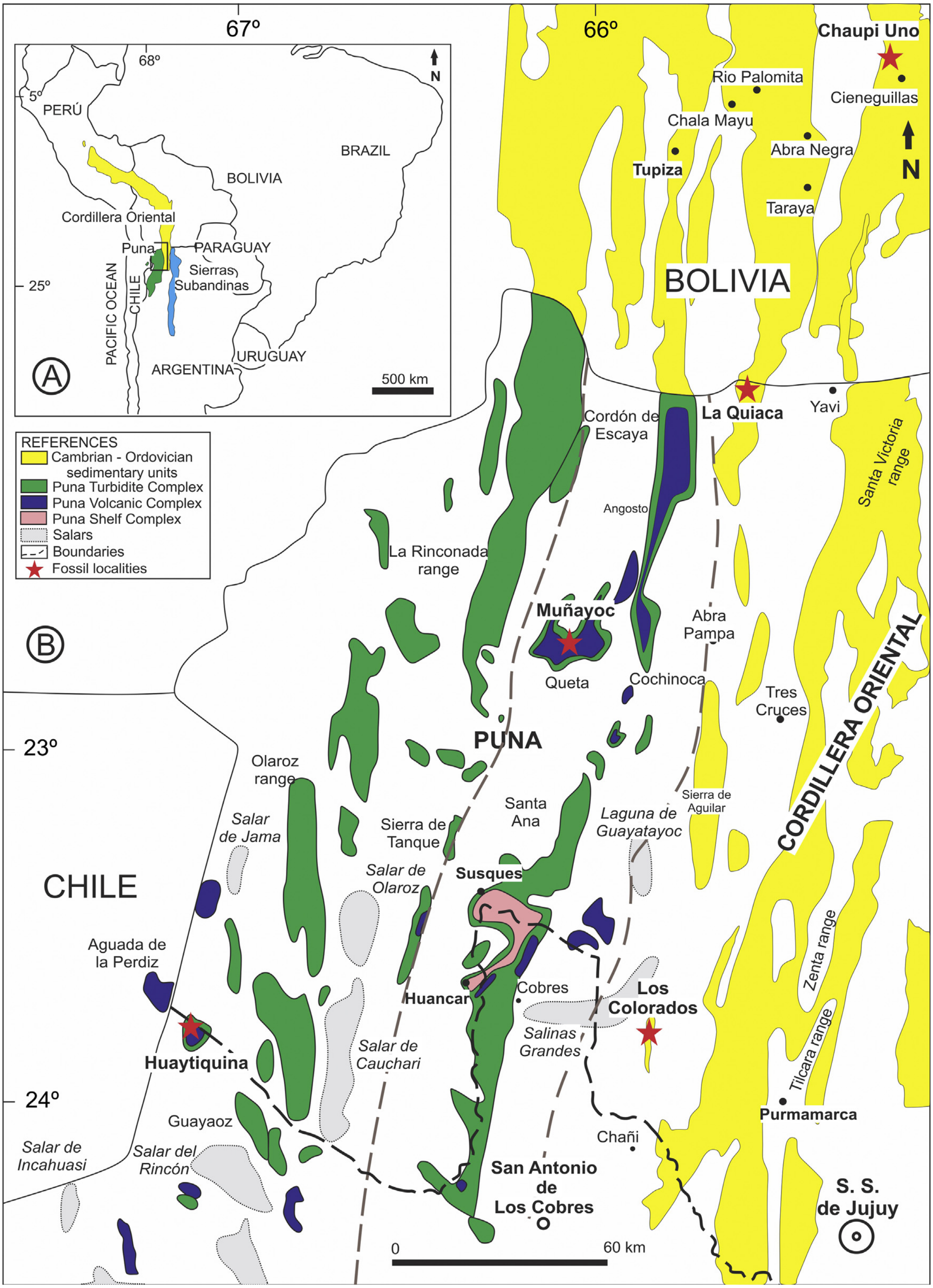

Fig. 1. **A:** Location map of the geomorphological provinces comprised in the Central Andean Basin. **B:** Fossiliferous localities studied in the Argentine Cordillera Oriental (Los Colorados, La Quiaca), the Argentine Puna region (Huaytiquina, Muñayoc), and the Bolivian Cordillera Oriental (Chaupi Uno).

Fig. 1. **A :** Schéma des provinces géomorphologiques du Bassin andin central. **B :** Les sites fossilifères étudiés dans la Cordillère orientale (Los Colorados, La Quiaca) et dans la région de la Puna (Huaytiquina, Muñayoc) en Argentine, ainsi que de la cordillère orientale (Chaupi Uno) de Bolivie.

2. The *Azygograptus* records of the Central Andean Basin

The Central Andean Basin (Sempére, 1995) was developed in an active margin at western Gondwana during the Cambrian-Ordovician times. It spreads over the northwestern Argentina and also encompass parts of Chile, Bolivia and Peru (Astini, 2003), corresponding to one of thicker (over 5000-m-thick) basins of the Lower Paleozoic, characterized by its rich fauna of invertebrate fossils.

Northwestern Argentina includes, from the west to the east, the geological provinces of the Puna, Cordillera Oriental, Sierras Subandinas and Sierras de Santa Bárbara (Fig. 1A). The Santa Victoria Group (Upper Cambrian–Lower Ordovician) is widely represented in the Cordillera Oriental. It is unconformably overlying the Lower to Middle Cambrian Mesón Group (see discussions about the nature of this unconformity in Buatois and Mángano, 2003, Moya, 1998, and references therein), whereas different age levels of this group are in turn overlain by glacial deposits of the Mecoyita Formation (northernmost equivalent of the Hirnantian Zapla Formation), involving a regional unconformity related to the Ocloyic Orogeny (cf. Astini, 2008).

Turner (1960, 1964) divided the Santa Victoria Group into two units, which are more commonly referred to in the literature as the Santa Rosita (upper Furongian–Tremadocian) and Acoite (Floian) formations. The biostratigraphic analysis we present here corresponds to the upper part of the Acoite Formation (upper Floian, Fl3 and lower Dapingian, Dp1) (Fig. 2C). In the type area, both units are composed of alternating sandy and shaly packages, but the Acoite Formation is distinguished by coarser grains and thicker beds, especially towards the top of the succession (Astini, 2003). Astini (2008) noted that the Santa Rosita and Acoite formations are hard to distinguish, because the Santa Victoria Group is a 3000-m-thick monotonous alternation of shaly intervals and sandstone beds, forming large-scale upward-shallowing cycles interpreted as deltaic lobes from a wave-dominated deltaic system. Sandstone bodies display great lateral variability as a result of onshore-offshore and along-shore variations, and are often diachronic; hence, they are difficult to correlate at a regional scale and graptolite biostratigraphy has been a useful tool in this way.

2.1. Argentine Cordillera Oriental

The Cordillera Oriental is a high-relief “thick-skinned type” thrust system with dominant east vergence, in which the Acoite Formation is widely represented by thick, upward-shallowing beds related to a storm-dominated deltaic system (Astini, 2003; Ramos, 2017; Waisfeld and Astini, 2003). At the Los Colorados area, located approximately 23° 33′ S and 65° 40′ W in the Jujuy Province, this unit reaches a maximum thickness of almost 2300 m. It is mainly composed of greenish gray shale and fine-sandstone, alternating with dark-gray and black shale and siltstone deposited in a middle to distal shelf setting (Waisfeld et al., 2003) during the Lower Ordovician (*Tetragraptus phyllograptoides*, *T. akzharensis*, *Baltograptus* cf. *B. deflexus* and *Didymograptellus bifidus* biozones). The upper part of the unit, in which the genus *Azygograptus* was formerly recognized at the western side of the Cordillera Oriental by Toro (2017), is a massive, highly bioturbated sandy facies abruptly developed, overlying an upward-thickening mesoscale cycle with tidal influence (Astini, 2003; Waisfeld and Astini, 2003). To the top of the Acoite Formation, a more restricted inshore environment is represented by few monospecific assemblages of eurytopic forms like *Azygogratus lapworthi* preserved in yellowish–green medium-grained sandstones (Fig. 3.1, 3,6). A few meters above those levels, a short transgressive green shales with bioturbated sandstones interval, assigned to the Lower Member of the Alto del Cóndor Formation by Carlorosi et al. (2013) produces conodonts (Fig. 2C). The index species *Baltoniodus triangularis* was first recorded in the Central Andean Basin by Carlorosi et al. (2013), indicating a Middle Ordovician (early Dapingian, Dp1) age for the bearer strata.

