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Darriwilian (Middle Ordovician) conodonts and graptolites from the Cerro La Chilca Section, Central Precordillera, Argentina

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ABSTRACT. The Ordovician System is extensively represented in the Precordillera of San Juan Province, Argentina. At the Cerro La Chilca in the Jáchal area, the limestone of the San Juan Formation is paraconformably overlain by interbedded limestone and shale of the Gualcamayo Formation. The present contribution reports new data on the conodont fauna and biostratigraphy of these darriwilian units, revising local and regional chronostratigraphic relationships. New information on the composition of conodont and graptolite associations through the stratigraphic sequence is presented. The presence of *Paroistodus horridus horridus*, *Yangtzeplacognathus crassus*, and *Histiodella sinuosa* constrain the uppermost strata of the San Juan Formation to the lower part of the *Y. crassus* Zone, according to the Baltoscandian scheme, and to the *H. sinuosa* Subzone of the *Periodon macrodentatus* Zone of the North American scheme. In the overlying Gualcamayo Formation the co-occurrence of *Y. crassus* with *Histiodella holodentata* enable the recognition of the *Y. crassus* Zone and the *H. holodentata* Subzone of the *P. macrodentatus* Zone. The identification of these zones allows for precise global and regional correlation. A graptolite assemblage that belongs to the epipelagic and deep-water biotopes with some components restricted to low paleolatitudes is recognized. This diverse assemblage is characteristic of the pelagic biofacies. The important diversity of graptolites in this section suggests a favorable environment for their development. Local changes in the taxonomic composition are recognized through the Gualcamayo Formation. When comparing this fauna with that of different study localities from the Central Precordillera (Cerro Potrerillo, Oculta Creek, Cerro Viejo de Huaco and Las Aguaditas Creek) slight differences in the generic composition are observed. Taxonomic differences support the preference of certain associations for particular environments; though, graptolites are more diverse in black shales facies, which represent deeper environments (the Los Azules Formation), in relation to the calcareous-shale facies of the Gualcamayo Formation from Cerro La Chilca and correlative unit at Las Aguaditas Creek.

Keywords: Conodonts, Biostratigraphy, Graptolites, Middle Ordovician, Argentine Precordillera.

RESUMEN. Conodontes y graptolitos darriwilianos (Ordovícico Medio) del Cerro La Chilca, Precordillera Central, Argentina. El Sistema Ordovícico se encuentra ampliamente representado en la Precordillera de la Provincia de San Juan, Argentina. En el cerro La Chilca, área de Jáchal, las calizas de la Formación San Juan infrayacen de manera paraconcordante a las calizas y lutitas de la Formación Gualcamayo. En este trabajo se brindan nuevos antecedentes sobre la bioestratigrafía de conodontes de estas unidades estratigráficas darriwilianas y se revisa su correlación cronoestratigráfica a nivel local y regional. Adicionalmente, se reportan nuevos datos sobre la composición de la asociación conodontes-graptolitos a lo largo de esta secuencia estratigráfica. La presencia de *Paroistodus horridus horridus*, *Yangtzeplacognathus crassus* e *Histiodella sinuosa* restringen los estratos cuspidales de la Formación San Juan a la parte inferior de la Zona de *Y. crassus*, según el esquema Báltico, y Subzona de *H. sinuosa* (Zona de *Periodon macrodentatus*) del esquema norteamericano. En la suprayacente Formación Gualcamayo la coexistencia de *Y. crassus* con *Histiodella holodentata* permite identificar la Zona de *Y. crassus* y la Zona de *Periodon macrodentatus* (Subzona de *H. holodentata*) para esta unidad. Estas zonas permiten realizar una correlación bioestratigráfica precisa a escala regional y global. A su vez, se reconoce una asociación de graptolitos perteneciente a los biotopos epipelágicos y de aguas profundas con algunos componentes de paleolatitudes bajas. Esta diversa asociación es característica de la biofacies pelágica. La gran riqueza y abundancia de graptolitos en esta sección sugiere un ambiente favorable para su desarrollo. Se observan cambios locales en la composición taxónomica de este grupo a través de la Formación Gualcamayo. Al comparar esta graptofauna con la documentada en otras secciones estratigráficas de la Precordillera Central (cerro Potrerillo, quebrada Oculta, Cerro Viejo de Huaco y quebrada de Las Aguaditas) se observan diferencias en la composición genérica de graptolitos. Esto sugiere una preferencia a determinados ambientes; de modo que, los graptolitos son más diversos en las facies pelíticas que representan ambientes más profundos (Formación Los Azules), en relación a las facies calcáreo-pelíticas de las formaciones Gualcamayo en el cerro La Chilca y quebrada Las Aguaditas.

Palabras clave: Conodontes, Bioestratigrafía, Graptolitos, Ordovícico Medio, Precordillera Argentina.

1. Introduction

The Precordillera is a geological province located in the western margin of Argentina, between the Frontal Cordillera to the West and the Pampean Range to the East, covering parts of La Rioja, Mendoza and San Juan provinces (Stelzner, 1873; Furque and Cuerda, 1979; Baldis *et al.*, 1982). It is characterized by a ~2,000 m thick succession of Cambrian-Ordovician sedimentary rocks preserved in an extensive fold-and-thrust orogenic belt (Astini *et al.,* 1996). In the Jáchal area of San Juan Province, Lower Paleozoic strata are extensively exposed and have been the subject of many paleontological and geological investigations (*e.g.,* Benedetto, 2003 and references therein). An important Ordovician exposure is represented in the Cerro La Chilca section, located approximately 40 km south of San José de Jáchal, in the San Juan Province, Argentina (Fig. 1).

The pioneering work of Stappenbeck (1910) was followed by numerous contributions on the geology, stratigraphy, and paleontology of the sedimentary rocks exposed in this area (*e.g.,* Cuerda, 1965, 1973, 1986; Blasco and Ramos, 1976; Furque, 1983; Sánchez *et al.,* 1996; Astini and Benedetto, 1992; Astini and Maretto, 1996; Benedetto, 2010; Ortega *et al.*, 2013).

Several contributions tackled the biostratigraphy of this section by studying the conodonts, trilobites and graptolites in these Ordovician rocks (*e.g.,* Lehnert, 1995; Peralta *et al.*, 2003; Tortello and Peralta, 2004; Mestre, 2012; Serra *et al.*, 2017). However, the graptolite and conodont fauna previously documented in the San Juan and Gualcamayo formations have been revised (Löfgren and Zhang, 2003; Serra *et al.*, 2017; Serra *et al.*, 2019); thus, an updated biostratigraphy for these units is needed. This contribution reports new data on the conodont fauna from the uppermost part of the San Juan Formation and the Gualcamayo Formation. Regional and global chronostratigraphic relationships are provided with a thorough revision of the conodont biostratigraphy. Also, new information on the composition of conodont and graptolite associations through the rock succession is presented, including the description of the diverse graptolite assemblage documented by Serra *et al.* (2017).

2. Cerro La Chilca section

2.1. Geologic framework

The Ordovician succession that crops out in this area consists of the San Juan (upper Tremadocian-lower Darriwilian), Gualcamayo (middle Darriwilian), Los Azules (lower Sandbian) and Don Braulio (Hirnantian) formations (Baldis *et al.*, 1982; Peralta, 2003). These units are successively overlain by the

