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RESEARCH ARTICLE

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Conodont and graptolite biostratigraphy of the lower–middle Darriwilian (Middle Ordovician), Cerro Viejo of Huaco, Argentine Precordillera

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Abstract

The distribution of conodonts and graptolites from the upper 13 m of the San Juan Formation and the first metre of the lower member of the Los Azules Formation, Los Gatos and Amarilla creeks, Cerro Viejo of Huaco, Central Precordillera from San Juan, Argentina, is studied. The conodonts from the top stratum of the San Juan Formation at the Los Gatos creek section correspond to the *Lenodus variabilis* Zone, whereas at the Amarilla creek section, they represent the *Yangtzeplacognathus crassus* Zone, verifying the diachronous top surface of the San Juan Formation. In the lower member of the Los Azules Formation, 81 conodont elements are recorded from bedding plane surfaces, where the presence of *Paroistodus horridus horridus* (Barnes & Poplawski) allows to recognize the *Y. crassus* Zone. On the basis of the graptolite and conodont association, we estimate that the top of the San Juan Formation at Los Gatos creek corresponds to the *Levisograptus dentatus* Zone, *L. dentatus* Subzone, whereas at the Amarilla creek, the *Arienigraptus angulatus* Subzone of the same zone is represented. The presence of the graptolite *A. angulatus* (Mu) in the lower member of the Los Azules Formation in both sections indicates the *L. dentatus* Zone (*A. angulatus* Subzone). The records of graptolites in limestones of the San Juan Formation and of abundant conodonts on bedding plane surfaces of the lower member of the Los Azules Formation are important, taking into account the type of facies where they occur. The conodont records in the referred type of preservation are scarce in the Ordovician, which allows for a more precise biostratigraphic correlation between conodont and graptolite biostratigraphy.

KEYWORDS

Argentine Precordillera, biostratigraphy, conodonts, graptolites, Middle Ordovician

1 | INTRODUCTION

The co-ocurrence of conodonts and graptolites is a great tool for the construction of robust biostratigraphic schemes, particularly, because these two index fossil groups do not usually occur in the same facies types. The conodonts are common in limestones of carbonate platforms or ramps, whereas graptolites are present in anoxic or dysoxic facies of deeper marine environments.

Records of graptolites in limestones are poor, and the type of preservation usually does not permit taxonomic determinations in the Precordillera. On the other hand, the records of conodonts in black shales are few, and in most cases, they are documented as casts. However, exceptional cases of conodonts preserved on bedding plane surfaces account for significant information, such as in the present contribution.

Cuerda (1986) mentions that the upper San Juan Formation at the Cerro La Chilca, Central Precordillera, bears graptolites of the

Paraglossograptus tentaculatus Zone. However, these graptolites do not originate from limestones but are found in the overlying calcareous and black shales succession, which is currently known as the Gualcamayo Formation (Astini & Benedetto, 1992). Recently, Serra, Feltes, Ortega, and Albanesi (2017) record *Levisograptus primus* (Legg) and a sinograptid indet. from the upper San Juan Formation, Cerro La Chilca, associated with conodonts of the *Yangtzeplacognathus crassus* Zone, representing the only records of graptolites in the limestones of the San Juan Formation so far. Another significant record of conodonts preserved as casts on bedding planes was reported by Albanesi, Hünicken, and Barnes (1998) from the middle member of the Gualcamayo Formation at Cerro Potrerillo, representing the upper *Eoplacognathus suecicus* Zone, based on the presence of *Pygodus anitae* Bergström. A few reports that will be described later illustrate conodonts on bedding plane surfaces of the Los Azules Formation, mostly preserved as casts, from the middle and upper members (Hünicken & Ortega, 1987; Ortega, 1987; Ottone, Albanesi, Ortega, & Holfeltz, 1999) and in the upper metre of the lower member (Ortega, Albanesi, & Frigerio, 2007), that is, 9 m above the base of the formation.

As a current reference, Bergström, Ahlberg, Maletz, Lundberg, and Joachimski (2018) evaluated the relationships between the Kargarde conodont zones and the Fågelsång graptolite zones, based on the Darriwilian chemostratigraphy in the Fågelsång-3 drill core, Scania, Sweden.

The objective of this work is to describe the graptolites recorded from the upper San Juan Formation and the conodonts from the first metre of the lower member of the Los Azules Formation, at the Los Gatos and Amarilla creeks sections, Cerro Viejo of Huaco, Central Precordillera. The records of these fossils in their unfavourable facies, respectively, enable the adjustment of the biostratigraphic zonation for the Cerro Viejo of Huaco area and to verify significant data for intercontinental correlation.

2 | GEOLOGICAL SETTING

The geological province of the Precordillera has a complete stratigraphic thickness estimated to be approximately 7,500 m (Astini, 1991). It involves extensive Palaeozoic deposits and a smaller extension of Mesozoic and Cenozoic deposits. The Precordillera is subdivided into three morpho-structural units based on its stratigraphic and structural characteristics, which are known as Eastern (Ortiz & Zambrano, 1981), Central (Baldis & Chebli, 1969), and Western Precordillera (Baldis, Beresi, Bordonaro, & Vaca, 1982).

The Central Precordillera includes, among others, the San Juan Formation and the overlying Los Azules Formation (Figure 1). The carbonate sequence of the San Juan Formation (Kobayashi, 1937; emend. Keller, Cañas, Lehnert, & Vaccari, 1994), approximately 330 m thick, consists of skeletal micritic limestones initially deposited in the later Tremadocian on a ramp topography (Cañas, 1995). The basal and middle levels of the San Juan Formation regionally represent, in general, shallow subtidal environments with frequent intercalations of storm layers.

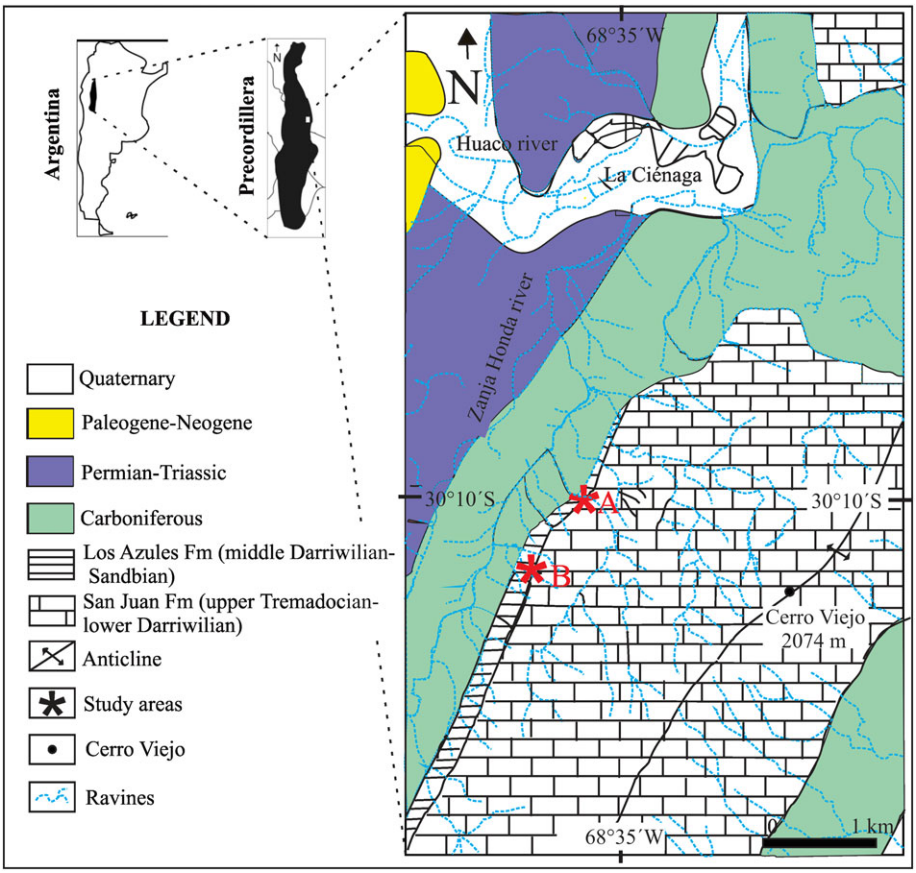

FIGURE 1 Geological map of the study areas and location of the stratigraphic sections. *A: Los Gatos creek and *B: Amarilla creek (modified from Ortega et al., 2007) [Colour figure can be viewed at wileyonlinelibrary.com]

The upper strata include deposits accumulated below the storm wave-base levels, in an external ramp environment (Sorrentino, Benedetto, & Carrera, 2009). At the Los Gatos creek section, Cerro Viejo of Huaco, the upper 13 m are made up of wackestones (Mango & Albanesi, 2018).

