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Lower Ordovician calcareous microfossils from the San Juan Formation, Argentina: a new type of calcitarch and its paleoenvironmental implications

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ABSTRACT. The calcareous microfossils present in the Ordovician and Silurian carbonate successions around the world are limited to few studies and their biological affinities and environmental preferences remain indefinite. In the carbonate Ordovician San Juan Formation from the Cerro La Chilca section, a group of calcareous microfossils was recognized and, based on their size, they are included in the calcitarch classification. Two types of calcitarchs have been recognized, Type-III calcitarch: large spheres with a thin to medium wall (diameter ~250 µm), and Type-0 calcitarch: small spheres with a thin wall (diameter ~80 µm). The carbonate microfacies analysis of the lower part of the San Juan Formation allowed defining five successive microfacies: burrowed bioclastic wackestone (M1), peloidal intraclastic packstone-grainstone (M2), intraclastic floatstone (M3), intraclastic wackestone-packstone (M4) and bioclastic boundstone (M5). These microfacies are interpreted to range from shallow subtidal facies below wave action to shoal and reef facies. It is possible to infer that the recovered calcitarchs show variations in size in relation to the facies that contain them. The calcitarchs recognized in wackestone-type facies are the Type-0 calcitarch and those recovered from the packstone-grainstone facies are the Type-III calcitarch. The calcitarch sizes variation probably is related to a gradual increase of energy within a shallow subtidal environment. Occurrences of calcitarchs within the Floian *Oepikodus evae-O. intermedius* conodont zone extends their fossil record into the Early Ordovician.

Keywords: Calcitarch, Floian, Precordillera, San Juan Formation, Ordovician.

RESUMEN. Microfósiles carbonáticos del Ordovícico Inferior de la Formación San Juan, Argentina: un nuevo tipo de *calcitarch* y sus implicaciones paleoambientales. Los microfósiles calcáreos presentes en las sucesiones carbonáticas ordovícicas y silúricas están limitados a unos pocos estudios, por lo que sus afinidades biológicas y preferencias ambientales aún están indefinidas. En los niveles carbonáticos de la Formación San Juan en la sección Cerro La Chilca, se reconoció un grupo de microfósiles calcáreos que, en función de su tamaño, se incluyen en la clasificación de *calcitarch*. Se han reconocido dos tipos de *calcitarchs, calcitarchs* tipo-III: esferas grandes con una pared delgada a mediana (diámetro ~250 µm) y *calcitarchs* tipo-0: esferas pequeñas con una pared delgada (diámetro ~80 µm). El análisis de las microfacies carbonáticas de los niveles inferiores de la Formación San Juan permitió definir cinco microfacies sucesivas: *wackestone* bioclástico bioturbado (M1), *packstone-grainstone* intraclástico peloidal (M2), *floatstone* intraclástico (M3), *wackestone-packstone* intraclástico (M4) y *boundstone* bioclástico (M5). Se interpreta que estas microfacies van desde facies submareales poco profundas por debajo de la acción de las olas hasta facies de barras y arrecife. Es posible inferir que los *calcitarchs* recuperados presentan variaciones de tamaño en relación con las facies que las contienen. Los *calcitarchs* reconocidas en las facies tipo *wackestone* son las *calcitarchs* tipo-0 y las recuperadas de las facies *packstone-grainstone* son las *calcitarchs* tipo-III. La variación del tamaño de los *calcitarchs* probablemente esté relacionada con un aumento gradual de energía dentro de un ambiente submareal poco profundo. La ocurrencia de *calcitarchs* dentro del intervalo comprendido por las zonas de *Oepikodus evae-O. intermedius* (Floiano) extiende su registro fósil hasta el Ordovícico Inferior.

Palabras clave: Calcitarch, Floiano, Precordillera, Formación San Juan, Ordovícico.

1. Introduction

Studies on spherical calcareous microfossils present in different Ordovician and Silurian carbonate lithology around the world are scarce (Munnecke *et al.,* 1999, 2000; Servais *et al.,* 2009; Kröger *et al.,* 2019). In this sense, their biological affinities remain unclear due to the limited number of diagnostic characteristics that allow accurate taxonomic assignments. Through the time this microfossil received different names, such as calcisphers (Munnecke and Servais, 2008) and calcitarchs (Versteegh *et al.,* 2009; Servais *et al.,* 2009; Kröger *et al.,* 2019).

The Lower-Middle Ordovician San Juan Formation is a classic unit from the Precordillera that is composed of fossiliferous limestone, marly limestone and reef facies (Beresi, 1986; Herrera and Benedetto, 1991; Beresi and Rigby, 1993; Vaccari, 1995; Sánchez *et al.,* 1996; Carrera, 1997; Cañas and Carrera, 2003; Benedetto *et al.,* 2007; Mestre *et al.*, 2020, among others). There are few descriptions and interpretations of the carbonate microfacies, as well as of the calcareous micro-organisms and problematic microfossils present in these carbonate facies (Beresi, 1986; Cañas, 1995; Soria *et al.*, 2017; Mestre *et al.,* 2020). Recently, Beresi and Luchinina (2018) provided new data on the calcareous microfossils of the Ordovician carbonate and mixed facies from Cuyania. These authors described calcareous microfossils from the San Juan Formation and illustrated fragments of spherical microfossil interpreted as spherical algae.

In a recent study on carbonate microfacies carried out in the lower and middle part of the San Juan Formation in the Cerro La Chilca section, several calcareous microfossils were observed which are closely similar to those spherical algae reported by Beresi and Luchinina (2018).

The aim of this contribution is to describe these spherical calcareous microfossils and provide new biostratigraphic information for the first time for the Precordillera. Also, we propose the possible paleoenvironmental implications of these calcareous microfossils in the Early Ordovician carbonate facies from the Precordillera.

