



Research paper

Darriwilian (Middle Ordovician) conodont biofacies from the Central Precordillera of Argentina

Fernanda Serra^{a,c,*}, Nicolás A. Feltes^{a,c}, Miles A. Henderson^b, Guillermo L. Albanesi^{a,c}^a CICTERRA (CONICET-UNC), Av. Vélez Sarsfield 1611, Córdoba X5016GCA, Argentina^b Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN 37996, United States^c CONICET, Museo de Paleontología, CIGEA, FCFyN, UNC, Av. Vélez Sarsfield 299, Córdoba, X5000FCO, Argentina

ARTICLE INFO

Article history:

Received 15 April 2016

Received in revised form 6 December 2016

Accepted 10 December 2016

Available online 14 December 2016

Keywords:

Conodont paleoecology

Middle Ordovician

Precordillera

Argentina

ABSTRACT

Conodont biofacies structure was recognized throughout detailed stratigraphic sampling at three localities from the Central Precordillera of Argentina; from north to south: Las Aguaditas Creek, Las Chacritas River and Cerro La Chilca sections. A total of 50 carbonate samples yielded over 9900 identified specimens, including a new conodont species, *Fahraeusodus jachalensis*, which is described due to its paleoecological connotations. The *Yangtzeplacognathus crassus* – *Eoplacognathus pseudoplanus* and *Periodon macrodentatus* zones are dominated by the ubiquitous species *Periodon macrodentatus* and *Paroistodus horridus* at the three study areas. This enables the recognition of the *Periodon*–*Paroistodus* biofacies in the Central Precordillera. Numerical cluster methodology allowed the identification of conodont sub-biofacies: the *Protopanderodus*–*Semiacontiodus* sub-biofacies in the Las Aguaditas Creek, the *Protopanderodus*–*Parapaltodus* sub-biofacies in the Las Chacritas River, the *Parapaltodus* sub-biofacies at the Cerro La Chilca and the *Fahraeusodus*–*Ansella* sub-biofacies in all of the study sections. These sub-biofacies present distinctive attributes, which are correlative with changes in the depositional environment. The diverse *Protopanderodus*–*Parapaltodus* sub-biofacies developed with a shallowing of the basin while the *Fahraeusodus*–*Ansella* sub-biofacies is characteristic of deep environments. Shallower water settings resulted in higher species richness, diversity, and evenness of conodont communities, the eustatic change that led to the drowning of the carbonate platform produced a shift to deeper, anoxic benthic conditions that in turn induced a change in the taxonomic composition of the fauna, and affected the diversity of the conodont communities.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

The paleoecology of conodonts has received much attention after the pioneering works of Barnes et al. (1973, 1996), Clark et al. (1981), Aldridge (1988) and Sweet (1988). Seddon and Sweet (1971) proposed a paleoecological model in which conodonts were pelagic animals and species were vertically segregated. An alternative model suggested that conodonts were nektobenthic organisms and were laterally segregated by environmental factors such as temperature, salinity, oxygen, physical and chemical conditions of the sea bottom and water turbulence (Barnes and Fähræus, 1975). More recently, the high diversity of Ordovician conodonts was used to suggest a combined ecological model, in which conodonts occupied a variety of available ecological niches with different modes of life (Zhen and Percival, 2003).

The distribution of conodonts was controlled by physical factors summarized by Seddon and Sweet (1971). Barnes and Fähræus (1975) noted that the spatial distribution of most conodonts was

environmentally controlled and their depositional settings could be predicted. A recurring theme in conodont paleoecology in recent years has been the effect of eustatic sea level change on conodont community structure (Sweet and Bergström, 1984; Rasmussen and Stouge, 1995; Mellgren and Eriksson, 2010; Wu et al., 2010, 2014). For example, patterns of Middle Ordovician conodont diversity change, in the Argentine Precordillera, were attributed mostly to oscillations in the sea level (Albanesi and Bergström, 2004, 2010).

Conodont biofacies and concomitant communities can be discriminated at different taxonomic levels; however, most studies recognize conodont communities at a generic-level since the diversity patterns of conodont genera do not significantly distort species level trends (Ji and Barnes, 1994; Albanesi and Bergström, 2004; Wu et al., 2014). Yet, some studies define conodont communities at species level in order to utilize more rigorous statistical and numerical methods (Zhang and Barnes, 2002, 2004; Zeballo and Albanesi, 2012).

The aim of this study is to identify and characterize Ordovician conodont biofacies through the middle Darriwilian, spanning the *Y. crassus* – *E. pseudoplanus* zones (*sensu* Löfgren and Zhang, 2003) (or the coeval *P. macrodentatus* Zone *sensu* Stouge, 2012) in the Argentine Precordillera. The biofacies are defined according to the predominant genera in

* Corresponding author at: CICTERRA (CONICET-UNC), Av. Vélez Sarsfield 1611, Córdoba X5016GCA, Argentina.

E-mail address: fserra@unc.edu.ar (F. Serra).

selected sections, and to the fact that certain species tend to co-occur in particular lithologies and environments. These associations of taxa, verified through cluster analysis, define sub-biofacies and are named by the more abundant conodont genera (cf. Ludvigsen et al., 1986). Samples with a similar taxonomic composition are grouped into clusters and represent particular environments. Detailed stratigraphic sampling for conodonts in three correlative localities allows the conodont communities to be examined through time. The resulting dataset provides the opportunity to investigate the community structure and relationships of conodont assemblages collected among different depositional environments.

2. Geological setting

The Precordillera of western Argentina extends 110 km zonally and 450 km meridionally, bounded by the Sierras Pampeanas to the east and the Cordillera Frontal to the west. The Precordillera is characterized by a thick Cambro-Ordovician succession (ca. 2200 m) of marine limestones that interdigitate with clastic slope deposits towards the west (Keller et al., 1993; Astini, 1995). Spanning a range of depositional environments, from shallow intertidal to marginal shelf and deep ramp settings (Cañas, 1999), the Precordillera is the only South American lower Paleozoic basin with a carbonate platform. The drowning of the carbonate platform associated with a rapid sea level rise led to the widespread deposition of graptolitic black shales during the early Middle Ordovician (e.g., Gualcamayo and Los Azules formations). The Las Chacritas, Sassito and Las Aguaditas formations are the only remnants of carbonate deposits in the entire Precordillera after the Cambro-Ordovician carbonate cycle, and the Las Aguaditas Formation is the only unit that shows a transition from platform to slope depositional environment that occurred in the Middle Ordovician (Keller et al., 1993; Astini, 1995).

Three localities in the area surrounding Jáchal City (Fig. 1) provide a robust dataset from different depositional settings, which is ideal for studying conodont paleoecology. The Las Aguaditas and the Las Chacritas formations are remnants of carbonate deposits laid down after the Cambro-Ordovician carbonate cycle in the Precordillera (Astini, 1995). The Gualcamayo Formation conformably overlies the San Juan limestones and is characterized by black shales interbedded with calcareous strata, deposited on the outer platform (Astini, 1994).

2.1. Las Aguaditas Creek section

The type section of the Las Aguaditas Formation is located on the eastern flank of the Los Blanquitos Range, in the Central Precordillera

of San Juan Province, 10 km to the southwest of Jáchal City (Fig. 1). Baldis and Blasco (1974) recognized and described four members, which comprise marlstone, limestones, and reef limestones, with a characteristic yellowish weathering color; posteriorly, Baldis et al. (1982) formally defined Las Aguaditas Formation. This formation conformably overlies the San Juan Formation that ends up with nodular limestones facies (Baldis et al., 1982), and its top conforms a regional hardground surface (Astini, 1995). Baldis and Blasco (1974) recognized a stratigraphic gap between the upper member of the Las Aguaditas Formation and the overlying La Chilca Formation of Late Ordovician to Silurian age.

The uppermost part of the San Juan Formation represents a distal ramp environment without storm influence. The transition between this unit and the overlying Las Aguaditas Formation is characterized by calcareous-pelitic deposits, whose depositional regime is interpreted to have been caused by a flooding event on the platform, since there is no evidence of a significant stratigraphic gap at the contact (Keller et al., 1993; Carrera and Astini, 1998). This local event led to a facies change with the deposition of hemipelagic limestones at the transition to the Las Aguaditas Formation (Keller et al., 1993). In the Las Aguaditas Formation, three transgressive and regressive cycles were distinguished by Astini (1995). This author also described two types of facies associations that replace each other through the formation, a distal ramp to slope-basin facies transition, and an upper to middle slope facies. The Las Aguaditas Formation is interpreted as deposited on structural heights (horsts) and slopes within the basin (Astini, 1995, 1997).

In this study we analyze the upper part of the San Juan Formation and the lower member of the Las Aguaditas Formation of middle Darriwilian age. A hiatus that spans the upper Darriwilian and the basal Sandbian separates the lower and middle members. It is indicated by the presence of the index graptolite *Nemagraptus gracilis* (Hall) and the index conodonts *Pygodus anserinus* (Lamont and Lindström) and *Baltoniodus variabilis* (Bergström) close to the base of the middle member (Brussa, 1996; Albanesi et al., 2013; Feltes et al., 2016).

The environmental changes recognized through the lithology are associated with faunal turnovers between the San Juan and the Las Aguaditas formations. Sponge remnants dominate the top of the San Juan limestone, while bryozoans dominate the Las Aguaditas Formation (Carrera, 1997; Carrera and Ernst, 2010). The outer-shelf deposits of the San Juan Formation and those of deeper water from the base of the Las Aguaditas Formation exhibit a high diversity of conodonts reflecting nutrient enrichment by upwelling currents and shallow to deep-water faunal exchange (Albanesi et al., 2006).

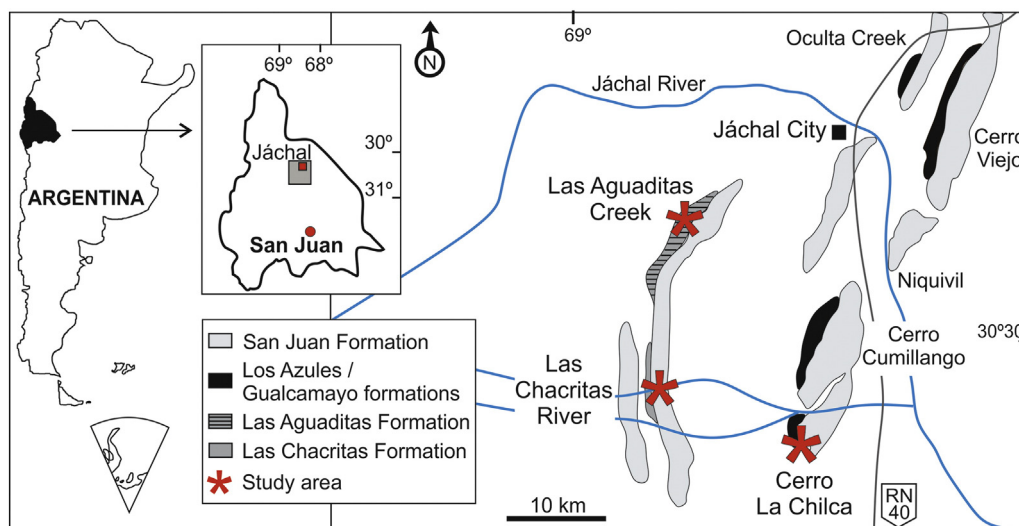


Fig. 1. Location map of the study areas. From north to south of the Central Precordillera: Las Aguaditas Creek, Las Chacritas River, and Cerro La Chilca sections.