Numerous specimens of *A. lapworthi* were additionally collected from equivalent levels corresponding to greenish-gray fine sandstones at La Quiaca area, Jujuy Province (Fig. 3.5, 8), close to the border between Argentina and Bolivia (Fig. 1B), where the key species is associated with *Tetragraptus* cf. *reclinatus* and *Expansograptus* sp.

Another specimen coming from the San Bernardo area, Salta Province, at the eastern side of the Cordillera Oriental was previously assigned to *Azygograptus* (?) *saltaensis* by Loss (1951: pl. 1, figure* 25), but, based on the below revision of this material (Fig. 3. 13, 14), we conclude that there is not enough evidence to include it into the genus *Azygograptus*. Accordingly, the new records coming from the exposures of the Los Colorados and the La Quiaca areas (Toro, 2017) are reconfirmed here as the first mentions of the *Azygograptus* for the Cordillera Oriental Argentina.

2.2. Argentine Puna

The Puna morpho-structural province is part of the high Andean plateau with average highs above 3500 m. The Lower Paleozoic is represented in this region by sedimentary deposits and an associated volcanism. It is widely accepted that the region comprises two submeridional belts corresponding to the Puna Oriental and Puna Occidental ones, which were developed from a Cambrian rifting margin to a Floian back-arc until a Darriwilian turbidite sequence in a foreland basin system (Astini, 2003, 2008 and literature therein).

Monteros et al. (1996) assigned to *Azygograptus eivionicus* Elles the material coming from the Huaytiquina section, Salta Province, in western Puna, northwestern Argentina. In this area, located close to the border between Argentina and Chile (Fig. 1B), the authors recognized two different stratigraphic units, the Aguada de la Perdíz Formation, comprising the volcano-sedimentary lower succession, and the “Coquena” Formation, which includes 1450-m-thick deposits dominated by turbidites yielding graptolites. They described *Azygograptus eivionicus*, *D.* (*Expansograptus*) sp. aff. *D.* (*E.*) *extensus*, *Dichograptus octobrachiatus*, *Pseudotrigonograptus minor* and *Tetragraptus* sp. in the lower third of the “Coquena” Formation, and they recorded *Xiphograptus svalbardensis* and *Xiphograptus* sp. in the

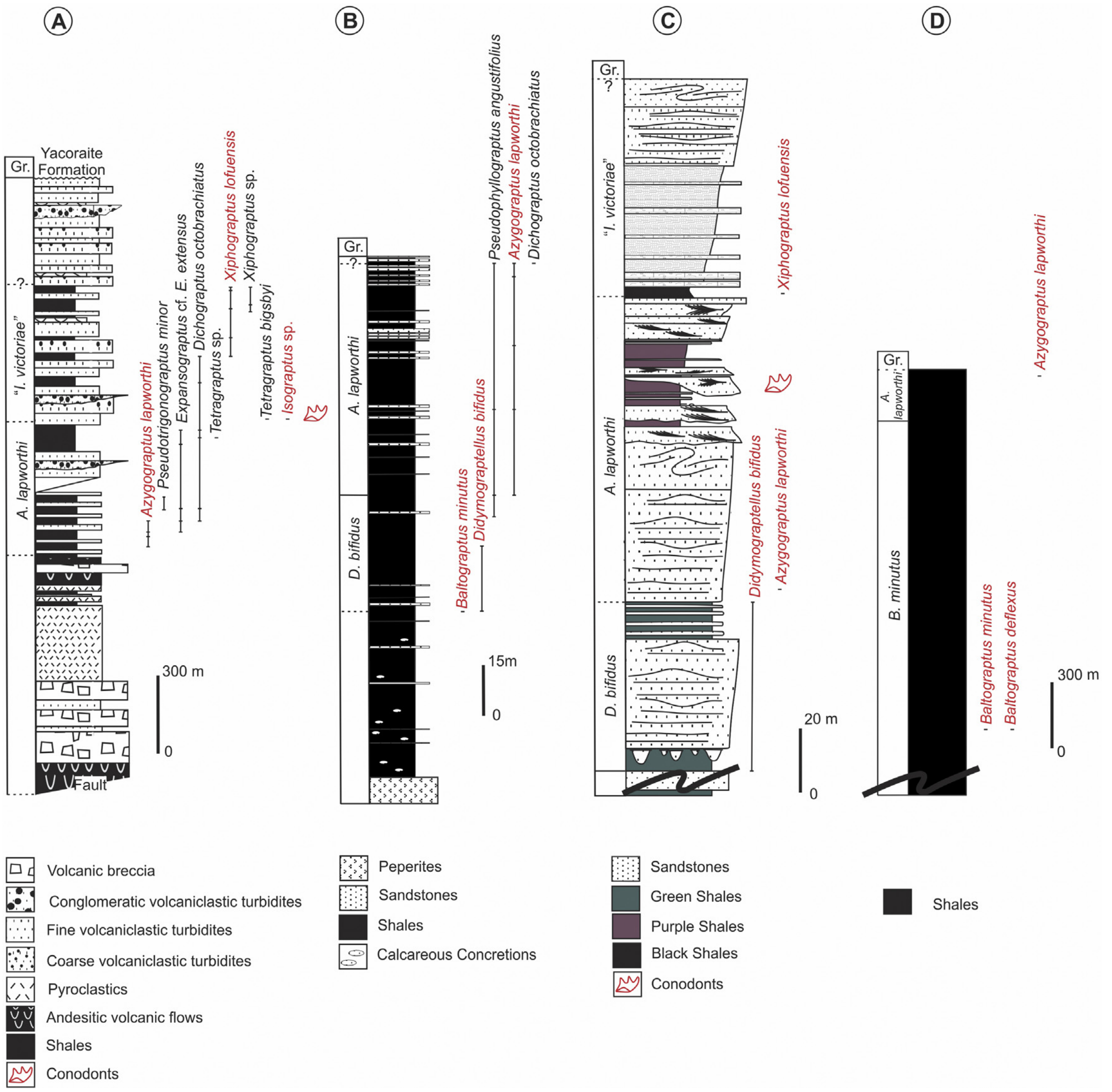

Fig. 2. Stratigraphic sections showing the ranges of the significant graptolite taxa (revised in this work in red) and the proposed biostratigraphic units (Gr). **A**: Huaytiquina, on the western flank of the Argentine Puna (modified from Monteros et al., 1996), including the conodont records discussed in Toro et al. (2019, in press). **B**: Muñayoc, in the northeastern Argentine Puna (modified from Martínez et al., 1999). **C**: Integrated stratigraphic column for Los Colorados and La Quiaca, on the western flank of the Argentine Cordillera Oriental (modified from Astini et al., 2004), including the conodont records studied by Carlorosi et al. (2013). **D**: Sama-Chaupi Uno section, in the Southern Cordillera Oriental of Bolivia (modified from Maletz et al., 1995).

Fig. 2. Colonnes stratigraphiques indiquant l'extension des graptolites significatifs et des unités biostratigraphique proposées (Gr). **A :** Huaytiquina, sur le flanc ouest de la Puna, en Argentine (modifié de Monteros et al., 1996), avec la position des conodontes discutés par Toro et al. (2019, in press). **B :** Muñayoc, au nord-est de la Puna en Argentine (modifié d'après Martínez et al., 1999). **C :** Colonne stratigraphique intégrée de Los Colorados et La Quiaca, sur le flanc ouest de la Cordillère orientale, en Argentine (modifié de Astini et al., 2004), avec la position des conodontes trouvées par Carlorosi et al. (2013). **D :** Sama-Chaupi Uno, au sud de la cordillère orientale de Bolivie (modifié de Maletz et al., 1995).

middle part of the unit. Afterward, Zimmermann and Bahlburg (2003) and Zimmermann (2011) grouped the previously defined stratigraphic units from the Argentine Puna into three different complexes, based on distinctive facies, including the studied section to the Puna Volcanic Complex and the Puna Turbidite Complex. According to these authors, the deposits in the Huaytiquina section are respectively characterized by associations of highly volcaniclastic rocks, andesites and rhyolites, tuffs and pyroclastic flows, turbidites, conglomerates and fine-grained sandstones, as well as immature coarse-grained wackes carrying graptolites and brachiopods; and large turbidite systems and channel systems, respectively. The graptolite-bearing deposits of this section correspond to the Puna Turbidite Complex *sensu* Astini (2003).