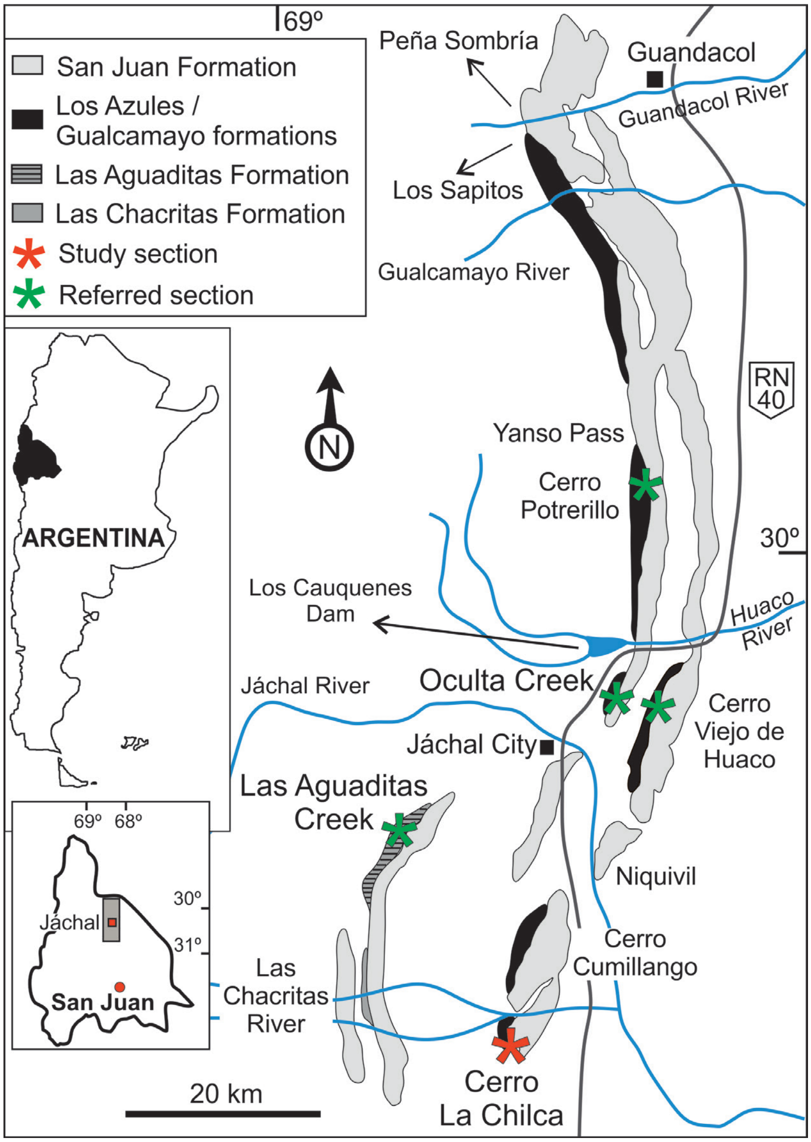

FIG. 1. Location map of the Cerro La Chilca section and reference sections from the Precordillera of San Juan Province.

La Chilca and Los Espejos formations of mostly Silurian age (Cuerda, 1969) and the Talacasto (Padula *et al.*, 1967) and Punta Negra (Bracaccini, 1950) formations of Devonian age (Cuerda and Furque, 1985; Cuerda, 1986; Astini and Benedetto, 1992).

The Ordovician rock sequence described by Cuerda (1965) at the Cerro La Chilca section was recognized as the San Juan and the Los Azules Formations (Furque, 1983; Cuerda, 1986). Later, the succession of interbedded shale and siltstone, overlying the San Juan Formation at this locality, was described by Astini and Benedetto (1992) as the Gualcamayo Formation and interpreted as transgressive deposits. These authors divided the Gualcamayo Formation into two members, equivalent respectively to the upper San Juan Formation *sensu* Cuerda (1986) and to the Los Azules Formation as previously identified by Furque (1983).

More recently, Peralta (1998) and Tortello and Peralta (2004) described the lower part of the Gualcamayo Formation at Cerro La Chilca as a 4.3 m thick unit with alternation of black, tabular marly limestones and dark laminated shales that overly the limestone of the San Juan Formation. The uppermost fossiliferous level of black limestone defines the upper-limit of the Gualcamayo Formation, which is unconformably overlain by the shaly Los Azules Formation (Peralta, 1998); formerly described as the upper member of the Gualcamayo Formation by Astini and Benedetto (1992). The Los Azules Formation consists of 78 m of black shales with occasional intercalations of lensoidal beds of dark limestones. A significant hiatus corresponding to the Guandacolic orogeny occurs between these units (Peralta, 2003).

In the present contribution, only the top strata of the San Juan Formation and the Gualcamayo Formation are analyzed. The former is characterized by 20 cm thick skeletal wackestones beds, which present a light gray to ochre color on weathered surfaces and dark gray in freshly broken planes. The Gualcamayo Formation, *ca*. 4 m in thickness, consists of 10-20 cm thick carbonate mudstones interbedded with black shales (Fig. 2). The Gualcamayo shales are light brown when weathered and black in fresh exposure surfaces, graptolite remnants are common on shale bedding planes.

2.2. Paleontological framework

Several paleontologic studies have been carried out in the Cerro La Chilca locality. For instance, conodont, sponge, bryozoan, and crinoid assemblages have been described for the uppermost part of the San Juan Formation (*e.g.,* Lehnert, 1995; Sánchez *et al.*, 1996; Carrera, 1997; Keller, 1999; Mestre, 2012; Carrera *et al.,* 2013; Serra *et al.,* 2017). In a recent contribution, graptolites were documented for the first time in the uppermost part of the formation, *ca*. 1 m below its contact with the Gualcamayo Formation (Serra *et al.*, 2017).

In the upper part of the San Juan Formation and the overlying Gualcamayo Formation, Mestre (2012) documented the presence of *Eoplacognathus pseudoplanus* (Viira), *Histiodella kristinae* (Stouge) and *Microzarkodina* sp. cf. *M. ozarkodella* (Lindström),

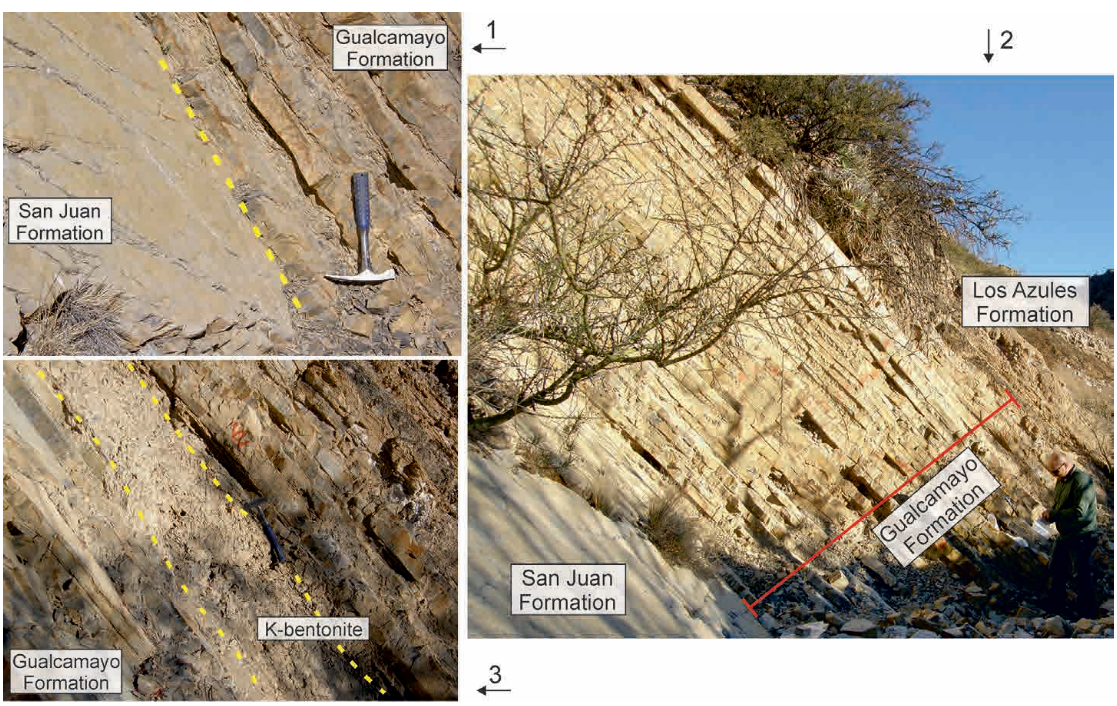

FIG. 2. Cerro La Chilca section. **1.** Detail of the contact between the San Juan and the overlying Gualcamayo formations. **2.** Detail of the study section (view to the SE): Top stratum of the San Juan Formation; 4 m thickness of the Gualcamayo Formation showing its characteristic chalcareous-shaly lithology; Los Azules Formation of Sandbian age overlying the Gualcamayo Formation. **3.** 25 cm K-bentonite layer (graptolite sample F) of the Gualcamayo Formation.

suggesting the presence of the upper *E. pseudoplanus* Zone in the contact between these formations. The identification of the *E. pseudoplanus* Zone at the top of the San Juan Formation at Cerro La Chilca has been questioned by recent studies (Carrera *et al.*, 2013; Serra *et al.*, 2017), which revise the age according to the presence of *H. sinuousa*.