2.2. Las Chacritas River section

The Las Chacritas Formation crops out in the northern La Trampa Range (Fig. 1). In this area, the Lower to Middle Ordovician San Juan Formation is conformably overlain by the middle Darriwilian Las Chacritas Formation. In the present study we analyze the northern section of the Las Chacritas river area, where the Las Chacritas Formation is paraconformably overlain by the lower Sandbian Las Aguaditas Formation (Carrera and Astini, 1998; Albanesi and Ortega, 1998), and part of middle to upper Darriwilian strata are missing.

The Las Chacritas Formation is a 55 m thick succession made up of fine-grained siliciclastic and carbonate sediments deposited on a continental shelf setting (Peralta et al., 1999; Carrera, 1997). The Las Chacritas Formation is divided into two members; the lower member is a 38 m thick series of tabular strata of thin to medium bedded fossiliferous, dark mudstones, nodular wackestones and packstones (Peralta et al., 1999). The 17 m thick upper member is comprised of thinly bedded mudstones and wackestones, with increasing bioclastic components towards the top of the unit (Carrera and Astini, 1998; Peralta et al., 1999). Astini (1995, 1997) suggested that it was deposited on structural heights (horsts) within the basin, which served as a reservoir of carbonate remnants. The Las Chacritas Formation is paraconformably overlain by the Las Aguaditas Formation expressing further drowning and cessation of carbonate deposition on the platform (Peralta et al., 1999).

The study published by Albanesi et al. (2013) demonstrates the occurrence of the middle Darriwilian Isotope Excursion Event (MDICE) in the Las Chacritas Formation at the *E. suecicus* Zone, which allows for precise global correlation by means of an independent method. The record of this event was in turn verified by means of conodont-graptolite biostratigraphy, within the expected chronostratigraphic time slice of Bergström et al. (2009).

2.3. Cerro La Chilca section

The Cerro La Chilca is located 18 km west of Tucunuco, a road reference in the San Juan Province (Fig. 1). This section comprises a succession of shales and siltstones overlying the San Juan Formation (Stappenbeck, 1910). Astini and Benedetto (1992) referred to these shales as the Gualcamayo Formation based on regional correlations, and interpreted them as the beginning of a transgressive event. At this locality, the Gualcamayo Formation is a 12.5 m thick transitional interval characterized by shales and dark gray laminated calcipelites (Astini and Benedetto, 1992). The Gualcamayo Formation is paraconformably overlain by the *Nemagraptus gracilis* bearing black shales of the Los Azules Formation (Cuerda and Furque, 1985).

In later works, Peralta (1998, 2003) and Tortello and Peralta (2004) described the Gualcamayo Formation in this section as a ca. 4.5 m sequence, which consists of an alternation of thin to medium layers of black, tabular marly limestones, and dark laminated shales, with beds of 5 to 28 cm in thickness.

3. Materials and methods

A total of 64 limestone samples were collected from the Las Aguaditas Creek, Las Chacritas River and Cerro La Chilca sections. The samples (2 kg each) were processed using 10% acetic acid and insoluble residues were hand-picked for conodonts, with a total collection of 17,300 elements recovered. Only samples that yielded conodonts from the *Y. crassus* – *E. pseudoplanus* and *Periodon macrodentatus* zones were used in this study (50 samples and 9927 elements in total) (Table 1, Fig. 2). The taxonomic databases used herein were carefully developed as part of the PhD theses of the authors Serra, F and Feltes, N (partly published by Feltes et al., 2016; Serra et al., 2015a).

Quantitative analytical methods are introduced to differentiate conodont biofacies and sub-biofacies occurring in the successions. These

analyses were based on abundance data of species obtained from the samples. In particular, data were analyzed using Hierarchical Cluster Analysis (HCA) to distinguish biofacies and their faunal composition, and Detrended Correspondence Analysis (DCA) was used to elucidate environmental gradients among the assemblages. Clustering was conducted using the average linkage method and the Morisita similarity index was used to measure similarity. Moreover, we performed an analysis of similarities (ANOSIM) to statistically examine significant differences between the associations recognized by the HCA. Finally, a series of diversity indices were determined in order to characterize the conodont associations identified by the HCA: richness (S), evenness, Shannon (H) and Effective numbers of species (ENS).

Conodont specimens were taxonomically identified at species level. Prior to the HCA, the species abundances were log-transformed in order to down-weight taxa with high abundances. Samples comprised of only one taxon and taxa occurring only in a single sample (considered rare species) were excluded from the analyses. With these exclusions, seventeen samples from the Las Aguaditas Creek section were analyzed, eight from the upper 17 m of the underlying San Juan Formation and nine samples from the first 23.5 m of the lower member of the Las Aguaditas Formation, with a total of 5445 elements corresponding to 45 species. Twenty-two samples were used from the Las Chacritas River section, 5 from the top 24 m of the San Juan Formation and 17 from the first 52.5 m of the Las Chacritas Formation. These samples yielded 3570 elements corresponding to 43 species. Finally, four samples corresponding to the upper 4.6 m of the San Juan Formation and 7 samples corresponding to the Gualcamayo Formation from the Cerro La Chilca section were used, providing 912 elements corresponding to 32 species.

The HCA, DCA and ANOSIM were performed using the PAST program (Hammer et al., 2001; Hammer and Harper, 2006).

4. Remarks on the biostratigraphy of the study sections

Comprehensive biostratigraphic studies for the interval spanning the contact between the San Juan Formation and Ordovician overlying units at the study areas were carried out by Serra et al. (2015a) and Feltes et al. (2016). In these papers, the records of species are illustrated in stratigraphic columns with their respective ranges and the conodont zonation is depicted. Accordingly, the following zones were determined in the Las Aguaditas Creek section: the *Lenodus variabilis* Zone, with the *Paroistodus horridus* Subzone following the Precordilleran scheme (*sensu* Albanesi and Ortega, 2002); the *Yangtzeplacognathus crassus*, and the *Eoplacognathus pseudoplanus* Zones according to the Scandinavian scheme (*sensu* Löfgren and Zhang, 2003); the *Periodon macrodentatus* Zone with the *Histiodela sinuosa*, *H. holodentata* and *H. cf. holodentata* Subzones, and the *Periodon zgierzensis* Zone with the *Histiodela kristinae* Subzone (*sensu* Stouge, 2012) that correlate with the North American scheme (Feltes et al., 2016). These biozones were identified in the Las Chacritas area, where the *Eoplacognathus suecicus* Zone and the *Histiodela bellburnensis* Subzone (*P. zgierzensis* Zone) were also recognized (Serra et al., 2015a). The *Y. crassus* Zone and the *Periodon macrodentatus* with the *Histiodela sinuosa* and *H. holodentata* Subzones were documented in the Cerro La Chilca locality (Carrera et al., 2013; Serra et al., 2015b). The standard conodont biozonation of the Precordillera was reviewed thoroughly in a recent contribution by Albanesi and Ortega (2016).

5. Cluster analysis: recognition of biofacies and sub-biofacies

The analyzed conodont zones are dominated by the ubiquitous species *Periodon macrodentatus* (Graves and Ellison) and *Paroistodus horridus* (Barnes and Poplawski) in the three study areas (the distribution and abundance of conodont species are represented in Fig. 3). This enables the recognition of the *Periodon*–*Paroistodus* biofacies in the Central Precordillera. In addition, Q-mode clustering of the samples from

Table 1 (continued)

La Chilca Hill section	4,6	3,6	1,6	1	0	0,5	1	1,6	2,1	3,3	4
Meters from the base of the Gualcamayo Fm	SJ-3	SJ-2	SJ-1	E	G0	G1	G2	G3	G4	G6	G7
	SJ-3	SJ-2	SJ-1	E	G0	G1	G2	G3	G4	G6	G7
<i>Ansella jemtlandica</i>	0	0	0	0	0	0	1	0	0	23	7
<i>Ansella sinuosa</i>	1	0	10	8	0	0	0	0	0	0	0
<i>Baltoniodus clavatus</i>	0	0	1	0	0	1	2	0	0	2	0
" <i>Bryantodina</i> " aff. <i>typicalis</i>	0	0	1	0	0	0	0	0	0	4	1
<i>Cornuodus longibasis</i>	1	0	1	2	0	0	0	0	0	0	0
<i>Drepanodus arcuatus</i>	0	0	6	0	1	0	1	0	0	2	2
<i>Drepanoistodus species</i>	0	0	9	5	1	0	0	0	3	2	1
<i>Erraticodon alternans</i>	0	0	1	0	0	0	1	0	0	1	1
<i>Fahraeusodus jachalensis</i>	1	0	6	1	0	0	7	0	1	35	15
<i>Histiodela holodentata</i>	0	0	0	0	0	0	1	1	0	0	2
<i>Microzarkodina hagetiana</i>	0	0	1	0	0	0	2	0	0	5	0
<i>Parapaltodus simplicissimus</i>	2	0	43	8	1	0	0	0	0	2	1
<i>Paroistodus horridus</i>	5	1	38	7	2	1	52	12	41	202	106
<i>Paroistodus originalis</i>	0	0	7	1	0	0	0	0	1	1	0
<i>Periodon macrodentatus</i>	3	1	39	11	0	0	13	0	24	36	24
<i>Protopanderodus gradatus</i>	1	1	5	1	1	0	0	0	0	8	0
<i>Pteracontiodus cryptodens</i>	1	0	2	0	0	0	0	0	1	1	0
<i>Scolopodus striatus</i>	0	0	9	0	0	0	0	0	0	0	0
<i>Venoistodus balticus</i>	0	0	0	0	0	0	1	0	0	2	12

the study sections allowed the identification of conodont sub-biofacies: the *Protopanderodus–Semiacontiodus* sub-biofacies in the Las Aguaditas Creek, the *Protopanderodus–Parapaltodus* sub-biofacies in the Las Chacritas River, the *Parapaltodus* sub-biofacies at the Cerro La Chilca and the *Fahraeusodus–Ansella* sub-biofacies in all of the study sections (Fig. 4). These associations were named after the genera that follow *Periodon* and *Paroistodus* in abundance.

5.1. Las Aguaditas Creek section

The Q-mode cluster analysis enables the recognition of two sub-biofacies, the *Protopanderodus–Semiacontiodus* and *Fahraeusodus–Ansella* sub-biofacies (Fig. 4a). The ANOSIM applied to test for significant differences between the identified clusters resulted in an R coefficient of 0.80 and *p* value of 0.0004*, providing a significant difference between the sub-biofacies identified, which supports the results of the HCA.

The *Protopanderodus–Semiacontiodus* sub-biofacies is represented in the upper 15 m of the San Juan Formation (samples ASJ0, ASJ1, ASJ2, ASJ3, ASJ4, ASJ5, ASJ6 and ASJ7) at the Las Aguaditas Creek section. This sub-biofacies shows a high conodont diversity ($H = 2.9$), with 44 species representing a community that integrates 18 equally distributed species (Table 2). It is mainly composed of *P. macrodentatus* and *P. horridus*, which denote 28% and 7% of the total abundance, respectively (Fig. 5a). *Protopanderodus gradatus* Serpagli and *Semiacontiodus potrerillensis* Albanesi follow in abundance contributing with 6% each, and the remaining 40 species have a minor participation, summing up to 53% in total.

The *Fahraeusodus–Ansella* sub-biofacies is represented in the Las Aguaditas Formation (samples A0, A1, A3, A8, A10, A15, A22 and A25) at the Las Aguaditas Creek. It consists of 21 species corresponding to 17 genera and exhibits low diversity ($H = 1.6$), equivalent to a community of 6 equally distributed species (Table 2). This association is dominated by *P. horridus* (55%) and *P. macrodentatus* (14%). *Fahraeusodus jachalensis* n. sp. and *Ansella jemtlandica* (Löfgren) represent this biofacies as the next most abundant taxa, 15% and 3%, respectively (Fig. 5b). The remaining 7 species contribute 13% of the conodont fauna.