2. Geological setting

The geological province of Precordillera is developed along a length of 400 km N-S with a width of 150 km E-W in western Argentina, and it extends through the provinces of La Rioja, San Juan, and Mendoza, where Cambrian-Ordovician carbonate and siliciclastic successions are developed in a shelf environment. The Lower-Middle Ordovician carbonate succession of the Precordillera is represented by the San Juan Formation (Baldis *et al.,* 1982; Keller, 1999; Mestre and Heredia, 2013; Mestre, 2014).

The San Juan Formation crops out in several classical localities at the Central and Eastern Precordillera, and it is considered an emblematic unit from Argentina.

Keller *et al.* (1994) redefined the lower and middle parts of the San Juan Formation at La Silla section (Central Precordillera) and the upper part at the Cerro La Chilca section. After that, the carbonate and mixed carbonate facies in the San Juan Formation were recognized in several sections by Cañas (1999), Keller (1999), Mestre (2014) and Soria *et al*. (2017), among others.

The first geological contribution for the Cerro La Chilca section was carried out by Stappenbeck (1910). Then, Cuerda (1965) mentioned the presence of Caradoc deposits in this section, which were later called Cerro La Chilca "Shales" by Blasco and Ramos (1976). Finally, Furque (1979) recognized and defined the San Juan and Los Azules formations. Keller (1999) completely surveyed the Ordovician San Juan Formation from the Cerro La Chilca section. This author verified that the lowermost beds of this unit are in contact with the La Silla Formation and it is transitionally overlain by Los Azules Formation (Fig. 1).

Lehnert (1995) retrieved the first Darriwilian conodonts from the uppermost beds of San Juan Formation in the La Chilca section, and recorded the *Eoplacognathus suecicus* Zone after finding the conodont *Histiodella kristinae* Stouge. Mestre (2012) and Mestre and Heredia (2013, 2020) recorded the *Lenodus variabilis, Lenodus crassus* and *Lenodus pseudoplanus* zones in those same levels of the San Juan Formation. On the other hand, the *Oepikodus evae* and *Oepikodus intermedius* zones were recently recognized in the San Juan Formation lower-middle beds by Moreno *et al.* (2020). Other paleontological studies were restricted to the last 20 or 30 m of the San Juan Formation, such as Sánchez *et al*. (1996), Benedetto (2015), among others.

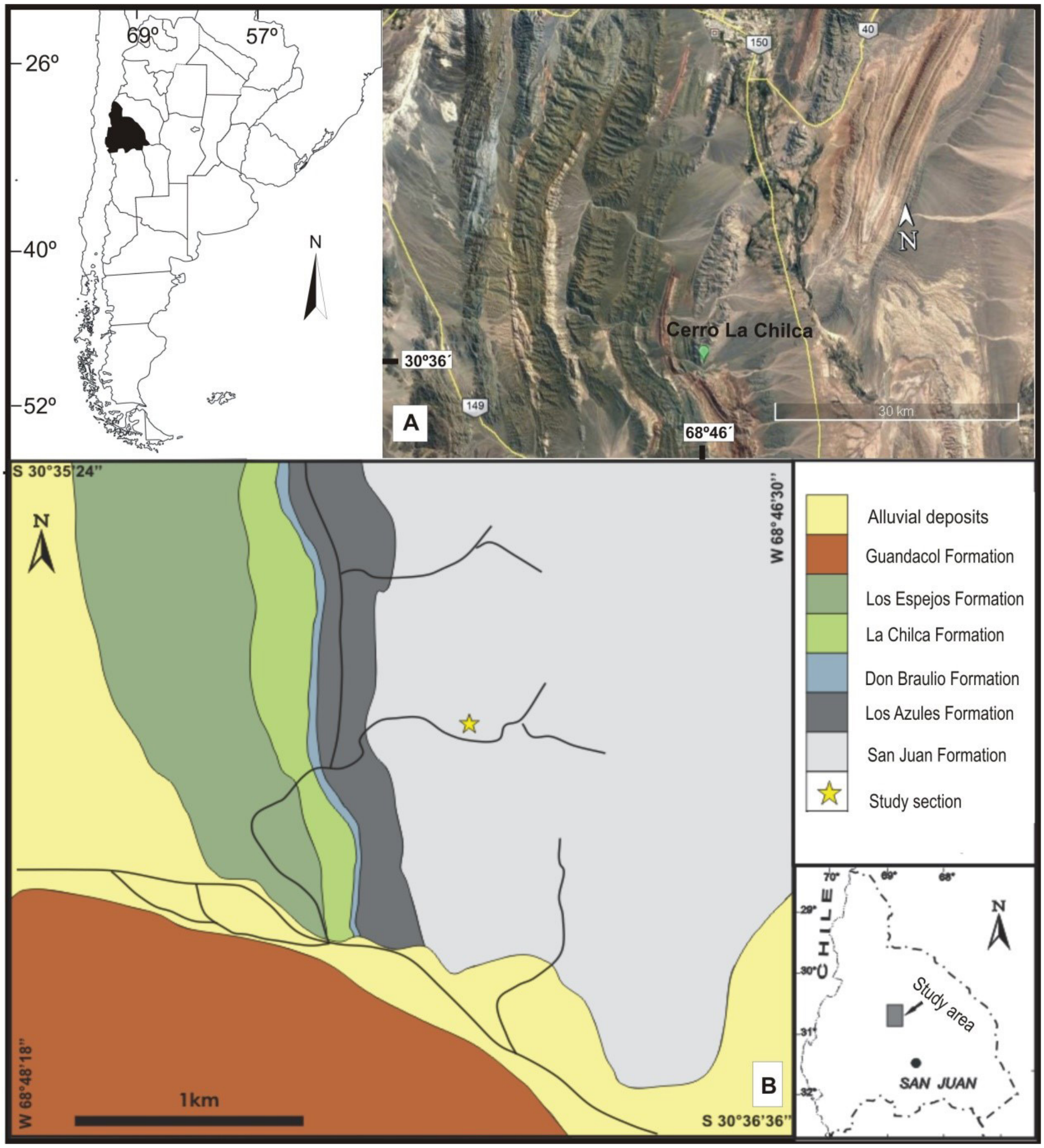


FIG. 1. Location of the study area. **A.** Image taken from Google Earth of the study section. **B.** Geological map of the Cerro La Chilca section (modified from Mestre, 2012).