Sclerites of plumulitids were recorded in the Gualcamayo Formation, representing the first record of machaeridians in Argentina (Benedetto, 2010; Ortega, 2010; Ortega *et al.*, 2013). In this formation a rich trilobite assemblage, characteristic of the *Kainisiniella cuyana* Zone, was documented. The referred assemblage is dominated by *Mendolaspis salagastensis* Rusconi, whereas *Geragnostus* sp., *Neptunagnostella superb* Shergold, *Porterfieldia* sp., *Nileusdepressus argentinensis* Tortello and Peralta, *Carolinites latus* Tortello and Peralta, *Carolinites* aff. *pardensis* Legg, and *Macrogrammus pengi* Edgecombe, Chatterton, Vaccari and Waisfeld are barely recorded (Tortello and Peralta, 2004). This formation also bears a rich graptolite fauna that consists of *Acrograptus* sp., *Holmograptus bovis* Williams and Stevens, *Xiphograptus lofuensis* Lee, *Pseudobryograptus parallelus* Mu, *Thamnograptus*? sp., *Jiangshanites*? sp.*, Pseudophyllograptus* sp., *Tetragraptus bigsbyi* (Hall), *T. quadribrachiatus* (Hall), *Arienigraptus zhejiangensis* Yu and Fang, *Parisograptus caduceus* (Salter), *Glossograptus* sp., *Paraglossograptus tentaculatus* (Hall), *Levisograptus austrodentatus* (Harris and Keble), *L. dentatus* (Brongniart), *L. primus* (Legg) and *L. sinicus* (Mu and Lee), a particular assemblage that corresponds to the *L. dentatus* Zone (Serra *et al.,* 2017).

3. Materials and methods

A total of 13 samples were collected (Fig. 3), including 5 samples from the upper part of the San Juan Formation and 8 from the Gualcamayo Formation. The samples of 2 kg each were digested in a 10% acetic acid solution, according to the method described by Stone (1987). The conodont elements picked up account for a total of 971 identifiable specimens (Table 1). These exhibit a color alteration index (CAI) of 2.5, reflecting burial paleotemperatures between 90 °C and 110 °C (Epstein *et al.*, 1977). The graptolite fauna from the Cerro La Chilca section was referred in a recent study (Serra *et al.*, 2017), where it was dealt for biostratigraphic purposes; whereas in the present paper a palaeoenvironmental appraisal is given to this fauna.

The fossil collection is housed in the Museo de Paleontología, Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba, under the repository codes CORD-MP, for conodonts, and CORD-PZ, for graptolites.

4. Biostratigraphy

4.1. Conodont fauna

A diverse conodont association was recovered from the study section, including the following species (Figs. 3, 4, 5): *Ansella jemtlandica* (Löfgren), *A. sinuosa* (Stouge), *Baltoniodus clavatus* Stouge and Bagnoli, *"Bryantodina"* aff. *typicalis* (Stauffer), *Coelocerodontus bicostatus* van Wamel, *Cornuodus longibasis* (Lindström), *Costiconus ethingtoni* (Fåhræus), *Dapsilodus* sp., *Decoriconus pesequus* Löfgren, *Drepanoistodus* sp. *Drepanoistodus bellburnensis* Stouge, *D. tablepointensis* Stouge, *Drepanodus arcuatus* Pander, *D. reclinatus* (Lindström), *Erraticodon alternans* (Hadding), *Fahraeusodus jachalensis* Feltes and Albanesi, *Histiodella serrata* Harris, *H. sinuosa, H. holodentata, Juanognathus jaanussoni* Serpagli, *Microzarkodina hagetiana* (Stouge and Bagnoli), *Parapaltodus simplicissimus* Stouge, *Paraprioniodus costatus* (Mound), *Paroistodus horridus* Barnes and Poplawski, *P. horridus secundus* Albanesi, *P. originalis* (Sergeeva), *Periodon macrodentatus*, *Polonodus* sp. *Protopanderodus gradatus* Serpagli, *Pteracontiodus cryptodens* (Mound), *Rossodus barnesi* Albanesi, *Scolopodus striatus* (Lindström), and *Semiacontiodus potrerillensis* Albanesi and *Yangtzeplacognathus crassus* (Chen and Zhang).

This species assemblage and the presence of key index taxa such as *Y. crassus*, *H. sinuosa* and *H. holodentata*, constrain the contact between the San Juan and Gualcamayo formations to the *Y. crassus* Zone as defined for the Baltoscandian region (assessed by Löfgren and Zhang, 2003) and to the *H. sinuosa* and *H. holodentata* subzones of the *P. macrodentatus* Zone following the scheme of Stouge (2012) for western Newfoundland (Fig. 6). The co-occurrence of *Paroistodus horridus horridus* with *Y. crassus* identifies the base of the *Y. crassus* Zone at the top of the San Juan Formation. This conodont zonal determination agrees with the identification of

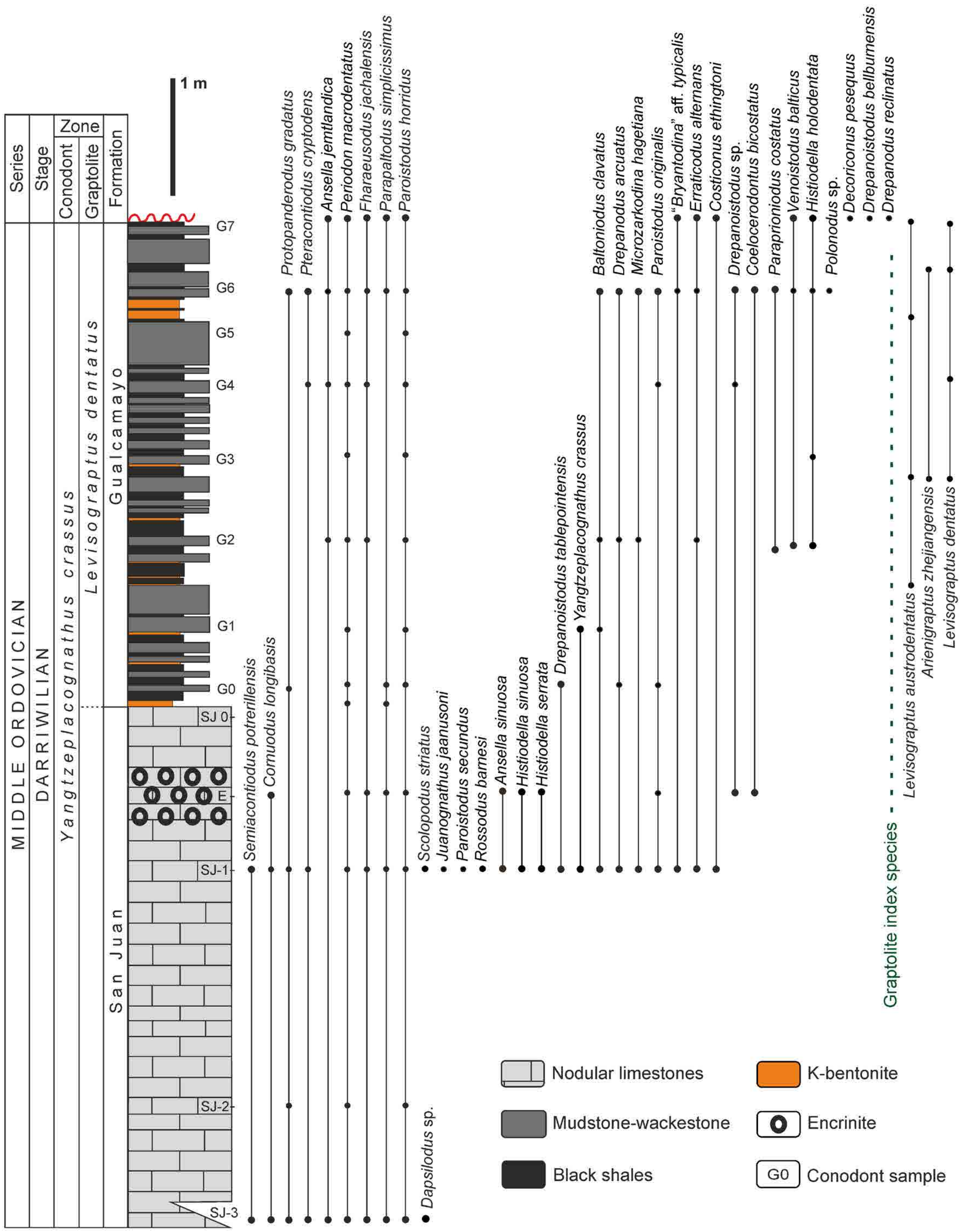

FIG. 3. Stratigraphic column showing conodont and key graptolite species ranges of the San Juan and Gualcamayo formations in the Cerro La Chilca section.

