

## Conodont biostratigraphy and global correlation of the middle Darriwilian-lower Sandbian (Ordovician) Las Aguaditas Formation, Precordillera of San Juan, Argentina

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**ABSTRACT.** Middle Darriwilian to lower Sandbian conodonts were recorded from the Las Aguaditas Formation at its type section in the Argentine Precordillera. A total of 9,974 conodont specimens were recovered from 46 carbonate samples, which represent 68 species of 38 genera. A biostratigraphic study verified a middle Darriwilian age for the interval spanning the contact between the San Juan and the Las Aguaditas formations. The following zones are determined in the study section: the *Lenodus variabilis* Zone, with the *Periodon gladysae* and *Paroistodus horridus* subzones following the Precordilleran scheme; the *L. variabilis*, *Yangtzeplacognathus crassus*, and the *Eoplacognathus pseudoplanus* zones with the *Microzarkodina hagetiana* and *M. ozarkodella* subzones, and the *Pygodus anserinus* Zone, according to the Scandinavian scheme; the *Periodon macrodentatus* Zone, with the *Histiodella sinuosa*, *H. holodentata* and *H. cf. holodentata* subzones, and the *P. zgierzensis* Zone with the *H. kristinae* Subzone that correlates the North American scheme. A stratigraphic gap was recognized between the lower and middle members of the Las Aguaditas Formation. It comprises the *Eoplacognathus suecicus* and *Pygodus serra* zones, and the lower subzone of the *Pygodus anserinus* Zone. The variation of conodont diversity through the study section conforms to shallowing and deepening patterns, which accompanies the changes of the provenance lithology. Three conodont assemblages were quantitatively recognized: **a)** Diverse conodont association, **b)** Low diversity conodont association and **c)** Recovery phase association. We propose to use the North American biozonal scheme of conodonts for the Central Precordillera because of the affinity of documented index taxa, which provides a more accurate intercontinental correlation for the global Middle Ordovician Series.

**Keywords:** Conodont, Darriwilian-Sandbian, Biostratigraphy, Paleoecology, Precordillera, Argentina.

**RESUMEN. Bioestratigrafía de conodontes y correlación global del Darriwiliano medio-Sandbiano inferior (Ordovícico) Formación Las Aguaditas, precordillera de San Juan, Argentina.** En la Formación Las Aguaditas, en su sección tipo en la precordillera Argentina, se registraron conodontes del Darriwiliano medio al Sandbiano bajo. Se recuperaron un total de 9.974 especímenes de 46 muestras carbonáticas; estos representan 68 especies pertenecientes a 38 géneros. Se llevó a cabo un estudio bioestratigráfico para verificar la edad del intervalo que incluye el contacto entre las formaciones San Juan y Las Aguaditas. La presencia de taxones guía indican una edad darriwiliana media para este intervalo. Las siguientes biozonas fueron determinadas en el área de estudio: Zona de *Lenodus variabilis*, con las subzonas de *Periodon gladysae* y *Paroistodus horridus*, correspondientes al esquema establecido para la precordillera; las zonas de *L. variabilis*, *Yangtzeplacognathus crassus* y la de *Eoplacognathus pseudoplanus* con la subzonas de *Microzarkodina hagetiana* y *M. ozarkodella*, y la Zona de *Pygodus anserinus*, según el esquema Báltico; la Zona de *Periodon macrodentatus*, con las subzonas de *Histiodella sinuosa*, *H. holodentata* y *H. cf. holodentata*, y la Zona de *P. zgierzensis* con la subzona de *H. kristinae* que se relaciona con el esquema norteamericano. Se reconoció una discontinuidad estratigráfica entre los miembros inferior y medio de la Formación Las Aguaditas. Esta comprende las zonas de *Eoplacognathus suecicus* y *Pygodus serra*, y la subzona inferior de la Zona de *Pygodus anserinus*. La variación en la diversidad de conodontes en la sección de estudio se corresponde con patrones de somerización y profundización, que a su vez son congruentes con los cambios en la litología. Luego de analizar la composición taxonómica de las muestras se reconocieron, de manera cuantitativa, tres asociaciones de conodontes: **a)** Asociación diversa de conodontes, **b)** Asociación de baja diversidad de conodontes, y **c)** Asociación de conodontes en fase de recuperación. Se propone aplicar para la precordillera central el esquema de biozonación de América del Norte debido a la afinidad de los taxones guía documentada, brindando una correlación intercontinental más precisa para el Ordovícico Medio a nivel global.

**Palabras clave:** Conodontes, Darriwiliano-Sandbiano, Bioestratigrafía, Paleoecología, Precordillera, Argentina.

**1. Introduction**

The Precordillera of western Argentina is bordered by the Sierras Pampeanas to the east and by the Cordillera Frontal to the west. This geological province which extends 450 km meridionally and 110 km from east to west (Fig. 1) is characterized by thick Lower Paleozoic marine units (Furque and Cuerda, 1979). The nature and origin of the Precordillera has been the subject of diverse studies (e.g., Astini et al., 1995; Aceñolaza et al., 2002; Benedetto, 2004; Voldman et al., 2009). It is interpreted as part of a major exotic terrane. The study of Cambrian and Ordovician faunas is crucial to understand the origin, migration and accretion to its present position. Some authors suggest an allochthonous origin for this terrane, with rifting from Laurentia, beginning drift across the Iapetus Ocean in the Cambrian and accretion to the western margin of Gondwana by the Mid or mid-Late Ordovician (Benedetto, 1993; Benedetto et al., 2009; Astini et al., 1995; Bordonaro and Banchig, 1995; Albanesi et al., 1995a; Albanesi and Bergström, 2010). An alternative hypothesis considers the Precordillera a para-autochthonous Gondwanan block, which drifted along the Gondwana margin

from its original position close to Antarctica and South Africa (Aceñolaza et al., 2002; Finney, 2007).

The stratigraphy of the Precordillera is characterized by a 2,300 m thick succession of Cambro-Ordovician limestones, which were deposited on a continental shelf to the east and interdigitate with clastic slope deposits toward the west (Keller et al., 1993; Astini, 1995). This supports the allochthonous hypothesis, due to the fact that deposits of limestones of such a great thickness could only be expected in warm seas, at lower latitudes than the position of Gondwana at that time (Benedetto, 2010). The Precordillera is the only South American Lower Paleozoic basin with a carbonate platform, representing depositional environments from shallow intertidal settings to marginal shelf or deep ramp settings (Cañas, 1999). The shelf experienced a rapid sea level rise to the east, which led to the drowning of the platform. This event interrupted the carbonate production and resulted in the widespread deposition of graptolitic black shales (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

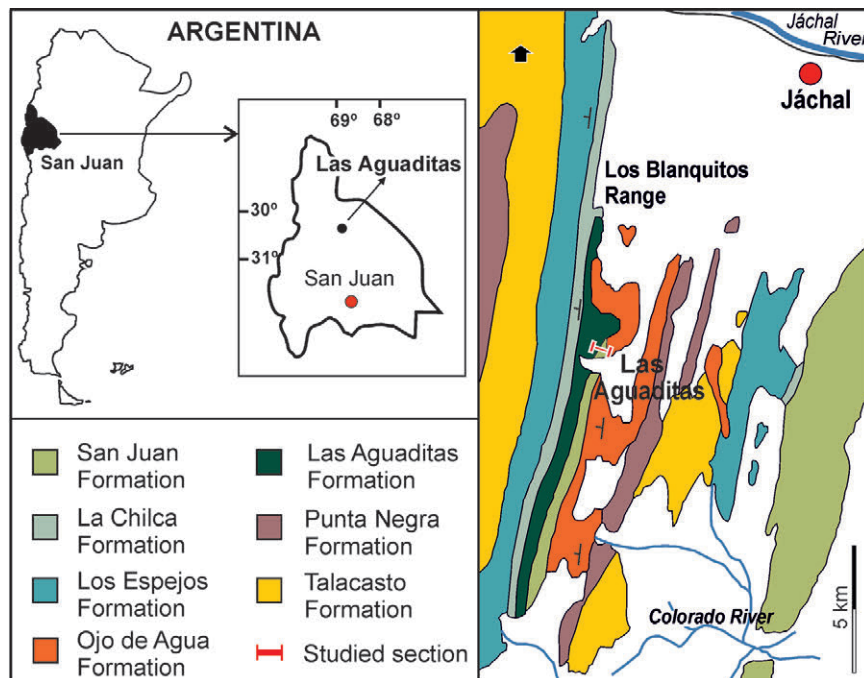


FIG. 1. Geologic map and location of the Las Aguaditas Creek section in the Los Blanquitos Range, Precordillera of San Juan, Argentina.