3. Conodont biostratigraphy

The sampled stratigraphic levels in the present contribution were recently studied in relation to their conodont content by Moreno *et al.* (2020). These author recorded the *O. evae* and *O. intermedius* zones in the San Juan Formation lower levels, and the conodont association was composed of the following conodont taxa: *Bergstroemognathus hubeiensis* An, *Bergstroemognathus extensus* (Graves and Ellison), *Juanognathus variabilis* Serpagli, *Microzarkodina* n. sp. (*sensu* Pyle and Barnes 2002), *"M." buggischi* Lenhert, *Oepikodus intermedius* Serpagli, *Periodon flabellum* (Lindström), *Reutterodus andinus* Serpagli, and *Scolopodus krummi* Lenhert (Moreno *et al.*, 2020). The most relevant findings of the former contribution are related to the first records of *B. hubeiensis* and *Microzarkodina* n. sp. in the Precordillera which provides significant information related to the possible ties of the Precordillera with Gondwana, peri-Gondwana, and Northwestern of the Midcontinent regions for this time interval.

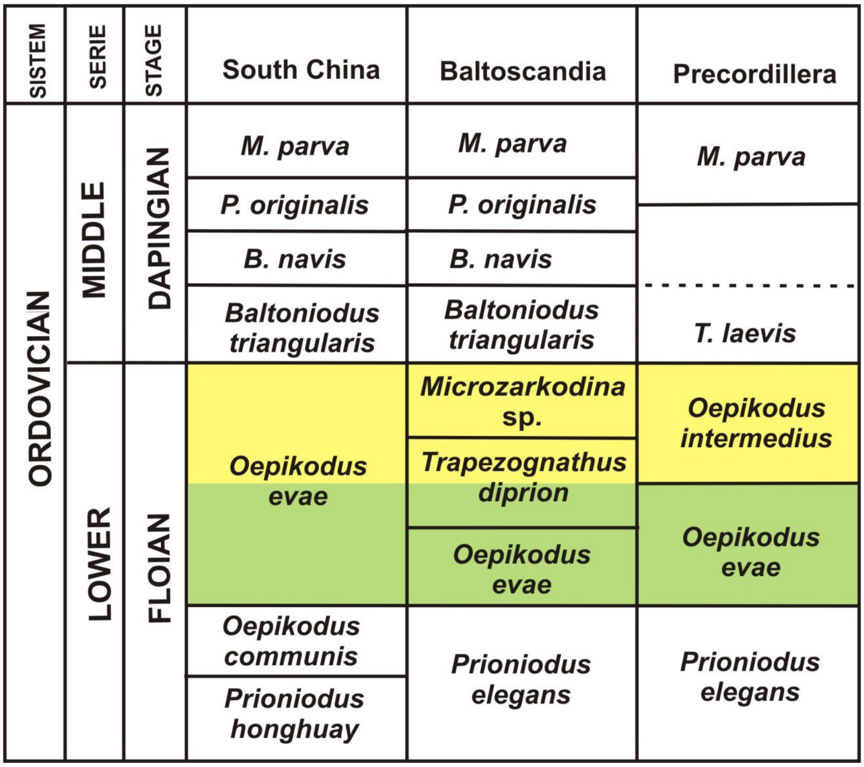
Taking into account the records of the conodont biozones registered by Moreno *et al.* (2020) for the same levels of the San Juan Formation studied in the present contribution, it is possible to extend the first appearance of calcitarchs into the Lower Ordovician (Fig. 2).

4. Material

This study is based on laboratory analyses of thin sections. All samples are limestone collected from the San Juan Formation in the Cerro La Chilca section (Fig. 3). Seven thin sections were made in order to identify fossils and analyze the distribution of the microfacies components in the Micropaleontology Laboratory of the Instituto de Investigaciones Mineras (IIM). A petrological investigation of the thin sections was performed using Leica DM2700 microscopes and Lanset binocular microscopes.

5. Microfacies description and environment interpretation

The microfacies described below correspond to the samples taken from the San Juan Formation lower-middle beds at the Cerro La Chilca section (Fig. 3). The *ca.* 35 m of the stratigraphic range studied begins with 8 m of light grey massive limestone succession (Ch1 sample), followed by 6 m of grey nodular limestone with abundant gastropods in contact with a 0.20 m bentonite bed (Ch2 and Ch3 samples). These levels are followed by 3 m of grey nodular limestone with well-preserved crinoids and brachiopod shells constituting middle grey bioclastic limestone (Ch4 sample). The section continues with 8 m of limestone, interbedded with fine layers



SISTEM	SERIE	STAGE	South China	Baltoscandia	Precordillera
ORDOVICIAN	MIDDLE	DAPINGIAN	*M. parva*	*M. parva*	*M. parva*
			P. originalis	*P. originalis*	
			B. navis	*B. navis*	
			Baltoniodus triangularis	*Baltoniodus triangularis*	*T. laevis*
	LOWER	FLOIAN	*Oepikodus evae*	*Microzarkodina* sp.	*Oepikodus intermedius*
				Trapezognathus diprion	
				Oepikodus evae	*Oepikodus evae*
			Oepikodus communis	*Prioniodus elegans*	*Prioniodus elegans*
			Prioniodus honghuay		

FIG. 2. Conodont biostratigraphic chart of the Lower-Middle Ordovician from Precordillera (Albanesi and Ortega, 2002; Soria *et al*., 2013; Moreno *et al*., 2020), correlated with those of the South China (Wang *et al*., 2019) and Baltoscandia (Bagnoli and Stouge, 1997).