5.2. Las Chacritas River section

Two sub-biofacies, the *Protopanderodus–Parapaltodus* sub-biofacies and the *Fahraeusodus–Ansella* sub-biofacies are recognized by Q- mode

cluster analysis (Fig. 4b). The ANOSIM applied to test for significant differences between the identified clusters resulted in an R coefficient of 0.82 and *p* value of 0.0001*. This provides a significant difference between the identified sub-biofacies and supports the results of the HCA.

The *Protopanderodus–Parapaltodus* sub-biofacies is identified in the upper strata of the San Juan Formation (samples CSJ-1 and CSJ-2) and in the middle-upper part of the Las Chacritas Formation (samples C6.5, C11, C12, C14, C16 and C17) at the Las Chacritas River section. The sub-biofacies is characterized by 43 species and exhibits a high conodont diversity ($H = 2.7$), equivalent to a community of 15 equally-common species (Table 2). The most abundant species are *Parapaltodus simplicissimus* Stouge and *P. gradatus* which represent 14% of the total abundance; although, the dominating species are *P. horridus* and *P. macrodentatus*, which cover 47% of the total abundance (Fig. 6a). The remaining 38 species are represented in a lower amount reaching up to 39%.

The *Fahraeusodus–Ansella* sub-biofacies spans the uppermost San Juan Formation and the lower-middle part of the Las Chacritas Formation (samples CSJ0, C0, C1, C2, C4, C5, C6, C8, C9 and C10) at the Las Chacritas River. This sub-biofacies has a richness of 17 species that corresponds to 14 genera and a low diversity ($H = 1.8$) equivalent to a community that integrates 6 species. Within this interval, *P. horridus* (35%) and *P. macrodentatus* (28%) also dominate the association and are followed by *F. jachalensis* and *A. jemtlandica*, representing 16% and 6% of the total conodont fauna respectively (Fig. 6b), the remaining 13 species represent 15%.

5.3. Cerro La Chilca section

The Q- mode cluster analysis enables the identification of the *Parapaltodus* sub-biofacies and the *Fahraeusodus–Ansella* sub-biofacies (Fig. 4c). The ANOSIM applied to test for significant differences between the identified clusters resulted in an R coefficient of 0.75 and *p* value of 0.029*. This provides a significant difference between the identified biofacies and supports the results of the HCA.

The *Parapaltodus* sub-biofacies is recorded through uppermost strata of the San Juan Formation (samples GSJ-3, GSJ-1, GE) at the Cerro La Chilca section. It presents a richness of 26 species, belonging to 22 genera, and its diversity is equivalent to a community with 12 species equally distributed (Table 2). The most abundant species are *P. macrodentatus* and *P. simplicissimus* representing 38% of the total

fauna, and *P. horridus* follows with 17.5% (Fig. 7a). The remaining 23 species contribute 44.5% to the total conodont fauna.

The *Fahraeusodus-Ansella* sub-biofacies is identified in the Gualcamayo Formation (samples G2, G4, G6 and G7) at the Cerro La

Chilca section. This sub-biofacies has a richness of 23 species belonging to 19 genera and its diversity is equivalent to a community composed of 4 species (Table 2). *Paroistodus horridus* dominates the association, representing 61% of the total abundance; *P. macrodentatus*, *F. jachalensis*

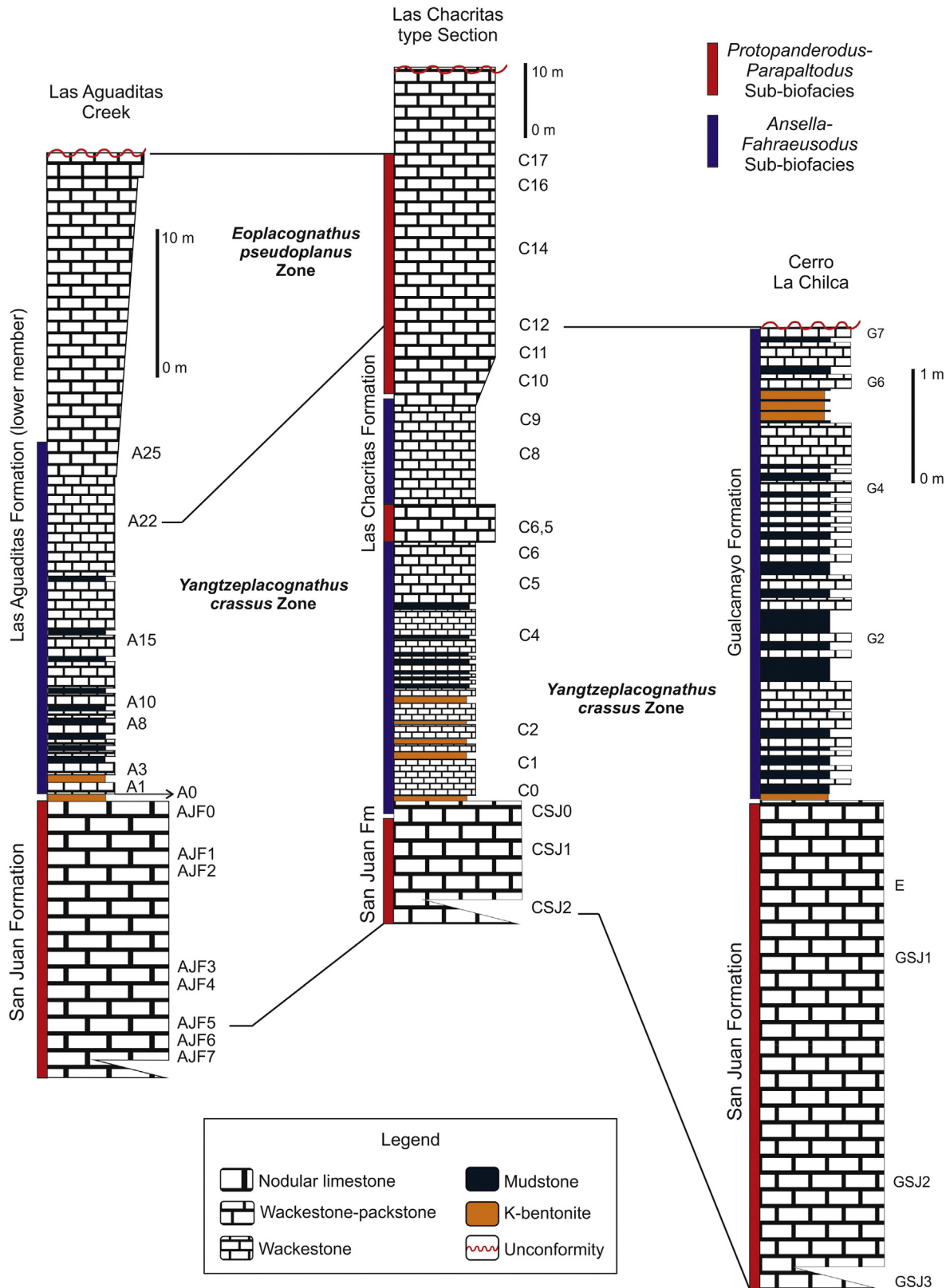


Fig. 2. Stratigraphic columns of the Las Aguaditas Creek, Las Chacritas and Cerro La Chilca sections from Central Precordillera, showing the sampled strata and the zones and sub-biofacies to which they belong.

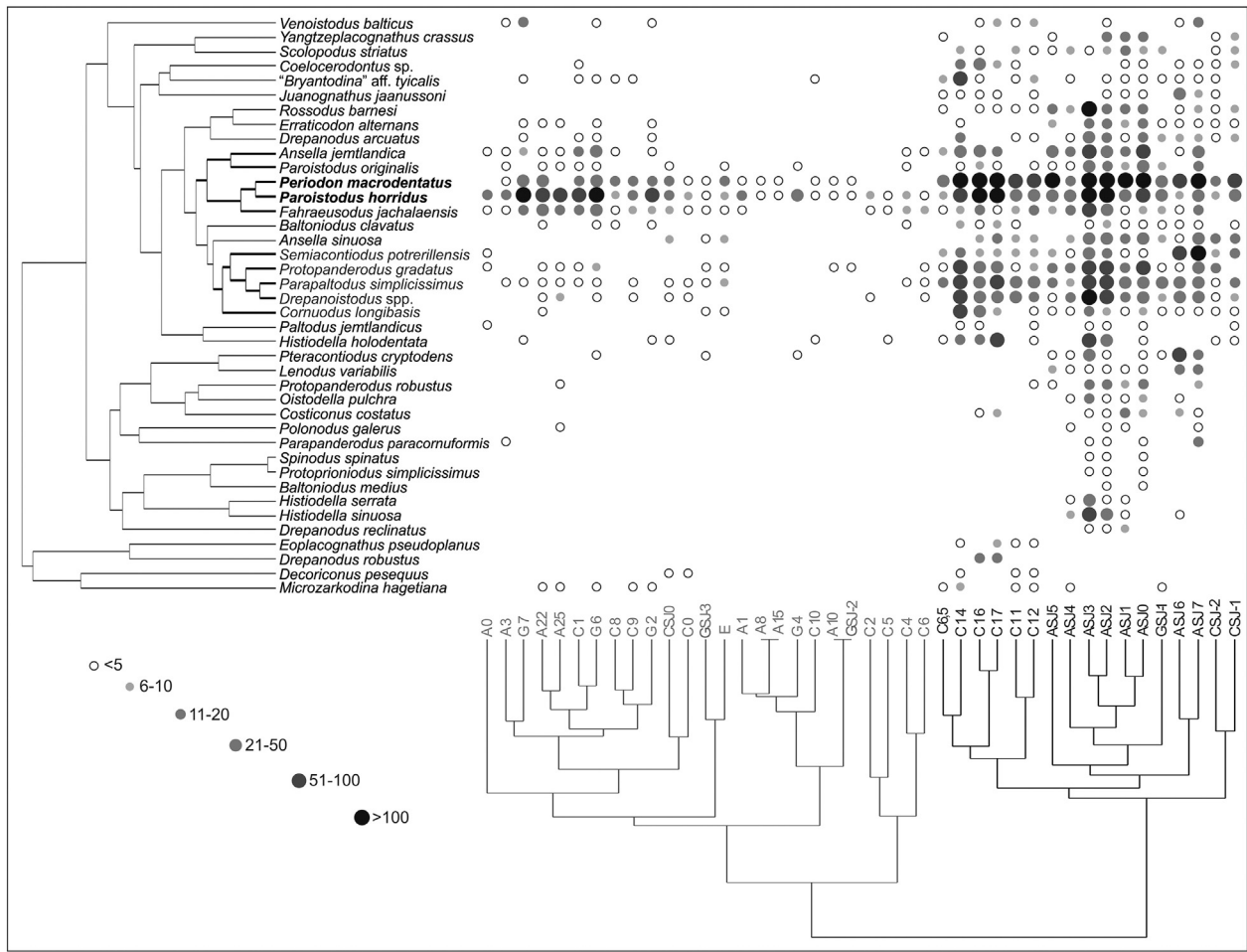


Fig. 3. Results of Q- and R-mode cluster analysis of 42 conodont-bearing samples from the Las Aguaditas Creek (samples ASJ and A), Las Chacritas River (samples CSJ and C) and Cerro La Chilca sections (samples GSJ and G). Samples are in Q-mode clustering order and taxa are in R-mode clustering order. Species abundance is expressed as a graded series of dots. The defined *Periodon*–*Paroistodus* biofacies for this area is marked in bolded letters.

and *A. jemtlandica* follow with 15%, 9% and 5%, respectively (Fig. 7b). The remaining 11% is represented by 19 species. This sub-biofacies presents a low conodont diversity, $H = 1.5$ (Table 2).