TABLE 1. CONODONT OCCURRENCE AND ABUNDANCE DATA FROM THE SAN JUAN AND THE GUALCAMAYO FORMATIONS AT THE CERRO LA CHILCA SECTION.

	Samples												
Species	**SJ-3**	**SJ-2**	**SJ-1**	**E**	**SJ0**	**G0**	**G1**	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**
Ansella jemtlandica	1	0	8	0	0	0	0	1	0	2	0	23	7
Ansella sinuosa	0	0	2	8	0	0	0	0	0	0	0	0	0
Baltoniodus clavatus	0	0	1	0	0	0	1	2	0	0	0	2	0
"Bryantodina" aff. *typicalis*	0	0	1	0	0	0	0	0	0	0	0	4	1
Coelocerodontus bicostatus	0	0	0	2	0	0	0	0	0	0	0	1	0
Cornuodus longibasis	1	0	1	2	0	0	0	0	0	0	0	0	0
Costiconus ethingtoni	0	0	3	0	0	0	0	0	0	0	0	0	2
Dapsilodus sp.	0	0	2	0	0	0	0	0	0	0	0	0	0
Decoriconus pesequus	0	0	0	0	0	0	0	0	0	0	0	0	2
Drepanodus arcuatus	0	0	6	0	0	1	0	1	0	0	0	2	0
Drepanodus reclinatus	0	0	0	0	0	0	0	0	0	0	0	0	2
Drepanoistodus sp.	0	0	0	5	0	0	0	0	0	3	0	2	0
Drepanoistodus bellburnensis	0	0	0	0	0	0	0	0	0	0	0	0	1
Drepanoistodus tablepointensis	0	0	9	0	0	1	0	0	0	0	0	0	0
Erraticodon alternans	0	0	1	0	0	0	0	1	0	0	0	1	1
Fahreusodus jachalensis	1	0	6	1	0	0	0	7	0	1	0	35	15
Histiodella holodentata	0	0	0	0	0	0	0	1	1	0	0	1	2
Histiodella serrata	0	0	3	0	0	0	0	0	0	0	0	0	0
Histiodella sinuosa	0	0	14	1	0	0	0	0	0	0	0	0	0
Juanognathus jaanusoni	0	0	3	0	0	0	0	0	0	0	0	0	0
Microzarkodina hagetiana	0	0	1	0	0	0	0	2	0	0	0	5	0
Parapaltodus simplicissimus	2	0	43	8	1	1	0	0	0	0	0	2	1
Paraprioniodus costatus	0	0	0	0	0	0	0	1	0	0	0	1	0
Paroistodus horridus	5	1	36	7	0	2	1	52	12	41	1	202	106
Paroistodus horridus secundus	0	0	2	0	0	0	0	0	0	0	0	0	0
Paroistodus originalis	0	0	7	1	0	1	0	0	0	1	0	1	0
Periodon macrodentatus	3	1	39	11	2	2	1	13	1	24	1	36	24
Protopanderodus gradatus	1	1	5	1	0	1	0	0	0	0	0	8	0
Polonodus sp.	0	0	0	0	0	0	0	0	0	0	0	1	0
Pteracontiodus cryptodens	1	0	2	0	0	0	0	0	0	1	0	1	0
Rossodus barnesi	0	0	4	0	0	0	0	0	0	0	0	0	0
Scolopodus striatus	0	0	9	0	0	0	0	0	0	0	0	0	0
Semiacontiodus potrerillensis	1	0	1	0	0	0	0	0	0	0	0	0	0
Venoistodus balticus	0	0	0	0	0	0	0	1	0	0	0	2	12
Yangtzeplacognathus crassus	0	0	3	0	0	0	1	0	0	0	0	0	0