Between the San Juan Formation and the overlying Los Azules Formation, a hardground surface is documented. This feature represents a paraconformable contact implying a brief hiatus (Astini, 1994; Ottone et al., 1999). The Los Azules Formation (Middle–Upper Ordovician; Harrington & Leanza, 1957) is exposed on the western flank of Cerro Viejo of Huaco, with a thickness of 318 m. It is divided into three members (Ortega, 1987; Ortega & Rickards, 2003); the lower member, 5–10 m thick, is composed mostly of dark, massive argillites, with subordinate sandstone and siltstone strata. The middle member, ca. 220 m thick in the El Nido creek, comprises 8–10 m of thin dark sandstone in its basal part, which is overlain by 210–212 m of grey laminated siltstones with some isolated levels of concretions. The upper member, ca. 88 m thick, presents grey calcareous silty shales interbedded with mudstones at the base and coquinas in the upper portion.

The top of the San Juan Formation and the lower and middle members of the Los Azules Formation contain K-bentonite strata, which represent a large-scale explosive volcanic event, associated with tectonism of collision zones (Bergström et al., 1996; Huff, Bergström, Kolata, Cingolani, & Astini, 1998; Huff, Bergström, Kolata, Cingolani, & Davis, 1995). These levels were dated as 464 ± 2 Ma in the Cerro Viejo of Huaco, using the U–Pb method in zircons present in K-bentonites (Huff et al., 1997).

3 | MATERIALS AND METHODS

The study area and stratigraphic profiles were surveyed for the upper part of the San Juan Formation (ca. 13 m) and the basal part of the lower member of the Los Azules Formation (ca. 1 m) at the Los Gatos and Amarilla creeks (Figure 1). Graptolites were searched for through the carbonatic upper strata of the San Juan Formation and the first metre of the Los Azules Formation at the Los Gatos creek section, where 10 siliciclastic samples of 3 kg each were taken for investigating graptolites and conodonts on bedding plane surfaces. At the Amarilla creek, graptolites were recovered from the top level of the San Juan Formation, as well as a 2-kg limestone sample for retrieving conodonts. Four siliciclastic samples (each 3 kg) were taken from the lowest metre of the Los Azules Formation for the study of graptolite and conodont fossils.

Limestone samples were digested in 10% acetic acid, following conventional techniques for the recovery of microfossils (Stone, 1987), and black shales were analysed under stereoscopic microscope for the search of graptolites and conodonts on bedding plane surfaces.

Selected fossil specimens are illustrated by conventional optical photomicrography and line-art drawings. The fossil collections are deposited at the Museo de Paleontología, Universidad Nacional de Córdoba, under repository codes CORD-MP and CORD-PZ.

4 | BIOSTRATIGRAPHIC FRAMEWORK OF THE STUDY AREA

In the Cerro Viejo of Huaco, Central Precordillera of San Juan, Ortega (1987) and Hünicken and Ortega (1987) analysed the conodonts and graptolites of the Los Azules Formation from the Honda, Los Gatos, Los Azules, Amarilla, Las Cuevas, El Nido, El Algarrobo, and El Silencio creek sections. Regarding the graptolite biostratigraphy, they proposed the *P. tentaculatus* Zone for the lower member of the Los Azules Formation, the *Hustedograptus teretiusculus* Zone for the middle member, and the *Nemagraptus gracilis* Zone (*Climacograptus bicornis* Subzone) for the upper member, detecting a hiatus between the middle/upper member boundaries, which spans the lower part of the *N. gracilis* Zone. The authors documented the conodont *E. suecicus* Bergström through the uppermost levels of the San Juan Formation, assigning the strata to the eponymous biozone (Figure 2). Additionally, they recovered specimens of *Pygodus serra* (Hadding) from the middle member of the Los Azules Formation, 20 m above the contact with the San Juan Formation, which allow to recognize the eponymous biozone. However, they did not publish any data on conodonts from the lower member.

Subsequently, Ottone et al. (1999) analysed the graptolite and conodont biostratigraphy in the uppermost levels of the San Juan Formation and the Los Azules Formation, in different creeks of the Cerro Viejo of Huaco (Los Gatos, Los Azules, Amarilla, and El Silencio), with the record of *Paroistodus horridus horridus*, which permitted the identification of the upper subzone of the *Lenodus variabilis* Zone (Albanesi et al., 1998), middle Darriwilian in age for the pre-existing schemes, contrasting the previous records of Ortega (1987) and Hünicken and Ortega (1987). The conodont colour alteration index is 1.5–2, suggesting a maximum burial paleotemperature of 140°C (Epstein, Epstein, & Harris, 1977). In addition, Ottone et al. (1999) recovered conodonts of the *E. suecicus* (*P. anitae* Subzone) and *P. serra* zones from the middle member of the Los Azules Formation and of the *Amorphognathus tvaerensis* Zone, from the upper member. Regarding graptolites, Ottone et al. (1999) documented four biozones, the *P. tentaculatus* Zone that extends from the top of the San Juan

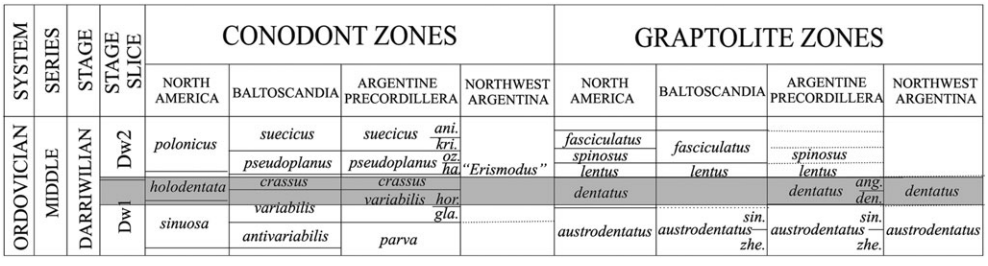

FIGURE 2 Biostratigraphic scheme of the lower–middle Darriwilian (Middle Ordovician), with conodonts and graptolites from North America and Baltoscandia and biozones of the Precordillera and north-western Argentina. The study interval is boxed in grey

Formation up to the top of the lower member of the Los Azules Formation, the *Pterograptus elegans* and *H. teretiusculus* zones that span the middle member, and the *N. gracilis* Zone (*C. bicornis* Subzone), which covers the upper member, modifying the original scheme proposed by Ortega (1987).

Later, Ortega et al. (2007) analysed conodonts of the uppermost San Juan Formation and lower member of the Los Azules Formation, from the Los Azules and Amarilla creek sections, and recorded key conodonts from the uppermost metre of the lower member of the latter formation. According to Brussa, Mitchell, Ortega, Maletz, and Astini (2003), Ortega and Rickards (2003), and Ortega et al. (2007), the *P. tentaculatus* Zone is replaced by the *Levisograptus dentatus* and *Holmograptus lentus* zones in the lower member of the Los Azules Formation. The upper part of the *L. dentatus* Zone can be recognized by the entrance of *Arienigraptus angulatus* despite the scarcity and difficult diagnosis of *L. dentatus* in the studied sections. The *H. lentus* Zone is marked by the appearance of the genus *Archiclimacograptus* and the record of *Bergstroemograptus crawfordi* (Harris) in its upper part.