6. Conodont paleoecology

The *Periodon*–*Paroistodus* biofacies recognized herein was first identified in Middle Ordovician successions of western Newfoundland by Stouge (1984) as characteristic of deep, open-sea biotopes and occupying upper to lower slope environments (upper slope as the preferred environment). Since then, this biofacies has been recognized in other regions of the world (Stouge, 1981, 1984; Bergstrom, 1979; Zhang, 1998; Feltes and Albanesi, 2013; Serra and Albanesi, 2013; Wu et al., 2014). The *Fahraeusodus*–*Ansella* sub-biofacies was documented in all of the localities of this study and the *Protopanderodus*–*Semiacontiodus*, *Protopanderodus*–*Parapaltodus* and *Parapaltodus* sub-biofacies were documented at the Las Aguaditas, Las Chacritas and Cerro La Chilca sections, respectively. The later mentioned sub-biofacies are recognized in equivalent paleoenvironments and exhibit similar attributes such as the species composition, richness and diversity. For this reasons, they are referred to as the *Protopanderodus*–*Parapaltodus* sub-biofacies hereafter.

The most frequent genera from the *Protopanderodus*–*Parapaltodus* sub-biofacies include *Protopanderodus*, *Parapaltodus*, *Semiacontiodus*, *Cornuodus*, *Histiodela* and *Rossodus*. These taxa are representative of deep subtidal settings and, with the exception of *Histiodela*, are interpreted as epipelagics (Pohler, 1994). According to Stouge (1984),

this fauna is found in off shore and relatively deep environments. Other common genera, such as *Rossodus* and *Yangtzeplacognathus*, are thought to have inhabited relatively deep waters (Albanesi and Bergström, 2004; Mellgren and Eriksson, 2010). The latter is represented in this association by *Y. crassus* in the San Juan Formation (at Las Aguaditas, Las Chacritas and Cerro La Chilca sections) and the younger *Yangtzeplacognathus* sp. B. (Stouge, 2012) in the upper part of the Las Chacritas Formation. The presence of *P. simplicissimus* in high abundances was suggested to represent an open shelf environment (Stouge, 1984). The taxa *Cornuodus* and *Semiacontiodus* are related with the shallowest environments in Central Baltoscandia (Löfgren, 1999, 2004); accordingly, their presence in the *Protopanderodus*–*Parapaltodus* sub-biofacies suggests shallower settings.

The *Fahraeusodus*–*Ansella* sub-biofacies appears with the environmental change shown by the replacement of the San Juan Formation carbonate facies to the mixed calcareous-pelitic strata at the base of the Las Aguaditas, Las Chacritas and Gualcamayo formations. *Ansella*, *Drepanoistodus* and *Fahraeusodus* are the most abundant genera in this association. Stouge (1984) proposed for the Table Head Formation in Newfoundland that *Ansella* and *Drepanoistodus* in association with *Periodon* represent deep, proximal to distal slope environments. *Cornuodus longibasis* (Lindström) and *S. potrerillensis* are absent in the *Fahraeusodus*–*Ansella* sub-biofacies, with the exception of sample A22 from the Las Aguaditas Formation where *C. longibasis* reappears after the adverse conditions of the lower part of the unit, indicating a shallowing pulse, which could be related to the sudden increase in diversity as well.

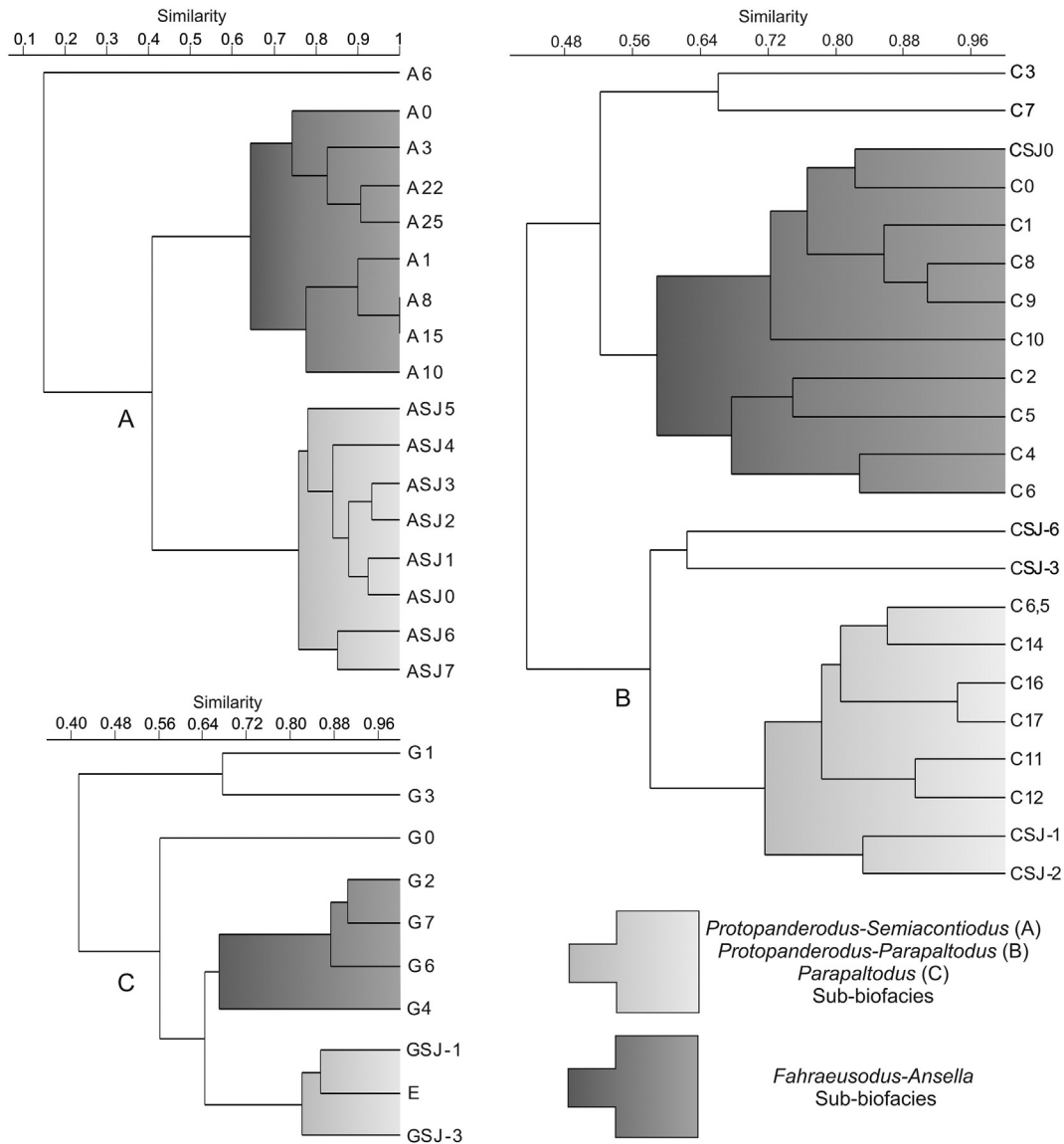


Fig. 4. Q-clusters from each section showing the sub-biofacies identified. (a) *Protopanderodus-Semiacontiodus* and *Fahraeusodus-Ansella* sub-biofacies from the Las Aguaditas Creek. (b) *Protopanderodus-Parapaltodus* and *Fahraeusodus-Ansella* sub-biofacies from the Las Chacritas River; (c) *Fahraeusodus-Ansella* sub-biofacies from the Cerro La Chilca section.

The genera *Drepanoistodus* and *Drepanodus* are distributed along the different lithofacies and present in both sub-biofacies, which suggest pelagic habits. Other taxa such as *Baltoniodus medius* (Dzik), *C. longibasis*, *Costiconus costatus* (Dzik), *Juanognathus jaanussoni* Serpagli, *Oistodella pulchra* Bradshaw, *Polonodus* spp. *Rossodus barnesi* Albanesi, *S. potrerillensis* and *Scolopodus striatus* Pander were only recorded in the carbonate samples that compose the *Protopanderodus-Parapaltodus*

Table 2

Diversity indexes calculated for the identified sub-biofacies of the Las Aguaditas Creek, Las Chacritas River and Cerro La Chilca sections. Abbreviations, P-S: *Protopanderodus-Semiacontiodus* sub-biofacies; F-A: *Fahraeusodus-Ansella* sub-biofacies; P-P: *Protopanderodus-Parapaltodus* sub-biofacies; P.: *Parapaltodus* sub-biofacies.

	Las Aguaditas Creek		Las Chacritas River		Cerro La Chilca	
	P-S	F-A	P-P	F-A	P	F-A
Richness (S)	44	21	43	17	26	23
Abundance	5063	382	3036	328	274	664
Evenness	0,4	0,2	0,3	0,4	0,2	0,5
Shannon (H)	2,9	1,6	2,7	1,8	2,5	1,5
ENS (expH)	18	5	15	6	12	4

sub-biofacies in the three study areas. Water depth seems to be a controlling factor for their distribution, with a preference to shallower settings. These species appear to be influenced by bottom conditions and their absence from the deeper *Fahraeusodus-Ansella* sub-biofacies indicates intolerance to deep, anoxic environments. The remaining species are documented in both sub-biofacies, although they are more abundant in the shallower *Protopanderodus-Parapaltodus* sub-biofacies. This suggests that they are more tolerant to a wide range of water depths, but prefer relatively more shallow water conditions.

The abundant genera documented in this study, such as *Periodon*, *Parioistodus*, *Protopanderodus*, *Parapaltodus*, *Ansella*, *Fahraeusodus*, *Histioidella* and *Drepanoistodus*, constitute an association that typically occurs in relatively deep environments at distal ramp to upper slope settings in different areas from North America (Bradshaw, 1969; Uyeno and Barnes, 1970; Barnes and Poplawski, 1973; Stouge, 1984). *Polonodus*, *Dzikodus* and *Periodon*, also recorded in our study area, are common genera from Baltica, North China, and South-Central China representing lower slope to open ocean settings with low diversity (Löfgren, 1978, 2000; Bergstrom, 1983; An and Zheng, 1990; Stouge and Bagnoli, 1990; Bagnoli and Stouge, 1997; Zhang, 1998; Rasmussen, 2001). In consistency with our interpretations, the

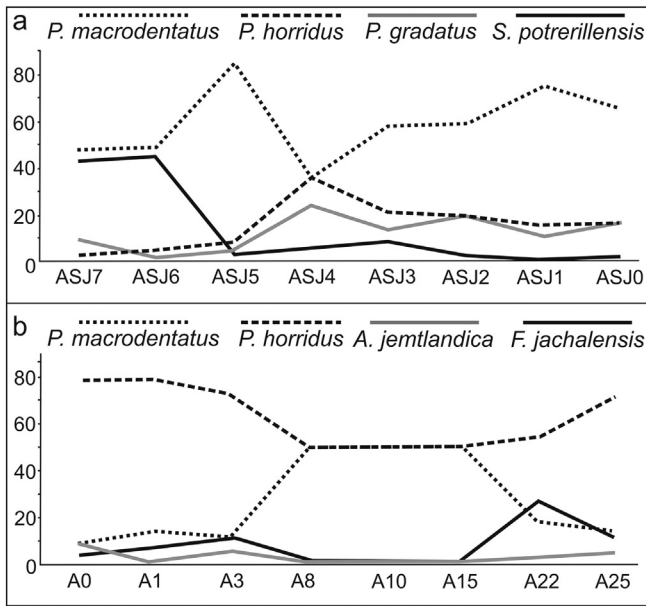


Fig. 5. (a) Relative abundance patterns of *Paroistodus horridus*, *Periodon macrodentatus*, *Protopanderodus gradatus* and *Semiacontiodus potrerillensis* from the *Protopanderodus-Semiacontiodus* sub-biofacies; (b) Relative abundance patterns of *Paroistodus horridus*, *Periodon macrodentatus*, *Fahraeusodus jachalensis* and *Ansella jemtlandica* from the *Fahraeusodus-Ansella* sub-biofacies.