Las Aguaditas Formation is the only unit that shows a transition from a platform to slope depositional environment (Astini, 1995; Keller *et al.*, 1993).

Establishing an accurate biostratigraphy for the upper part of the San Juan Formation and the lower member of the Las Aguaditas Formation is necessary for determining with precision the deepening event that affected the whole Precordillera. Although some previous conodont studies have been carried out on the Las Aguaditas Formation at its type section (Eberlein, 1990; Keller *et al.*, 1993), the present contribution is based on detailed sampling, which allow us to recognize a hiatus between the lower and the middle members of the Las Aguaditas Formation. Also, a detailed biostratigraphic scheme for the middle Darriwilian to Lower Sandbian interval of the Argentine Precordillera is presented based on new conodont data from this section, which allows a precise correlation at the regional and global level. Moreover, the biogeographic affinity of the conodont associations recognized through the stratigraphic range is investigated, and compared with those of Laurentian, Baltoscandian, and Gondwanan localities to contribute to a better understanding of the position of the Precordillera during this time span.

## 2. Las Aguaditas Formation

The type section of the Las Aguaditas Formation is on the eastern flank of the Los Blanquitos Range, in the Central Precordillera of San Juan Province, 10 km to the southwest of Jachal City (Keller *et al.*, 1993). Baldis and Blasco (1974) recognized four members in their original stratigraphic description of the unit, namely a 54 m thick lower member; a 110 m thick slaty member; a 40 m thick middle member; and an 80 m thick upper member. Later, it was formally defined by Baldis *et al.* (1982) at its type section. Lithologically, the formation consists of marls, limestones, and reef limestones, with a characteristic yellowish weathering color. This formation overlies paraconformably the San Juan Formation (Astini, 1995), which is easily distinguished by its nodular limestones (Baldis *et al.*, 1982), with the contact marked by 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 latest Ordovician to earliest Silurian age.

Astini (1995) distinguished three transgressive and regressive cycles in the whole formation. 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 elevations (horsts) within the basin (Astini, 1995, 1997).

The top part of the San Juan Formation represents a distal ramp environment with minor storm influence. The transition interval between the latter unit and the overlying Las Aguaditas Formation includes calcareous-pelitic deposits, whose depositional regime is interpreted to be caused by a flooding event on the platform, since there is no evidence of a 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). It may coincide with a sea level rise caused by a rapid warming after the cooling peak reached during the middle Darriwilian (Webby, 1984), which caused the deposition of black shales and mudstones (Fortey, 1984). The environmental change recognizable in the lithology is associated by a remarkable faunal turnover between the San Juan and the Las Aguaditas formations. Porifera remnants are common in the top part of the former unit, while bryozoans dominate the Las Aguaditas Formation (Carrera, 1997; Carrera and Ernst, 2010). This change could be caused by local and global changes adverse for sponges but favorable for bryozoans, such as an increase in nutrients and turbidity that restricts the development of the carbonate platform (Wood, 1993). This condition is supported by the record of K-bentonite levels in the transition between the San Juan and the overlying units (Huff *et al.*, 1997). Another possible cause is a decrease in the sea water temperature as a consequence of the migration of the Precordillera to higher latitudes and a sea level rise of global scale (Astini, 1995; Webby *et al.*, 2004).

The shallow outer-shelf strata represented by the San Juan Formation and those of the deeper water environment represented by the lower member of the Las Aguaditas Formation exhibit a high diversity of conodonts. Albanesi *et al.* (2006) explain that this is probably due to nutrient enrichment as a product of upwelling currents, as well as to a shallow-deep water faunal exchange through the thermocline.

## 2.1. Previous conodont biostratigraphic studies

The lower member of the Las Aguaditas Formation correlates with several formations in the Precordillera, such as the lower member of the Gualcamayo Formation (Albanesi *et al.*, 1998; Astini, 1995), the lower member of the Los Azules Formation (Ortega *et al.*, 2007), the Las Chacritas Formation (Serra *et al.*, 2015), with the lower Sierra de la Invernada Formation (Albanesi *et al.*, 2009) and the Yerba Loca Formation at the Ancaucha Creek (Albanesi *et al.*, 1995b; Voldman *et al.*, 2008).

The first conodont biostratigraphic dating proposed a Floian age for the top part of the San Juan Formation at the Las Aguaditas creek section (Sarmiento *et al.*, 1986). Albanesi *et al.* (1998) reviewed this interval and referred it to the middle Darriwilian based on the identification of the *Lenodus variabilis* Zone. More recently, Feltes *et al.* (2014) recognized the *Yangtzeplacognathus crassus* Zone, based on the identification of the eponymous index species, in the contact interval between the San Juan and the Las Aguaditas formations at the Las Aguaditas Creek section.

The index conodont *Pygodus serra* was reported by Keller *et al.* (1993) above the lower member of the Las Aguaditas Formation, indicating a late Darriwilian age for most of the unit. Eberlein (1990) and Lehnert (1995) recognized the *P. serra* and *P. anserinus* zones in the middle and upper parts of the Las Aguaditas Formation. In the upper portion of the formation Albanesi and Ortega (1998) identified the conodont index species of the lower Sandbian *Amorphognathus tvaerensis* in association with *Baltoniodus variabilis*, *Baltoniodus gerdae* and *Cahabagnathus sweeti* (cf. Lehnert *et al.*, 1999). Recently, Serra *et al.* (2013) confirmed the presence of *P. anserinus* from the base of the middle member to the top of the upper member of the Las Aguaditas Formation.

## 3. Materials and Methods

Over 66 kg of rocks were processed, which correspond to 46 carbonate samples from the upper part of the San Juan Formation and the lower member, and base of the middle member, of the Las Aguaditas Formation. A total of 9,974 conodont specimens have been recovered, which represent 68 species that belong to 38 genera (Fig. 2).

Our statistical analysis is based on the frequency of conodont genera in each sample. Patzkowsky (1995) considered that the identification of genera rather than species gives more reliable results and the former represents a longer time span permitting environmental association of fossil taxa to be more easily identified. Only samples with more than 2 genera were included in the analysis and taxa that occurred in only one sample were excluded. This produced a final data matrix consisting of 25 samples and 32 genera. Conodont associations were identified quantitatively on the basis of Q-mode cluster analysis of samples based on the unweighted pair group method using arithmetic averages (UPGMA) and the Bray-Curtis similarity coefficient. Raw counts were logarithmically (ln) transformed.

Hierarchical cluster analysis was performed using PAST 2.15 (Hammer *et al.*, 2001). The abundance pattern was analyzed using the Inkspot tool in R 3.1.2 from the rioja package (Juggins, 2015).

The conodont elements have a color alteration index (CAI) of 3, which indicates paleotemperatures ranging from 110° to 190 °C (Epstein *et al.*, 1977). The specimens recorded from the San Juan Formation and the uppermost part of the lower member of the Las Aguaditas Formation are abundant, well preserved and taxonomically diverse, whereas the specimens recovered from the basal parts of the lower and middle members of the Las Aguaditas Formation are scarce, and their preservation is poor. The fossil collection is housed in the Museo de Paleontología, FCEFyN, UNC, under repository code CORD-MP.

## 4. Conodont biostratigraphy

The first formal conodont-graptolite biostratigraphic scheme for the middle Darriwilian of the Precordillera was published by Albanesi *et al.* (1995b, 1998) and later revised by Albanesi and Ortega (2002). The conodont zonal units included the *Lenodus variabilis* Zone with the *Periodon gladysae* and *Paroistodus horridus* subzones, and the *Eoplacognathus suecicus* Zone, with the *Histiodella kristinae* and *Pygodus anitae* subzones.