The studies carried out by Heredia and Mestre (2011), Albanesi et al. (2013), Feltes, Albanesi, and Bergström (2013), Carrera, Fenoglio, Albanesi, and Voldman (2013), Serra, Albanesi, and Bergström (2013), and Voldman, Ortega, and Albanesi (2013) updated the Precordillera biostratigraphic schemes, proposing the *Y. crassus* Zone that occupies the uppermost portion of the former *L. variabilis* Zone, making it possible precise biostratigraphic adjustments (Figure 2). According to these authors, the occurrence of *P. horridus horridus* is verified as nominal species for the upper subzone of the *L. variabilis* Zone, although its range extends upwards.

The uppermost San Juan Formation at the Los Azules and the Amarilla creeks studied by Ortega (1987), Ottone et al. (1999), and Ortega et al. (2007) corresponds to the *Y. crassus* Zone, although it is observed that the index species of the eponymous zone was illustrated by Ortega et al. (2007, figure 6e,j) as *L. variabilis*.

Mestre, Beresi, Heredia, and Nestell (2013) analysed the conodonts of the uppermost San Juan Formation at the Del Aluvión creek (or Honda creek at the Cerro Viejo de Huaco), about 1 km to the north of the Los Gatos creek. The authors published conodonts from the *Y. crassus* Zone associated with spicules of sponges and foraminifers.

Recently, Mango and Albanesi (2018) studied the conodonts of the upper section of the San Juan Formation in the Los Gatos creek, Cerro Viejo of Huaco, recognizing the *Oepikodus evae*, *Oepikodus intermedius*, *Tripodus laevis*, and *L. variabilis* zones, although the interspersing *Baltoniodus navis* and *Microzarkodina parva* zonal intervals appear barren of conodonts, probably due to facial or environmental bias. In this section, the authors record the conodonts *Paroistodus horridus primus* Albanesi and *L. variabilis* from the top of the San Juan Formation, recognizing the *Paroistodus horridus* Subzone of the *L. variabilis* Zone for these strata, revealing biostratigraphic differences with other creeks of the Cerro Viejo of Huaco studied in previous works, which proves the diachronous contact of the San Juan Formation with overlying units (Hünicken, 1985).

5 | BIOSTRATIGRAPHY

5.1 | Conodonts

At the Los Gatos creek, the three lowest samples from the Los Azules Formation (FLA 0, 0.1, and 0.15) were barren; conversely, 81 conodont elements were recovered from the seven upper samples, preserved on bedding plane surfaces. The specimens belong to the following taxa: *Ansella jemtlandica* (Löfgren), "*Bryantodina*" aff. *typicalis* Stauffer, *Costiconus costatus* (Dzik), *Erraticodon alternans* (Hadding), *Fahraeusodus jachalensis* Feltes & Albanesi, *Histiodella sinuosa* (Graves & Ellison), *Microzarkodina hagetiana* Stouge & Bagnoli, *P. horridus horridus*, *Periodon macrodentatus* (Chen & Zhang), *Protopanderodus gradatus* Serpagli, and *Protopanderodus robustus* (Hadding) (Figures 3 and 4).

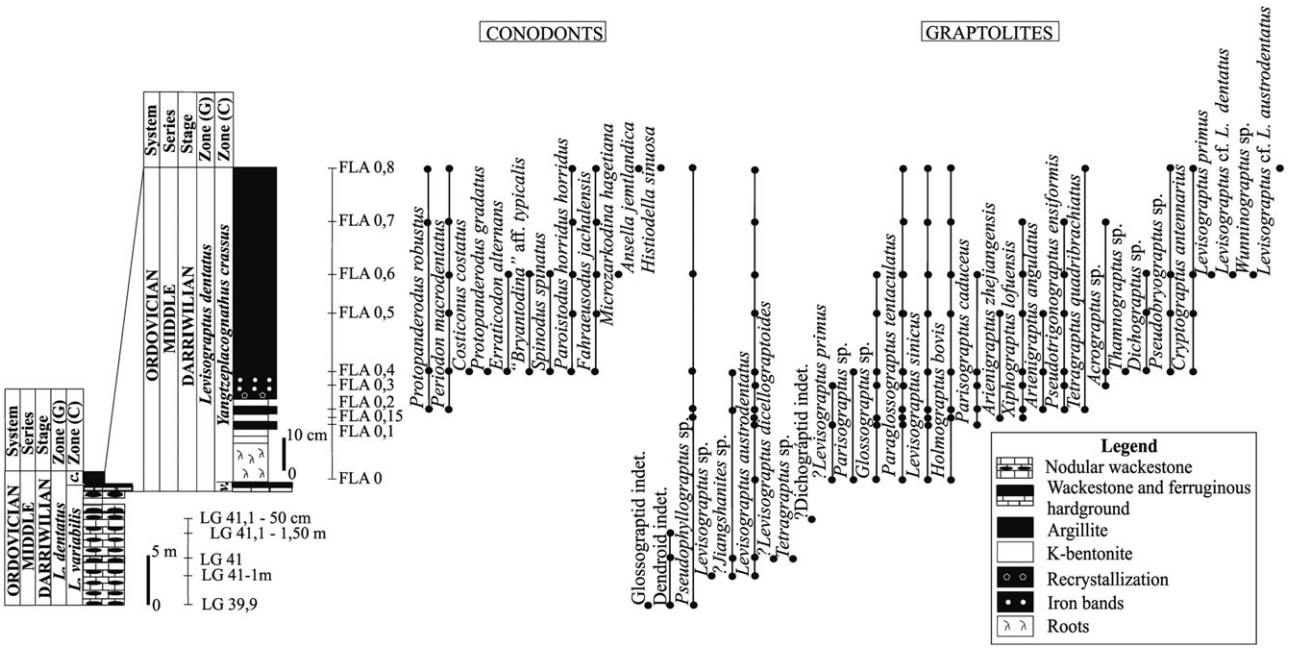

FIGURE 3 Stratigraphic column of the upper San Juan Formation and the lowest metre of the lower member of the Los Azules Formation at the Los Gatos creek, and the conodont and graptolite species ranges. *v.*: *Lenodus variabilis*. *c.*: *Yangtzeplacognathus crassus*