Protopanderodus, *Paroistodus* and *Periodon* biofacies from the South China paleocontinent represent relatively deep settings (Wu et al., 2014), although the *Protopanderodus* biofacies indicate mid-subtidal environments, and a preference to shallower waters than *Periodon* (Pohler, 1994; Bagnoli and Stouge, 1996; Wu et al., 2014). A similar conodont assemblage to the one documented herein was recorded from the Wuhai area and Laoshidan section in North China, where *Ansella*, *Drepanoistodus*, *Histiodella*, *Coelocerodontus*, *Costiconus*, *Periodon*, *Protopanderodus*, *Spinodus* and *Venoistodus* are abundant common

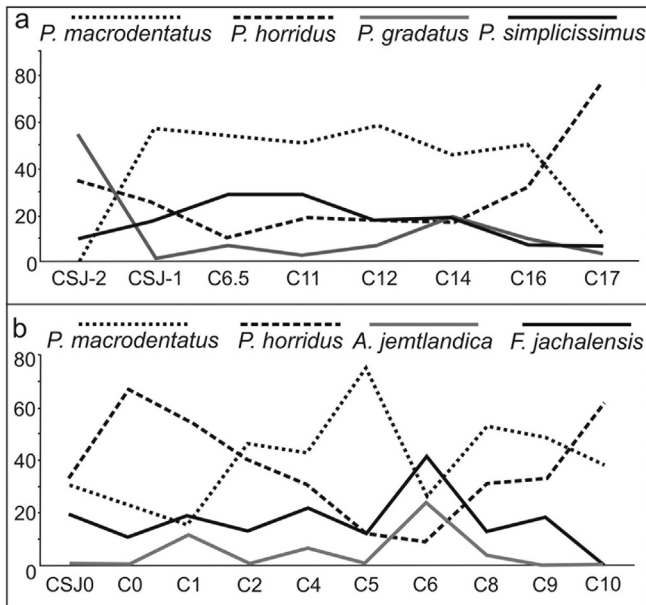


Fig. 6. (a) Relative abundance patterns of *Paroistodus horridus*, *Periodon macrodentatus*, *Protopanderodus gradatus* and *Parapaltodus simplicissimus* from the *Protopanderodus-Parapaltodus* sub-biofacies; (b) Relative abundance patterns of *Paroistodus horridus*, *Periodon macrodentatus*, *Fahraeusodus jachalensis* and *Ansella jemtlandica* from the *Fahraeusodus-Ansella* sub-biofacies.

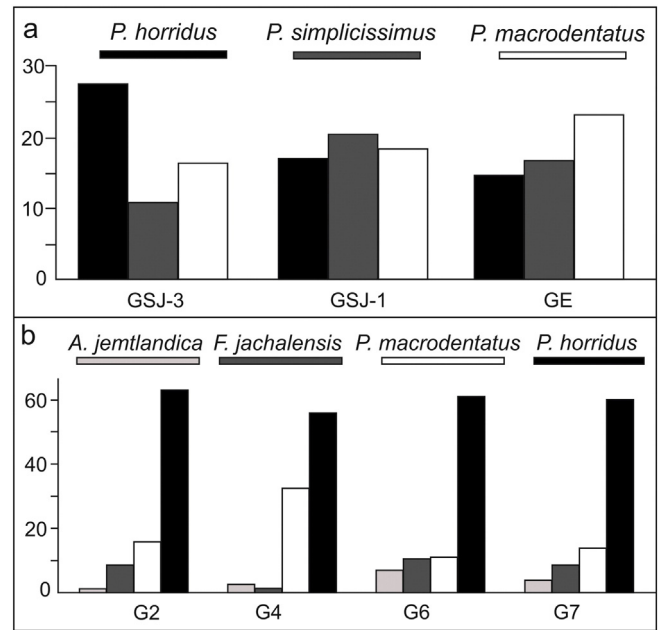


Fig. 7. (a) Relative abundance patterns of *Paroistodus horridus*, *Periodon macrodentatus* and *Parapaltodus simplicissimus* from the *Parapaltodus* sub-biofacies; (b) Relative abundance patterns of *Paroistodus horridus*, *Periodon macrodentatus*, *Fahraeusodus jachalensis* and *Ansella jemtlandica* from the *Fahraeusodus-Ansella* sub-biofacies.

genera (Jing et al., 2016a,b). Accordingly, in our study *Spinodus spinatus* (Hadding) is a rare species, only occurring in some samples from the Las Aguaditas and Las Chacritas sections in low frequencies; on the other hand, *Periodon* and *Protopanderodus* are abundant in the shallower sub-biofacies of the Precordillera.

The conodont association described in this study has been previously recognized in several localities of the Precordillera. At the Cerro Viejo de Huaco section, the *Periodon-Pygodus* biofacies is recognized, which is characteristic of slope environments (Albanesi and Ortega, 1998), also a diverse conodont fauna was documented in the San Juan and Gualcamayo formations at the Cerro Potrerillo section (Albanesi, 1998) and in the San Juan Formation at the Los Cauquenes Range (Voldman et al., 2013) and Cerro La Chilca section (Carrera et al., 2013). In a previous study at the Las Aguaditas Creek section, the *Periodon* biofacies was recognized at the top of the San Juan Formation and the upper part of the lower member of Las Aguaditas Formation and the *Paroistodus* biofacies at the base of the Las Aguaditas Formation (Feltes and Albanesi, 2013). Furthermore, Serra and Albanesi (2013) documented the *Periodon-Paroistodus* biofacies at the top of the San Juan Formation and Las Chacritas Formation and the *Ansella-Fahraeusodus* sub-biofacies in the middle part of the Las Chacritas Formation at a different outcrop from the Las Chacritas River section (300 m south from the present study section). However, the recognition of these biofacies by Feltes and Albanesi (2013) and Serra and Albanesi (2013) were interpreted conceptually since the authors did not apply multivariate methods for their identification.

7. Conodont biofacies and sea level change

Stouge (1984) suggested that *Periodon*, a nekto-benthic genus, was mainly oceanic and only appeared sporadically on the shelf as well as *Paroistodus*, although the latter was probably pelagic. An antithetical relationship between these species occurs at the three sections (Fig. 8). Although both taxa are typical of deep, proximal to distal slope environments, *Paroistodus* represents a biotope constrained to lower temperatures or deeper conditions when compared to *Periodon*. Marked changes in the abundance of *Periodon* in relation to *Paroistodus* are evident (Fig. 8); indicating local fluctuations in sea level, in accordance

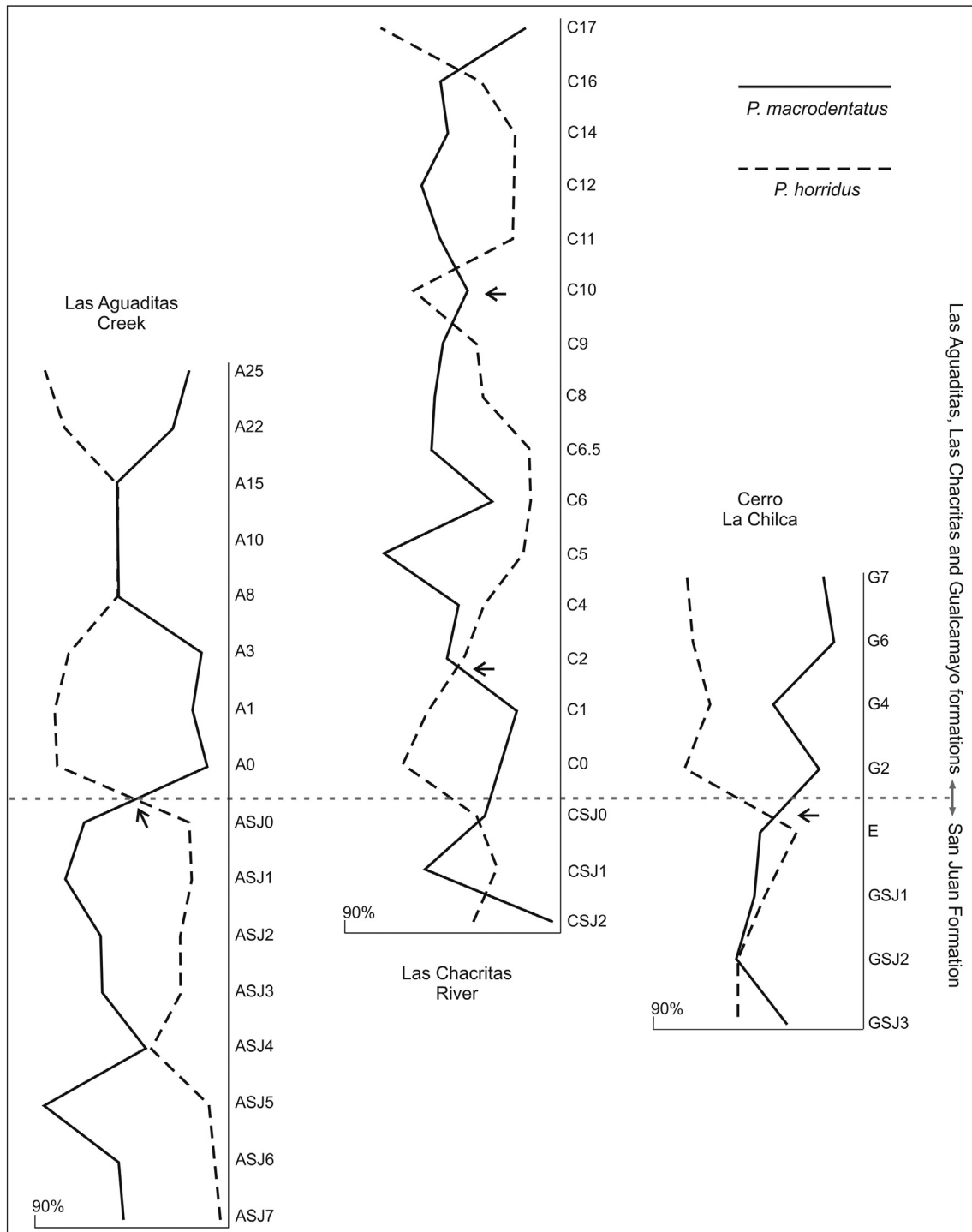


Fig. 8. Relative abundance patterns of *Periodon macrodentatus* and *Paroistodus horridus* along the study units in the respective sections.