More recently, Brussa et al. (2008) proposed a biostratigraphic framework based on graptolite and trilobite records for the Lower Paleozoic of this region, and preliminary results regarding the first Middle Ordovician conodont records of the Puna region indicate that

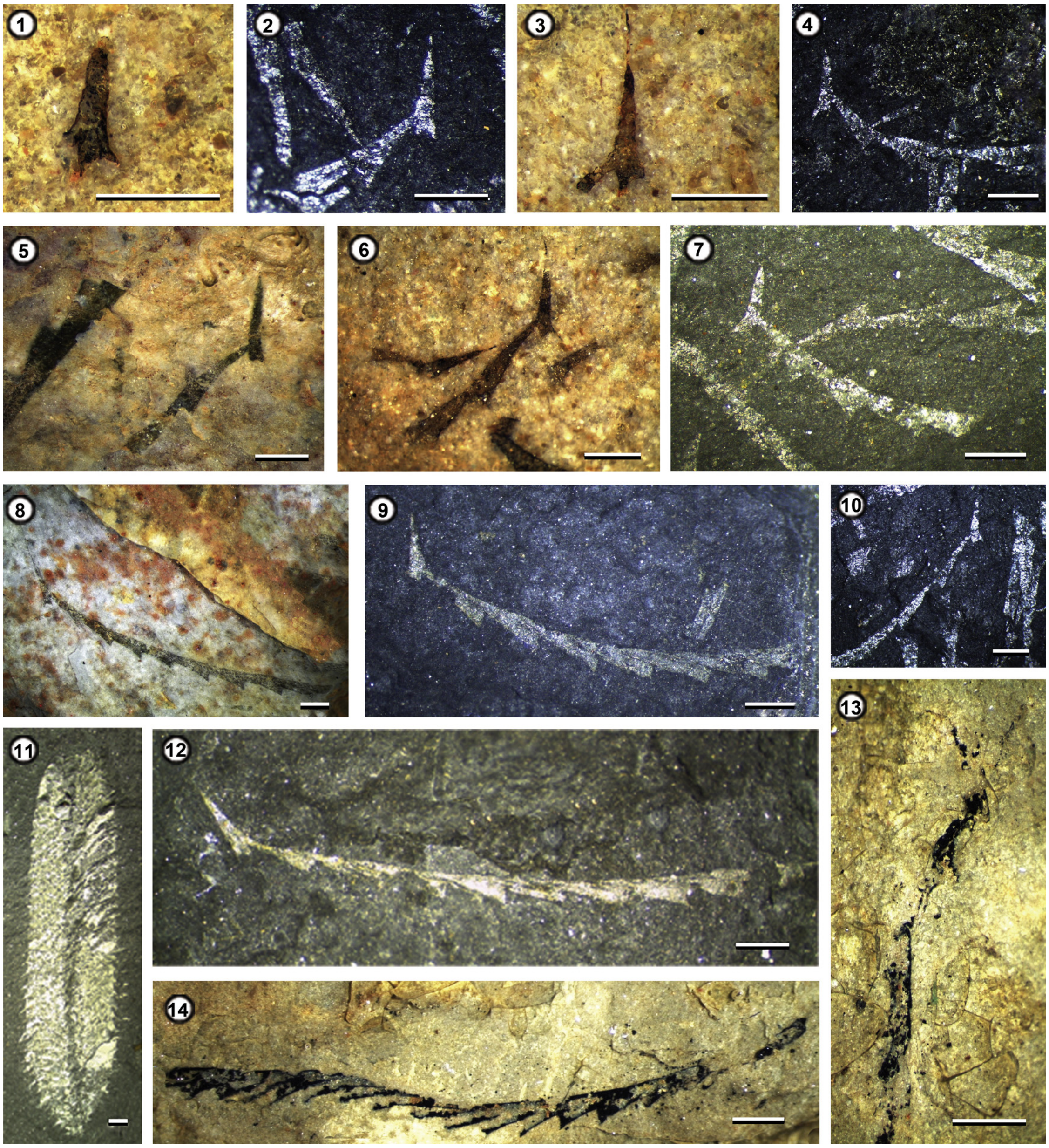

Fig. 3. Relevant graptolite taxa from the ***Azygograptus lapworthi*** Biozone (lower Dapingian) of the Central Andean Basin. **1–10, 12: *Azygograptus lapworthi*** Nicholson. **1**: Sicula in relief with broken apex showing the growing of the first theca, Los Colorados, Jujuy Province, CEGH-UNC 24950. **2**: Juvenile with complete sicula, Muñayoc, Jujuy Province, CEGH-UNC 24955. **3:** Flattened proximal end exhibiting prominent sicula with nema and proximal portion of the first theca, Los Colorados, CEGH-UNC 24945. **4:** Flattened specimen with short sicular rutellum, Muñayoc, CEGH-UNC 24961. **5:** Proximal and distal parts of associated specimens exhibiting strong widening of the tubarium, La Quiaca, Jujuy Province, CEGH-UNC 24953. **6:** Juvenile specimen preserving conspicuous sicula with nema, and short rutellum, Los Colorados, CEGH-UNC 24947. **7:** Flattened associated specimens, Muñayoc, CEGH-UNC 24956. **8:** Complete large flattened tubarium with long ventral free wall of the sicula, La Quiaca, CEGH-UNC 24952. **9:** complete mature specimen, Chaupi Uno, S Bolivia, CEGH-UNC 24960. **10**: Distorted specimen showing long free wall of the sicula and short rutellum, Muñayoc, CEGH-UNC 24957. **12:** Complete mature specimen, Chaupi Uno, CEGH-UNC 24938. **11:** *Pseudophyllograptus* sp. associated with *Azygograptus lapworthi* at Muñayoc, CEGH-UNC 24975. **13, 14:** Both counterparts of the fragmentary stipe previously assigned to "*Azygograptus* (?) *saltaensis*" (*sensu* Loss, 1951), San Bernardo, Salta Province, UNJU (B. 163-164)/JUY-P-63-64. Scale bar = 1 mm.

graptolite–conodont associations of Dapingian (Dp2) age are present in the Huaytiquina section above the levels with *Azygograptus* (Toro et al., 2019, in press), confirming the biostratigraphical framework proposed here (Fig. 6).

Martínez et al. (1999) also mentioned the presence of *Azygograptus eivionicus* in the western belt of the Quichagua range in northeastern Puna. The authors described the Muñayoc section (Fig. 2B) as a 150-m-thick volcano-sedimentary succession that evidences an upward progression from mudstone-dominated dysaerobic outer shelf deposits to sandstone-dominated deposition under storm and wave influence, with an upper sandier part related to a general regressive trend. Based on the recognition of 18 graptolite taxa, they constrain the age of the lower portion of the studied succession to the middle Arenig, or its equivalent Chewtonian1–Ch2 of the Australian sequence, and suggested a Castlemainian1–Ca2 or Ca3 age, equivalent to the late middle Arenig of the British sequence for the upper third of the Muñayoc section, based on the occurrence of *Azygograptus eivionicus.*

Graptolites collected from Muñayoc section are still under revision, but preliminary results regarding the revision of the azygograptids records permit to assign them to *Azygograptus lapworthi* (Fig. 3.2, 4, 7, 10; Fig. 4.3, 5, 8, 13), extending the stratigraphic range of this taxon to the upper 60 m of the studied section (Fig. 2B).

2.3. Cordillera Oriental of Bolivia

Egenhoff et al. (2004) suggested that a transition from an extensional to a compressional basin occurred in the late Early Ordovician (*Expansograptus holmi* Biozone) in southern Bolivia and northwestern Argentina, and Egenhoff (2007) compared the southern Bolivian basin evolution with equivalent reconstructions from northwestern Argentina. The author postulated for the region three main zones, bounded by major Andean over-thrusts, with rocks that are younger from east to west. The oriental zone that comprises the eastern portion of the Cordillera Oriental and the Subandean belt, the central zone where Middle Ordovician rocks are cropping out, and the western part of the Cordillera Oriental and scattered outcrops of the Altiplano region. In the first mentioned zone, the Lower Ordovician shelf succession comprises the Obispo, Taraya, Pircancha, Sella, and Rumi Orkho formations (Egenhoff, 2000; Rivas et al., 1969).