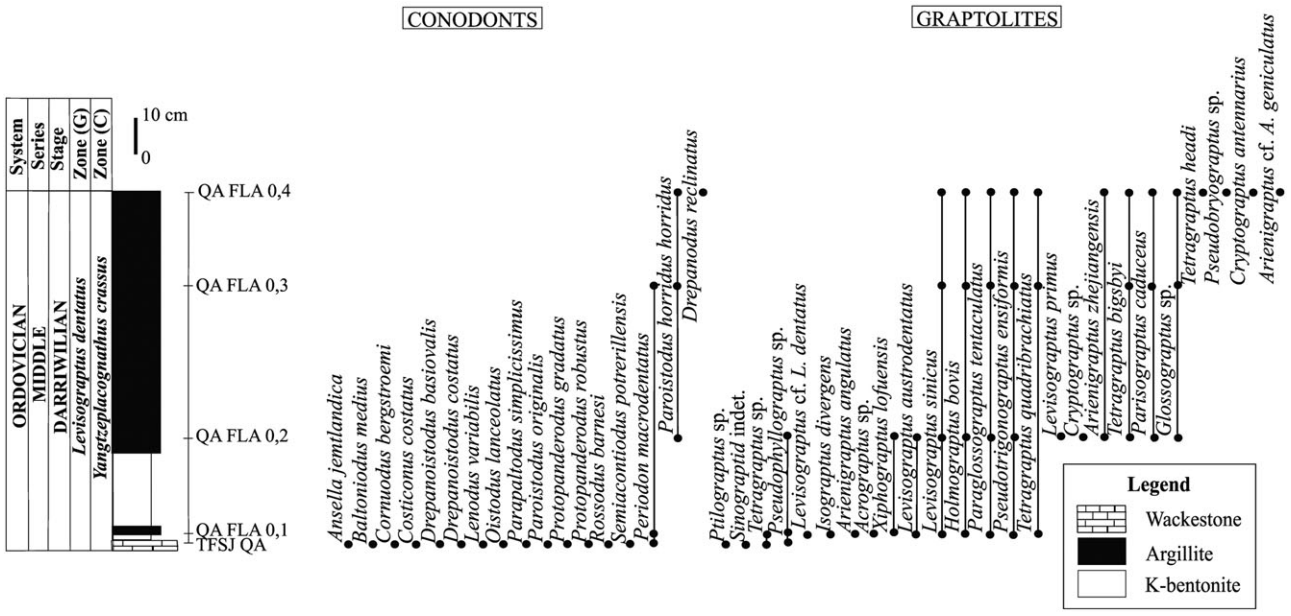

FIGURE 4 Stratigraphic column of the San Juan Formation (top level) and the basal metre of the lower member of the Los Azules Formation, at the Amarilla creek, and the conodont and graptolite species ranges

At the Amarilla creek, 72 conodont elements were recovered from the top stratum of the San Juan Formation including a diverse conodont fauna as depicted in Figure 4. Strata of the lower member of the Los Azules Formation yielded 10 conodont elements, preserved on bedding plane surfaces. These elements are assigned to the species *Drepanodus reclinatus*, *P. macrodentatus*, and *P. horridus horridus*.

In this work, we follow the biostratigraphic scheme updated by Albanesi and Ortega (2016), where the *L. variabilis* Zone is divided into two intervals: the lower *Periodon gladysae* Subzone and the upper *P. horridus* Subzone. The lower limit of the *P. gladysae* Subzone coincides with the first occurrence of the nominal species, whereas the upper limit is indicated by the lowest record of *Baltoniodus medius*, which is associated with *P. horridus primus* representing the *P. horridus* Subzone. Although the upper limit of this subzone could not be recognized for the Cerro Potrerillo section (Albanesi et al., 1998), it would be defined by the first appearance of *Y. crassus* (Chen & Zhang) in other Precordilleran localities (Albanesi et al., 2013; Serra, Albanesi, Ortega, & Bergström, 2015; Serra et al., 2017), which in turn marks the base for the homonymous zone. The upper boundary coincides with the first appearance of *Eoplacognathus pseudoplanus* (Viira), the eponymous species of the succeding biozone.

Accordingly, the occurrences of *P. horridus primus* and *L. variabilis* indicate the *L. variabilis* Zone, and the *P. horridus* Subzone is determined for the top of the San Juan Formation at the Los Gatos creek. *Y. crassus*, reported as *L. variabilis* by Ortega et al. (2007) from the top bed of the same unit at the Amarilla creek, in association with *P. horridus horridus* refers to the *Y. crassus* Zone, verifying the diachronous uppermost strata of the San Juan Formation in the study area.

In the lower member of the Los Azules Formation at the Los Gatos and Amarilla creeks, *P. horridus horridus* (Figures 5 and 6) indicates the correspondence of these strata with the *Y. crassus* Zone. Therefore, the transition from the *L. variabilis* Zone to the *Y. crassus* Zone at Los Gatos creek should be represented at the top of the San Juan Formation and the sample FLA 0.4 of the Los Azules Formation, which covers an interval of 40 cm within the condensed sequence.

5.2 | Graptolites

The upper 13 m of the San Juan Formation at the Los Gatos bear graptolite remains identified as dendroid indet., ?dichograptid indet., glossograptid indet., *?Jiangshanites* sp., *Pseudophyllograptus* sp., *Tetragraptus* sp., *Levisograptus austrodentatus* (Harris & Keble), *Levisograptus* sp., and *?Levisograptus dicellograptoides* (Maletz) (Figures 7 and 8). The top strata of the San Juan Formation at the Amarilla creek contains *Ptilograptus* sp., *Pseudophyllograptus* sp., *Tetragraptus* sp., and stipes of sinograptid indet., whereas in the overlying lower member of the Los Azules Formation (Figure 9), at Los Gatos and Amarilla creeks, there appears a more diverse and abundant fauna linked to a favourable facies, as is shown in Figures 3 and 4.

On the base of previous records of conodonts (Mango & Albanesi, 2018) in the upper part of the San Juan Formation at Los Gatos creek, the *P. horridus* Subzone of the *L. variabilis* Zone is recognized, which refers to the lower subzone of the *L. dentatus* Zone (*L. dentatus* Subzone of Maletz, 2011). The uppermost strata of the San Juan Formation at the Amarilla creek correspond to the *Y. crassus* Zone, which can be correlated with the *A. angulatus* Subzone of the *L. dentatus* Zone.

The occurrence of *A. angulatus* (Figure 9, 2) in the lowest metre of the Los Azules Formation in the referred sections allows for the recognition of the respective subzone of the *L. dentatus* Zone.

6 | REGIONAL AND INTERCONTINENTAL CORRELATION

6.1 | Conodonts

6.1.1 | *Lenodus variabilis* Zone

Sarmiento (1985) formerly identified the *L. variabilis* Zone in the Argentine Precordillera from outcrops of the San Juan and Gualcamayo formations in the eastern flank of the Villicum Range,