with the lithology. The species *P. macrodentatus* seems to dominate the conodont fauna in the upper part of the San Juan Formation and in the upper beds of the Las Chacritas Formation at the Las Chacritas River section, which also exhibits the greatest diversity of conodont species. In the uppermost strata of the San Juan Formation a decline in abundance of *P. macrodentatus* is observed and within the overlying units, at all localities, *P. horridus* increases and outnumbers the former species and is accompanied by a decrease in conodont diversity. This change is reflected in the conodont associations, where the *Protopanderodus-Parapaltodus* sub-biofacies are characterized as having diverse conodont communities while the *Fahraeusodus-Ansella* sub-biofacies exhibits a

decrease in species richness and abundance. At the Las Aguaditas Creek section, *P. gradatus* and *S. potrerillensis*, also show a slight antithetical relation in the *Protopanderodus-Semiacontiodus* sub-biofacies (Fig. 5a). The same trend is observed at the Las Chacritas River section with *P. gradatus* and *P. simplicissimus*, except in the highest stratigraphical samples where both species decrease in abundance. In these samples (C16 and C17), *P. horridus* outnumbers *P. macrodentatus* for the first and only time in the biofacies suggesting an unfavorable increase in water depth for these species (Fig. 6a). This is not the case for *A. jemtlandica* and *F. jachalensis* that represent the most abundant taxa of the second sub-biofacies; the fluctuation of their abundance curves in

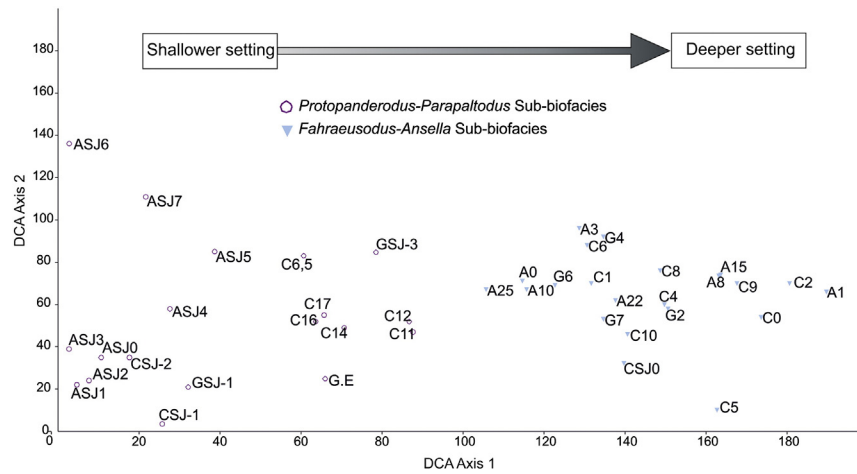


Fig. 9. DCA (Detrended Correspondence Analysis) of the conodont fauna from the Las Aguaditas Creek, Las Chacritas River, and Cerro La Chilca sections.

the different study areas show similar responses to environmental changes (Figs. 5b, 6b).

The DCA shows a trend for conodont associations extending from the *Protopanderodus-Parapaltodus* sub-biofacies to the *Fahraeusodus-Ansella* sub-biofacies (Fig. 9), also these changes correspond with lithologic changes. The San Juan Formation consists of nodular limestones and grainstones deposited on a distal platform below the wave base. This facies represents shallower environments suitable for the development of a wide variety of conodont taxa with diverse lifestyles. The diverse *Protopanderodus-Parapaltodus* sub-biofacies occurs within these shallower environments. The lower part of the Las Aguaditas, the Las Chacritas and Gualcamayo formations consist of lime-mudstones, which are characteristic of deep-water environments. The *Fahraeusodus-Ansella* sub-biofacies is represented in this deeper water setting. Species typical of deeper water conditions, such as *P. horridus*, *P. originalis*, *F. jachalensis*, *A. jemtandica* and pelagic species belonging to the *Drepanodus* and *Drepanoistodus* genera were recovered from these deeper water environments; moreover, faunas associated with deep-water, such as that of graptolites were also documented in the Las Aguaditas Creek, Las Chacritas River and Cerro La Chilca sections (Serra et al., 2015b). In the case of the Las Chacritas River section, a shallowing event is recorded by a change in the lithology from wackestones to grainstones, as well as an increase in macro- and microfossils towards the middle and upper parts of the Las Chacritas Formation. This shallowing event causes the *Protopanderodus-Parapaltodus* association to reappear in the middle and upper parts of the unit at this section.

Local environmental changes in the Precordillera had varied effects on the diversity of conodonts within the *Periodon-Paroistodus* biofacies. Our results indicate that the diversity in the *Protopanderodus-Parapaltodus* sub-biofacies is higher than the *Fahraeusodus-Ansella* sub-biofacies in all of the study sections. The former not only has a greater number of species present, but the individuals are distributed more equitably among these species. The environmental shift to deeper, anoxic conditions induced changes in the taxonomic composition and affected the diversity of conodont communities, while shallower settings represented more favorable environments for the development of conodont communities during the study interval recorded in the Precordillera. These positive effects in the conodont fauna seem to be a generalized phenomenon across the Precordillera during the middle-Darriwilian, or at least at the Las Aguaditas Creek, Las Chacritas River and Cerro La Chilca sections. Consequently, we conclude that the conodont diversity and faunal dynamics in the study area of the Argentine Precordillera was mainly controlled by regional fluctuations of the sea-level.

8. Systematic paleontology

The conodont taxa from our database are identifiable with species that have been adequately described in numerous publications. Therefore, the definition and description of one new species with important paleoecological implications for this study is considered. All specimens of this study are stored at the Museo de Paleontología of the Universidad Nacional de Córdoba.

GENUS *Fahraeusodus* Stouge and Bagnoli, 1988.

Type species? *Microzarkodina adentata* McTavish, 1973.

Fahraeusodus jachalensis Feltes and Albanesi n. sp.

Synonymy. - *Fahraeusodus marathonsensis* (Bradshaw) Albanesi, 1998, pl. 4, fig. 19–23; Serra and Albanesi, 2013, p. 107, fig. 3. 6; Feltes and Albanesi, 2013, p. 20., fig. 3. 4, 18; Serra et al., 2015a, p. 819, fig. 4. v. *Fahraeusodus* n. sp. Feltes et al., 2016, table 1; Albanesi and Ortega, 2016, fig. 7.5.

Derivation of name. - The specific name derives from the Jáchal locality, San Juan Province.

Type locality. - Las Aguaditas Creek, Las Chacritas River, and Cerro La Chilca sections, Precordillera of San Juan, Argentina.

Type stratum. - Lower member of the Las Aguaditas Formation, sample LAF33, *Eoplacognathus pseudoplanus* Zone (middle Darriwilian).

Holotype. - CORD-MP 34853 (Fig. 10e), Pa element.

Diagnosis. - The Pa element is dolobrate to carminate with erect cusp and posterior denticles with sharp edges. The anterobasal margin develops as an anticusp slightly flexed to anterior, and may carry incipient denticles. The posterior process is arcuate, fully denticulated. Denticles have sharp edges and are basally fused with free spiny apices that progressively decrease in height to the posterior end. The cusp is always higher than the posterior denticles, and both are ornamented with a strong lateral costa on each side. In the M element, the posterior process is longer than the cusp.

Description. - The P element has a relatively short posterior, fully denticulated process that bears up to 12 compressed and apically free denticles. The denticles are always shorter than the cusp in descending order of height. The basal margin is arcuate and exhibits a wide basal cavity. The cusp is 350 μm in height and 67 μm wide measured at its base in adult specimens. The basal margin at its wider part is 100 μm and the posterior process is 170 μm long. The anterobasal margin of the Pa element develops as an anticusp slightly flexed to anterior, and may carry incipient denticles. This character differs from the Pb element in which the anticusp forms a right angle with the basal margin posterior process.

The S elements share similar morphologies as those described for *Fahraeusodus marathonsensis* (see Bradshaw, 1969; Ethington and

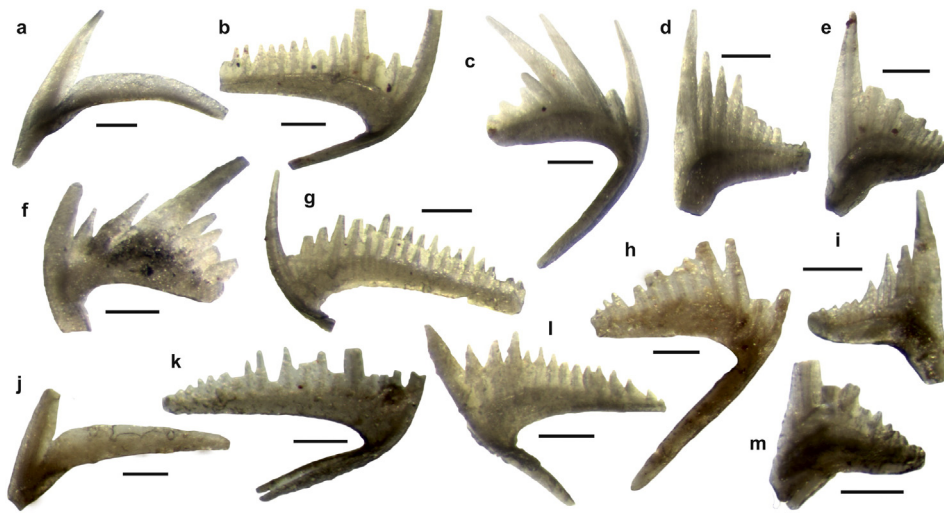


Fig. 10. Conodont morphotypes of the *Fahraeusodus jachalensis* n. sp. apparatus (a–g, l) sampled at 43 m from the base of the Las Aguaditas Formation at the Las Aguaditas Creek section; (a) M element, lateral view, CORD-MP 34849; (b) Sd element, lateral view, CORD-MP 34850; (c) Sc element, lateral view, CORD-MP 34851; (d) Pb element, lateral view, CORD-MP 34852; (e) Pa element, lateral view, CORD-MP 34853 (Holotype); (f) Sb element, lateral view, CORD-MP 34854; (g) Sa element, lateral view, CORD-MP 34855; (l) Sd element, lateral view, CORD-MP 34856; (h–k) sampled at 3.3 m from the base of the Gualcamayo Formation at the Cerro La Chilca section; (h) Sc element, lateral view, CORD-MP 44001; (i) Pa element, lateral view, CORD-MP 44002; (j) M element, lateral view, CORD-MP 44003; (k) Sa element, lateral view, CORD-MP 44004; (m) Pa element, lateral view, CORD-MP 34021, sampled at 39.3 m from the base of the Las Chacritas Formation at the Las Chacritas River section.

Clark, 1981; Repetski, 1982; Stouge and Bagnoli, 1988; Smith, 1991; Albanesi, 1998). The ramiform elements of the transition series exhibit a fully denticulated posterior process. The Sc element presents cusp and denticles reclined. It bears a prominent anticusp longer than the cusp. The second and the third denticles are longer than the cusp. The Sb element is the more robust, with the third denticle wider and longer than the cusp. The cusp bears a lateral costa in a lateral face. The Sa is the symmetric element with two lateral processes that start up as a pronounced keel in the cusp and continues aborally as a non denticulated process. This element bears a fully denticulated posterior process with apically free denticles that are shorter than the cusp. The Sd element has two asymmetrical lateral processes that extend posteriorly. Similar to the Sa element, the denticles are shorter and more slender than the cusp. The M element is coniform and geniculated. The cusp is slightly reclined. A short anticusp develops from the base. The posterior process is longer than the cusp.