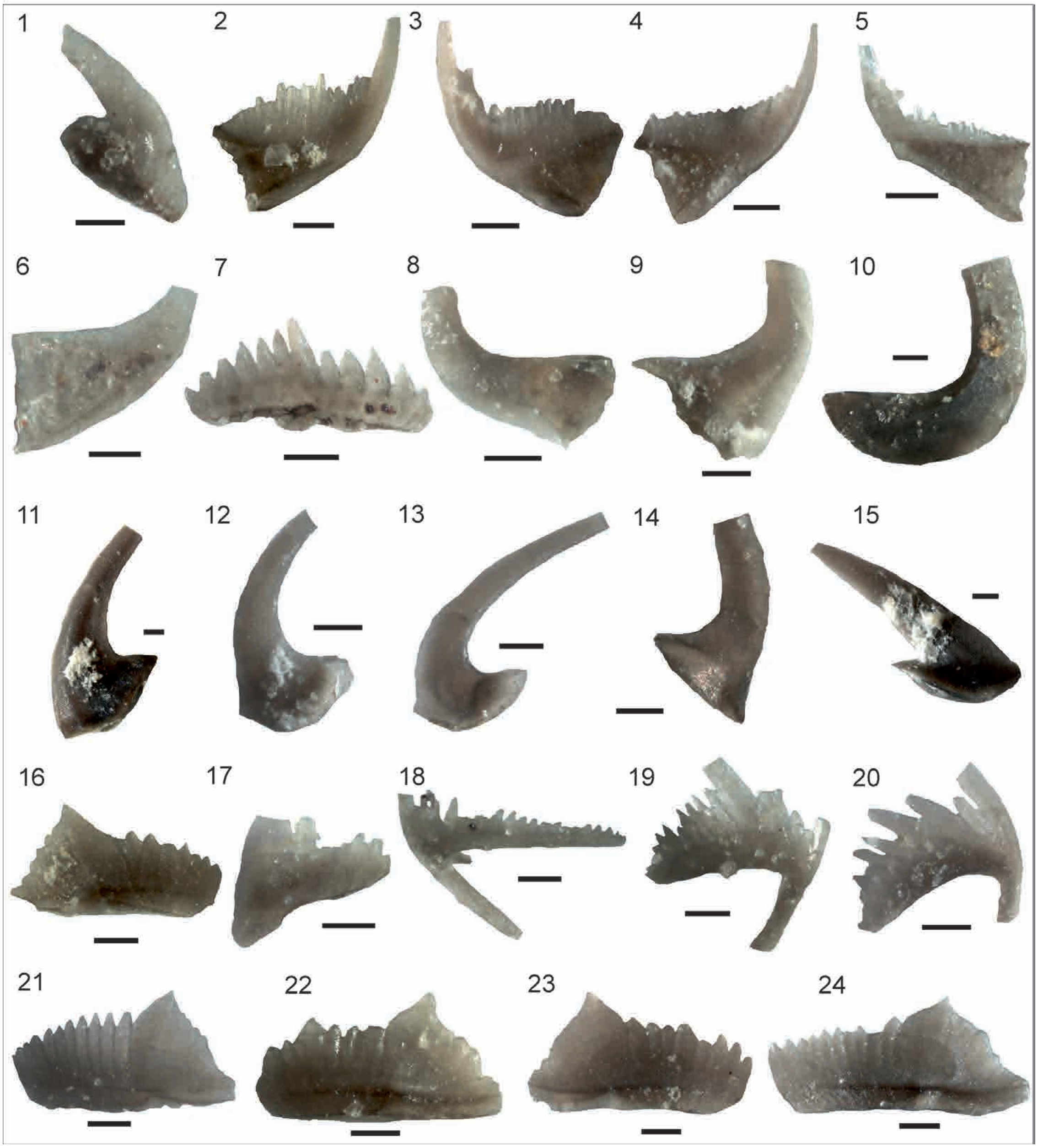

FIG. 4. Conodont species from the San Juan and Gualcamayo formations at the Cerro La Chilca section. **1-6.** *Ansella jemtlandica* (Löfgren); **1.** M element, sample G6, CORD-MP 77037; **2.** Sa element, sample SJ-1, CORD-MP 77038; **3-4.** Sb elements, sample SJ-1, CORD-MP 77039-77040; **5.** Sc element, sample G6, CORD-MP 77041; **6.** P element, sample G6, CORD-MP 77042. **7.** *"Bryantodina"* aff. *typicalis* Stauffer, Pa element, sample G6, CORD-MP 77043. **8.** *Cornuodus longibasis* Lindström, sample SJ-3, CORD-MP 77044. **9.** *Dapsilodus* sp., Sample SJ-3, CORD-MP 77045. **10.** *Drepanodus reclinatus* (Lindström), Sb element, sample G7, CORD-MP 77046. **11.** *Drepanoistodus costatus* Abaimova, Sb element, sample SJ-1, CORD-MP 77047. **12-13.** *Drepanodus arcuatus* Pander, late forms, sample SJ-1, Sc element, CORD-MP 77048-77049. **14-15.** *Drepanoistodus tablepointesis* Stouge, sample SJ-1; **14.** Sc element, CORD-MP 77050; **15.** M element, CORD-MP 77051. **16, 21-22.** *Histiodella serrata* Harris, Pa elements, sample SJ-1, CORD-MP 77052-77054. **17-20.** *Faraheusodus jachalensis* Feltes and Albanesi; **17.** P element, sample SJ-1, CORD-MP 77055; **18-20.** S elements, CORD-MP 77056-77058 (18, 19: sample G6; 20: sample SJ-1). **23-24.** *Histiodella sinuosa* (Graves and Ellison), Pa element, sample SJ-1, CORD-MP 77059-77060. Sacle bar: 0.1 mm

FIG. 5. Conodont species from the San Juan and Gualcamayo formations at the Cerro La Chilca section. **1-3.** *Microzarkodina hagetiana* Stouge and Bagnoli, Sa elements, sample G6, CORD-MP 77061-77063. **4.** *Costiconus ethingtoni* (Fåhræus), M element, sample SJ-1, CORD-MP 77064. **5-7.** *Parapaltodus simplicissimus* Stouge, sample SJ-1; **5.** Sc element, CORD-MP 77065; **6.** M element, CORD-MP 77066; **7.** P element, CORD-MP 77067. **8-9.** *Paroistodus originalis* (Sergeeva), sample SJ-1; **8.** M element, CORD-MP 77068; **9.** Sa element, CORD-MP 77069. **10.** *Paroistodus horridus secundus* Albanesi, Sc element, sample SJ-1, CORD-MP 77070. **11-14.** *Paroistodus horridus horridus* (Barnes and Poplawski), **11.** M element, sample SJ-1, CORD-MP 77071; **12.** Sa element, sample G6, CORD-MP 77072; **13.** Sc element, sample SJ-1, CORD-MP 77073; **14.** P element, sample G6, CORD-MP 77074. **15-18.** *Periodon macrodentatus* (Graves and Ellison), **15.** M element, sample SJ-1, CORD-MP 77075; **16.** Sa element, sample G7, CORD-MP 77076; **17.** Sc element, sample SJ-1, CORD-MP 77077; **18.** Pa element, sample G7, CORD-MP 77078. **19.** *Protopanderodus gradatus* Serpagli, Sa element, sample G6, CORD-MP 77079. **20-21.** *Pteracontiodus cryptodens* Mound, sample SJ-1, **20.** Sc element, CORD-MP 77080; **21.** P element, CORD-MP 77081. **22-23.** *Scolopodus striatus* Pander, sample SJ-1, **22.** Sc element CORD-MP 77082; **23.** M element CORD-MP 77083. **24-25.** *Yangtzeplacognathus crassus* (Chen and Zhang), sample SJ-1; **24.** Pa elements CORD-MP 77084; **25.** Pb element CORD-MP 77085. Sacle: 0.1 mm.

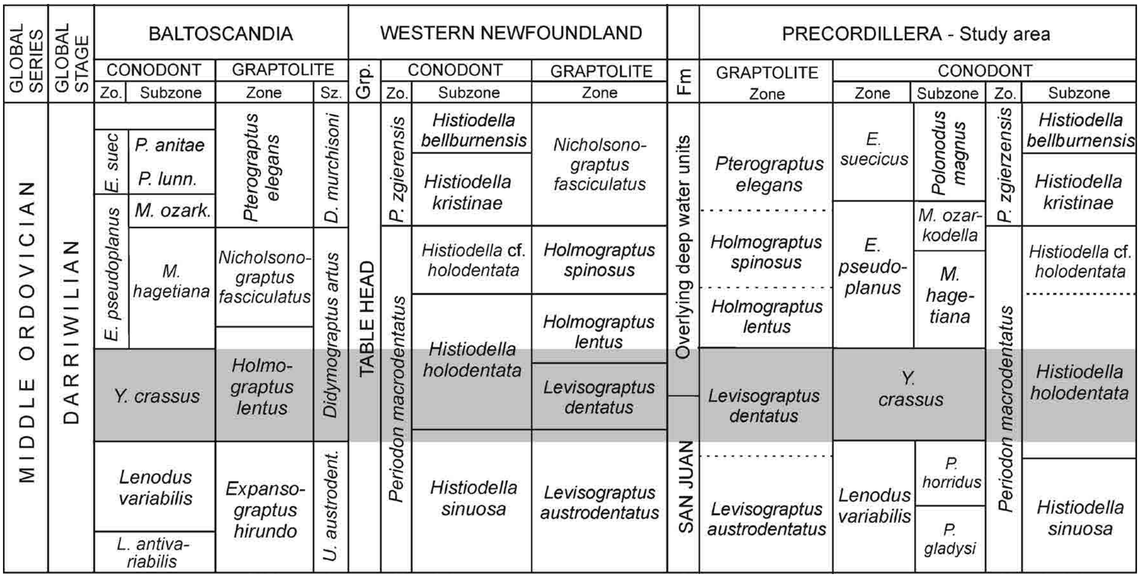

FIG. 6. Biostratigraphic chart of the Middle-Upper Ordovician showing conodont and graptolite zones from Baltoscandia (modified from Löfgren and Zhang, 2003), Western Newfoundland (modified from Stouge, 2012; Maletz, 2009, 2011), Argentine Precordillera (adapted from Feltes *et al.*, 2016; Albanesi and Ortega, 2016 and Serra *et al.*, 2017). Abbreviations: **Zo.:** Zone; **Sz.:** Subzone; **Grp.:** Group; ***E. suec.*:** *E. suecicus*; ***P. lunn.*:** *P. lunnensis*; ***L. austrodent.*:** *L. austrodentatus*.

the *Levisograptus dentatus* Zone, confirming their mutual biostratigraphic correspondence (Albanesi and Ortega, 2016; Serra *et al.*, 2017).