Based on the conodont index species identified in the study section, the middle Darriwilian conodont zones proposed in Scandinavia can be recognized. These comprise the *Lenodus variabilis*, *Yangtzeplacognathus crassus*, and *Eoplacognathus pseudoplanus* zones, and the *M. hagetiana* and

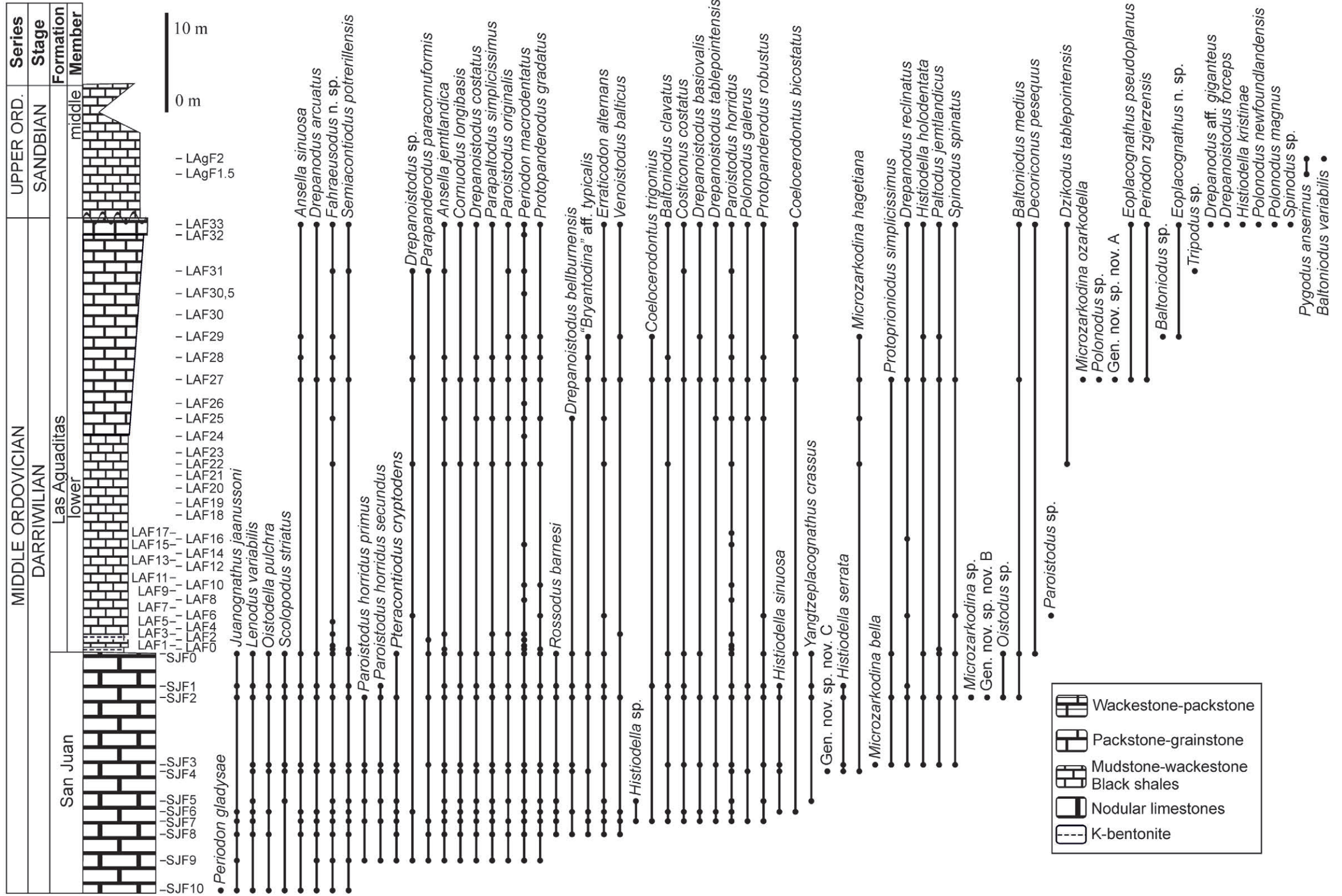


FIG. 2. Stratigraphic column showing conodont species ranges and zones of the Las Aguditas Formation (lower and basal middle members). **ORD:** Ordovician.

*M. ozarkodella* subzones of the latter zone. It was also possible to recognize the lineage zones of the same time span proposed for North America that consists of the *Periodon macrodentatus* Zone with its *Histiodela sinuosa* and *Histiodela holodentata* subzones and the *Periodon zgierzensis* Zone, *Histiodela kristinae* Subzone (Fig. 3). Additionally, the *Lenodus variabilis* Zone with its *Periodon gladysae* and *Paroistodus horridus* subzones which were proposed by Albanesi and Ortega (2002) for the Precordillera, were also identified, following the emendation by Carrera et al. (2013). The uppermost biozone identified in the studied section is the upper subzone of the *Pygodus anserinus* Zone, of Sandbian age (Fig. 4), although the recorded presence of *Amorphognathus tvaerensis* at the top of the section cannot be discarded based on our current records.

#### 4.1. *Lenodus variabilis* Zone

In our study interval, the lower Darriwilian conodont zonation begins with the FAD of *Lenodus variabilis* (in the stratigraphic lowest sample SJF10), using the Scandinavian scheme. This sample was taken from the lowest visible stratum in the study section, in the upper part of the San Juan Formation, 24 m below the contact with the overlying Las Aguaditas Formation. In this sample *Periodon gladysae* was also identified, indicating the *Periodon gladysae* Subzone of the *Lenodus variabilis* Zone. The M element of *L. variabilis* was identified, which according to Löfgren and Zhang (2003) is the diagnostic morphotype of the species. In sample SJF7, ca. 7 m above SJF10, Pa elements of *L. variabilis* were recovered confirming its presence. Sample SJF9 carries elements of *P. horridus primus* and *P. horridus secundus*, which indicate the *P. horridus* Subzone of the *L. variabilis* Zone defined by Albanesi and Ortega (2002) for regional correlation, and recently well documented by Carrera et al. (2013), following this concept. The upper boundary of this zone is defined by the FAD of *P. h. horridus* that indicates the beginning of the *Yangtzeplacognathus crassus* Zone at 17 m below the base of the Las Aguaditas Formation (SJF7). This biozone is 7 m thick at the study section.

The *Periodon gladysae* Subzone is characterized by the presence of several species associated with the index species, such as *Ansella sinuosa*, *Juanognathus jaanussoni*, and *Semiacontiodus*

*potrerillensis*. In the *Paroistodus horridus* Subzone, the biodiversity increases greatly, with the presence of *Ansella jemtlandica*, *Baltoniodus clavatus*, *Cornuodus longibasis*, *Drepanoistodus basiovalis*, *Drepanoistodus costatus*, *Erraticodon alternans*, *Parapaltodus simplicissimus*, *Parapanderodus paracornuformis*, *Periodon macrodentatus*, *Pteracontiodus cryptodens*, *Rossodus barnesi*, *Paroistodus originalis*, *Paroistodus horridus primus* and *P. h. secundus* (Table 1). In *Paroistodus* the speciation process documented by Albanesi and Barnes (2000) occurs in the studied section between samples SJF9 and SJF0. In the oldest sample, the ancestor *P. originalis* was recovered along with the intermediate forms, *Paroistodus h. primus* and *Paroistodus h. secundus*, and 4 m higher (SJF7) the derived species, *P. h. horridus*, makes its entrance in lower frequency than the older species. In the interval of the samples SJF6 to SJF2, *P. horridus* tends to increase in relative abundance until *Paroistodus h. primus* and *Paroistodus h. secundus* disappear in samples SJF1 and SJF0, respectively. Above SJF0, only *P. horridus* was recovered and extends to the top of the lower member of the Las Aguaditas Formation. These records allow for a precise correlation at regional level, where this speciation event may have occurred.

##### 4.1.1. Regional and global correlation

The conodont species *L. variabilis* has previously been reported from the San Juan and Gualcamayo formations in the Villicum Range (Sarmiento, 1985; Heredia and Mestre, 2013a,b; Mestre, 2013), and at Cerro Viejo of Huaco (Ottone et al., 1999; Ortega et al., 2007), in the uppermost part of the San Juan Formation at Portezuelo de Yanzo and Cerro Potrerillo (Ortega et al., 1995; Albanesi et al., 1998; Albanesi and Ortega, 2002), and also in the Yerba Loca Formation from the western Precordillera (Albanesi et al., 1995b).

The *Lenodus variabilis* Zone of the Las Aguaditas Formation correlates with coeval strata of other regions such as the St. Petersburg area in Russia where it was originally described by Sergeeva (1963), and in central and southern Estonia (Viira, 1974), Sweden (Löfgren, 1978; Stouge and Bagnoli, 1999; Löfgren, 2000; Mellgren and Eriksson, 2009), and elsewhere in Baltoscandia. In south-central China this index taxon was identified at the Yangtze Valley (Ni and Li, 1987; Zhang, 1998a; Wang and Bergström, 1999).