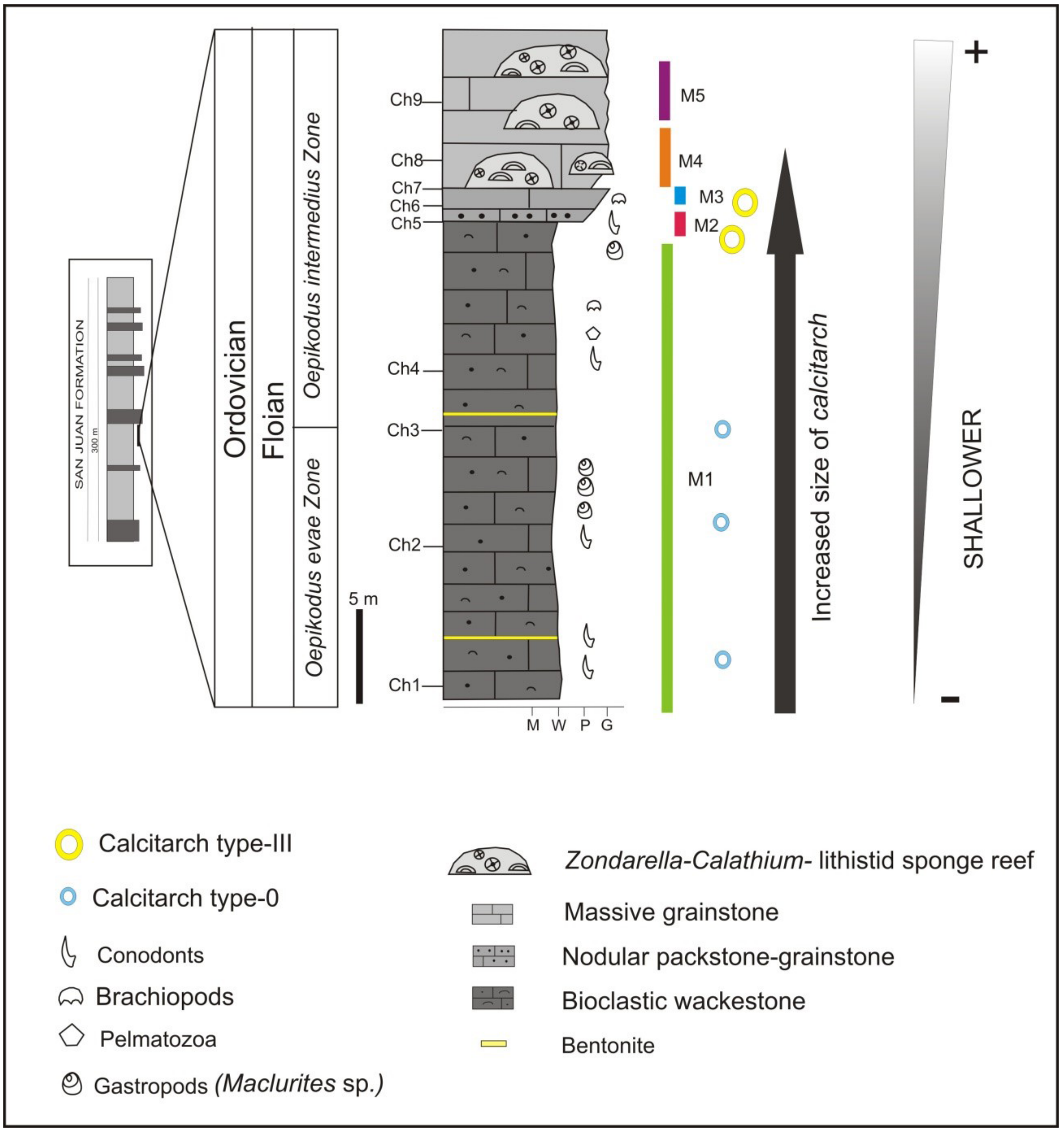


FIG. 3. Stratigraphic column of the Cerro La Chilca section, Central Precordillera, showing the sampled levels and vertical distribution of the two types of calcitarch along the section.

of bentonite (0.05 m thick) with large gastropods, trilobites and brachiopods. The studies levels finally with 10 m of coarse limestone interbedding with reef facies (Ch8 and Ch9 samples).

M1-Burrowed bioclastic wackestone (Ch1, Ch2, Ch3 and Ch4 samples) is characterized by poorly sorted pelmatozoans, trilobites, and gastropod fragments randomly orientated. It also contains cyanobacteria, calcareous algae, spherical calcareous microfossils and microproblematica, such as *Nuia síbirica* Maslov, *Girvanella* rafts and *Girvanella* intraclasts (Rong *et al.,* 2014). Some skeletal allochems show geopetal infilled by equant, drusy and blocky spar. The matrix is micritic although it is partially recrystallized as blocky sparite. Stylolithic surface is observed (Fig. 4).