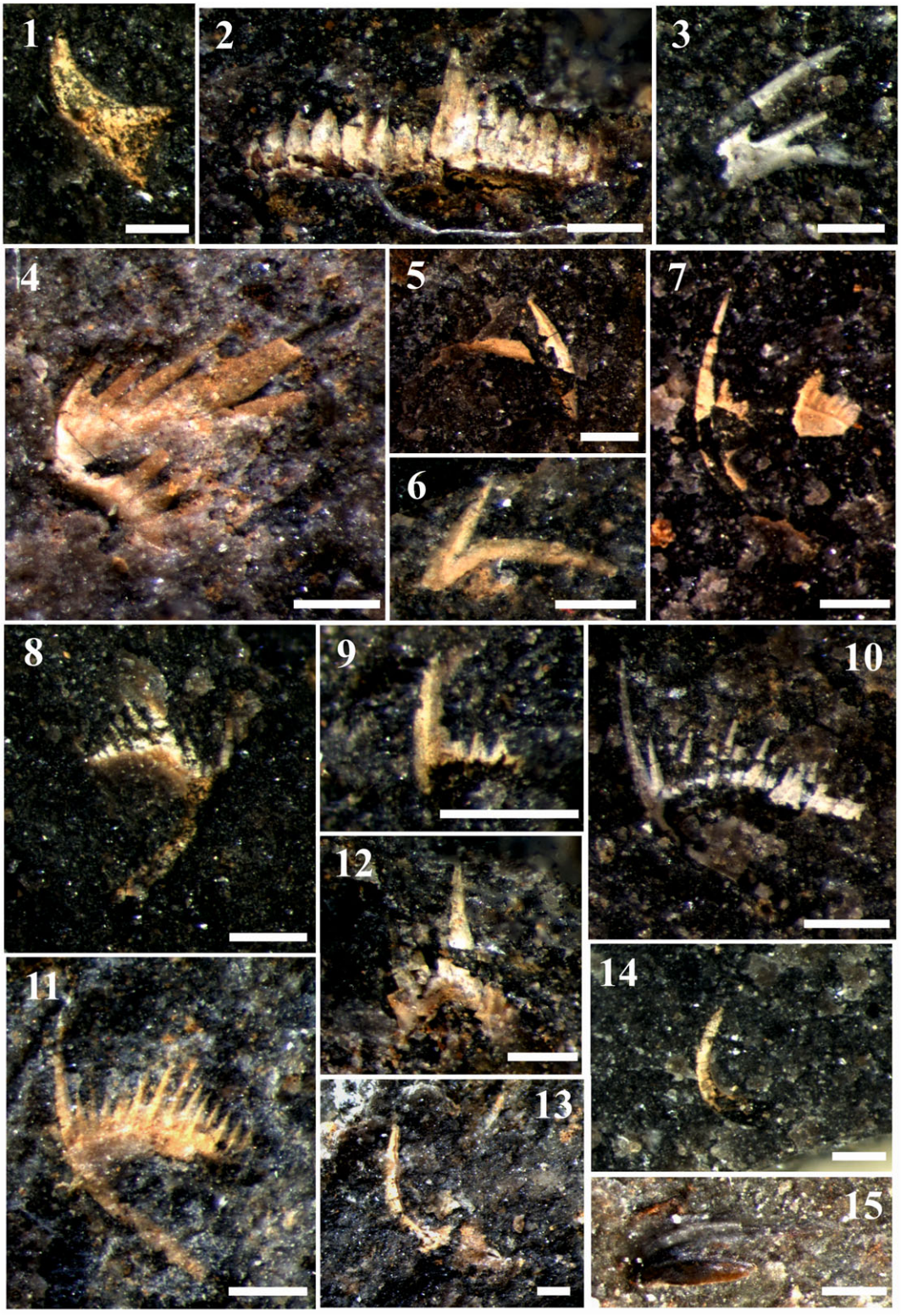

FIGURE 5 Conodonts on bedding plane surfaces of the *Yangtzeplacognathus crassus* Zone, from the Los Azules Formation: 1: *Ansella jemtlandica* (Löfgren), P element (CORD-PZ 37802, FLA 0.8, Los Gatos creek); 2: "*Bryantodina*" aff. *typicalis* Stauffer, P element (CORD-PZ 37675, FLA 0.4, Los Gatos creek); 3–4: *Erraticodon alternans* (Hadding), 3: M element (CORD-PZ 37764, FLA 0.6, Los Gatos creek) and 4: Sc element (CORD-PZ 37702, FLA 0.4, Los Gatos creek); 5–11: *Fahraeusodus jachalensis* Feltes & Albanesi, 5–6: M elements (5: CORD-PZ 37697, FLA 0.4, Los Gatos creek; 6: CORD-PZ 37787, FLA 0.7, Los Gatos creek), 7: Sa element (CORD-PZ 37689, FLA 0.4, Los Gatos creek), 8: Sb element (CORD-PZ 37817, FLA 0.8, Los Gatos creek), 9: Pa element (CORD-PZ 37713, FLA 0.5, Los Gatos creek), and 10–11: Sd elements (10: CORD-PZ 37759, FLA 0.6, Los Gatos creek; 11: CORD-PZ 37783, FLA 0.7, Los Gatos creek); 12: *Microzarkodina hagetiana* Stouge & Bagnoli, Sa element (CORD-PZ 37741, FLA 0.6, Los Gatos creek); 13–14: *Protopanderodus robustus* (Hadding), a–b elements (13: CORD-PZ 37789, FLA 0.7, Los Gatos creek; 14: CORD-PZ 37818, FLA 0.8, Los Gatos creek); and 15: *Paroistodus horridus horridus* (Barnes & Poplawski), M element (CORD-PZ 37904, QA FLA 0.3, Amarilla creek). Graphic scale: 200 μm [Colour figure can be viewed at wileyonlinelibrary.com]