#### 4.2. Yangtzeplacognathus crassus Zone

The *Yangtzeplacognathus crassus* Zone overlies the *L. variabilis* Zone in the studied section. The index taxon *Y. crassus* was identified in sample SJF5, from 15 m below the contact with the Las Aguaditas Formation. However, the lower boundary of this biozone is marked by the presence of *P. h. horridus*, which appears 17 m below the top of the San Juan Formation (SJF7). The upper boundary is determined by the FAD of *Dzikodus tablepointensis* at level LAF22, 19 m above the base of the Las Aguaditas Formation, which indicates the beginning of the *Eoplacognathus pseudoplanus* Zone. The *Y. crassus* Zone is 36 m thick at the Las Aguaditas type section. The index species *Y. crassus* was identified on the basis of several elements of its multielemental apparatus, including Pa elements that are diagnostic at the species level. Although the morphotypes Pa and Pb change considerably through the ontogeny (Zhang, 1997), their range barely overlaps with that of *Lenodus* at our study section. This is similar to their occurrences in Swedish and southern Chinese sections, as shown by Löfgren and Zhang (2003).

A total of 52 conodont species were identified within the interval of this zone. Apart from the index species, the more abundant are *A. jemtlandica*, *A. sinuosa*, *D. basiovalis*, *D. bellburnensis*, *D. tablepointensis*, *Fahraeusodus* n. sp., *H. holodentata*, *H. sinuosa*, *P. simplicissimus*, *P. horridus*, *P. originalis*, *P. macrodentatus*, *P. gradatus*, *Pteracontiodus cryptodens*, *R. barnesi* and *Semiacontiodus potrerillensis*. Other associated taxa are less abundant, such as

*B. clavatus*, *B. medius*, *C. longibasis*, *C. costatus*, *D. arcuatus*, *E. alternans*, *Oistodella pulchra*, *Paltodus jemtlandicus*, *P. horridus primus*, *P. h. secundus*, *Polonodus galerus*, *P. robustus*, *Protoprioniodus simplicissimus* and *Scolopodus striatus* (Table 1). The record of *B. medius* in sample SJF2 verifies the biostratigraphic definition of Albanesi (1998), who indicates that the lower boundary of the *P. horridus* Subzone of the *L. variabilis* Zone coincides with the presence of the latter zone index species.

This zone includes the transition interval between the San Juan Formation and the overlying Las Aguaditas Formation. The latter formation begins with a change in lithology that shows a deepening of the basin. The samples from the lower part of the lower member are virtually barren of conodonts, with many yielding pyrite cubes indicating an anoxic paleoenvironment, up to the level of LAF22 where the fauna began to recover. It is worth noting that in samples LAF2, LAF6, LAF12 and LAF24 fossil metallic spherulites were recovered. These levels, except for sample LAF24, span the coeval interval as occurs at Kinnekulle, Sweden, where micrometeorites were found (Schmitz et al., 2003, 2008; Mellgren and Eriksson, 2009).

##### 4.2.1. Regional and global correlation

Huff et al. (1997) dated the top part of the San Juan Formation and lower part of the Los Azules Formation at Cerro Viejo of Huaco, using the U-Pb method on zircons present in the K-bentonites, as  $464 \pm 2$  Ma, which provides an absolute dating of the *Y. crassus* Zone. This interval correlates with the

FIG. 3. Scale bar 0,2 mm. **A.** *Histiodella sinuosa* Graves and Ellison, Pa, SJF3, CORD-MP 34948; **B.** *Histiodella serrata* Harris, Pa, SJF3, CORD-MP 35043; **C, E-G.** *Histiodella holodentata* Ethington and Clark; **C.** Pa, SJF3, CORD-MP 35077; **E.** Pb?, LAF33, CORD-MP 35190; **F.** Sc, LAF33, CORD-MP 35191; **G.** Sc, LAF33, CORD-MP 35192; **D.** *Histiodella cf. holodentata* Stouge, Pa, LAF33, CORD-MP 20579; **H.** *Histiodella kristinae* Stouge, Pa, LAF33, CORD-MP 35193; **I-K.** *Lenodus variabilis* (Sergeeva); **I.** Sb, SJF6, CORD-MP 35312; **J.** M, SJF6, CORD-MP 35269; **K.** Pa, SJF6, CORD-MP 35280; **L.** *Periodon macrodentatus* (Graves and Ellison), Pa, LAF33, CORD-MP 36740; **M.** *Periodon zgierzensis* Dzik, Pa, LAF33, CORD-MP 38933; **N.** *Periodon gladysae* Albanesi, Pa, SJF10, CORD-MP 36736; **O.** *Paroistodus originalis* (Sergeeva), Sc, LAF27, CORD-MP 36612; **P.** *Paroistodus horridus primus* Albanesi, Sa, SJF5, CORD-MP 35624; **Q.** *Paroistodus horridus secundus* Albanesi, Sa, SJF7, CORD-MP 35670; **R-T.** *Paroistodus horridus* (Barnes and Poplawski); **R.** Sc, LAF27, CORD-MP 35900; **S.** Sb, LAF27, CORD-MP 36300; **T.** M, LAF27, CORD-MP 35774; **U-V.** *Ansella sinuosa* Stouge; **U.** M, SJF3, CORD-MP 33321; **V.** Pa, SJF3, CORD-MP 33520; **W-X.** *Ansella jemtlandica* (Löfgren); **W.** M, LAF27, CORD-MP 33000; **X.** Pa, SJF3, CORD-MP 33320; **Y-Z.** *Baltoniodus clavatus* Stouge and Bagnoli; **Y.** M, SJF3, CORD-MP 33521; **Z.** Pa, SJF3, CORD-MP 33551; **AA.** *Microzarkodina bella* Löfgren, Sa, SJF3, CORD-MP 35314; **AB.** *Microzarkodina hagetiana* Stouge and Bagnoli, Sa, LAF27, CORD-MP 21601; **AC.** *Drepanoistodus basiovalis* (Sergeeva), M, LAF27, CORD-MP 33901; **AD.** *Drepanoistodus bellburnensis* Stouge, M, SJF7, CORD-MP 33946; **AE.** *Pteracontiodus cryptodens* (Mound), P, SJF6, CORD-MP 40008; **AF.** *Yangtzeplacognathus crassus* (Chen and Zhang), Pa, SJF1, CORD-MP 40721; **AG.** *Microzarkodina ozarkodella* Lindström, Sa, LAF27, CORD-MP 25001; **AH.** *Drepanoistodus tablepointensis* Stouge, M, LAF33, CORD-MP 34113.





transition from the San Juan Formation to the overlying Las Aguaditas, Las Chacritas, and Gualcamayo formations where the same index species and the K-bentonites beds were identified as well (Heredia et al., 2011; Serra et al., 2011).

The presence of the index taxon, *Y. crassus* was first recorded in the Precordillera from the upper San Juan Formation (Lehnert, 1995), and subsequently it was found at numerous localities. At a regional level, this zone correlates with coeval strata in the Las Chacritas River section, Villicum range, Cerro Viejo of Huaco and Oculta creek, where the transition from the San Juan Formation to the overlying units occurs in a similar way as in the Las Aguaditas creek section (Albanesi et al., 2013; Feltes et al., 2014; Serra et al., 2015). The fauna associated with *Y. crassus* also allows the correlation with the Yerba Loca Formation at Ancaucha creek (Albanesi et al., 1995b; Voldman et al., 2008) and with the Los Sombrosos Formation at Los Túneles of Jáchal river (Voldman et al., 2009).

The presence of *Y. crassus* along with the associated fauna, enables a precise global correlation with stratigraphic successions at several areas of south China, such as Yichang in the Hubei Province (Zhang, 1997), Shitai in the Anhui Province (Chen and Zhang, 1989), and at Kalping in the Xinjiang Province, northwest China (Wang et al., 1996). It also correlates with several areas in Scandinavia, for instance, Kinnekulle and Billingen (Zhang, 1997, 1998b; Mellgren and Eriksson, 2009), Scania (Erlström et al., 2001; Stouge and Nielsen, 2003), Öland (Stouge and Bagnoli, 1999), and in the East

Baltic (Männik and Viira, 2012) among others. In our study section *Y. crassus* appears associated with the uppermost record of *L. variabilis*, as recorded by Löfgren and Zhang (2003) for the Baltic region. However, unlike Scandinavia, it disappears well before the first record of *E. pseudoplanus*. This may be due to the deepening in this interval, where virtually no conodonts were recovered, except for few species such as *Periodon macrodentatus*, *Paroistodus horridus* and *Protopanderodus gradatus*.