Interpretation: The microfacies M1 was developed in a shallow subtidal environment. The high abundance of *Nuia sibírica*, calcareous algae and fine siliciclastic sediments suggest low energy conditions below wave action within the shallow euphotic zone in the inner

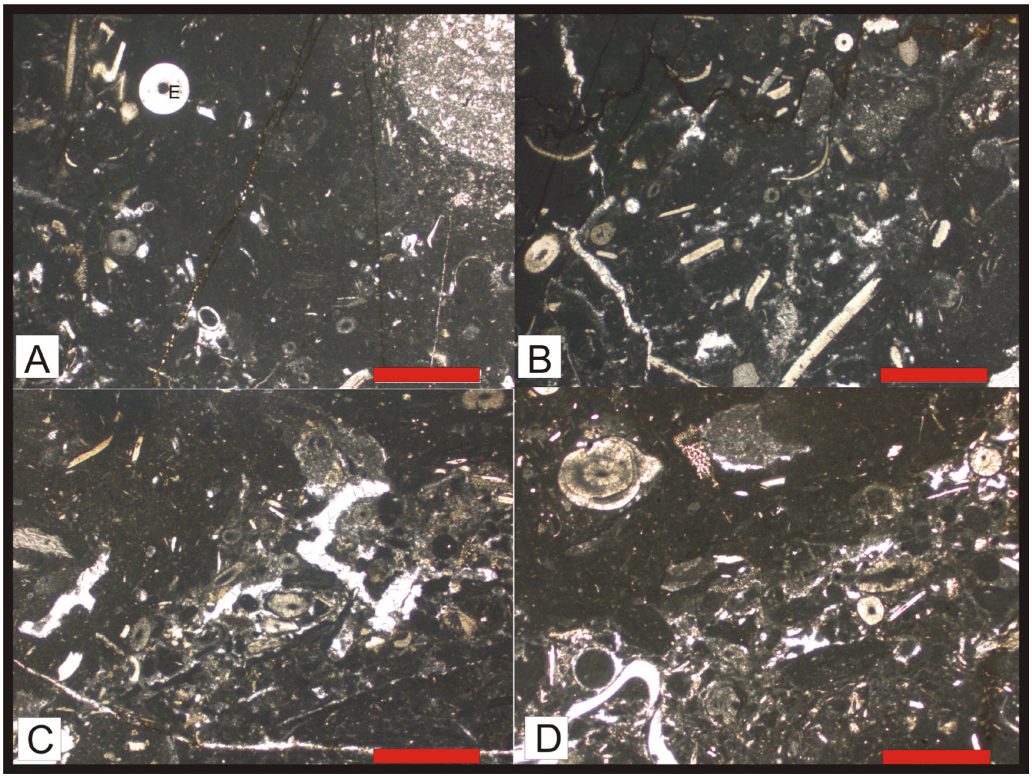


FIG. 4. Photomicrograph of the microfacies M1. **A-D.** Bioclastic component. **E.** Echinoderm ossicle, *Nuia sibiria* (N)*,* trilobites, gastropod fragments and micrite matrix. The length of the scale bar is 1 mm.

platform. Furthermore, the presence of *Girvanella* intraclasts and *Girvanella* rafts suggest transport due to wave action and moderate energy conditions (Flügel, 2010; Rong *et al.,* 2014; Vachard *et al.*, 2017; Pandey and Parcha, 2018; Kröger *et al.,* 2019).

M2-Peloidal intraclastic packstone-grainstone (Ch5 and Ch6 samples) is composed predominantly of micritic peloids of elongate and irregular shape with a size <1 mm, and subrounded oncoides with thin-cortex (Han *et al.,* 2014). The diameter of the oncoids ranges from 0.5 to 3 mm. Their nuclei comprise pelmatozoan ossicles and *Nuia sibirica* coated by a thin micritic envelope. Other components include bioclast fragments, calcareous spherical microfossil and intraclast of *Girvanella,* with a size <1mm, moderately sorted (Fig. 5).

M3-Intraclastic floatstone (Ch7 sample) comprises predominantly subrounded and elongated micritic intraclasts, with sizes ranging from 2mm to 1cm. Skeletal grains are micritized. The matrix is bioclastic packstone (Fig. 6).

M4-Intraclastic wackestone-packstone (Ch8 sample) is dominated by subrounded, elongated and irregular intraclasts with a size of 0.2-1.5 mm. It also comprises skeletal components surrounded by micritic envelopes, *Girvenella* raft and *Halysis moniliformis* Høeg (Fig. 7).

M5-Bioclastic boundstone (Ch9 sample) represents the main microfacies of the biogenic structure. The reefs components consist of *Zondarella communis* (pulchrilaminids), lithistid sponges and *Calathium* sp. It also contains cyanobacteria, calcareous algae, *Girvanella* raft and *Girvanella* crust. *Nuia sibirica*, *Halysis moniliformis* and pelmatozoan ossicles are poorly represented (Fig. 7).

Interpretation: These microfacies represent reef and shoal facies and suggest high energy episodes produced by fair or storm weather that alternated with low energy moments in the inner open platform (Flügel, 2010; Han *et al.,* 2014; Rong *et al.,* 2014; Mestre *et al.*, 2020). The relatively high abundance of *Nuia sibirica* and calcareous algae in the limestone