Specimens assigned to *Azygograptus lapworthi* were first recorded and illustrated for South America near Tarija, in southern Bolivia, by Beckly and Maletz (1991: Text-figure 11). Afterwards, Maletz et al. (1995), Maletz and Egenhoff (2003), and Egenhoff et al. (2004) defined the local *Azygograptus lapworthi* Biozone based on the first occurrence of the key species at the top of the Pircancha Formation in the Sama–Chaupi Uno and Cieneguillas–Chaupi Uno sections (Fig. 2D). More recently, Toro and Maletz (2018: figure 4.13) included extra material of this species in the overview of the graptolite faunas of Bolivia, and the present revision also confirms its presence in the Chaupi Uno section (Fig. 3.9, 12; Fig. 4. 9, 11).

3. Materials and methods

Additionally to the material resulting from the detailed sampling carried out along the upper part of the Acoite Formation, exposed in the Los Colorados area, in the western belt of the Argentine Cordillera Oriental (Fig. 1B), other specimens from the Central Andean Basin, which were included in the *Azygograptus* genus in the past, are reviewed in this paper. Focus was placed on the detailed description and comparison of the material housed in the paleontological collection of the Centro de Investigaciones en Ciencias de la Tierra (CICTERRA), CONICET and Universidad Nacional de Córdoba, Córdoba, Argentina, under the prefix CEGH-UNC, which are from the La Quiaca area (western belt of the Cordillera Oriental), Muñayoc section (northeastern Puna), and the Chaupi Uno section (southern Bolivia). One further specimen assigned to the *Azygograptus* (?) *saltaensis* by Loss (1951), coming from the Cerro San Bernardo area (eastern flank of the Cordillera Oriental), was borrowed from the "Loss Collection" of the Instituto de Minería y Geología de Jujuy, UNJU, Argentina, to be analyzed in this paper. Regarding the material coming from the Huaytiquina section (western Puna) assigned to *A. eivionicus* by Monteros et al. (1996), it is unfortunately missing from the collection (CNS-I 119/697:1-14) of the "Cátedra de Paleontología General de la Universidad Nacional de Salta, Argentina", where it was deposited by the authors. For that reason, we based our revision on two specimens (Fig. 4. 2, 7) described and illustrated by Monteros et al. (1996: pl. 1, figures 1, 2) which were included in the following geomorphometric analysis.

The geomorphometric approach was applied recently in the framework of the PhD thesis of one of the authors (Herrera Sánchez et al., 2019) to evaluate the differentiation between the specimens of *Azygograptus* from the Central Andean Basin, and to test the systematic

Fig. 3. Graptolites pertinents de la biozone à ***Azygograptus lapworthi*** (Dapingien inférieur) du Bassin andin central. **1–10, 12 :** ***Azygograptus lapworthi*** Nicholson. **1:** Sicula en relief, avec sommet cassé indiquant la croissance de la première thèque, Los Colorados, province de Jujuy, Argentine, CEGH-UNC 24950. **2 :** Juvénile avec sicula complète, Muñayoc, province de Jujuy, Argentine, CEGH-UNC 24955. **3 :** Extrémité proximale aplatie illustrant la sicula proéminente avec nema et une portion proximale des premières thèques, Los Colorados, CEGH-UNC 24945. **4 :** Spécimen aplati avec un court rutellum siculaire, Muñayoc, CEGH-UNC 24961. **5 :** Parties proximales et distales des spécimens associés, indiquant un fort élargissement du tubarium, La Quiaca, province de Jujuy, Argentine, CEGH-UNC 24953. **6 :** Spécimen juvénile préservant la sicula visible avec nema, et un court rutellum, Los Colorados, CEGH-UNC 24947. **7 :** Spécimens associés aplatis, Muñayoc, CEGH-UNC 24956. **8 :** Grand tubarium complet et aplati avec une longue partie libre de la sicula, La Quiaca, CEGH-UNC 24952. **9 :** Spécimen mature complet, Chaupi Uno, S Bolivia, CEGH-UNC 24960. **10 :** Spécimen déformé indiquant une longue partie libre de la sicula et un court rutellum, Muñayoc, CEGH-UNC 24957. **12 :** Spécimen mature complet, Chaupi Uno, CEGH-UNC 24938. **11 :** *Pseudophyllograptus* sp. associé à *Azygograptus lapworthi* à Muñayoc, CEGH-UNC 24975. **13, 14 :** Deux contreparties fragmentaires du stipe anciennement assigné à « *Azygograptus* (?) *saltaensis* » (*sensu* Loss, 1951), San Bernardo, province de Salta, UNJU (B. 163-164)/JUY-P-63-64. Barre d'échelle = 1 mm.