Remarks. - The multielemental apparatus of this species resembles *Fahraeusodus marathonsensis* (Bradshaw), except for the P and M elements, which are diagnostic at species level. All of the P and M elements recovered from the study localities of the Precordillera share the same morphologic characteristics. The stratigraphic range of the species extends throughout the study interval (upper part of the San Juan Formation and the overlying shaly-calcareous units). The Pa element of *Fahraeusodus jachalensis* differs from the homologous of *Fahraeusodus mirus* Stouge and Bagnoli in bearing up to 12 compressed and apically free denticles, rather than a maximum of 6 in the posterior process. *Fahraeusodus marathonsensis* does not bear incipient denticles close to the antero-basal margin of the anticusp, which are diagnostic of the new species (cf. Stouge and Bagnoli, 1988). *Fahraeusodus adentatus* (McTavish) does not present a well-developed anticusp, but an acute antero-basal margin (Ethington and Clark, 1981). The M element of *F. jachalensis* differs from that of *F. marathonsensis* illustrated in Bauer (2010, pl.1, fig.13) in having a posterior process that is longer than the cusp. These elements lack the indentation above the antero-basal corner, which is typical in *F. mirus*.

Discussion. - This species was identified as *F. marathonsensis* (Bradshaw, 1969) in previous studies from the Las Aguaditas Creek (Feltes and Albanesi, 2013) and Las Chacritas River (Serra and Albanesi, 2013; Serra et al., 2015a) localities. More recently, Feltes et al. (2016) recognized the differences in the P morphotypes and referred it as *Fahraeusodus* n. sp. The fully reconstructed apparatus presented

herein enables the definition of the new species. The M element illustrated in Albanesi (1998) as *F. marathonsensis*, actually belongs to *F. jachalensis*, according to the length of the posterior process in relation to the cusp. Another difference with *F. marathonsensis*, its closest relative, is observed on the flanks of the elements which present a remarkable ledge in this species, instead of in *F. jachalensis* where this character is rather faint.

Occurrence. - Upper 25 m of the San Juan Formation, lower member of the Las Aguaditas Formation at the Las Aguaditas Creek, Las Chacritas Formation at Las Chacritas River and Gualcamayo Formation at Cerro La Chilca.

Material. - 644 elements (Las Aguaditas Creek); 119 elements (Las Chacritas River); 66 elements (Cerro La Chilca).

Acknowledgments

We thank the Centro de Investigaciones en Ciencias de la Tierra CICTERRA (CONICET-UNC) and Centro de Investigaciones Geológicas Aplicadas CIGEA (FCEfyN-UNC) where this research was carried out, and Svend Stouge and Annalisa Ferretti for their valued comments on the manuscript. We also wish to acknowledge the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET, Argentina), Secretaría de Ciencia y Tecnología (SECYT-UNC) and Student grants for fieldwork from Sigma Xi, the Geological Society of America, and SEPM (to Hendersson) for granting the present work.

References

- Albanesi, G.L., 1998. Taxonomía de conodontes de las secuencias ordovícicas del cerro Potrerillo, Precordillera Central de San Juan, R. Argentina. *Actas Acad. Nac. Cienc.* 12, 7–72.
- Albanesi, G.L., Bergström, S.M., 2004. Conodonts: Lower to Middle Ordovician record. In: Webby, B.D., Paris, F., Droser, M.L., Percival, I.G. (Eds.), *The Great Ordovician Biodiversification Event*. Columbia University Press, New York, pp. 312–336.
- Albanesi, G.L., Bergström, S.M., 2010. Early-Middle Ordovician conodont paleobiogeography with special regard to the geographic origin of the Argentine Precordillera: a multivariate analyses. *Geol. Soc. Am. Special Papers* vol. 466, pp. 119–139.
- Albanesi, G.L., Ortega, G., 1998. La Biofacies *Periodon-Pygodus* (Conodontia) en las secuencias euxínicas del Ordovícico de la Precordillera Argentina. VII Congreso Argentino de Paleontología y Bioestratigrafía. Bahía Blanca, p. 79.
- Albanesi, G.L., Ortega, G., 2002. Advances on conodont-graptolite biostratigraphy of the Ordovician System of Argentina. In: Aceñolaza, F.G. (Ed.), *Aspects of the Ordovician System in Argentina*. Instituto Superior de Correlación Geológica, Serie Correlación Geológica, San Miguel de Tucumán vol. 16, pp. 143–165.

- Albanesi, G.L., Ortega, G., 2016. Conodont and graptolite biostratigraphy of the Ordovician system of Argentina. In: Montanari, M. (Ed.), *Stratigraphy & Timescales*, pp. 61–121.
- Albanesi, G.L., Ortega, G., Hünicken, M.A., 2006. Bioestratigrafía de conodontes y graptolitos silúricos en la sierra de Talacasto, Precordillera de San Juan, Argentina. *Ameghiniana* 43, 43–112.
- Albanesi, G.L., Bergström, S.M., Schmitz, B., Serra, F., Feltes, N.A., Voldman, G.G., Ortega, G., 2013. Darrivilian (Middle Ordovician) $\delta^{13}\text{C}_{\text{carb}}$ chemostratigraphy in the Precordillera de Argentina: documentation of the Middle Darrivilian Isotope Carbon Excursion (MDICE) and its use for intercontinental correlation. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 389, 48–63.
- Aldridge, R.J., 1988. Extinction and survival in the Conodonta. In: Larwood, G.P. (Ed.), *Extinction and Survival in the Fossil Record* Systematics Association Special Volume vol. 34. Clarendon Press, Oxford, pp. 231–256.
- An, T.-X., Zheng, Z., 1990. The conodonts of the marginal areas around the Ordos Basin, north China. *Science Press*, pp. 1–101.
- Astini, R., 1994. Geología e interpretación de la Formación Gualcamayo en su localidad clásica (suroeste de Guadaco y cordón de Perico-Potrillo), Precordillera septentrional. *Rev. Asoc. Geol. Argent.* 49 (1–2), 55–70.
- Astini, R.A., 1995. Sedimentología de la Formación Las Aguaditas (talud carbonático) e implicancias estratigráficas en la cuenca precordillerana durante el Ordovícico medio. *Rev. Asoc. Geol. Argent.* 50, 143–164.
- Astini, R.A., 1997. Las unidades calcáreas del Ordovícico Medio y Superior de la Precordillera Argentina como indicadores de una etapa extensional. *Actas de la 2ª Jornadas de Geología de Precordillera*, San Juan, pp. 8–14.
- Astini, R.A., Benedetto, J.L., 1992. El Ashgilliano tardío (Hirnantiano) del Cerro La Chilca, Precordillera de San Juan, Argentina. *Ameghiniana* 29, 249–264.
- Bagnoli, G., Stouge, S., 1996. Changes in conodont provincialism and biofacies during the Lower Ordovician in Öland, Sweden. *Palaeopelagos* 6, 19–29.
- Bagnoli, G., Stouge, S., 1997. Lower Ordovician (Billingenian-Kunda) conodont zonation and provinces based on sections from Horns Udde, north Öland, Sweden. *Boll. Soc. Paleontol. Ital.* 35, 109–163.
- Baldis, B.A., Blasco, G., 1974. Trilobites ordovícicos de la comarca de Jáchal, Precordillera Argentina. I. Telephiniidae. *Ameghiniana* 11, 71–87.
- Baldis, B.A., Beresi, M., Borbonaro, O., Vaca, A., 1982. Síntesis evolutiva de la Precordillera argentina. *Actas 5º Congreso Latinoamericano de Geología*, Buenos Aires vol. 4, pp. 399–445.
- Barnes, C.R., Fähræus, L.E., 1975. Provinces, communities, and the proposed nektonic habit of Ordovician conodontophorids. *Lethaia* 8, 133–149.
- Barnes, C.R., Poplawski, M.L.S., 1973. Lower and Middle Ordovician conodonts from the Mystic Formation, Quebec, Canada. *J. Paleontol.* 47 (4), 760–790.
- Barnes, C.R., Rexroad, C.B., Miller, J.F., 1973. Lower Paleozoic conodont provincialism. In: Rhodes, F.H.T. (Ed.), *Conodont Paleontology*. Geological Society of America Special Paper vol. 141, pp. 157–190.
- Barnes, C.R., Fortey, R.A., Williams, S.H., 1996. The pattern of global bioevents during the Ordovician period. In: Walliser, O.H. (Ed.), *Global Events and Event Stratigraphy*. Springer-Verlag, New York, pp. 140–172.
- Bauer, J.A., 2010. Conodonts and conodont biostratigraphy of the Joins and Oil Creek formations, Arbuckle Mountains, South-central Oklahoma. *Oklahoma Geol. Surv. Bull.* 150, 1–44.
- Bergström, S.M., 1979. Whiterockian (Ordovician) conodonts from the Hølanda Limestone of the Trondheim Region, Norwegian Caledonides. *Nor. Geol. Tidsskr.* 59, 295–307.
- Bergström, S.M., 1983. Biostratigraphy, evolutionary relationships, and stratigraphic significance of Ordovician platform conodonts. In: Martinson, A., Bengtson, S. (Eds.), *Taxonomy, Ecology and Identity of Conodonts*. Proceedings of the Third European Conodont Symposium (ECOS III). Fossils and Strata, Lund vol. 15, pp. 35–58.
- Bergström, S.M., Chen, X., Gutiérrez-Marco, J.C., Dronov, A., 2009. The new chronostratigraphic classification of the Ordovician System and its relations to major regional series and stages and $\delta^{13}\text{C}$ chemostratigraphy. *Lethaia* 42, 97–107.
- Bradshaw, L.E., 1969. Conodonts from the Fort Peña Formation (Middle Ordovician), Marathon Basin, Texas. *J. Paleontol.* 43, 1137–1168.
- Brussa, E.D., 1996. Las graptofaunas ordovícicas de la Formación Las Aguaditas, Precordillera de San Juan, Argentina. Parte I Familias Thamnograptidae, Dichograptidae, Abrograptidae y Glossograptidae. *Ameghiniana* 33 (4), 421–434.
- Cañas, F.L., 1999. Facies and sequences of the Late Cambrian–Early Ordovician carbonates of the Argentine Precordillera: a stratigraphic comparison with Laurentian platforms. In: Ramos, V.A., Keppie, J.D. (Eds.), *Laurentian–Gondwanan Connections before Pangaea*. Geological Society of America Special Paper vol. 336, pp. 43–62.
- Carrera, M.G., 1997. Análisis paleoecológicos de la fauna de poríferos del Llanvirniano tardío de la Precordillera Argentina. *Ameghiniana* 34, 309–316.
- Carrera, M.G., Astini, R.A., 1998. Valoración de las restricciones ambientales durante la transición Arenigiano–Llanvirniano, Ordovícico de la Precordillera. *Rev. Asoc. Geol. Argent.* 53, 41–56.
- Carrera, M.G., Ernst, A., 2010. Darrivilian bryozoans from the San Juan Formation (Ordovician), Argentine Precordillera. *Ameghiniana* 47 (3), 343–354.
- Carrera, M.G., Fenoglio, F., Albanesi, G.L., Voldman, G., 2013. Conodonts sequence stratigraphy and the drowning of the San Juan carbonate platform in the Ordovician of the Argentine Precordillera. In: Albanesi, G.L., Ortega, G. (Eds.), *Conodonts from the Andes International Conodont Symposium*. Asociación Paleontológica Argentina, Buenos Aires vol. 3, pp. 5–12.
- Clark, D.L., Sweet, W.C., Bergström, S.M., Klapper, G., Austin, R.L., Rhodes, F.H.T., Müller, K.J., Ziegler, W., Lindström, M., Miller, J.F., Harris, A.G., 1981. Treatise on Invertebrate Paleontology. In: Robison, R.A. (Ed.), *Part W, Miscellaneous, Supplement 2, Conodonta* vol. 1–28. Geological Society of America and University of Kansas Press, Lawrence, Kansas, p. W1–W202.
- Cuerda, A., Furque, G., 1985. Graptolitos del techo de la Formación San Juan, Precordillera de San Juan. *Actas 1 Jornadas de Geología de la Precordillera de San Juan* Vol. 1, pp. 113–118.
- Ethington, R.L., Clark, D.L., 1981. Lower and Middle Ordovician conodonts from the Ibex area, western Millard County, Utah. *Geology Stud. Brigham Young University* Vol. 28 (2) (155 pp.).
- Feltes, N.A., Albanesi, G.L., 2013. The *Periodon* and *Paroistodus* conodont biofacies in the lower member of the Las Aguaditas Formation (Middle Ordovician), Central Precordillera, Argentina. In: Albanesi, G.L., Ortega, G. (Eds.), *Conodonts from the Andes International Conodont Symposium*. Asociación Paleontológica Argentina, Buenos Aires vol. 3, pp. 17–23.
- Feltes, N.A., Albanesi, G.L., Bergström, S.M., 2016. Conodont biostratigraphy and global correlation of the Middle Darrivilian – Lower Sandbian Las Aguaditas Formation, Precordillera de San Juan, Argentina. *Andean Geology* 43 (1), 60–85.
- Hammer, Ø., Harper, D.A.T., 2006. *Paleontological Data Analysis*. Blackwell Publishing, Oxford, p. 351.
- Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. PAST: paleontological statistics software package for education and data analysis. *Palaeontol. Electron.* 4, 1–9.
- Ji, Z., Barnes, C.R., 1994. Lower Ordovician conodonts of the St. George Group, Port au Port Peninsula, western Newfoundland, Canada. *Palaeontogr. Can.* 11, 1–149.
- Jing, X., Zhou, H., Wang, X., 2016a. Ordovician (middle Darrivilian–earliest Sandbian) conodonts from the Wuhai area of Inner Mongolia, North China. *J. Paleontol.* <http://dx.doi.org/10.1017/jpa.2015.54>.
- Jing, X., Zhou, H., Wang, X., 2016b. Biostratigraphy and biofacies of the Middle Darrivilian (Ordovician) conodonts from the Laoshian section in the western margin of the North China Craton. *Mar. Micropaleontol.* 125, 51–65.
- Keller, M., Eberlein, S., Lehnert, O., 1993. Sedimentology of Middle Ordovician carbonates in the Argentine Precordillera: evidence of regional relative sea-level changes. *Geol. Rundsch.* 82, 362–377.
- Löfgren, A., 1978. Arenigian and Llanvirnian conodonts from Jämtland, northern Sweden. *Fossils Strata* 13, 1–129.
- Löfgren, A., 1999. The Ordovician conodont *Semiacontiodus cornuiformis* (Sergeeva, 1963) and related species in Baltoscandia. *Geol. Palaeontol.* 33, 71–91.
- Löfgren, A., 2000. Early to early middle Ordovician conodont biostratigraphy of the Gillberga quarry, northern Öland, Sweden. *GFF* 122, 321–338.
- Löfgren, A.M., 2004. The conodont fauna in the Middle Ordovician *Eoplacognathus pseudoplanus* Zone of Baltoscandia. *Geol. Mag.* 141, 505–524.
- Löfgren, A., Zhang, J.H., 2003. Element association and morphology in some middle Ordovician platform–equipped conodonts. *J. Paleontol.* 77 (4), 721–737.
- Ludvigsen, R., Westrop, S.R., Pratt, B.R., Tuttnell, P.A., Young, G.A., 1986. Dual biostratigraphy: zones and biofacies. *Geosci. Can.* 13 (3), 139–154.
- Mellgren, J.I.S., Eriksson, M.E., 2010. Untangling a Darrivilian (Middle Ordovician) paleoecological event in Baltoscandia: conodont faunal changes across the “Täljsten” interval. *Earth Environ. Sci. Trans. R. Soc. Edinb.* 100, 353–370.
- Peralta, S.H., 1998. Graptolites of the *N. gracilis* Zone in the black shale sequences of the San Juan Precordillera, Argentina: its biostratigraphic and paleoenvironmental significance. In: Gutiérrez-Marco, J.C., Rábano, I. (Eds.), *Proceedings of the Sixth International Graptolite Conference of the GWG (IPA) and the SW Iberia Field Meeting of the International Subcommission on Silurian Stratigraphy (ICS–IUGS)*, Madrid vol. 23, pp. 244–247.
- Peralta, S.H., 2003. Ordovician and Silurian of the Precordillera, San Juan Province, Argentina. In: Peralta, S.H., Albanesi, G.L., Ortega, G. (Eds.), *Field Trip Guide 9th International Symposium on the Ordovician System 7th International Graptolite Conference & Field Meeting of the Subcommission on Silurian Stratigraphy*, Serie Correlación Geológica, Tucumán vol. 10, pp. 23–43.
- Peralta, S., Heredia, S., Beresi, M., 1999. Upper Arenig–Lower Llanvirn sequence of the Las Chacritas River, Central Precordillera, San Juan Province, Argentina. In: Raft, P.K., Atka, F.O. (Eds.), *Quo vadis Ordovician? Short papers of the 8 th International Symposium on the Ordovician System*. Acta Universitatis Carolinae Geologica vol. 43, pp. 123–126.
- Pohler, S.M.L., 1994. Conodont biofacies of Lower to Lower Middle Ordovician megaglomerates, Cow Head Group, Western Newfoundland. *Geological Survey of Canada Bulletin* vol. 459, pp. 1–71.
- Rasmussen, J.A., 2001. Conodont biostratigraphy and taxonomy of the Ordovician shelf margin deposits in the Scandinavian Caledonides. *Fossils Strata* 48, 1–179.
- Rasmussen, J.A., Stouge, S., 1995. Late Arenig–Early Llanvirn conodont biofacies across the lapetus Ocean. In: Cooper, J.D., Droser, M.L., Finney, S.C. (Eds.), *Ordovician Odyssey: Short Papers for the Seventh International Symposium on the Ordovician System*. Las Vegas, California, pp. 443–447.
- Repetski, J.E., 1982. Conodonts from El Paso Group (Lower Ordovician) of west Texas and southern New Mexico. *New Mexico Bureau of Mines and Mineral Resources Memoir* vol. 40 (121 pp.).
- Seddon, G., Sweet, W.C., 1971. An ecologic model for conodonts. *J. Paleontol.* 54, 869–880.
- Serra, F., Albanesi, G.L., 2013. Paleogeology and paleobiogeography of Darrivilian conodonts from the Las Chacritas Formation, Central Precordillera of San Juan, Argentina. In: Albanesi, G.L., Ortega, G. (Eds.), *Conodonts from the Andes International Conodont Symposium*. Asociación Paleontológica Argentina, Buenos Aires vol. 3, pp. 103–108.
- Serra, F., Albanesi, G.L., Ortega, G., Bergström, S.M., 2015a. Biostratigraphy and paleoecology of Middle–Late Ordovician conodont and graptolite faunas of the Las Chacritas River section, Precordillera de San Juan, Argentina. *Geol. Mag.* 152 (5), 813–829.
- Serra, F., Feltes, N., Ortega, G., Albanesi, G., 2015b. Early–Middle Darrivilian graptolite and conodont faunas from the Central Precordillera of San Juan Province, Argentina. In: Leslie, S.A., Goldman, D., Orndorff, R.C. (Eds.), *The Ordovician Exposed: Short Papers, Abstracts, and Field Guides for the 12th International Symposium on the Ordovician System*. Harrisonburg, Virginia, pp. 67–69.