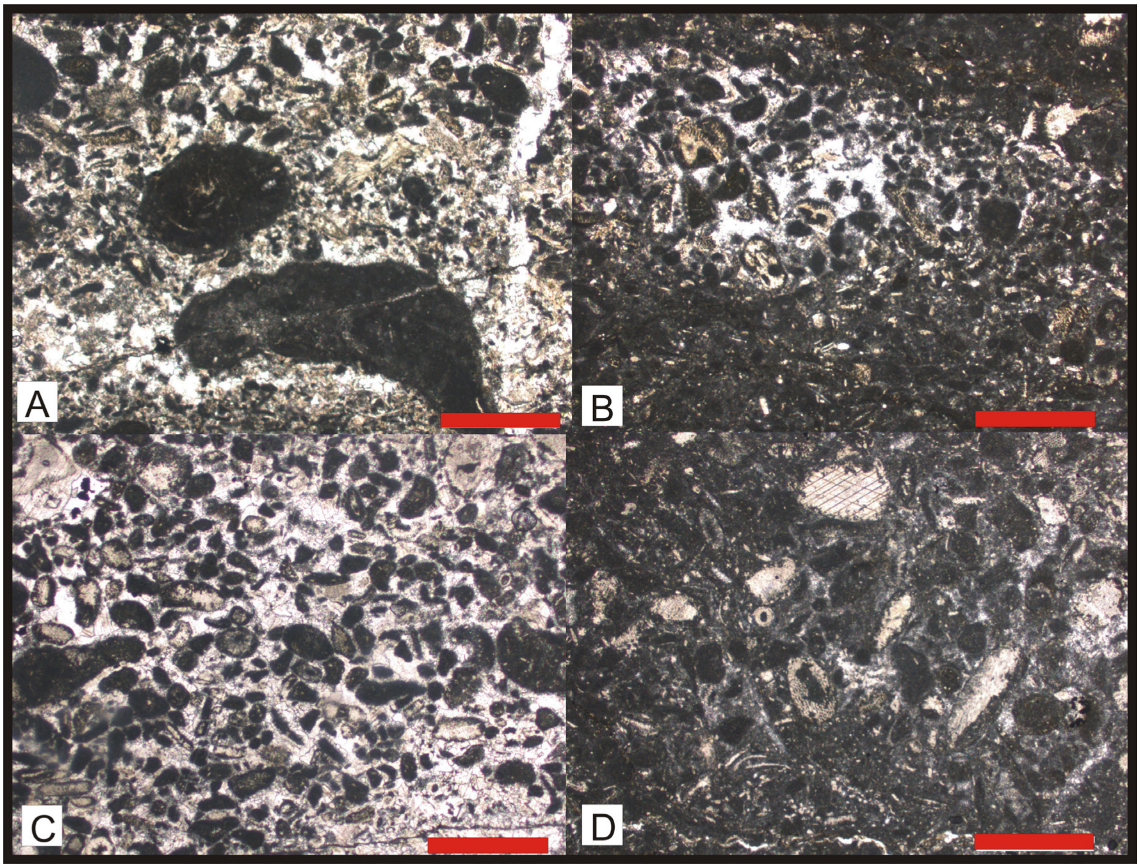


FIG. 5. Photomicrograph of the microfacies M2. **A.** bioclastic intraclast surrounded by a micrite crust, and peloids moderately-well sorted. **B-D.** Peloidal intraclastic packstone-grainstone with bioclastic components. The length of the scale bar is 1 mm.

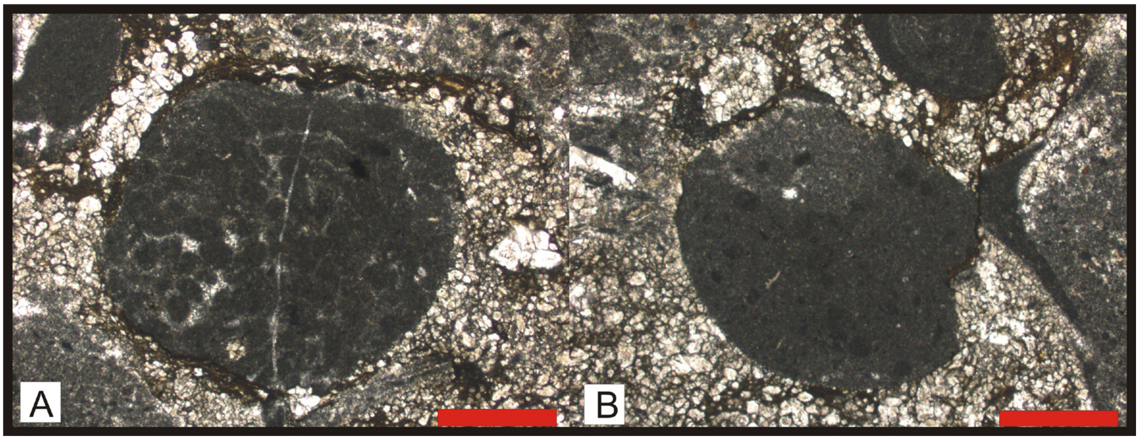


FIG. 6. **A-B.** Photomicrograph of the microfacies M3. Peloidal intraclast. The length of the scale bar is 1 mm.