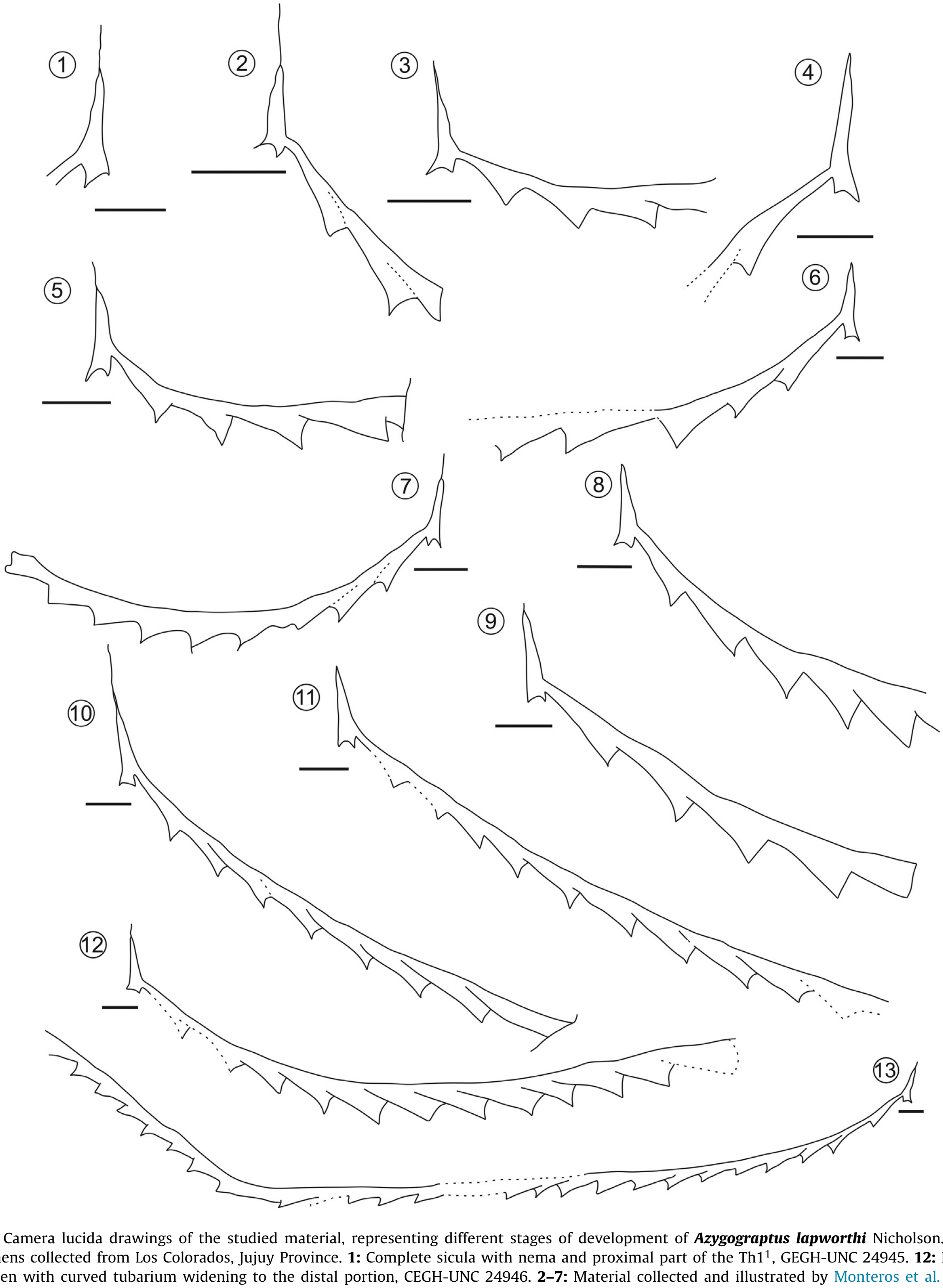

Fig. 4. Camera lucida drawings of the studied material, representing different stages of development of ***Azygograptus lapworthi*** Nicholson. **1, 12:** Specimens collected from Los Colorados, Jujuy Province. **1:** Complete sicula with nema and proximal part of the Th1[1], GEGH-UNC 24945. **12:** Mature specimen with curved tubarium widening to the distal portion, CEGH-UNC 24946. **2–7:** Material collected and illustrated by Monteros et al. (1996: pl. I, figs. 1-2) from Huaytiquina, Salta Province. **2:** Juvenile with sicula exhibiting nema, CNS-I 119 [697 (3)]. **7:** Complete mature specimen, CNS-I 119 [697 (7)]. **3, 5, 8, 13:** Specimens coming from Muñayoc, Jujuy Province. **3:** Juvenile specimen with complete sicula exhibiting nema and short rutellum, CEGH-UNC 24956. **5:** Specimens showing a large ventral free part of the sicula, CEGH-UNC 24961. **8:** Tubarium showing an increasing width to the distal portion, CEGH-UNC 24954. **13:** Complete large tubarium with conspicuous sicula, CEGH-UNC 24957. **4, 6, 10:** New material from La Quiaca, Jujuy Province. **4:** Proximal end with long sicula, CEGH-UNC 24953. **6:** Incomplete specimen showing a long free ventral portion of the sicula, CEGH-UNC 24951. **10:** Complete mature specimen exhibiting sicula with long nema, CEGH-UNC 24952. **9, 11:** Material coming from Chaupi Uno, southern Bolivia. **9:** Flattened specimen with long sicula, CEGH-UNC 24959. **11:** Flattened mature specimen, CEGH-UNC 24938. Scale bar = 1 mm.

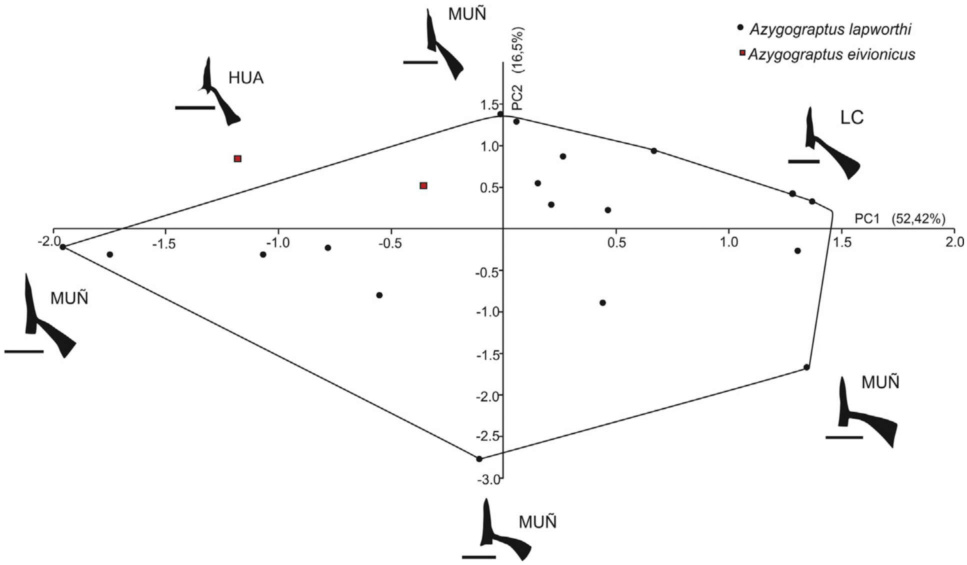

Fig. 5. Morphospace depicted by PC1 and PC2 showing the distribution of the 20 *Azygograptus* specimens from the Central Andean Basin. HUA = Huaytiquina section, MUÑ = Muñayoc section, LC = Los Colorados area.

Fig. 5. Morphospace représenté par PC1 et PC2 montrant la distribution des 20 exemplaires d'*Azygograptus* du Bassin andin central. HUA = Huaytiquina section, MUÑ = Muñayoc section, LC = Los Colorados zone.

classification at species level (Fig. 5). This analysis allows capturing extra information about the shape of an organism using marks, points or figures in a context mathematically analyzable (Zelditch et al., 2004), avoiding misinterpretation of previous descriptions. The contour of the proximal end of the individuals was evaluated using elliptic Fourier analysis (software: SHAPE 1.3; Iwata, 2006). This method decomposes the contour into harmonically related ellipses (Kuhl and Giardina, 1982). From each ellipse, or harmonic, four coefficients are obtained: An and Bn, and Cn and Dn for *X* and *Y*, respectively, and finally, the incremental changes of the *X* and *Y* coordinates are analysed. Herein, 40 harmonics were subjected to the analysis except for the four first coefficients of the first harmonic, following the suggestion of Crampton (1995). Then, the resulting coordinates were subjected to an exploration using a principal components and cluster analysis (software: PAST 3.16; Hammer et al., 2001) to examine groupings.

4. Systematic paleontology

We follow the recent proposal of Maletz et al. (2018) for the taxonomic classification at levels higher than the genus. According to these authors, the *Azygograptus* genus is easily identified due to its loss of all capacity for branching and the fact it bears a single slender stipe usually curved, growing from the sicula.

Beckly and Maletz (1991: Text-figure 7) separated two groups of *Azygograptus* species based on the development of the Th1[1] downwards first, adpressed, or immediately from the metasicula. It is noteworthy that all the material from South America that was included in *Azygograptus* until now corresponds to the group with the first theca growing directly out of the sicular wall, which includes *A. lapworthi*, *A. eivionicus*, *A. hicksii*, and *A. suecicus*. Nevertheless, the material coming from South America was successively assigned to *Azygograptus lapworthi* and *A. eivionicus* by different authors based on subtle differences between the two species and the significant intraspecific variations of some characters. To avoid misidentifications, we include in this revision a greater number of azygograptid populations, collected from known and new localities, with a bigger amount of specimens representing different stages of development (Figs. 3, 4).

Phyllum HEMICHORDATA Bateson, 1885,
(emend. Fowler, 1892)

Fig. 4. Dessins à la chambre claire du matériel étudié, représentant les différents stades de développement d'***Azygograptus lapworthi*** Nicholson. **1, 12 :** Spécimens collectés à Los Colorados, province de Jujuy. **1 :** Sicula complète avec le nema et la partie proximale de Th1[1], GEGH-UNC 24945. **12 :** Spécimen mature avec le tubarium courbé s'élargissant dans sa portion distale, CEGH-UNC 24946. **2–7:** Matériel collecté et illustré par Monteros et al. (1996: pl.1, figs. 1–2) provenant de la section de Huaytiquina, province de Salta. **2 :** Juvénile avec sicula montrant le nema, CNS-I 119 [697 (3)]. **7 :** Spécimen mature complet, CNS-I 119 [697 (7)]. **3, 5, 8, 13 :** Spécimens provenant de Muñayoc, province de Jujuy. **3 :** Spécimen juvénile avec sicula complète, montrant le nema et un court rutellum, CEGH-UNC 24956. **5 :** Spécimens montrant une longue partie libre ventrale de la sicula, CEGH-UNC 24961. **8 :** Tubarium montrant un élargissement de la portion distale, CEGH-UNC 24954. **13 :** Grand tubarium complet avec sicula visible, CEGH-UNC 24957. **4, 6, 10 :** Nouveau matériel de La Quiaca, province de Jujuy. **4 :** Terminaison proximale avec longue sicula, CEGH-UNC 24953. **6 :** Spécimen incomplet montrant une longue portion ventrale libre de la sicula, CEGH-UNC 24951. **10 :** Spécimen mature complet montrant la sicula avec un long nema, CEGH-UNC 24952. **9, 11 :** Matériel provenant de Chaupi Uno, Sud de la Bolivie. **9 :** Spécimen aplati avec une longue sicula, CEGH-UNC 24959. **11 :** Spécimen mature aplati, CEGH-UNC 24938. Barre d'échelle = 1 mm.