- Smith, M.P., 1991. Early Ordovician conodonts of East and North Greenland Meddelelser om Grønland. *Geoscience* 26, 1–81.
- Stappenbeck, R., 1910. La Precordillera de San Juan y Mendoza. *An. Min.Agric., Sec. Geo., Mineral Y Min Vol. IV(3)*, pp. 1–187.
- Stouge, S., 1981. Cambrian–Middle Ordovician stratigraphy of Salmon River region, southwest Hare Bay, Great Northern Peninsula. In: O'Driscoll, C.F., Gibbons, R.Y. (Eds.), *Current Research, Newfoundland Department of Mines and Energy. Mineral Development Division. Report Vols. 81-1*, pp. 1–16.
- Stouge, S., 1984. Conodonts of the Middle Ordovician Table Head Formation, Western Newfoundland. *Fossils Strata* 16, 145.
- Stouge, S., 2012. Middle Ordovician (late Dapingian–Darrivillian) conodonts from the Cow Head Group and Lower Head Formation, western Newfoundland, Canada. *Can. J. Earth Sci.* 49, 59–90.
- Stouge, S., Bagnoli, G., 1988. Early Ordovician conodonts from Cow Head Peninsula, western Newfoundland. *Palaeontogr. Ital.* 75, 89–178.
- Stouge, S., Bagnoli, G., 1990. Lower Ordovician (Volkhovian–Kundan) conodonts from Hagudden, northern Öland, Sweden. *Palaeontogr. Ital.* 77, 1–54.
- Sweet, W.C., 1988. The conodonta: morphology, taxonomy, paleoecology, and evolutionary history of a long-extinct animal phylum. *Oxford Monographs on Geology and Geophysics*, New York vol. 10. Oxford University Press, p. 212.
- Sweet, W.C., Bergström, S.M., 1984. Conodont provinces and biofacies of the Late Ordovician. In: Clark, D.L. (Ed.), *Conodont Biofacies and Provincialism. Geological Society of America Special Paper* vol. 196, pp. 69–87.
- Tortello, M.F., Peralta, S.H., 2004. Trilobites del miembro inferior de la Formación Gualcamayo (Llanvirniano temprano) en el Cerro La Chilca, Precordillera de San Juan, Argentina. *Bol. Geol. Min.* 115, 665–62.
- Uyeno, T.T., Barnes, C.R., 1970. Conodonts from the Levis Formation (zone D1) (Middle Ordovician), Levis, Quebec. *Geol. Surv. Can. Bull.* 87, 99–123.
- Voldman, G.G., Ortega, G., Albanesi, G.L., 2013. Middle Ordovician conodonts and graptolites at Los Cauquenes Range, Central Precordillera of San Juan, Argentina. In: Albanesi, G.L., Ortega, G. (Eds.), *Conodonts from the Andes. 3rd International Conodont Symposium. Asociación Paleontológica Argentina, Buenos Aires* vol. 13, pp. 117–121.
- Wu, R.C., Percival, I.G., Zhan, R.B., 2010. Biodiversification of Early to Middle Ordovician conodonts: a case study from the Zitai Formation of Anhui Province, East China. *Alcheringa* 34, 75–86.
- Wu, R.C., Stouge, S., Percival, I.G., Zhan, R.B., 2014. Early–Middle Ordovician conodont biofacies on the Yangtze Platform margin, South China: applications to palaeoenvironment and sea-level changes. *J. Asian Earth Sci.* 96, 194–204.
- Zeballos, F.J., Albanesi, G.L., 2012. Biofacies and palaeoenvironments of conodonts in Cambro–Ordovician sequences of the Quebrada de Humahuaca, Cordillera Oriental of Jujuy, Argentina. *Geol. J.* 48, 170–193.
- Zhang, J.H., 1998. Conodonts from the Guniutan Formation (Llanvirnian) in Hubei and Hunan provinces, south–central China. *Stockh. Contrib. Geol.* 46, 1–161.
- Zhang, S., Barnes, C.R., 2002. Paleocology of Llandovery conodonts, Anticosti Island, Québec. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 180 (1–3), 33–55.
- Zhang, S.X., Barnes, C.R., 2004. Arenigian (Early Ordovician) sea level history and the response of conodont communities, western Newfoundland. *Can. J. Earth Sci.* 41, 843–865.
- Zhen, Y.Y., Percival, I.G., 2003. Ordovician conodont biogeography – reconsidered. *Lethaia* 36, 357–369.