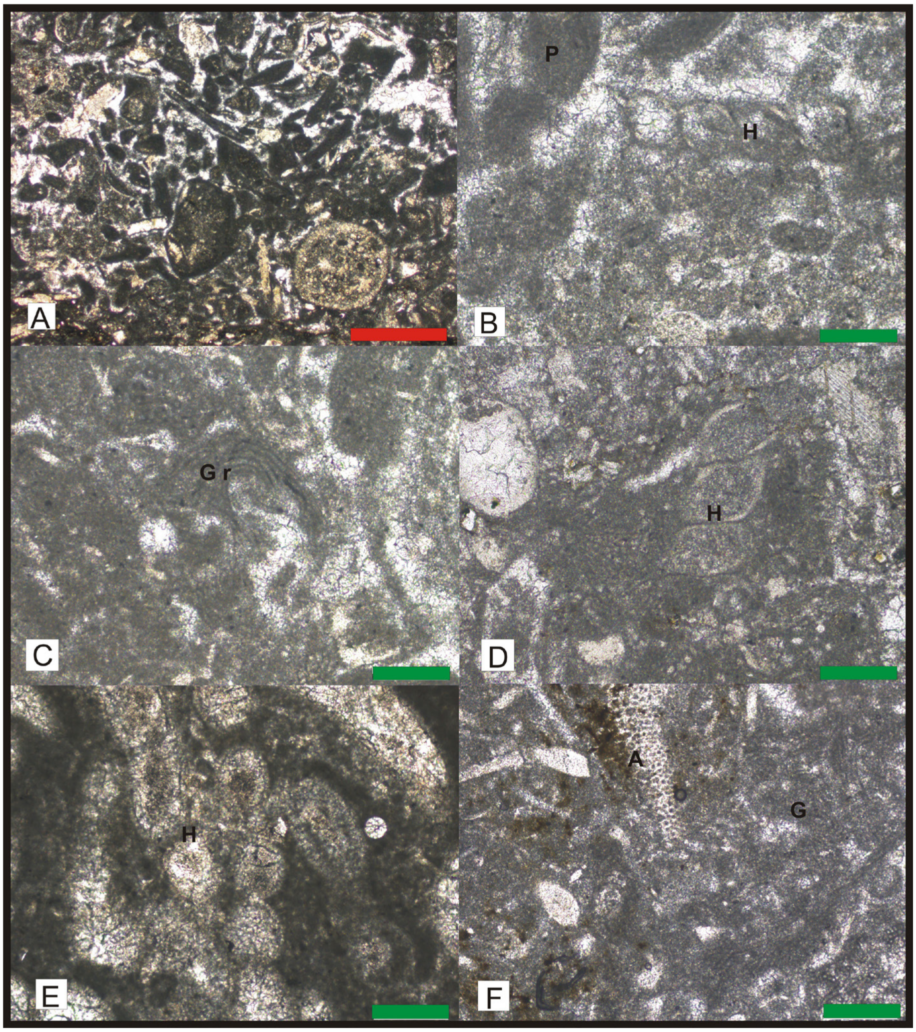


FIG. 7. Photomicrograph of the microfacies M4 (intraclasitc wackestone-packstone) and M5 (bioclastic boundstone). **A.** Photomicrograph of the microfacies M4, subrounded, elongate intraclast and bioclastic component occurring in moderately sorted wackestone-packstone. **B-D.** Bioclastic component of the microfacies M4; **H:** *Halysis moniliformis*; **Gr:** *Girvanella* raft; **P:** micritized peloids and fragments skeletal component. **E-F.** Photomicrograph of the microfacies M5, bioclastic components **H:** Halysys moniliformis; **A:** calcareous algae; **G:** encrustating of *Girvanella* (horizontally growing *Girvanella*-like tubes). The length of the scale bar in A is 1 mm and the length of the scale bar in B-F is 200 µm.

is evidence of a shallow-water environment with a depositional depth of less than 25 m within the shallow euphotic zone (Granier, 2012; Kröger *et al.*, 2019).

6. Calcareous microfossils: calcitarchs

The term "calcisphere" was used as a general term to describe the calcareous, more or less spherical microfossils, irrespective of their biological source (Flügel, 2004). Later, Versteegh *et al*. (2009) indicated that the term calcispheres was inconsistently used, due to the morphological and taxonomical concepts were mostly unclear, and a formal definition was needed. To solve this issue, the former authors proposed a new group called Calcitarcha (by analogy with the Acritarchs) this group is proposed as an informal category, which include all calcareous microfossils with a central cavity for which the biological affinities remain unknown. The calcitarchs should thus be considered a polyphyletic group, with most of the Mesozoic microfossils being probably calcareous cysts of dinoflagellate species. However, the biological affinities of Lower Palaeozoic calcitarchs are challenging to establish.

Munecke and Servais (2008) recorded a group of carbonate spherical microfossils from different Silurian facies from Gotland (Sweden). These microfossils were of variable sizes, between 60-100 µm, and termed them calcispheres (Young *et al.,* 1997). These authors also illustrated littler microfossils, 10-25 µm, termed "nanospheres". Then, Kröger *et al.* (2019) proposed a classification recognizing 3 types of spherical microfossils from the Late Ordovician Baltic limestone facies: type I calcitarch, type II calcitarch and type III calcitarch.

An older diagnosis carried out by Munnecke *et al.* (2000) included spherical to subspherical forms in the *Ovommuridae* family. However, those specimens illustrated by Munnecke and Servais (2008), were considered *incertae sedis* due to the lack of biologic affinities with some living organism groups. According to Servais *et al.* (2009), some calcitarchs from the Paleozoic may be interpreted as calcaerous cysts of organisms that might have been the ancestors of the dinoflagellates, whose earliest fossil record is in the Mesozoic. Nevertheless, it should be noted that many other calcitarchs should probably be attributed to other biological phyla (algal groups, foraminifers or radiolarians). The authors emphasize that it is difficult to establish biological affinities because many of the Paleozoic rocks are poorly preserved and diagenetically altered.

Kröger *et al.* (2019) proposed that the calcitarchs correspond to aplanosporas (green algae) and are probably related to taxa that cannot be preserved as articulate fossils, like *Acetabularia* which vanishes quickly. This interpretation is related to the idea that limestone matrix (mud) was originated from aragonitic algae.

In the Precordillera, Beresi and Luchinina (2018) showed fragments of spherical microfossils from the Las Chacritas (Plate I, figs. g, f, j, l) and Talacasto (Plate II, figs. m, n, o) sections and described them as problematic spherical algae, but they were not able to identify due to the lack of morphological characteristics.

Nevertheless, the spherical microfossils here reported from the lower-middle part of the San Juan Formation are denominated calcitarch according to the classification of Kröger *et al.* (2019). These spherical microfossils were recognized in the Floian facies (*O. evae-O. intermedius* zones), and they represent the earliest worldwide record for this type of microfossil. However, the taxonomy and biological affinity of these organisms are beyond the scope of this contribution.

6.1. Classification

The Floian spherical microfossils recognized in the samples collected from the Cerro La Chilca section are described following the size criterion proposed by Kröger *et al.* (2019) based on the observation of thin sections only. The poor preservation of the microfossils limited the possibility to analyzed under Scanning Electron Microscope (SEM). Consequently, some features of the wall such as its width and pores are not provided.