Class PTEROBRANCHIA Lankester, 1877
Subclass GRAPTOLITHINA Bronn, 1846,
(emend. Lapworth, 1875)
Order GRAPTOLOIDEA Lapworth, 1875 in Hopkinson and Lapworth, 1875
Suborder SINOGRAPTINA Mu, 1957
Family SIGMAGRAPTIDAE Cooper and Fortey, 1982
Genus ***Azygograptus*** Nicholson and Lapworth, in Nicholson, 1875

Type species: Azygograptus lapworthi Nicholson, 1875

Diagnosis: (*sensu* Maletz *et al.*, 2018) Single-stipe tubarium; th1[1] originating from the metasicula, growing downwards first or immediately outwards from lower part of the metasicula; stipe either straight or dorsally curved; sicula straight or slightly curved, moderate widening towards aperture; thecae simple, elongated and inclined at low angle to the dorsal margin and with low thecal overlap; prothecal folds in one species.

Azygograptus lapworthi Nicholson, 1875

Fig. 3 1–10, 12; Fig. 4. 1–13.

1875 *Azygograptus lapworthi* Nicholson, p. 270, pl. 7, figure 2–2c.

1898 *Azygograptus lapworthi* Nicholson; Elles, p. 513.

1902 *Azygograptus lapworthi* Nicholson; Elles and Wood, p. 93, text, figure 54; pl. 13, figure 1a–b.

1915 *Azygograptus lapworthi* Nicholson; Nicholas, pp. 112, 121.

1938 *Azygograptus eivionicus* Elles; Matley, p. 559.

1943 *Azygograptus lapworthi* Nicholson; Fearnsides and Davies, p. 253.

?1979 *Azygograptus lapworthi* Nicholson; Mu et al., pp. 109–110, pl. 38, figures 3–7.

1984 *Azygograptus lapworthi* Nicholson; Zalasiewicz, p. 427, figure 2e–f.

1988 *Azygograptus lapworthi* Nicholson; Beckly, p. 235.

1991 *Azygograptus lapworthi* Nicholson; Beckly and Maletz, pp. 896–903, pl.1, figure 2; text-figures 10A–O, 11A–E, 12.

1995 *Azygograptus lapworthi* Nicholson; Maletz et al., p. 170, figure 3.7.

1996 *Azygograptus eivionicus* Elles; Monteros et al., pp. 735–737, figure 2, pl. I, 1–2; pl. II, a.

1999 *Azygograptus eivionicus* Elles; Martínez et al., pp. 349–350, figure 2.

2002 *Azygograptus priscus* Xiao and Chen; Mu et al., p. 349.

2002 *Azygograptus taipingensis* Li; Mu et al., p. 349.

2003 *Azygograptus lapworthi* Nicholson; Maletz and Egenhoff, p. 109, figure 4.a.

2004 *Azygograptus lapworthi* Nicholson; Egenhoff et al., p. 293, figure 5.b.

2005 *Azygograptus lapworthi* Nicholson; Maletz, p. 770, text, figure 5F.

2018 *Azygograptus lapworthi* Nicholson; Maletz et al., p. 8, figure 6.2c.

2018 *Azygograptus lapworthi* Nicholson; Toro and Maletz, pp. 61–63, figures 4.8, 13.

Material. Numerous specimens regularly preserved as flattened films and internal molds in semi-relief. The illustrated specimens are identified as CEGH-UNC 24938, 24945–24947, 24950–24957, 24959–24961. Additional material, illustrated by Monteros et al. (1996) under the prefix CNS-I 119 (697, 3) and CNS-I 119 (697, 7), was included for comparison.

Description. Complete tubaria preserved at different stages of development that reach a maximum of 45 mm of length in a gerontic specimen (Fig. 4, 13). The length of the sicula varies within 1.3–1.7 mm, but more frequently it is 1.5 mm, and a small rutellum is present (Fig. 3.6, 10; Fig. 4.2, 3). The apertural diameter of the sicula is about 0.3 mm and a prominent basal free length of 0.25–0.35 mm is commonly observed (Fig. 3.1, 5, 7–8; Fig. 4.1, 5–6).

The stipe diverges immediately from the sicula with an angle of about 130°–140°. It originates at about 0.80–1.3 mm from the apex of the sicula and generally presents a slightly concave dorsal margin (Fig. 3.6; Fig. 4.6, 8). The stipe width at th1[1] is 0.5–0.6 mm and it rapidly increases to 0.9–1.1 mm to the distal part.

Thecae are slightly curved to the distal portion. The thecal inclination is approximately 14° and the thecal density is about 8 thecae in 10 mm.

Discussion. All the azygograptids specimens of the Central Andean Basin reviewed in this paper agree with the general morphology of *Azygograptus lapworthi*, with a narrow and curved stipe that rapidly widens up to more than 1 mm, and more inclined and closely-spaced thecae than in *A. eivionicus*.

On the other hand, having as reference the re-description of the type species of *Azygograptus* from Scandinavia and Britain made by Beckly and Maletz (1991), we consider of great importance the proximal end characters, like sicular length, apertural diameter and basal free length of the sicula, to compare and assign the specimens previously mentioned for the Central Andean Basin to any of the two species *Azygograptus eivionicus* or *A. lapworthi*. Even though there is not much variation in terms of the length of the sicula between *A. lapworthi* and *A. eivionicus*, there is an important disparity in the values of the apertural diameter and mainly in the basal free wall length of the sicula; the latter in *A. eivionicus* only rarely exceeds 0.2 mm.

On the other hand, our material is easily distinguished from *A. suecicus* by the absence of rutellum in the latter species, while *A. hicksii* has a wider stipe, up to 1.5 mm, and a bigger apertural diameter of the sicula, with more prominent elongate rutellum than *A. lapworthi*.

The material recently found in La Quiaca and Los Colorados sections is more closely related to *Azygograptus lapworthi* Nicholson. All the measurements of the proximal end, as the long free ventral wall of the sicula reaching more than 0.2 mm, agree with those presented in this species. Also, a wider distal part of the tubarium, reaching a maximum width of 1.1 mm, is coincident with *A. lapworthi*.

Regarding the reviewed specimens from the Muñayoc section at Quichagua range (Fig. 3.2, 4, 7, 10; Fig. 4.3, 5, 8, 13), previously assigned by Martínez et al. (1999) to *A. eivionicus*, their diagnostic proximal parameters make it impossible to differentiate them from those that are characteristics of *A. lapworthi*; then, we suggested reassigning them to *A. lapworthi*.

As we commented before, the specimens described as *A. eivionicus* by Monteros et al. (1996) are not available for their revision, but, based on the geomorphometric analysis presented below (Fig. 5), we suggest that they should also be reassigned to *A. lapworthi*.

Finally, the material assigned to *Azygograptus* (?) *saltaensis* that is regularly preserved in green pelitic deposits, and stored as part of the "Loss Collection" under the prefix UNJU (B. 163-164/JUY-P-63-64), probably corresponds to a broken and distorted fragment of some older didymograptid, like *Baltograptus vacillans* or *B. deflexus* (Fig. 3.13, 14). It is noteworthy that Loss (1951) recorded both species associated in the same horizon, in which he mentioned *Azygograptus* (?) *saltaensis*, but after that all the appearances of the *Azygograptus* species were always recorded in younger levels than those with baltograptids in the Central Andean Basin.

Geographic and stratigraphic provenance. *Azygograptus lapworthi* was formerly mentioned for South America by Beckly and Maletz (1991) in Bolivia. Later on, Maletz et al. (1995) and Maletz and Egenhoff (2003) described its occurrences in the eponymous biozone at the top of the Pircancha Formation in the Sama-Chaupi Uno and Cieneguillas-Chaupi Uno sections. Afterwards, Monteros et al. (1996) documented the first records of the *A. eivionicus* from deposits of the western Argentine Puna. This material, reassigned here to *A. lapworthi*, indicates the presence of lower Dapingian (Dp1) deposits in the lower part of the Huaytiquina section, underlying younger levels with *Isograptus* sp. (Dp2) and the key conodont *Baltoniodus* cf. *B. navis* (Toro et al., 2019, in press). *A. lapworthi* is also present in the Quichagua range, in the northeastern Puna region (Martínez et al., 1999 and this work), and its record is also confirmed for the first time in the Cordillera Oriental Argentina in the upper part of the Los Colorados and La Quiaca sections, Jujuy Province (Toro, 2017, and this work).