### 4.3. *Eoplacognathus pseudoplanus* Zone

In the middle part of the lower member of the Las Aguaditas Formation the index taxa *E. pseudoplanus* and *Dzikodus tablepointensis* were identified. The latter was documented in sample LAF22, 19 m above the base of the formation, while *E. pseudoplanus* was identified in younger strata, in sample LAF27 at 8.5 m above *D. tablepointensis*. Zhang (1998a) regarded the *D. tablepointensis* Zone as equivalent to the *E. pseudoplanus* Zone in south-central China. In the Jämtland sections of Sweden, the upper subzone of the *E. pseudoplanus* Zone contains a great abundance of *D. tablepointensis*. In our study section, *D. tablepointensis* appears first in the succession probably due to environmental restrictions for *E. pseudoplanus* as a consequence of the sudden deepening event in the transition between the San Juan to the Las Aguaditas formations. *Dzikodus* is more typical of south-central China (Zhang, 1998a) and western Newfoundland (Stouge, 1984) where it occurs in deep water environments (Pyle and Barnes, 2002).

FIG. 4. Scale bar 0,2 mm. **A.** *Eoplacognathus pseudoplanus* (Viira), Pa, LAF33, CORD-MP 34394; **B.** *Eoplacognathus* n sp., Pa, LAF33, CORD-MP 34383; **C-D.** *Baltoniodus variabilis* (Bergström); **C.** Pa, LAF2, CORD-MP 44201; **D.** Sc, LAF2, CORD-MP 44202; **E.** *Decoriconus pesceus* Löfgren, S, LAF33, CORD-MP 33758; **F.** *Pygodus anserinus* Lamont and Lindström, Pa, LAF1,5, CORD-MP 44100; **G-H.** *Polonodus magnus* Albanesi; **G.** Pb, LAF33, CORD-MP 39213; **H.** Pa, LAF33, CORD-MP 39214; **I.** *Polonodus newfoundlandensis* (Stouge), Pb, LAF33, CORD-MP 39209; **J.** *Dzikodus tablepointensis* (Stouge), Pb, LAF33, CORD-MP 21723; **K-L.** *Spinodus spinatus* (Hadding); **K.** Sc, LAF27, CORD-MP 40650; **L.** P, LAF33, CORD-MP 40662; **M-N.** *Polonodus galerus* Albanesi; **M.** Pa, LAF27, CORD-MP 39194; **N.** Sc, LAF27, CORD-MP 39180; **O.** *Scolopodus striatus* Pander, Sc, SJF0, CORD-MP 40620; **P-Q.** *Erraticodon alternans* (Hadding); **P.** P, LAF27, CORD-MP 34449; **Q.** M, LAF27, CORD-MP 34395; **R.** *Oistodella pulchra* Bradshaw, P, SJF1, CORD-MP 35369; **S-T.** *Rossodus barnesi* Albanesi; **S.** M, SJF3, CORD-MP 40009; **T.** Sa, SJF3, CORD-MP 40140; **U.** *Drepanoistodus costatus* Abaimova, M, SJF7, CORD-MP 34007; **V.** *Protopanderodus gradatus* Serpagli, Sb-Sc, LAF27, CORD-MP 39400; **W.** *Costiconus costatus* (Dzik), Sb, SJF3, CORD-MP 33743; **X.** *Parapanderodus paracornuiformis* Ethington and Clark, Pb, SJ, CORD-MP 35617; **Y.** *Drepanodus arcuatus* Pander, M, LAF33, CORD-MP 33760; **Z.** *Drepanodus reclinatus* (Lindström), Pa, LAF33, CORD-MP 33890; **AA.** *Cornuodus longibasis* (Lindström), Sa, SJF3, CORD-MP 33692; **AB.** *Protopanderodus robustus* (Hadding), Sb-Sc, LAF27, CORD-MP 39750; **AC.** *Juanognathus jaanussoni* Serpagli, M, SJF6, CORD-MP 35209; **AD.** *Venoistodus balticus* (Löfgren), M, LAF2, CORD-MP 40665; **AE.** *Semiacontiodus potterillensis* Albanesi, Sb, SJF6, CORD-MP 40441; **AF.** *Paltodus jemtlandicus* Löfgren, P, SJF3, CORD-MP 35380; **AG.** *Parapaltodus simplicissimus* Stouge, Sa, SJF3, CORD-MP 35615.



*E. pseudoplanus* is more common in northern Estonia (Viira et al., 2001) where there are slightly shallower settings. In the Precordillera, *D. tablepointensis* was recovered on bedding planes from the lowest part of the middle member of the Los Azules Formation, along with other species that lived above euxinic bottom conditions (Ortega et al., 2007). The presence of *E. pseudoplanus* and *D. tablepointensis* may be used for the definition of an association zone for the Precordilleran region as they have similar ranges but different environmental requirements.

The index species *Microzarkodina hagetiana* and *M. ozarkodella*, which define the lower and upper subzones of the *Eoplacognathus pseudoplanus* Zone in the Baltoscandic region (Zhang, 1998b; Löfgren, 2004) have also been identified in the Precordillera. The upper boundary of this biozone is missing from the top of the lower member of the Las Aguaditas Formation because a stratigraphic gap separates the lower and middle members, indicated by the presence of Sandbian conodonts of the *Pygodus anserinus* Zone in the middle member. Although being the index of the lower subzone of the *E. pseudoplanus* Zone, *M. hagetiana* appears in the *L. variabilis* Zone (Löfgren and Tolmacheva, 2008). Because in the Las Aguaditas Formation this species was first documented from sample SJF4, in the *Yangtzeplacognathus crassus* Zone, it is necessary to find this species associated with *D. tablepointensis* or *E. pseudoplanus* in order to identify the *M. hagetiana* Subzone, as it was documented in sample LAF22. The top part of the lower member is a highly productive 1.1 m thick coquina. The *E. pseudoplanus* Zone is 24 m thick in the study section. In spite of the hiatus, it is thought that virtually the whole *E. pseudoplanus* Zone is represented in this section, based on the associated fauna and the fact that other index species typical of the topmost part of this zone were identified in the uppermost sample (LAF33). The index species *Histiodela kristinae* defines the lower subzone of the *E. suecicus* Zone in the Precordillera (Albanesi, 1998). However, in Scandinavia *H. kristinae* appears earlier in the record, in an interval where *E. suecicus* is not yet present (Zhang, 1998b; Löfgren, 2004). Also, this species was recovered along with its ancestor *H. holodentata*, which indicates early forms of *H. kristinae* as the evolving species. In addition, elements of *Polonodus magnus* Albanesi 1998 (synonym of *Pygodus lunnensis* Zhang, 1998c) were recovered, which in the Baltic scheme defines the lower subzone

of the *E. suecicus* Zone. This may indicate that the level represents the *E. suecicus* Zone but the eponymous species was not recorded. This sample yields elements of *E. pseudoplanus* and previously unrecognised elements of *Eoplacognathus*. The Pa elements of the latter species exhibit an expansion of the platform of the posterior process, but they do not have a secondary denticle row in the posterior-lateral process, which Zhang (1998b, 1999) defines as a diagnostic character of *E. suecicus*. The Pa elements may belong to a new species of *Eoplacognathus* or considering the presence of some characters shared by *E. pseudoplanus* and its descendant *E. suecicus* (Zhang, 1999, Löfgren and Zhang, 2003), they may be intermediate forms, which could suggest a mosaic evolution of this genus.

This zone is represented by a conodont association including *A. jemtlandica*, *A. sinuosa*, *B. clavatus*, *Bryantodina* aff. *typicalis*, *Coelocerodontus bicostatus*, *C. trigonius*, *Drepanodus arcuatus*, *Drepanodus robustus*, *Drepanodus* aff. *giganteus*, *D. costatus*, *D. tablepointensis*, *Fahraeusodus* n. sp., *H. holodentata*, *P. horridus*, *P. macrodentatus*, *P. zgierzensis*, *P. gradatus*, *P. robustus* and *Spinodus spinatus* among others (Table 1).

#### 4.3.1. Regional and global correlation

The *E. pseudoplanus* Zone of the lower member of the Las Aguaditas Formation correlates with the Las Chacritas Formation (Albanesi and Astini, 2000; Serra et al., 2013, 2015), Sierra de La Invernada Formation (Albanesi et al., 2009; Ortega et al., 2010) and the Los Azules Formation (Ortega et al., 2007) in the Precordillera.

This zone correlates with strata in the Yangtze valley of south-central China (Ni and Li, 1987; Zhang, 1998a), New Zealand (Zhen et al., 2011b) as well as at diverse localities in Baltoscandia, such as some from Estonia (Viira, 1974; Viira et al., 2001; Löfgren, 2004; Viira, 2011; Männik and Viira, 2012), Norway (Rasmussen, 2001), and Poland (Dzik, 1994). Since stratigraphically late forms of *E. pseudoplanus* were recovered, they enable a precise correlation with the Kunda-Aseri stage boundary interval in Sweden (Löfgren and Zhang, 2003; Mellgren and Eriksson, 2009).