4.2. Discussion

A number of biostratigraphic studies were accomplished in the Cerro La Chilca section. Lehnert (1995) documented the *E. suecicus* Zone in the upper part of the San Juan Formation according to specimens that he determined as belonging to the eponymous species, from the neighboring Las Chacritas River section, and of ?*Histiodella kristinae* from strata of the Cerro La Chilca section (see plate 10, figs. 1, 10, 14, of the referred author). However, the specimen illustrated as ?*H. kristinae* is a fragmentary Pa element (lacking the base and cusp), which cannot be attributed to a particular species of the genus *Histiodella*. Additionally, the P elements identified as *E. suecicus* were reassigned to *Y. crassus* by Löfgren and Zhang (2003), which is consistent with our records. Mestre (2012) published a conodont species range chart from the uppermost San Juan and the Gualcamayo formations (the latter referred to as the Los Azules Formation), where *Eoplacognathus pseudoplanus* (Viira), *Histiodella kristinae* (Stouge) and *Microzarkodina* sp. cf. *M. ozarkodella* (Lindström) are identified from the upper 4 m of the San Juan Formation and the overlying Gualcamayo Formation, proposing the presence of the upper part of the *E. pseudoplanus* Zone. However, the Pa element identified as *H. kristinae* (fig. 5.6, Mestre, 2012) shows a cusp higher than the anterior denticles, being this relation diagnostic for the identification of *H. holodentata* (Stouge, 1984, 2012). Additionally, the stratigraphic range of *H. sinuosa* does not overlap the range of *H. kristinae,* which is a descendant of *H. holodentata,* a succeeding form of *H. sinuosa* (see Stouge, 1984). In a subsequent study, the conodont association obtained from the uppermost strata of the San Juan Formation at this locality (1 m below the contact between the San Juan and Gualcamayo formations) yielded the key species *H. sinuosa*, *P. horridus* and *P. macrodentatus* (Carrera *et al.*, 2013). This association verified an older age by identifying a transitional interval from the upper subzone of the *Lenodus variabilis* Zone to the succeeding *Yangtzeplacognathus crassus* Zone, at the top of the San Juan Formation. Recently, Serra *et al.* (2017) described a rich graptolite fauna assigned to the *Levisograptus dentatus* Zone (lower middle Darriwilian) in the Gualcamayo Formation and the presence of *H. sinuosa* and *Y. crassus* at the top of the San Juan Formation and *Y. crassus* with *H. holodentata* at the base of the Gualcamayo Formation.

Our sample SJ-1 (*ca.* 1.6 m below the top of the San Juan Formation, see Fig. 3) yielded conodont elements of *P. horridus secundus* (Fig. 5.10), which would indicate the *P. horridus* Subzone of the *L. variabilis* Zone of the Argentine general conodont biozonation, as previously suggested by Carrera *et al.* (2013) and Feltes *et al.* (2016), and finally revised by Albanesi and Ortega (2016). Although, the co-occurrence of *P. horridus horridus* with *Y. crassus* in the same sample indicates the base of the *Y. crassus* Zone instead. Also, Pa elements of *Y. crassus* are found with *H. sinuosa* in this sample and in the subsequent one (1 m below the top of the San Juan Formation). The latter species is not reported, elsewhere, for the *E. pseudoplanus* Zone. The rich conodont association including index species such as *Y. crassus*, *M. hagetiana*, *H. sinuosa*, *H. holodentata* and *P. macrodentatus*, accompanied by the key graptolite species *L. dentatus* (Figs. 3, 7), verify the actual recognition of the *Y. crassus* Zone for the upper part of the San Juan Formation and the Gualcamayo Formation in the study section.

4.3. Regional correlation

The key taxa *Y. crassus* was first recorded in the San Juan Formation at Central Precordillera by Lehnert (1995), although this author identified it as *E. suecicus* Bergström, and was then documented in numerous works (*e.g.,* Albanesi *et al.*, 2006, 2013; Heredia *et al.*, 2005; Heredia and Mestre, 2011; Mestre and Heredia, 2013; Feltes *et al.*, 2016; Serra *et al.*, 2015, 2017).

Regionally, this zone correlates with coeval strata of the Las Aguaditas Creek section (Feltes *et al.*, 2016), Las Chacritas River section (Heredia *et al.*, 2005; Serra *et al.*, 2015), Cerro Potrerillo (Albanesi *et al.*, 1998), Villicum range (Sarmiento, 1991; Mestre, 2013), Cerro Viejo de Huaco (Ottone *et al.*, 1999; Ortega *et al.*, 2007) and Oculta Creek (Voldman *et al.*, 2013), where the *Y. crassus* Zone is recognized in transitional facies from the San Juan Formation and overlying units. In a recent study, Mango and Albanesi (2018) recognized the *L. variabilis* Zone in the top strata of the San Juan Formation at the Los Gatos Creek, Cerro Viejo de Huaco area; differing with previous works (Ortega, 1987; Ottone *et al.*, 1999; Ortega *et al.*, 2007) that report the *Y. crassus* Zone in the stratigraphic sections located towards the south of Cerro Viejo de Huaco. However, the referred authors conclude that this difference is due to a diachronism occurring at the top of the San Juan Formation, where the younger strata (*Y. crassus* Zone) are exposed in sections located towards the south of the Cerro Viejo de Huaco (Mango and Albanesi, 2018). The conodont fauna associated with *Y. crassus* also allows the correlation with the Yerba Loca Formation at Ancaucha creek (Albanesi *et al.*, 1995; Voldman *et al.*, 2008) and with the Los Sombreros Formation at Los Túneles of Jáchal river (Voldman *et al.*, 2009).

Heredia *et al.* (2005) reported, with doubt, the presence of *Y. crassus* in the Las Chacritas River section and Albanesi *et al.* (2006) published the presence of this index species at Cerro Viejo de Huaco. Later, Albanesi *et al.* (2013) and Serra *et al.* (2015) verified it's the record across the contact between the San Juan Formation and the overlying Las Chacritas Formation. Mestre (2012), Heredia and Mestre (2011, 2013) and Mestre and Heredia (2013) identified *Y. crassus* in the uppermost meters of the San Juan Formation at the El Aluvión Creek (Cerro Viejo de Huaco area), Cerro La Chilca and in the Las Chacritas River sections. Mestre (2013) identified the *Y. crassus* Zone through transitional beds between the San Juan and Gualcamayo formations in the Villicum Range. On the other hand, a rich conodont fauna was documented in association with the index species *Y. crassus* and *H. holodentata* in the upper strata of the San Juan Formation at the Oculta Creek section (Voldman *et al.*, 2013). In a recent study, the first appearance datum of *Y. crassus* was recorded 15 m below the top of the San Juan Formation at the Las Aguaditas Creek section, delimiting the lower boundary of this biozone, whereas the upper limit is marked by the presence of *Dzikodus tablepointensis* (Stouge), 19 m above the base of the Las Aguaditas Formation (Feltes *et al.*, 2016). These authors recognized a similar faunal relationship and recovered elements of *L. variabilis*, *H. sinuosa*, *H. holodentata* and *P. horridus* co-occurring with *Y. crassus*. These faunal relationships are in accordance with those obtained from the Cerro La Chilca, and reinforce the identification of the *Y. crassus* Zone through the uppermost strata of the San Juan Formation and the lower part of the Gualcamayo Formation.

4.4. Global correlation

The presence of *Y. crassus* in the Cerro La Chilca section is significant for intercontinental correlation, used as an index species in the stratigraphic schemes of Baltoscandia (Löfgren, 2004), South China (Zhang, 1998), and recently incorporated in the biozonal scheme of the Argentine Precordillera (Heredia *et al.*, 2011; Albanesi and Ortega, 2016). The abundance of *Histiodella* species at the Cerro La Chilca section allow for a precise correlation with western Newfoundland (Stouge, 2012) and North China (Wang *et al.*, 2014; Jing *et al.*, 2016).

The *Y. crassus* Zone is widely recognized in the Baltoscandian Region, for example in Kinnekulle and Gullhögen at Billingen (Zhang, 1997, 1998), Scania (Erlström *et al.*, 2001), Gulf of Bothnia (Löfgren, 1985; Zhang, 1997), Gillberga and Hagudden on Öland (Stouge and Bagnoli, 1990; Zhang, 1997; Löfgren, 2000), southern Gotland (Zhang, 1998) and Estonia (Zhang, 1997; Viira *et al.*, 2001); although, there are exceptions such as Norway, where the species was not recorded (Rasmussen, 2001). Löfgren and Zhang (2003) reported that *Y. crassus* first appearance co-occurs with *L. variabilis* and it disappears in the basal part of the interval bearing few specimens of *E. pseudoplanus*.

In China, *Y. crassus* appears together with *P. horridus* and *P. macrodentatus* (Chen *et al.,* 2006). The species *P. macrodentatus* is recorded with *H. holodentata* in the Kuniutan Formation of South China (Zhang, 1998), and these species, together with *H. sinuosa* occur in the Dawangou Formation of the Tarim Region (Du *et al.,* 2005). The *Y. crassus* Zone was also documented in the Kuniutan Formation (Dw2) from the Yichang Region of the Yangtze Platform, South China (Zhang, 1998; Wu *et al.*, 2014).