Azygograptus lapworthi is a common species from regions located in high to mid latitudes, like Great Britain, Sweden, SW China, Argentina, and Bolivia, and it is also present in Canada (Maletz et al., 2018). In Great Britain, Beckly and Maletz (1991) mentioned the presence of this taxon in the *Isograptus gibberulus* Zone. After that, Maletz (2005: text-figure 8) reported *A. lapworthi* in the *Arienigraptus dumosus* type/*Pseudisograptus manubriatus* Zone from Swedish drill cores.

5. Geomorphometric analysis

We include 20 individuals characterized by the absence of adpressed growth of $th1^1$ along the sicula, previously assigned to *Azygograptus lapworthi* and *A. eivionicus* (Martínez et al., 1999; Monteros et al., 1996, this work) from the Central Andean Basin.

The analysis of the main components of the taxa showed that the first three components explain 78.77% (PC1, PC2 and PC3) of the variation in the shape of the specimens. PC1 (52.42%) roughly represent the stipe width at $th1^1$ and differences in the sicula morphology: narrow stipes at $th1^1$ and large and elongated sicula (negative) vs. wide stipe at $th1^1$ and short and stouter sicula (positive). Meanwhile, PC2 (16.50%) explained the variation in the stipe divergence angle: 90° (negative) vs. greater than 90° (positive). Moreover, dendrograms illustrated that the individuals assigned to different species in the Central Andean Basin are related and should be grouped together.

Thus, the resulting morphospace and clusterings allow us to infer that the specimens previously assigned to two different species, *A. lapworthi* and *A. eivionicus*, in the Central Andean Basin, are geomorphometrically indistinguishable (Fig. 5). Therefore, we can conclude that all the specimens could correspond to the single *A. lapworthi* species, with intraspecific variations.

This analysis constitutes a useful tool for supporting that the specimens previously assigned to *A. eivionicus* in the Huaytiquina section (Monteros et al., 1996), as well as those from the Quichagua range (Martínez et al., 1999, and systematic revision in this work), have to be reassigned to *A. lapworthi*.

6. Biostratigraphic framework and correlations

In spite of the widespread distribution around the world and the valuable taxonomical revisions of the azygograptids and xiphograptids carried out respectively by Beckly and Maletz (1991) and Maletz (2010), the biostratigraphic range of the species in both groups include uncertain records and dissimilar global correlations that remain confusing in the literature. The significant taxa used for defining the proposed biostratigraphic framework (Fig. 6) are represented in each studied stratigraphic column in Fig. 2. Nevertheless, the taxonomic revision of all the identified species as well as the description of all the additional biozones recognized in the studied sections are beyond the scope of this study, and will be accomplished in a future work, as part of the PhD thesis of one of the authors (N.C.H.S.). Further descriptions and comments are given below only for the underlying *Didymograptellus bifidus* and the overlying "*Isograptus victoriae*" biozones, in order to identify precisely the boundaries and regional correlation of the proposed *Azygograptus lapworthi* Biozone. Additionally, an updated graptolite framework for the Lower Ordovician (early Floian) to Middle Ordovician (early Dapingian) in the Central Andean Basin is presented in Fig. 6 as a complete reference for the discussion of the global correlations.

The described biostratigraphic units were based on the first appearances of the index species or the occurrences of characteristic taxa associations previously recognized at different levels of the unit in different stratigraphic sections in northwestern Argentina and southern Bolivia. As the Early–Middle Ordovician graptolite taxa in the Central Andean Basin clearly indicate their cold to temperate faunal affinities, we here referred them to the global stage slices (Bergström et al., 2009) to solve previous misunderstandings that resulted from the correlation with the Australian standard stages, which are defined by key species of warm faunal affinities.

This analysis allows one to extend the local and regional value of the discussed *Azygograptus* interval in different certain sections of Argentina and Bolivia (Fig. 2) to the Central Andean Basin (Fig. 6). It is based mainly on the completeness of the exposed sequences in the Los Colorados area, which range from the basal Floian (*Tetragraptus phyllograptoides* graptolite zone, *sensu* Toro, 1997) to the early

GLOBAL (Bergström *et al.* 2009) SERIES	STAGES	STAGE SLICES	CENTRAL ANDEAN BASIN: NW ARGENTINA (Toro *et al.* 2015; Toro *et al.* 2018, 2019)	CENTRAL ANDEAN BASIN: BOLIVIA (Egenhoff *et al.* 2004; Toro and Maletz, 2018)	SCANDINAVIA (Maletz, 2005; Maletz and Ahlberg, 2011)	SOUTH CHINA (Zhang and Zhang, 2014; Zhang *et al.* 2019)	NORTH AMERICA (Williams and Stevens, 1988; Goldman *et al.*, 2007)
MIDDLE ORDOVICIAN	DAPINGIAN	Dp2	? "*Isograptus victoriae*"	*Isograptus victoriae*	*Isograptus victoriae*	*Expansograptus hirundo*	*Isograptus v. victoriae*
		Dp1	*Azygograptus lapworthi*	*Azygograptus lapworthi*	*Pseudophyllograptus a. elongatus*	*Isograptus c. imitatus* / *Azygograptus suecicus*	*Isograptus v. lunatus*
LOWER ORDOVICIAN	FLOIAN	Fl3	*Didymograptellus bifidus*	*Baltograptus minutus*	*Baltograptus minutus*	*Azygograptus suecicus* / *Corymbograptus deflexus* / *Didymograptellus eobifidus*	*Didymograptellus bifidus*
		Fl2	*Baltograptus* cf. *B. deflexus*	*Expansograptus holmi*	*Baltograptus* sp. cf. *B. deflexus*	*Tshallograptus fruticosus/ Acrograptus filiformis*	*Tshallograptus fruticosus*
		Fl1	*Tetragraptus akzharensis*	*Cymatograptus protobalticus*	*Baltograptus vacillans* / *Cymatograptus protobalticus*		*Tetragraptus akzharensis*
			Tetragraptus phyllograptoides	*Tetragraptus phyllograptoides*	*Tetragraptus phyllograptoides*	*Paratetragraptus approximatus*	*Paratetragraptus approximatus*

Fig. 6. Biostratigraphic framework of the Lower–Middle Ordovician (Fl1 to Dp2) proposed for the Central Andean Basin and global correlation.
Fig. 6. Cadre biostratigraphique de l'Ordovicien inférieur–supérieur (Fl1 à Dp2) proposé pour le Bassin andin central et corrélation globale.

Dapingian (*Baltoniodus triangularis* conodont zone, *sensu* Carlorosi et al., 2013) and to the recently documented levels with *Xiphograptus lofuensis* (Dp2, *sensu* Toro et al., 2018), and on the Huaytiquina section, in which the biostratigraphic sequence composed of the *Azygograptus lapworthi* Biozone (Dp1) and the "*Isograptus victoriae*" Biozone (Dp2) is in agreement with the related conodont records recently studied by Toro et al. (2019, in press).

6.1. *Didymograptellus bifidus* = *Baltograptus minutus* Biozone (upper Floian, Fl3)

The *Didymograptellus bifidus* Biozone was described for the first time in the Central Andean Basin by Toro (1994) at the Los Colorados area, in the western flank of the Cordillera Oriental, Argentina. It was defined by the presence of the eponymous species associated with *Baltograptus minutus* and *B. deflexus* in the upper part of the Acoite Formation at the Los Colorados and Chamarra sections, where it overlies the thicker *Baltograptus* cf. *B. deflexus* (*sensu* Toro and Maletz, 2007, 2008; Toro et al., 2015) corresponding to the middle Floian, Fl2 (Fig. 2C). Subsequently, the *Didymograptellus bifidus* Biozone was recognized in different sections along the western and eastern flanks of the Argentine Cordillera Oriental, close to the border with Bolivia, such as Santa Victoria and La Quiaca (Toro, 1999b; Toro et al., 2015; Vento, 2013); and Bahlburg et al. (1990) also mentioned the occurrence of *Didymograptellus* cf. *bifidus* in the Aguada de La Perdíz Formation, at the Puna of Chile.

After that, Martínez et al. (1999: figure 2) described a graptolite assemblages corresponding to the *D. bifidus* Biozone in the Quichagua range, in the Argentine northeastern Puna, in the lower and middle portions of the volcano-sedimentary succession of the Muñayoc section. Nevertheless, the present revision indicates that the lower boundary of the *Didymograptellus bifidus* Biozone corresponds to the first record of *B. minutus*, 50 m above the base of the section, and consequently this biostratigraphic unit is developing only in the middle portion of the Muñayoc section (Fig. 2B).