#### 4.4. *Pygodus anserinus* Zone

The paleontological record from the basal part of the middle member of the Las Aguaditas

Formation is very restricted, in marked contrast with the highly productive upper part of the lower member. A clear difference in lithology indicates the boundary between the lower member with a calcareous coquina as the uppermost bed, and the middle member characterized by 5 to 20 cm thick beds of gray mudstone. The index species *Pygodus anserinus* was identified 4.5 m from the base, in sample LAGF1.5. The presence of the upper subzone of the *P. anserinus* Zone was confirmed by the identification of *B. variabilis* in LAGF2 which, according to Bergström (1971), indicates this interval. Moreover, a typical Sandbian graptolite association which consists of *Leptograptus*, *Pseudoclimacograptus*, *Archiclimacograptus*, *Dicranograptus*, *Acrograptus* and *Dicellograptus*, was recovered 10 m above the base of the middle member of the Las Aguaditas Formation (Albanesi *et al.*, 2013). *Nemagraptus gracilis* indicating the Sandbian Stage was identified *ca.* 100 m above the base of the middle member (Serra *et al.*, 2013).

A stratigraphic gap between the lower and middle members was recognized by the recovery of the index species *P. anserinus* in the lower part of the middle member. The hiatus spans the *Eoplacognathus suecicus* and *Pygodus serra* zones and the lower subzone of the *P. anserinus* Zone. It is worth noting that this hiatus is recorded in the Siberian platform, in the Baltoscandic region and in China as well (Dronov *et al.*, 2009; Schmitz *et al.*, 2010).

#### 4.4.1. Regional and global correlation

In the Precordillera, this zone has been identified in the Ponón Trehué Formation, in the Mendoza province (Heredia and Rosales, 2006), the Las Aguadita Formation in the Las Chacritas River section (Serra *et al.*, 2013, 2015), in the La Invernada Formation (Ortega *et al.*, 2008), and in Los Azules Formation at the La Chilca Hill (Albanesi, *in Peralta et al.*, 2003).

This zone correlates with equivalent strata in Newfoundland (Bergström *et al.*, 1974), the Marathon basin, Texas (Bergström, 1978), strata in the Great Basin and Rocky Mountains (Harris *et al.*, 1979), Poland (Dzik, 1994), Sweden (Bergström, 1971, 2007), northwestern China (Zhen *et al.*, 2011a), Thailand (Agematsu *et al.*, 2007), Kazakhstan (Tolmacheva *et al.*, 2009), and New South Wales in Australia (Zhen *et al.*, 2003).

#### 4.5. *Periodon macrodentatus* Zone

*Periodon* Hadding, 1913, is a widely distributed lineage, with a long stratigraphic range from the early Floian to the Late Ordovician (Löfgren and Tolmacheva, 2008). The zonal index species *P. macrodentatus* is the most abundant species in the study section. The lowest record occurs in the San Juan Formation (Sample SJF9), 21 m below the contact with the Las Aguaditas Formation. *P. macrodentatus* is present throughout the study interval in 28 of 45 samples. *P. macrodentatus* is also the most abundant species in the correlative interval at Newfoundland (Stouge, 2012). The upper boundary of this zone is defined by the FAD of *Periodon zgierzensis* in sample LAF27. The *P. macrodentatus* Zone is 48.5 m thick in the study section.

The three subzones of the *P. macrodentatus* Zone as defined by Stouge (2012) for Newfoundland were identified in the study section. The index species *Histiodela sinuosa*, which defines the lower subzone, was documented in sample SJF6 and 4 m above, in sample SJF4, where it is associated with *Histiodela serrata*, an intermediate form that connects *H. sinuosa* with *H. holodentata*. The latter species appears in sample SJF3 and defines the middle subzone up to the upper part of the lower member of the Las Aguaditas Formation, where elements of *H. holodentata* that belong to late forms of the species were recorded. These late forms are referred to by Stouge (2012) as *Histiodela cf. holodentata*, marking an evolutionary transition between *H. holodentata* and *H. kristinae*.

Several elements of the *Oistodella pulchra* apparatus have been identified from the San Juan Formation in the study section. Together with those documented for the Las Chacritas River section (Serra *et al.*, 2015), these represent the few records of this species outside Laurentia. In North America, the species has been recovered from strata in the Cow Head Group in Newfoundland (Johnston and Barnes 2000; Stouge, 2012), and the Fort Peña Formation in the Marathon basin, Texas (Bradshaw, 1969).

The sequence of index species recorded in this study also matches the stratigraphic scheme proposed for the Tarim region, western China, by Chen *et al.* (2006), where the *Periodon macrodentatus* Zone is subdivided, in ascending order, into the *H. holodentata*, *Y. crassus* and *Histiodela* sp. A subzones. According to our records, we agree with

Stouge (2012) in considering that the *Histiodella* cf. *holodentata* Subzone may be equivalent to the “*Histiodella holodentata*” Subzone of Chen *et al.* (2006).

#### 4.5.1. Regional and global correlation

In the Precordillera, the recognition of the *Periodon macrodentatus* Zone allows the identification of coeval strata in the section of Cerro Potrerillo (Albanesi, 1998), Oculita Creek (Voldman *et al.*, 2013), Las Chacritas River (Serra *et al.*, 2013), Sierra de la Invernada (Albanesi *et al.*, 2009), Ancaucha Creek (Voldman *et al.*, 2008), Cerro la Chilca (Mestre and Heredia, 2012; Carrera *et al.*, 2013), and Cerro Viejo de Huaco (Ortega *et al.*, 2007), among others.

The *Periodon* and *Histiodella* lineages have great potential for global correlation (Stouge, 1984, 2012; Stouge *et al.*, 2011; Chen *et al.*, 2006; Stouge and Zhao, 2006) and support a correlation with equivalent strata in Canada (Uyeno and Barnes, 1970; Barnes and Poplawski, 1973; Pyle *et al.*, 2003; Stouge, 2012), USA (Bauer, 2010; Graves and Ellison, 1941; Bradshaw, 1969), Norway (Rasmussen and Stouge, 1995; Rasmussen, 2001), Sweden (Stouge and Bagnoli, 1999; Löfgren, 2004; Mellgren and Eriksson, 2009), Estonia (Löfgren, 2004), China (*e.g.*, Zhang, 1998a; Chen *et al.*, 2006; Zhang and Gao, 1991; Zhao *et al.*, 2000; Stouge and Zhao, 2006; Stouge *et al.*, 2011; Zhen *et al.*, 2011a), Australia (Zhen and Percival, 2004), New Zealand (Zhen *et al.*, 2009; Zhen *et al.*, 2011b), and Kazakhstan (Zhylkaidarov, 1998; Tolmacheva *et al.*, 2004).

#### 4.6. *Periodon zgierzensis* Zone

The lower boundary of this biozone is determined by the FAD of *P. zgierzensis* in sample LAF 27, and it extends to the top of the lower member of the Las Aguaditas Formation. The contact with the middle member represents a hiatus, with Sandbian conodonts present in the basal strata of the latter unit. The index species appears together with its ancestor, *P. macrodentatus*, which also ranges up to the top of the lower member. However, in this time span we detect an increase in the representation of the younger species over its ancestor to the top of the column. *H. kristinae* was identified in the highest sample, LAF33, which indicates its lower subzone following Stouge (2012). Its thickness is 15.5 m in the study section.

#### 4.6.1. Regional and global correlation

This interval was constrained in the Las Aguaditas (Feltes *et al.*, 2013) and Las Chacritas formations (Serra *et al.*, 2015), but may be present at many localities. Some collections from the Precordillera should be revised because several elements that may belong to *P. zgierzensis* have been described as *P. aculeatus zgierzensis* or *P. aculeatus sensu lato* (*e.g.*, Albanesi, 1998; Ortega *et al.*, 2008; Heredia *et al.*, 2011; Heredia, 2012; Heredia and Mestre, 2013b; Ortega *et al.*, 2007). The index species *H. kristinae* that was first identified in the Precordillera by Sarmiento (1991) in the Gualcamayo Formation, at Sierra of Villicum, allows for precise correlation between several localities (for detail see the *E. pseudo-planus* Zone).

This biozone correlates with similar biostratigraphic intervals in western Newfoundland (Stouge, 1984, 2001, 2012; Stouge and Zhao, 2006), USA (Landing, 1976), China (Chen *et al.*, 2006; Stouge *et al.*, 2011), Scandinavia (Rasmussen, 2001) and New Zealand (Zhen *et al.*, 2011b).

### 5. Conodont abundance

We examined patterns of conodont fauna replacement vertically within a single transgressive-regressive cycle. The conodont richness and abundance variation through the studied section shows strong evidence for shallowing and deepening patterns, in concordance with the lithology. This is shown in figure. 5, where genera are ordered in terms of R-mode cluster, the diameter of the dot reflecting conodont taxa abundance.