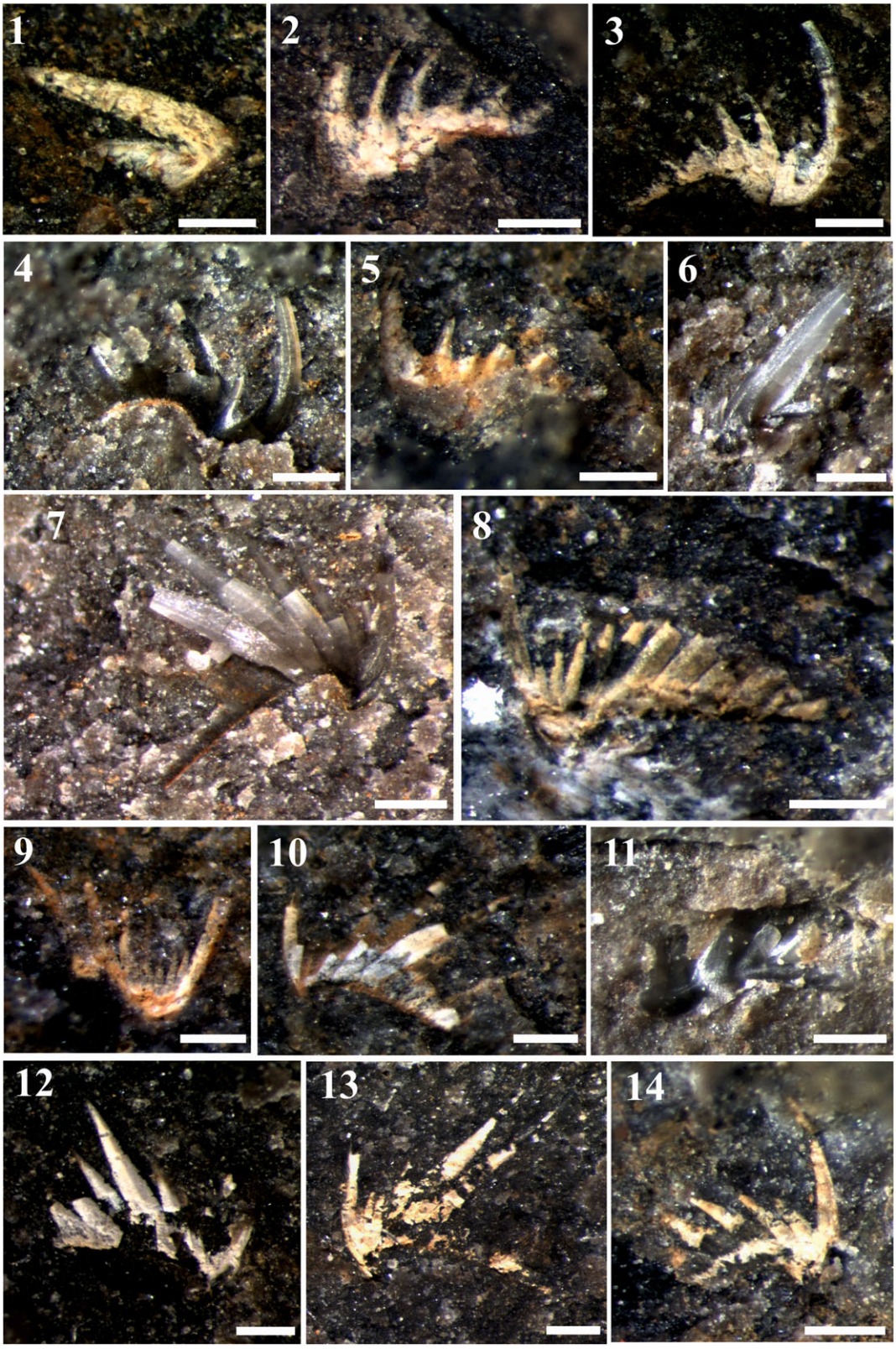

FIGURE 6 Conodonts on bedding plane surfaces of the *Yangtzeplacognathus crassus* Zone, from the Los Azules Formation: 1–5: *Paroistodus horridus horridus* (Barnes & Poplawski), 1: M element (CORD-PZ 37765, FLA 0.6, Los Gatos creek), 2: Sb element (CORD-PZ 37759, FLA 0.6, Los Gatos creek), 3–4: Sc elements (3: CORD-PZ 37745, FLA 0.6, Los Gatos creek; 4: CORD-PZ 37902, QA FLA 0.3, Amarilla creek), and 5: P element (CORD-PZ 37713, FLA 0.5, Los Gatos creek); 6–13: *Periodon macrodentatus* (Chen & Zhang), 6: M element (CORD-PZ 37905, QA FLA 0.3, Amarilla creek), 7: Sb element (CORD-PZ 37907, QA FLA 0.3, Amarilla creek), 8–9: Sc elements (8: CORD-PZ 37790, FLA 0.7, Los Gatos creek; 9: CORD-PZ 37718, FLA 0.5, Los Gatos creek), 10: Sd element (CORD-PZ 37717, FLA 0.5, Los Gatos creek), 11: Pa element (CORD-PZ 37836, QA FLA 0.1, Amarilla creek), and 12–13: Sd element (CORD-PZ 37655, CORD-PZ 37677, FLA 0.4, Los Gatos creek); and 14: *Spinodus spinatus* (Hadding), M element (CORD-PZ 37699, FLA 0.4, Los Gatos creek). Graphic scale: 200 μm [Colour figure can be viewed at wileyonlinelibrary.com]

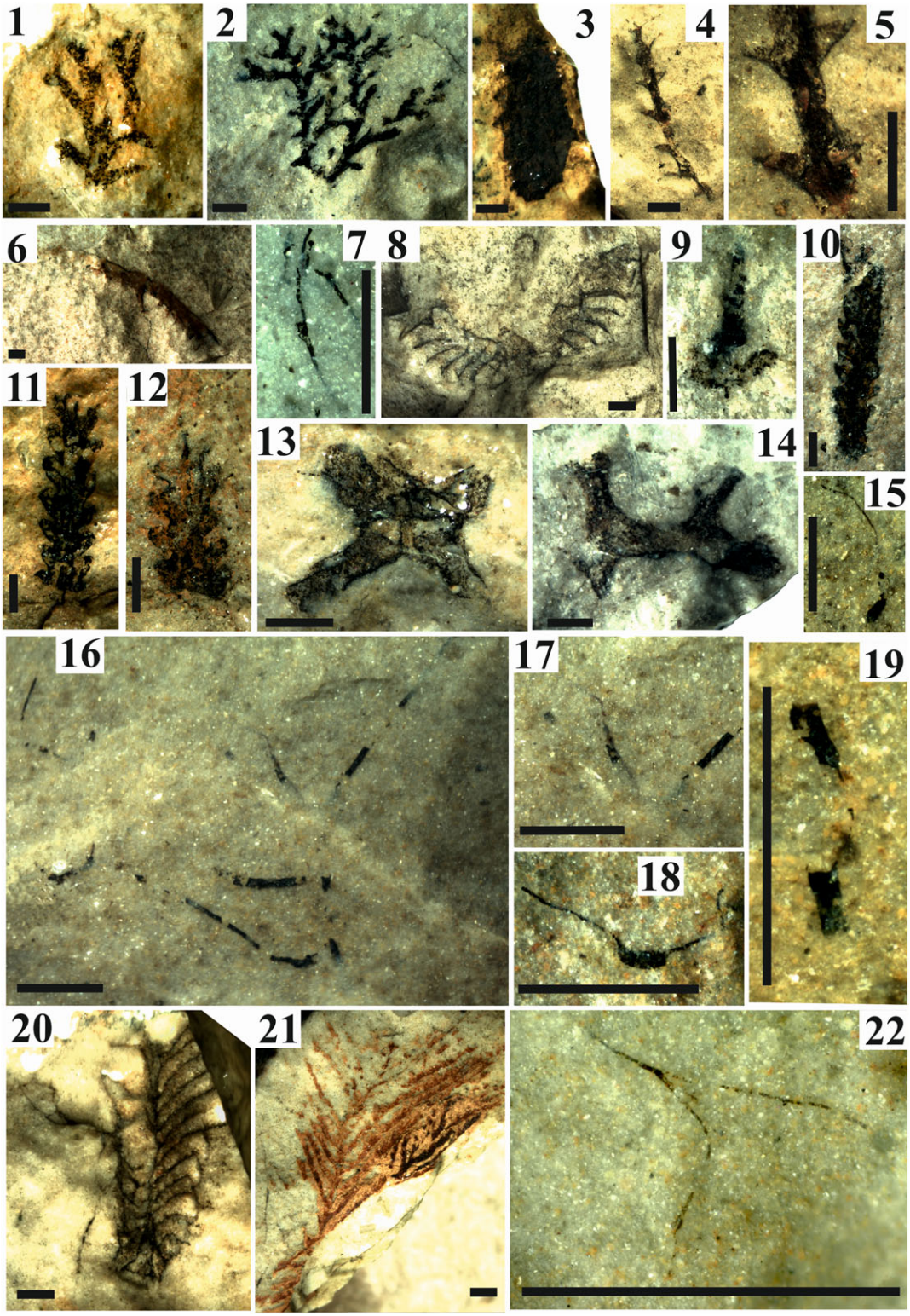

FIGURE 7 Graptolites of the San Juan Formation at Los Gatos and Amarilla creeks: 1–2: dendroids indet. (1: CORD-PZ 37540, LG 39.9, Los Gatos creek; 2: CORD-PZ 37570, LG 41, Los Gatos creek); 3: glossograptid indet. (see thecae; CORD-PZ 37547, LG 39.9, Los Gatos creek); 4: stipe of sinograptid gen. et sp. indet. (CORD-PZ 18519B, TFSJ QA, Amarilla creek); 5: detail of the theca of figure 4; 6: ?dichograptid indet. (CORD-PZ 37552, LG 41.1–50 cm, Los Gatos creek); 7: ?*Jiangshanites* sp. thecae (CORD-PZ 37585, LG 41, Los Gatos creek); 8: *Tetragraptus* sp. (CORD-PZ 25925, TFSJ QA, Amarilla creek); 9: *Levisograptus* sp. proximal end (CORD-PZ 37574, LG 41, Los Gatos creek); 10–12: *Levisograptus austrodentatus* (Harris & Keble; 10: CORD-PZ 37595, LG 41-1 m, Los Gatos creek; 11: CORD-PZ 37576, LG 41, Los Gatos creek; and 12: CORD-PZ 37595, LG 41-1 m, Los Gatos creek); 13: *Pseudophyllograptus* sp. cruciform cross-section (CORD-PZ 37596, LG 39.9, Los Gatos creek); 14: *Tetragraptus* sp. (CORD-PZ 37587, LG 41, Los Gatos creek); 15–19, 22: ?*Jiangshanites* sp., 15: thecae (CORD-PZ 37595, LG 41-1 m, Los Gatos creek), 16: colony with its sicula (CORD-PZ 37595, LG 41-1 m, Los Gatos creek), 17: detail of the sicula of figure 15, 18: thecae (CORD-PZ 37583, LG 41, Los Gatos creek), 19: thecae (CORD-PZ 37595, LG 41-1 m, Los Gatos creek), and 22: colony with bifurcations and thecae (CORD-PZ 37571, LG 41, Los Gatos creek); 20: *Pseudophyllograptus* sp. (CORD-PZ 25924, TFSJ QA, Amarilla creek); and 21: *Ptilograptus* sp. (CORD-PZ 14392, TFSJ QA, Amarilla creek). Graphic scale: 1 mm [Colour figure can be viewed at wileyonlinelibrary.com]