In western Newfoundland, the *Y. crassus* Zone corresponds to the *P. macrodentatus* Zone, although restricted to the intermediate *H. holodentata* Subzone (Stouge, 2012). The presence of *Periodon macrodentatus* in the Middle Ordovician strata of the Oslobreen Group (Svalbard Archipelago) allows for correlation with the respective interval of the Laurentian margin (Lehnert *et al.*, 2013), the authors also mention the high abundance of *P. originalis*. Originally, in the Argentine Precordillera, the transitional forms between *Paroistodus originalis* and *P. horridus* were recorded through the upper part of the *L. variabilis* Zone, in the lower member of the Gualcamayo Formation at the Cerro Potrerillo section (Albanesi *et al.*, 1998; Albanesi and Barnes, 2000), allowing for the definition of the upper interval of the *L. variabilis* Zone; namely, the *P. horridus* Subzone (Albanesi and Ortega, 2002). At the Cerro La Chilca section, the record of *P. originalis*, *P. horridus secundus,* and *P. horridus horridus* coexist with *H. sinuosa* in the upper strata of the San Juan Formation suggesting stratigraphically younger strata than observed in the Oslobreen Group.

The conodont fauna from Thompson Creek, New Zealand, is referred to the middle Darriwilian (Zhen *et al.*, 2009), comparable with contemporaneous units of central New South Wales (Zhen and Percival, 2004). The conodont association described by the authors resembles that of the Cerro La Chilca section; namely, *A. jemtlandica*, *C. longibasis*, *D.* cf. *reclinatus*, *D. tablepointensis*, *P. simplicissimus*, *V. balticus*, *P. macrodentatus*, *H. holodentata*, *P. originalis* and *P. horridus*. The co-occurrence of the latter four species enables correlation of the uppermost strata of the San Juan Formation and the Gualcamayo Formation with the Thompson Creek succession in New Zealand.

5. Graptolite fauna

A diverse graptoloid assemblage is recognized in the Gualcamayo Formation at the Cerro La Chilca section (Fig. 7): *Acrograptus* sp., *H. bovis*, *Holmograptus* sp., *P. parallelus*, *X. lofuensis*, *Xiphograptus* sp., *Thamnograptus* sp., *Jiangshanites*? sp., *Pseudophyllograptus* sp., *T. bigsbyi*, *T. quadribrachiatus*, *A. zhejiangensis*, *Arienigraptus* sp., *P. caduceus, Glossograptus* sp., *P. tentaculatus*, *L. austrodentatus*, *L. dentatus*, *L. primus*, *L. sinicus* and *Levisograptus* sp. (Serra *et al.,* 2017). This assemblage belongs to the epipelagic and deep-water biotopes; most part of the recorded taxa are pandemic forms but few components are endemic of low paleolatitudes as genus *Paraglossogrpatus*. Epipelagic biotope is represented principally by biserial Axonophora (genus *Levisograptus*) and the deep-water biotope is characterized by isograptids and glossograptids (Goldman *et al.*, 2013, and references therein). The documented taxa allow the recognition of the pelagic biofacies defined by Cooper *et al.* (2012) which represents a diverse graptoloid assemblage in offshore environments.

As referred in Serra *et al.* (2017), the graptolite assemblage is dominated by the genus *Pseudo-*

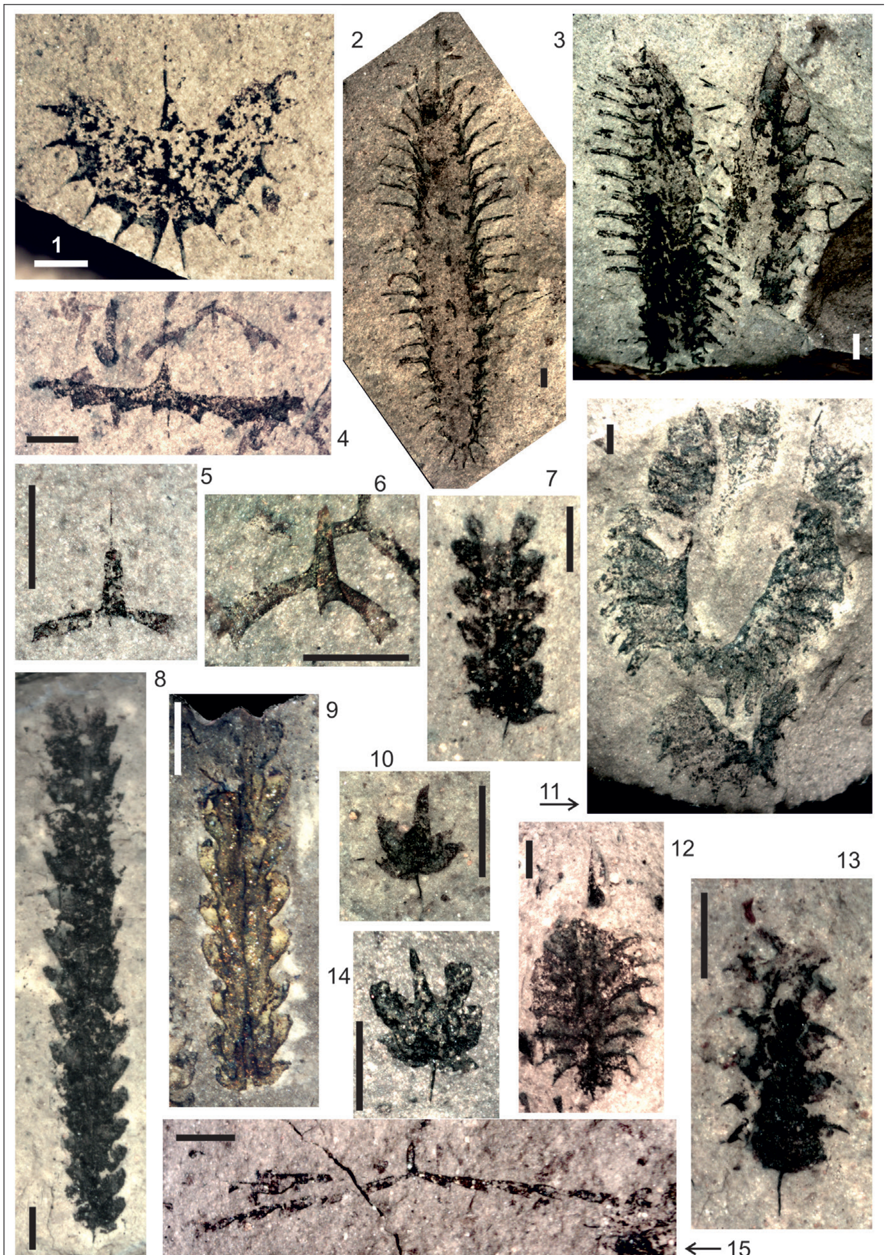

FIG. 7. Graptolites from the Gualcamayo Formation at the Cerro La Chilca section. **1.** *Arienigraptus zhejiangensis* (Yu and Fang), sample G4, CORD-PZ 25778. **2-3.** *Paraglossograptus tentaculatus* Hall; **2.** Sample Gf4 (see Serra *et al.*, 2017), CORD-PZ 22272; **3.** Sample G4, CORD-PZ 25779; **4.** *Xiphograptus lofuensis* **Lee**, sample G7, CORD-PZ 22458; **5, 15.** *Holmograptus bovis* Williams and Stevens, sample G75; **5.** CORD-PZ 22459; **15.** CORD-PZ 25728. **6.** *Pseudobryograptus parallelus* Mu, sample G3, CORD-PZ 25777; **7-8.** *Levisograptus dentatus* (Brongniart), k-bentonite strata between samples G5 and G6 (sample Gf7 in Serra *et al.*, 2017); **7.** CORD-PZ 22361; **8.** CORD-PZ 22354. **9.** *Levisograptus austrodentatus* (Harris and Keble), k-bentonite strata between samples G5 and G6 (sample Gf7 in Serra *et al.*, 2017), CORD-PZ 22443; **10, 14.** *Levisograptus* sp. **10.** k-bentonite strata between samples G5 and G6 (sample Gf7 in Serra *et al.*, 2017), CORD-PZ 22384; **14.** Sample G7, CORD-PZ 22456; **11.** *Tetragraptus bigsbyi* (Hall), sample Gf4 (see Serra *et al.*, 2017), CORD-PZ 25778. **12.** *Pseudophyllograptus* sp. Sample Gf2 (see Serra *et al.*, 2017), CORD-PZ 22221. **13.** *Levisograptus sinicus* Mu and Lee, k-bentonite strata between samples G5 and G6 (sample Gf7 in Serra *et al.*, 2017), CORD-PZ 22328. Scale bar: 1 mm.