The upper part of the San Juan Formation exhibits the greatest diversity of conodont genera, which are mostly well preserved. The lithology consists of nodular limestones and grainstones, which were deposited on a distal platform below the wave base and contain abundant fossils. Trilobites, brachiopods, orthocerid nautiloids and sponge spicules are also present in this unit. This facies indicates shallow environments suitable for the development of a wide variety of taxa with diverse lifestyles.

The first 18 m of the lower member of the Las Aguaditas Formation consists of dark grey mudstones interbedded with graptolitic black shales, which are characteristic of deep water environments. This is also supported by a marked decrease in the conodont fauna. The samples from this interval were almost barren; only a few, poorly preserved elements of

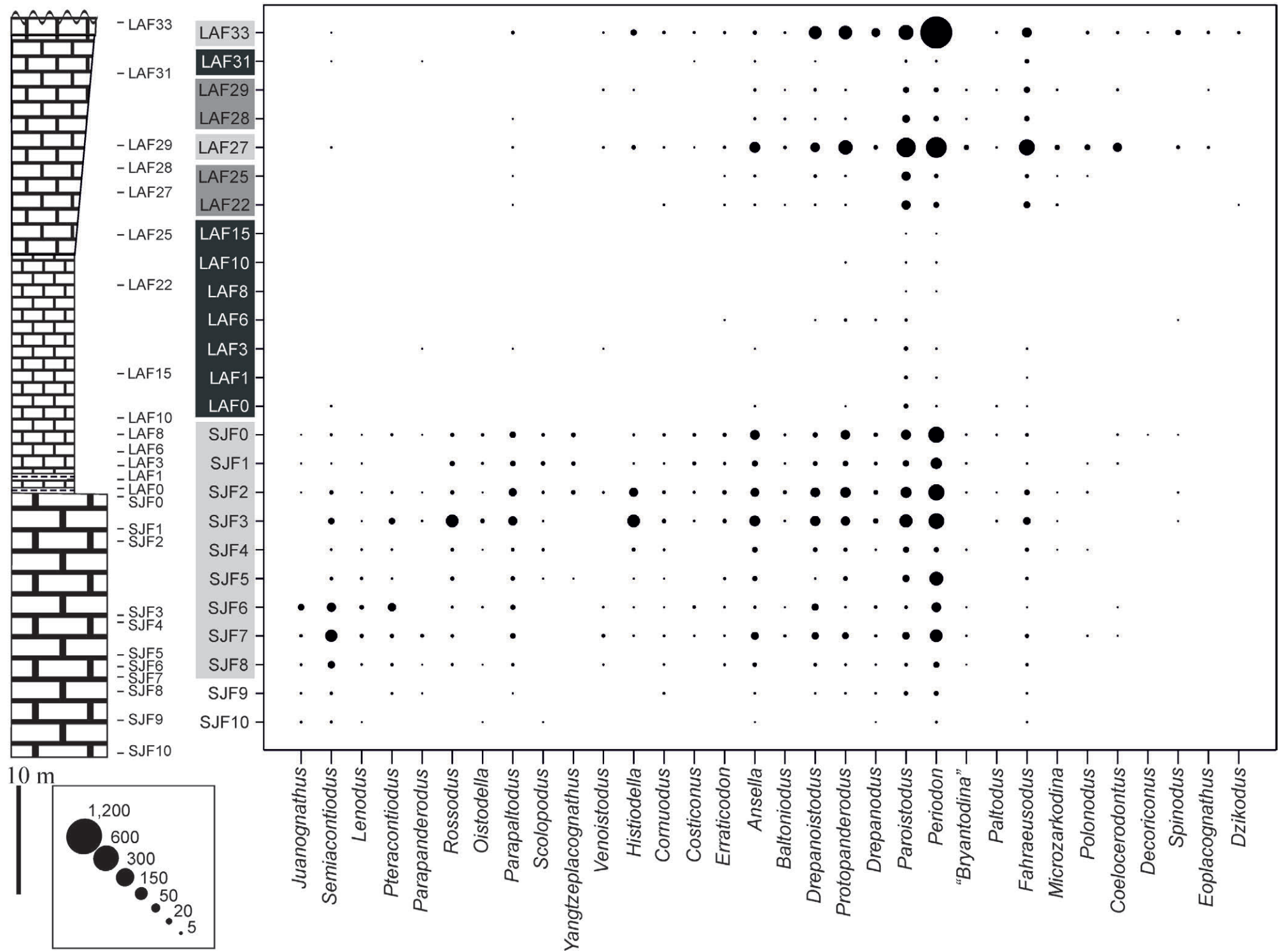


FIG. 5. Stratigraphic column of the upper San Juan Formation and the lower member of the Las Aguaditas Formation and inkspot plot showing the relative abundance of conodont species per sample, represented by the diameters of the dots (R 3.1.2).

diminished size were recovered. Only genera typical of a deep water environment, such as *Periodon* and *Fahraeusodus*, and pelagic taxa of *Drepanodus*, *Paroistodus* and *Protopanderodus*, were documented (Fortey and Barnes, 1977; Stouge, 1984; Bagnoli and Stouge, 1991; Albanesi, 1998). Pelagic trilobite larvae and ostracods were also recovered.

In the middle part of the lower member of the Las Aguaditas Formation there is a recovery in the conodont fauna. We also observed a change in the lithology from mudstone to wackestone-packstone, without significant packages of interbedded shales. This indicates a change in the depositional environment, which is supported by the fossil record.

A fluctuation in the conodont diversity in the upper half of the unit can be observed in Fig. 5. The conodont fauna diversity increases, reaching a peak in sample LAF27, and declining afterwards to zero values in some samples (these samples LAF30, LAF30.5 and LAF32 were eliminated from the analysis and thus cannot be seen in figure 5). A final diversity peak is reached in the top stratum of the unit (LAF33), which indicates a favorable environment for conodonts, this being also shown by the presence of robust elements.

The sudden recovery of the conodont fauna diversity is interpreted as reflecting a migration event into the basin, as most temporarily absent taxa reappear after the period of restrictive paleoenvironmental conditions. It is well established that conodonts were strongly environmentally controlled (e.g., Barnes and Fåhraeus, 1975; Fortey and Barnes, 1977; Sweet and Bergström, 1984; Rasmussen and Stouge, 1995; Zhang and Barnes, 2004). It is suggested that water temperature was probably the principal factor that governed their distribution (Sweet and Bergström, 1974).

A hierarchical cluster analysis was performed in order to determine the relationship of the samples (Fig. 6). Three associations were identified according to the taxonomic composition: **a)** Diverse conodont association, **b)** Low diversity conodont association and **c)** Recovery phase association.

a. Diverse conodont association: this association presents the highest richness values (samples yield 16 to 27 genera) and includes all the most productive samples from the study section (a total of 9,196 elements). The dominant genera are *Periodon* (3142 elements) and *Paroistodus* (1,264 elements), followed by *Protopanderodus* (800), *Drepanoistodus* (622), *Ansella* (579), *Fahraeusodus* (506) and *Histiodela* (313). This

clustering reflects a similarity in the faunal composition and abundance of taxa between the top part of the San Juan Formation and the upper part of the Las Aguaditas Formation, suggesting recurrent environmental conditions. Most temporarily absent taxa reappear indicating local migration events. New genera are also recorded in samples LAF27 and LAF33, as a result of the time span between the latter samples (*E. pseudoplanus* Zone) and those from the San Juan Formation (*L. variabilis*-*Y. crassus* zones), where speciation or complex diversification events could have taken place.

- b. Low diversity conodont association: this association includes the samples from the lower part of the lower member of the Las Aguaditas Formation, which are almost barren, and sample LAF31 from the upper part, reflecting the diversity fluctuation that began in LAF22, as described above. The conodont abundance and diversity and richness is very low compared to the other associations. In most samples only the genus *Paroistodus* is present, though sometimes it is accompanied by *Periodon*, *Fahraeusodus* and pelagic forms, such as *Drepanodus*, *Protopanderodus* and *Drepanoistodus*.
- c. Recovery phase association: four samples from the middle part of the lower member of the Las Aguaditas Formation were clustered. These represent the beginning of a shallowing event which is supported by a change in the lithology and the reappearance of *Cornuodus* (Löfgren, 1999a). The intermediate environmental setting, in relation to the previous associations, allowed the conodont fauna to emigrate to the basin which is reflected in the recovery of conodont genera and their abundance. The most abundant taxa are *Paroistodus* (260 elements), *Fahraeusodus* (111 elements) and *Periodon* (85 elements), which are characteristic of deep water conditions as in the previous association, although the appearance of new genera indicates different, more favorable, environmental conditions.