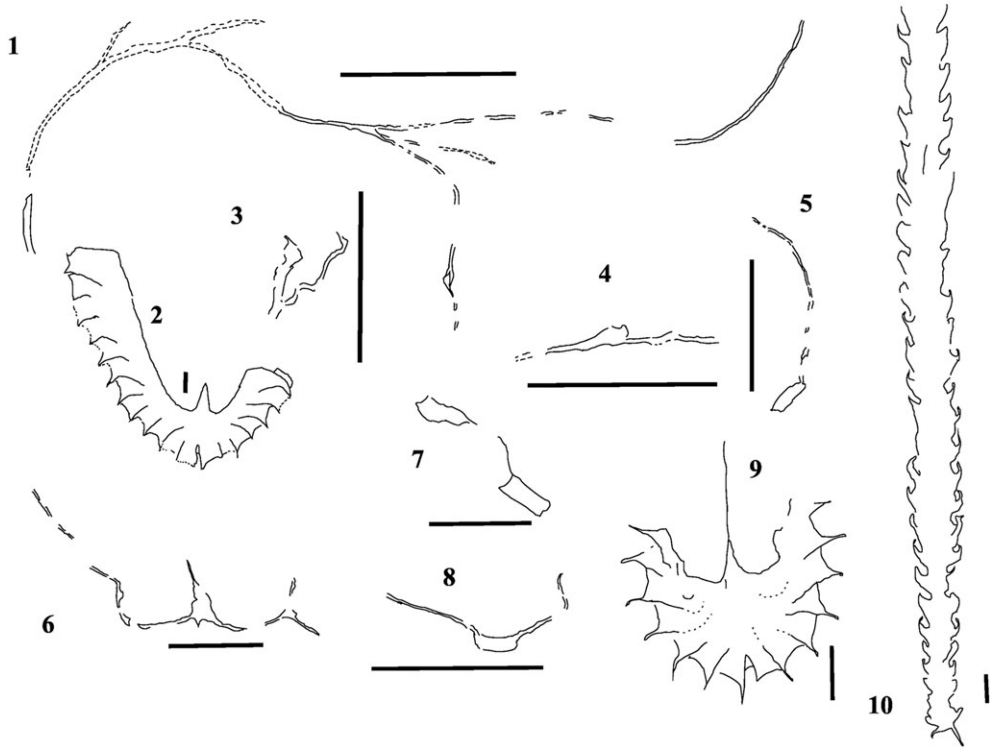

FIGURE 8 Line drawings of graptolites from the Los Gatos and Amarilla creeks: 1, 3–8: ?*Jiangshanites* sp., 1: colony with bifurcations and a thecae (CORD-PZ 37571, LG 41-1 m, San Juan Fm, Los Gatos creek), 3: bifurcation (CORD-PZ 37571, LG 41, San Juan Fm, Los Gatos creek), 4, 8: thecae (CORD-PZ 37585, CORD-PZ 37583, LG 41, San Juan Fm, Los Gatos creek), 6: proximal end (CORD-PZ 37630, FLA 0.2, Los Azules Fm, Los Gatos creek), and 5, 7: thecae (CORD-PZ 37595, CORD-PZ 37595, LG 41-1 m, San Juan Fm, Los Gatos creek); 2: *Isograptus divergens* Harris (CORD-PZ 37855, QA FLA 0.1, Los Azules Fm, Amarilla creek); 9: *Arienigraptus zhejiangensis* Yu & Fang (CORD-PZ 37868A, QA FLA 0.2, Los Azules Fm, Amarilla creek); and 10: *Levisograptus* cf. *Levisograptus dentatus* (Brongniart; CORD-PZ 25922, QA FLA 0.1, Los Azules Fm, Amarilla creek). Graphic scale: 4, 7: 0.5 mm; 1–3, 5–6, and 8–10: 1 mm

with precise locations by Mestre (2014). The lower strata of the Rinconada Formation are characterized by species that represent the upper *L. variabilis* Zone according to the latter author (Sarmiento, Vaccari, & Peralta, 1988). In the Cerro La Chilca, Central Precordillera of San Juan, the *L. variabilis* Zone is recognized from the upper San Juan Formation (Carrera et al., 2013; Heredia & Mestre, 2013; Serra et al., 2017). In turn, Feltes, Albanesi, and Bergström (2016) analysed samples corresponding to the upper San Juan Formation and recognized the *L. variabilis* Zone with its subzones, at the Las Aguaditas creek section, in the Los Blanquitos range, Central Precordillera. The *L. variabilis* Zone was described further in the Cerro Potrerillo section, 40 km north-east of Jáchal city (Albanesi et al., 1998). This biozone was also recognized for the lowest strata of the Yerba Loca Formation at the Ancaucha creek section in the Western Precordillera (Albanesi, Ortega, & Hünicken, 1995).

Lindström (1971) defined the *Amorphognathus variabilis* Zone (= *L. variabilis*) in the condensed sequence of limestones from the Baltic Shield, which corresponds to the Kundan Stage (BIII) of the Oelandian Series. Later, Löfgren (1978) remarked that the temporal extension of the index species is restricted to the early Kundan.

This biostratigraphic unit correlates with the *H. sinuosa* Zone and part of the *Histiodella holodentata* Zone of different North American schemes (Ethington & Clark, 1981; Sweet, 1984). The *L. variabilis* Zone also correlates with the *P. macrodentatus* Zone of Stouge (2012), which was recognized in the Shallow Bay Formation and the Green Point Formation of the Cow Head Group, western Newfoundland, Canada.

6.1.2 | *Yangtzeplacognathus crassus* Zone

This zone is regionally correlated with strata of the Las Aguaditas and the Oculta creeks, and Villicum sections spanning from the uppermost San Juan Formation to the lower part of the overlying formations (Carrera et al., 2013; Feltes et al., 2016; Mestre, 2014; Serra et al., 2017; Voldman et al., 2013). Regarding the present associations, it can also be correlated with the Los Sombreros Formation at the Los Túneles section of the Río Jáchal (Voldman, Albanesi, & Ramos, 2009) and with the Yerba loca Formation at Puerta de Ancaucha section (Voldman, Albanesi, & Do Campo, 2008). In the La Trampa Range, the equivalent strata of this biozone were mistakenly assigned to the *E. pseudoplanus* Zone by Heredia, Beresi, and Peralta (2005) (Feltes et al., 2013).

Considering the Las Chacritas and the Cerro La Chilca sections, the referred biozone is correlated with strata of the uppermost San Juan Formation and the lower parts of overlying units, the Las Chacritas and Las Aguaditas formations, respectively (Albanesi et al., 2013; Carrera et al., 2013; Serra et al., 2015; Serra et al., 2017). It is interesting to note that the referred strata were orginally