This upper Floian (Fl3) biostratigraphical interval in northwestern Argentina can be regionally correlated with the *Baltograptus minutus* Biozone in southern Bolivia, which was first recognized by Maletz et al. (1995) in the upper part of the Pircancha Formation, exposed in the Sama–Chaupi Uno and Sella areas. This correlation was recently confirmed by the first record of *D. bifidus* in the Chaupi Uno section (Toro and Maletz, 2018).

Regarding the global correlation of the *D. bifidus* biozone (Fig. 6), it could be correlated with the *D. bifidus* Biozone of North America (Goldman et al., 2007; Williams and Stevens, 1988), the *Baltograptus minutus* Biozone of Scandinavia (Maletz and Ahlberg, 2011), and the *Didymograptellus eobifidus* Biozone, the *Corymbograptus deflexus* Biozone, and probably the lower part of the *Azygograptus suecicus* Biozone in South China (Zhang and Zhang, 2014; Zhang et al., 2019).

6.2. *Azygograptus lapworthi* Biozone (lower Dapingian, Dp1)

The biostratigraphic range of *Azygograptus lapworthi* in South America was first analyzed in Bolivia by Maletz et al. (1995) in the Sama–Chaupi Uno area (Fig. 2D), who also proposed its correlation with the middle Arenig and the Ch2–Ca2 of Australian stages. Afterwards, Maletz and Egenhoff (2003) and Egenhoff et al. (2004: figure 7) described in more details the *Azygograptus lapworthi* Biozone in southern Bolivia, defining its base at the first occurrence of the eponymous species. They identified *Pseudophyllograptus angustifolius elongatus*, *Tetragraptus amii*, *T. serra*, and *Expansograptus* sp. in this interval, and proposed an international correlation with the Ca1 interval of Australia, *Pseudophyllograptus angustifolius elongatus* Biozone of Scandinavia and the *Isograptus v. lunatus* of eastern North America.

The azygograptid specimens first described in Argentina by Monteros et al. (1996) from the lower portion of the "Coquena" Formation in the Huaytiquina section as *Azygograptus eivionicus* are here reassigned to

Azygograptus lapworthi. This reassignment indicates that the eponymous biozone is also present in the Argentine Puna region, reaching approximately 500 m in thickness. Monteros et al. (1996) assigned the yielding levels to an age corresponding to the Ca1- Ca2 of the Australian sequence, but recent findings of key conodonts related to *Isograptus* sp. in the overlying levels, suggest an early Dapingian age (Dp1) for this interval (Toro et al., 2019, in press). The present revision also allows defining the base of the *Azygograptus lapworthi* Biozone as the first appearance of the key taxa in the middle portion of the Muñayoc section (Fig. 2B). Recent findings of *Azygograptus lapworthi* at Los Colorados and La Quiaca areas (Toro, 2017, and this work) permitted to extend the distribution of this biostratigraphical interval to the western flank of the Cordillera Oriental, where related conodont records also indicate an early Dapingian (Dp1) age. On this basis, we propose a regional correlation for all the records of the *Azygograptus lapworthi* Biozone from the Central Andean Basin, here assigned to the lower Dapingian (Dp1), and consequently we agree with the global correlation of this interval with the *Isograptus v. lunatus* Biozone of North America, previously proposed by Egenhoff et al. (2004) (Fig. 6).

On the other hand, it is noteworthy that there is similarity between the stratigraphic distribution of the key conodont species *Baltoniodus triangularis*, associated with azygograptids, which occurs in the Huanghuachang GSSP section, in Yichang, South China (Cooper and Sadler, 2012: figure 20.4, and references therein), and that from the Central Andean Basin discussed above. Accordingly, we suggest the correlation of the proposed *Azygograptus lapworthi* Biozone with the upper part of the *Azygograptus suecicus* of South China (Zhang et al., 2019). This biozone is furthermore correlated with the *Pseudophyllograptus a. elongatus* Biozone of Scandinavia (Maletz, 2005). Finally, considering the remarkable similarities between the biostratigraphic succession recently described by Gutiérrez-Marco and Martin (2016: figure 5) for southern Morocco and the biostratigraphic framework here proposed for the Central Andean Basin, as well as their close paleogeographic relationship of both Gondwanan affinities, a correlation of the concerned intervals with azygograptids should not be discarded.

6.3. "Isograptus victoriae" Biozone (Dapingian, Dp2)

The first record of *Isograptus* sp. associated with conodonts in the Huaytiquina section, Argentine Puna (Toro et al., 2019, in press), indicates an early Dapingian (Dp2) age for the bearer strata and allows us to define the base of the "*Isograptus victoriae*" Biozone in the Central Andean Basin (Fig. 2A), but its upper boundary remain uncertain. Monteros et al. (1996) previously described the first records of *Xiphograptus svalbardensis*, later reassigned to *X. lofuensis* by Toro and Brussa (2003), from the upper part of this section, which, according to the new records, is assigned to the early Dapingian (Dp2). More recently, Toro et al. (2018) described the first records of *X. lofuensis* in the Argentine Cordillera Oriental, from the equivalent green shales of the "Sepulturas" Formation (*sensu* Astini *et al*., 2004) that overlies the conodont-bearing levels of early Dapingian (Dp1) age at the upper part of the Los Colorados section (Fig. 2C). The equivalent levels of the "Coquena" Formation with isograptids of the *I. victoriae* group, in the Tafna area, on the western flank of the Argentine Puna (Brussa and Toro, 2005; Toro and Lo Valvo, 2017), could also be regionally correlated with this biozone. It is also correlated with the *Isograptus victoriae* Biozone of southern Bolivia, first mentioned in the Chala Mayu section by Müller (2000), and subsequently described by Egenhoff et al. (2004) and Toro and Maletz (2018). These authors mentioned the eponymous species associated with *Xiphograptus* cf. *X. lofuensis*, *Pseudophyllograptus* sp. and *Tetragraptus* sp. in the *Isograptus victoriae* Biozone, assigning it to the lower Dapingian.

A global correlation of this biozone is tentatively proposed with levels corresponding to the *Isograptus v. victoriae* Biozone of North America (Williams and Stevens, 1988), the *Isograptus victoriae* Biozone of Scandinavia (Maletz, 2005), and the *Expansograptus hirundo* Biozone of South China (Zhang et al., 2019) (Fig. 6).

7. Conclusions

A taxonomic study of the *Azygograptus* species from South America is conducted, which indicates that the new specimens of this species from the western flank of the Argentine Cordillera Oriental, as well as all the previous records of this genus in South America, can be assigned to *Azygograptus lapworthi*.

The *Azygograptus lapworthi* Biozone spread out from the previously known Sama-Chaupi Uno area in southern Bolivia, and the Huaytiquina and Muñayoc sections in the Argentine Puna, to the classical localities on the western flank of the Cordillera Oriental of Argentina, including the Los Colorados and La Quiaca.

We assigned the *A. lapworthi* Biozone of the Argentine Cordillera Oriental to the Middle Ordovician (lower Dapingian, Dp1), as it is closely related to previous records of the key conodont *Baltoniodus triangularis*. This interval overlies deposits corresponding to the *Didymograptellus bifidus* Biozone (Lower Ordovician, upper Floian, Fl3) and it is overlain by levels with *Xiphograptus lofuensis* (Dp2).

A comprehensive biostratigraphic framework is proposed for the Floian–Dapingian deposits in northwestern Argentina, which expands the topmost graptolitic levels from the uppermost Floian (Fl3) to the lower Dapingian (Dp2).

The graptolite–conodont records of Dapingian (Dp2) age ("*Isograptus victoriae*" Biozone) recently described from deposits overlying the *Azygograptus lapworthi* Biozone at the Huaytiquina section confirm the proposed framework and correlations for the Central Andean Basin.

The *Azygograptus lapworthi* Biozone fills the gap of the high-resolution regional correlation of the widely known Lower Ordovician graptolite succession from the Argentine Cordillera Oriental with the younger biostratigraphic units from the Puna region and Cordillera Oriental of Bolivia. Nevertheless, until further certainties for its global correlation are confirmed, this interval is regionally useful.

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