## 6. Discussion

Albanesi (1998) defined the *P. gladysae* Subzone as the lower unit of the *L. variabilis* Zone in the Cerro Potrerillo and Portezuelo de Yanso sections in the Central Precordillera. Mestre and Heredia (2009) attempted to remove the *P. gladysae* Subzone based on an incorrect interpretation of the index species *P.*



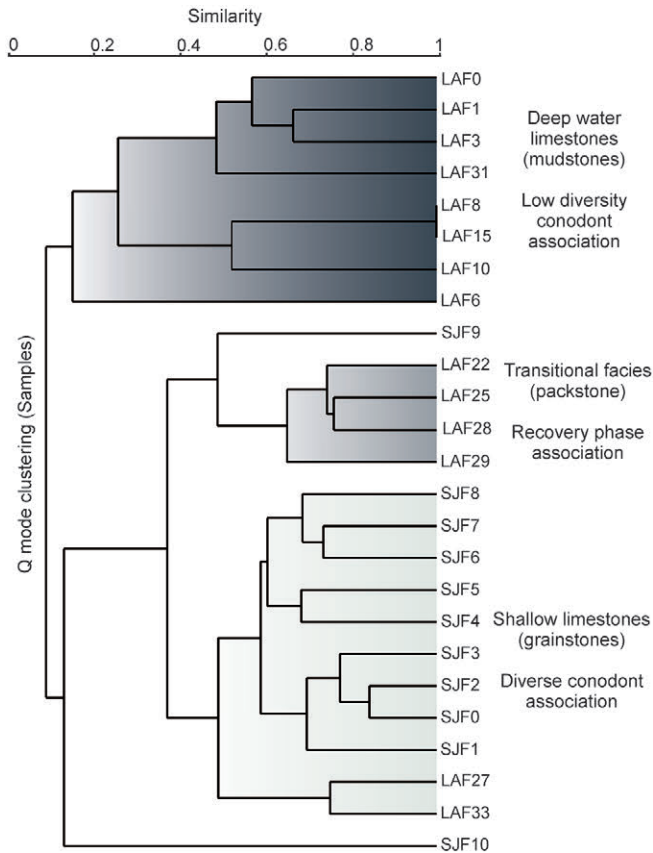


FIG. 6. Q-mode cluster analysis of samples from the upper San Juan Formation and the lower member of the Las Aguaditas Formation showing the three conodont associations (PAST 2.15).

*gladysae* and *L. variabilis* as determined by Albanesi (1998), reassigning those elements to *M. ozarkodella* and *E. pseudoplanus*, respectively. The present study agrees with Albanesi (1998) because in the equivalent levels the diagnostic M and Pa elements of *L. variabilis* are identified in association with *P. gladysae*. In addition, *M. ozarkodella* is identified in the upper part of the formation and is derived from *M. hagetiana*, which is consistent with the phylogeny of the genus described by Löfgren and Tolmacheva (2008) and associated conodont index species.

The report of the occurrence of *P. serra* by Eberlein (1990), Keller *et al.* (1993) and Lehnert (1995), was not confirmed. The stratigraphic gap between the lower and the middle members of the Las Aguaditas Formation embraces the *E. suecicus*, *P. serra* and the lower subzone of the *P. anserinus* zones. It is unlikely that *P. serra* could be present in the middle member since according to Zhang (1997)

its range barely overlaps with *P. anserinus*. The hiatus in between the members is interpreted as representing the Oclöyic tectonic phase (Astini, 1994).

*Periodon* represents 33% of the conodont elements in the collection. It is present in 29 of the total 46 samples that encompass a wide variety of environments. Although the species that represent the *Histiodelia* lineage are not as abundant as those of *Periodon*, they show a continuous record through the study interval. This is not the case for the zonal index species of the Baltic scheme, *L. variabilis*, *Y. crassus* and *E. pseudoplanus*, which are not abundant in the study section, and the same is the case at other localities on the Precordilleran basin. In addition, platform-bearing taxa are less useful as zonal index species as they are restricted to specific facies (Rasmussen, 2001). Moreover, in south-central China *E. pseudoplanus* was not sufficiently abundant to be useful as an index fossil (Zhang, 1998a). The *Periodon* and *Histiodelia*

assemblages have a demonstrated usefulness for correlation across the Iapetus Ocean (Rasmussen and Stouge, 1995; Rasmussen, 2001).

The record of *Oistodella pulchra* in only the Precordillera and Laurentia indicates a faunal exchange between these two regions. This species was recovered from samples of the upper San Juan Formation at the study section and at the Las Chacritas River section (Serra et al., 2015), in platform facies. In the Cow Head Group, Newfoundland, Stouge (2012) recovered *O. pulchra* from 7 samples of wackstone-packstone. In the original paper that defines the species, Bradshaw (1969) did not specify the provenance of each sample. However, it was explained that conodonts were recovered from limestones, conglomeratic limestones and conglomerate beds, and samples that consist of shales and chert did not yield conodonts.

The presence of *Cornuodus longibasis* and the high abundance of *Semiacontiodus potrerillensis* in the upper part of the San Juan Formation, their subsequent disappearance in the lower part of the lower member of the Las Aguaditas Formation and the reappearance of both species in the middle and upper parts, suggest their preferences for shallower settings in the basin. According to Löfgren (1999a, 1999b, 2003, 2004) *Semiacontiodus* and *Cornuodus* are associated with shallowest settings in central Baltoscandia. In contrast, in the same intervals *Costicomus costatus*, and the highest abundance of *Periodon* were documented, which are reliable indicators of relatively deep water (Barnes and Fåhræus, 1975; Lindström, 1976; Pohler, 1994). These intervals were the most productive intervals in the study section (99.9% of the total number of elements in the collection were recovered from samples of those intervals). The lower part of the lower member (from LAF0 to LAF21) was nearly barren except for a few taxa, such as *Periodon macrodentatus*, *Paroistodus horridus* and *Protopanderodus gradatus* that were recorded in low numbers, apparently representing the referred interval a conditioning environment for most taxa.

## 7. Conclusions

The index conodont species and associated fauna recorded from the San Juan Formation, and the lower member and basal strata of the middle member of the Las Aguaditas Formation at its type section, allow the establishment of a high resolution biostratigraphic scheme for the middle Darriwilian to Sandbian in the

Precordillera, which is useful for global correlation. The following biozones are identified in the study section (Fig. 7): the *Lenodus variabilis* Zone, with the *Periodon gladysae* and *Paroistodus horridus* Subzones according to the Precordilleran scheme (Albanesi and Ortega, 2002); the *Lenodus variabilis*, *Yangtzeplacognathus crassus*, and the *Eoplacognathus* zones with the *Microzarkodina hagetiana* and *M. ozarkodella* subzones, as well as the *Pygodus anserinus* Zone, representing the Scandinavian scheme (Löfgren and Zhang, 2003); the *Periodon macrodentatus* Zone, with the *Histiodella sinuosa*, *Histiodella holodentata* and *H. cf. holodentata* subzones, and the *P. zgierzensis* Zone with the *H. kristinae* Subzone proposed recently for North America (Stouge, 2012). A stratigraphic gap that encompasses the *E. suecicus*, *P. serra* and the lower subzone of the *P. anserinus* zones was recognized between the lower and middle members of the Las Aguaditas Formation.

The variation in conodont diversity and the recovery of some particular taxa through the studied section show strong evidence for shallowing and deepening patterns which is in accordance with the lithology. Three associations were quantitatively identified according to the taxonomic composition of the samples: **a)** Diverse conodont association, **b)** Low diversity conodont association and **c)** Recovery phase association. Also a local migration event is suggested to explain the conodont association recurrence between the upper part of the San Juan Formation and the upper part of the lower member of the Las Aguaditas Formation.

Based on the notable difference in the abundance of the zonal index taxa in stratigraphic units on diverse localities in the Central Precordillera, we propose to use the North American biozonal scheme for the Precordillera. This also allows further correlation with Australia, New Zealand and Kazakhstan, where the index species of the Baltic scheme are either scarce or absent. Also the resolution of correlation by the application of phylozones is more reliable than other biostratigraphic methods.

The current conodont biostratigraphy for the Las Aguaditas Formation establishes a lower member 43 m thick of middle Darriwilian age, and a middle and upper member of Sandbian age. Further work is in progress with the goal of establishing a detailed conodont biostratigraphic scheme for the middle member and the upper members of the Las Aguaditas Formation.



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