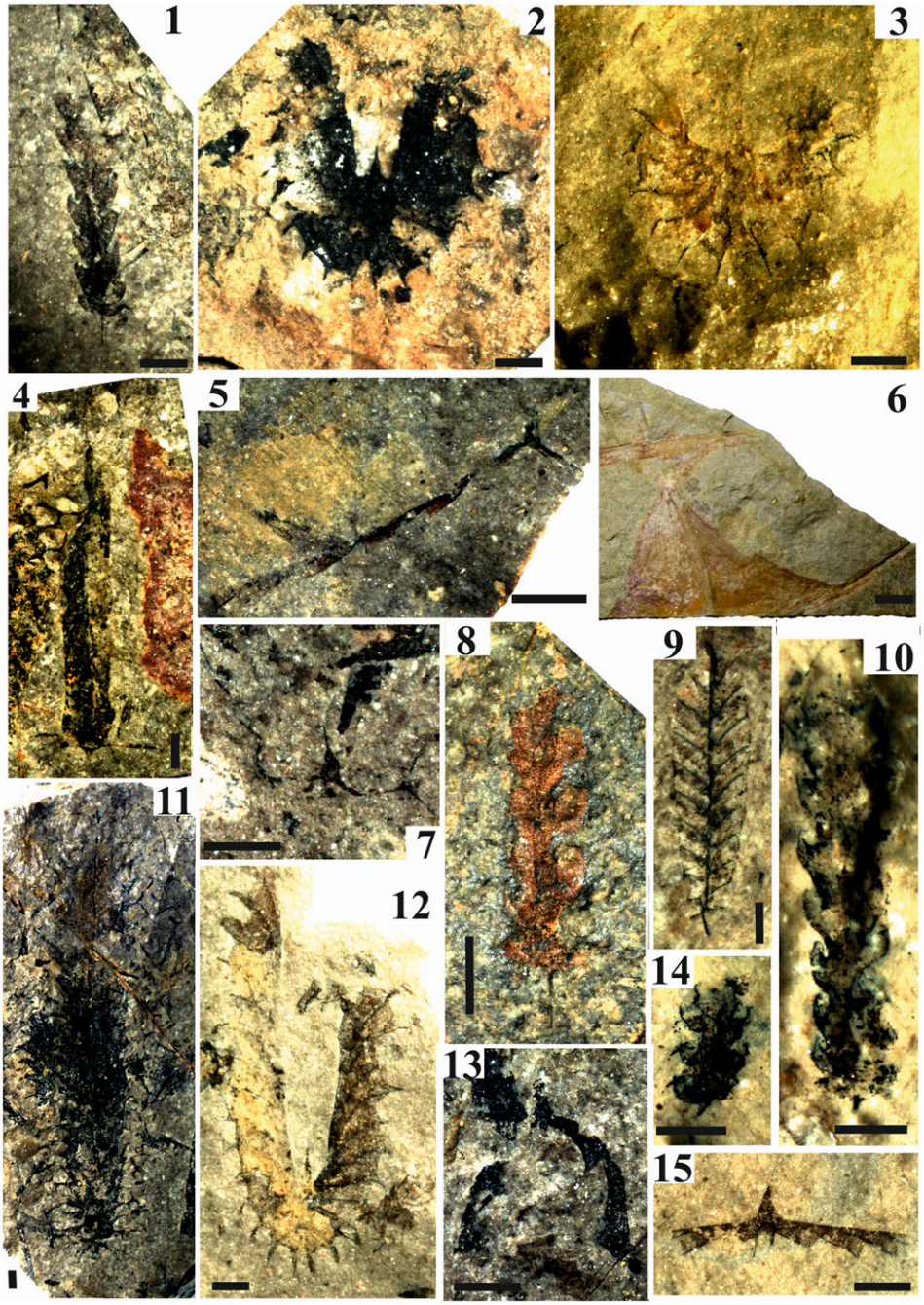

FIGURE 9 Graptolites from the basal metre of the Los Azules Formation: 1: *Levisograptus* cf. *Levisograptus austrodentatus* (CORD-PZ 37819A, FLA 0.8, Los Gatos creek); 2: *Arienigraptus angulatus* (Mu; CORD-PZ 25923, QA FLA 0.1, Amarilla creek); 3: *Arienigraptus zhejiangensis* Yu & Fang (CORD-PZ 37868A, QA FLA 0.2, Amarilla creek); 4: *Cryptograptus antennarius* (Hall; CORD-PZ 37682B, FLA 0.4, Los Gatos creek); 5: *Holmograptus bovis* Williams & Stevens (CORD-PZ 37672B, FLA 0.4, Los Gatos creek); 6: *Tetragraptus headi* (Hall; CORD-PZ 37824, QA FLA 0.4, Amarilla creek); 7: ?*Jiangshanites* sp. proximal end (CORD-PZ 37630, FLA 0.2, Los Gatos creek); 8: *Levisograptus primus* (Legg; CORD-PZ 37773, FLA 0.6, Los Gatos creek); 9: *Pseudotrigonograptus ensiformis* (Hall; CORD-PZ 37850A, QA FLA 0.1, Amarilla creek); 10: *L. austrodentatus* (Harris & Keble; CORD-PZ 37518, FLA 0.15, Los Gatos creek); 11: *Paraglossograptus tentaculatus* (Hall; CORD-PZ 37651, FLA 0.4, Los Gatos creek); 12: *Parisograptus caduceus* (Salter; CORD-PZ 37894, QA FLA 0.3, Amarilla creek); 13: *Pseudobryograptus* sp. (CORD-PZ 37677A, FLA 0.4, Los Gatos creek); 14: *Levisograptus sinicus* (Mu & Lee; CORD-PZ 37518, FLA 0.15, Los Gatos creek); and 15: *Xiphograptus lofuensis* (Lee; CORD-PZ 25926, QA FLA 0.1, Amarilla creek). Graphic scale: 1 mm [Colour figure can be viewed at wileyonlinelibrary.com]

assigned to the *E. pseudoplanus* Zone by Heredia (2012) but later verified as corresponding to the *Y. crassus* Zone in the referred citations.

The North American *H. holodentata* Zone (Ethington & Clark, 1981; Sweet, 1984) is correlated with the Scandinavian and Chinese *Y. crassus* Zone (Löfgren, 2003; Zhang, 1997), as also verified for the Precordilleran scheme (Albanesi & Ortega, 2016).

6.2 | Graptolites

6.2.1 | *Levisograptus dentatus* Zone

The *L. dentatus* Zone is recorded in the Cerro Potrerillo and the Cerro La Chilca sections, from the lower Gualcamayo Formation (Ortega et al., 2007; Serra et al., 2017). These authors estimated that

this biozone is represented in correlative levels of the Oculta creek. At the La Corridita creek section, Precordillera of San Juan, the biozone corresponds to the basal part of the middle member of the Gualcamayo Formation (Máspero Castro, Ortega, & Albanesi, 2003).

The *L. dentatus* Zone was defined by Maletz (1997) for the Lévis area, Quebec, Canada, divided into the *L. dentatus* Subzone and the *A. angulatus* Subzone (Maletz, 2011). Contrary to the records of Maletz (1997), Brussa et al. (2003) documented an assemblage that consists of *L. austrodentatus*, *L. dentatus*, *A. angulatus*, and *Arienigraptus zhejiangensis* coexisting in the upper *L. dentatus* Zone. In the Scandinavian region, it correlates with part of the *Didymograptus hirundo* Zone (Maletz, 1995, 1997). The *L. dentatus* Zone could be also present in the succession of Chilianshan, China, according to Maletz (2011), although few biserial forms have been recovered from that section.

7 | CONCLUSIONS

The basal metre of the lower member of the Los Azules Formation, at the Los Gatos and Amarilla creek sections, Cerro Viejo of Huaco, corresponds to the *Y. crassus* Zone (conodont).

Regarding graptolites, the upper 10 m of the San Juan Formation and the lowest metre of the Los Azules Formation, at the Los Gatos and Amarilla creeks, Cerro Viejo of Huaco, correspond to the *L. dentatus* Zone. Most probably, at the Los Gatos creek section, the *L. dentatus* Subzone is represented in the upper San Juan Formation linked to the correlative *P. horridus* Subzone of the *L. variabilis* Zone. The *A. angulatus* Subzone ranges from the basal lower member of the Los Azules Formation, where the index graptolites are in correspondence with conodonts of the *Y. crassus* Zone.

A slight difference is verified at the Amarilla creek section, where the *A. angulatus* Subzone is represented both in the uppermost San Juan Formation, based on the identification of the *Y. crassus* Zone, and in the lower member of the Los Azules Formation, indicated by the record of *A. angulatus*.

The abundant conodonts preserved on bedding plane surfaces of black shales as duripartics allow to perform a precise biostratigraphic analysis with associated graptolites in the same facies.

The occurrence of graptolites in the San Juan Formation represents one of the singular records of this fossil group in carbonate facies of the Argentine Precordillera.

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