bryograptus in the lower part of the Gualcamayo Formation at the Cerro La Chilca, which decreases to the top where the genus *Levisograptus* becomes a common component of the fauna and some taxa, such as *L. primus*, *P. caduceus* and *Pseudophyllograptus* sp. appear for the first time. Although environmental conditions are interpreted to be homogeneous through the unit (Henderson *et al.*, 2018), local changes in the taxonomic composition could be the consequence of immigration due to subtle environmental changes in the conditions of the water column, not observed in the lithofacies. Also, in this unit a constant alternation of carbonate and shale is recorded, sea level change could have affected the graptolite assemblages accounting for the local replacement of species.

The lower middle Darriwilian graptolite assemblages present in different sections of the Central Precordillera (Cerro Potrerillo, Cerro Viejo de Huaco, Quebrada Oculta, Quebrada de Las Aguaditas, and Cerro La Chilca sections) contain rich and abundant epi- and mesopelagic components that belong to the pelagic biofacies (*sensu* Cooper *et al.,* 2012). However, in the different localities a slightly different association of graptolites is developed, which reflects preference to different environmental conditions for graptolite associations. Although these units record the drowning of the carbonate platform, the Los Azules Formation (Cerro Viejo section) and the Gualcamayo Formation (Cerro Potrerillo section) represent deeper depositional environment compared to that of the Las Aguaditas Formation (Las Aguaditas Creek section) and the Gualcamayo Formation (Cerro La Chilca section). It is worth mentioning the diachronous nature of the Gualcamayo Formation, where the black shales from the base of the middle member in the Cerro Potrerillo section (north of Precordillera) are equivalent in age to the alternating carbonate and black laminated shale unit in the Cerro La Chilca section (to the south in the Central Precordillera).

In the Oculta Creek, Los Cauquenes Range, the lower member of the Los Azules Formation is dominated by *T. acanthonotus*, and to a lesser extent by *P. ensiformis* and *A. zhejiangensis*, the first two species absent in the Las Aguaditas Formation and the Gualcamayo Formation (Cerro La Chilca section). Also, *Isograptus divergens* Harris and *Brachiograptus etaformis* Harris and Keble are only present in the Los Azules Formation, indicating deeper-water environments. On the other hand, *P. parallelus* is particularly abundant in the Gualcamayo Formation of the Cerro La Chilca. The species *Cryptograptus antennarius* (Hall) was documented in the Los Azules and Las Aguaditas formations and *C.* cf. *antennarius* in the lower member of the Gualcamayo Formation at Cerro Potrerillo section. The scheme of figure 8 represents the spatial arrangement of the main genera of lower middle Darriwilian graptolites in the in the Cerro La Chilca section and other areas of the Central Precordillera. As in the Cerro La Chilca section, the early middle Darriwilian graptolite assemblages in other sections of the Central Precordillera belong to the epipelagic and deep-water biotopes, preserved in outer-shelf facies.

6. Concluding Remarks

A diverse conodont association was recovered from the uppermost San Juan Formation and the Gualcamayo Formation exposed at the Cerro La Chilca classical locality. The presence of *Paroistodus horridus horridus*, *Y. crassus* and *H. sinuosa* allows constraining the top of the San Juan Formation to the base of the *Y. crassus* Zone of the Baltic scheme and to the *H. sinuosa* Subzone of the *P. macrodentatus* Zone of the North American scheme. In the overlying Gualcamayo Formation the co-existence of *Y. crassus* with *H. holodentata* enable the recognition of the *Y. crassus* Zone and the *H. holodentata* Subzone of the *P. macrodentatus* Zone of the relative schemes.

The identification of the *Y. crassus* Zone, as well as the *H. sinuosa* and *H. holodentata* subzones enable the correlation between the study interval with coeval strata at the Las Aguaditas Creek section, Las Chacritas River section, Cerro Potrerillo section, Villicum range, Cerro Viejo de Huaco, Oculta Creek, with the Yerba Loca Formation at Ancaucha creek, and with the Los Sombreros Formation at Los Túneles of Jáchal river, and globally with Baltoscandia, China, western Newfoundland, New Zealand and New South Wales.

A graptolite assemblage belonging to the epipelagic and deep-water biotopes with some components restricted to low paleolatitudes is recognized. This diverse assemblage belongs to the pelagic biofacies, in coherence with the offshore sedimentation environment suggested for the Gualcamayo Formation at the Cerro La Chilca. The local changes observed in the taxonomic

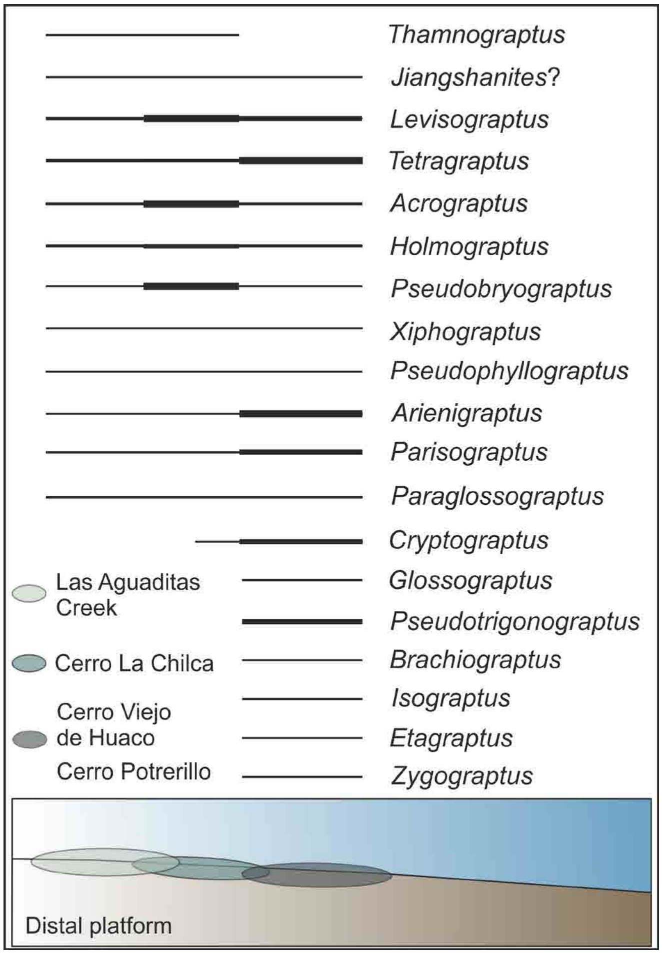

FIG. 8. Scheme showing the distribution of the graptolite genera documented along the distal platform in different areas from the Central Precordillera (Cerro Potrerillo, Oculta Creek, Cerro Viejo de Huaco, Las Aguaditas Creek and Cerro La Chilca sections). Thickness of lines represents the relative abundance of the genera. Figure adapted from Boucot and Chen (2009).

composition along this unit could be the consequence of immigration due to environmental changes in the conditions of the water column, not observed in the lithofacies. On the other hand, the constant alternations of carbonate and shale of this formation driven by sea level change, could also affect the graptolite assemblages accounting for the local replacement of the graptolite species.

Slight differences in the taxonomical composition of different study localities from the Central Precordillera supports the preference of certain associations for particular environments. Graptolites are more diverse in the lower member of the Los Azules Formation, in black shales facies that represent a deeper environment, in relation to the calcareous-shale facies of the Gualcamayo and Las Aguaditas formations of the Cerro La Chilca and Las Aguaditas Creek, respectively.

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