In the studied microfossils we recognized two groups. The first one is a group that could be placed into 'calcispheres' with a radial shell layer (*sensu* Munnecke and Servais, 2008), or could be determined as calcitarch with a small size. This group of spherical microfossils (Figs. 8 and 10) exhibits smaller sizes than those described by Kröger *et al.* (2019) in their three categories (Type-I calcitarchs, type-II calcitarchs and type-III calcitarchs). Consequently, a fourth group in this classification is proposed termed type-0. The second one is a larger spherical microfossils group described herein (Fig. 10) which are similar in general appearance and structure to type-III calcitarchs (Kröger *et al.,* 2019).

Type-0 calcitarch: Small spheres with thin wall. Diameter ~80 µm. The specimens of figures 8A, C and 9 have a diameter of 100 µm, those of the figure 8B have a diameter of 111 µm, those of the figure 8D have a diameter of 95 µm, and those figure 8C, B have a diameter of 50 µm. They occur in burrowed bioclastic wackestone.

Type-III calcitarch: Large spheres with thin to medium wall. Diameter ~250 µm. The specimens of figure 10A, C and D have a diameter of 200 µm and those of the figure 10B have a diameter of 250 µm. They occur in peloidal intraclastic packstone-grainstone.

Based on a vertical distribution analysis of the different calcitarch types along the section, it is possible to recognize that the recovered specimens show variations in size in relation to the facies that contain them. The calcitarchs recognized in

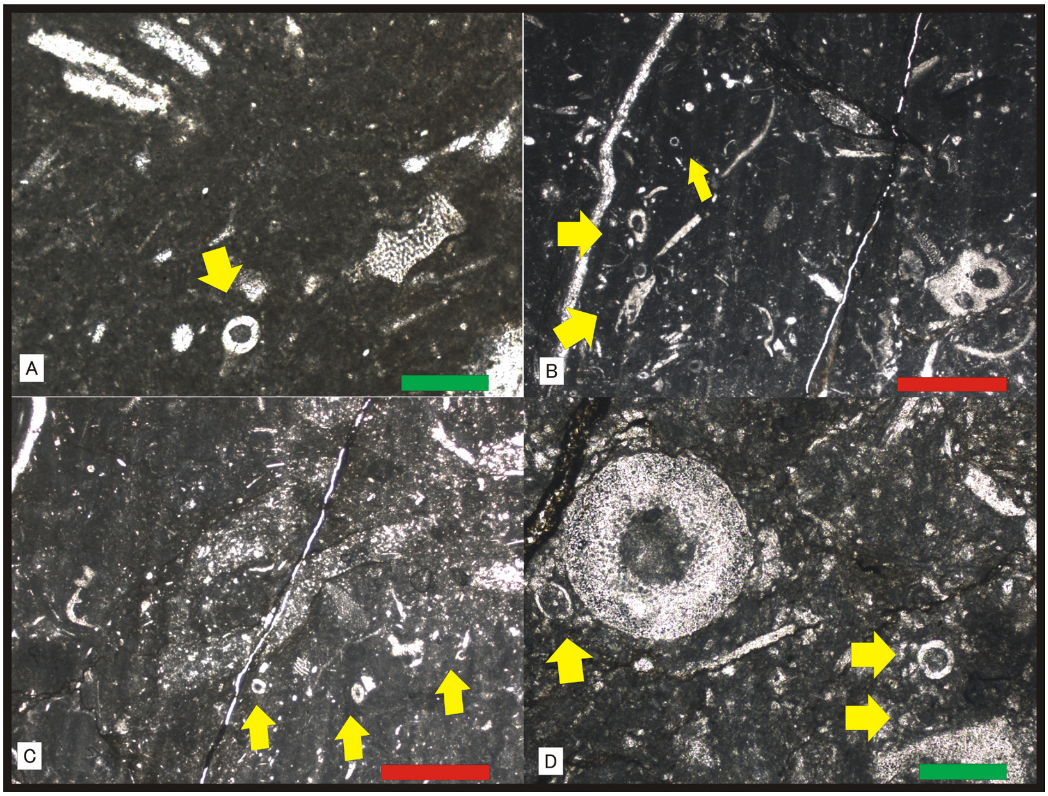


FIG. 8. Calcitarch from San Juan Formation (Precordillera), Floian Stage. **A-D.** Calcitarch type-0. The length of the scale bar in A and D is 1 mm and the length of the scale bar in B and C is 200 μm. The samples correspond to microfacies M1.

wackestone-type facies are smaller (Fig. 4) than those recovered from the packstone-grainstone facies (Fig. 5). Such a distribution pattern is recognized for the first time in the Paleozoic, showing great potential for evaluating the possible paleoenvironment preferences of these microfossils.

Taking into account their size, the San Juan Formation Floian type-0 calcitarch could be considered similar to the Silurian calcitarchs described by Munnceke and Servais (2008) and Servais *et al.* (2009). These authors interpreted that these specimens belong to the calcareous microplankton and consider cysts of a possible ancestor of the organic-walled dinoflagellates that probably belong to calcareous micro- and nannoplankton. However, considering their morphology, they are like the Ordovician calcitarchs described by Kröger *et al.* (2019), who interpreted this microfossil as possible spores of several green algae because they are associated with reef facies. Although we cannot assign the studied microspheres to any fossil group, we consider that they are related with the Kröger *et al.* (2019) classification as follows: we suggest that the largest microfossils correspond to type-III calcitarch and we propose a new group, type-0 calcitarch, for calcareous microfossils smaller than 100 μm.

7. Paleoenvironment interpretation of the different types of calcitarchs from the San Juan Formation

The applicability of calcareous spherical microfossils as paleoenvironmental indicators has not yet been satisfactorily investigated (Kaźmierczak and Kremer, 2005). However, according to Klovan (1964), Stanton (1963, 1967), Racki and Soboń-Podgórska (1993), and Kaźmierczak (1976), the presence of these microfossils has been interpreted as evidence of shallow-marine depositional environment within basins characterized by unstable and high eutrophication level. Flügel (2004) stated that most

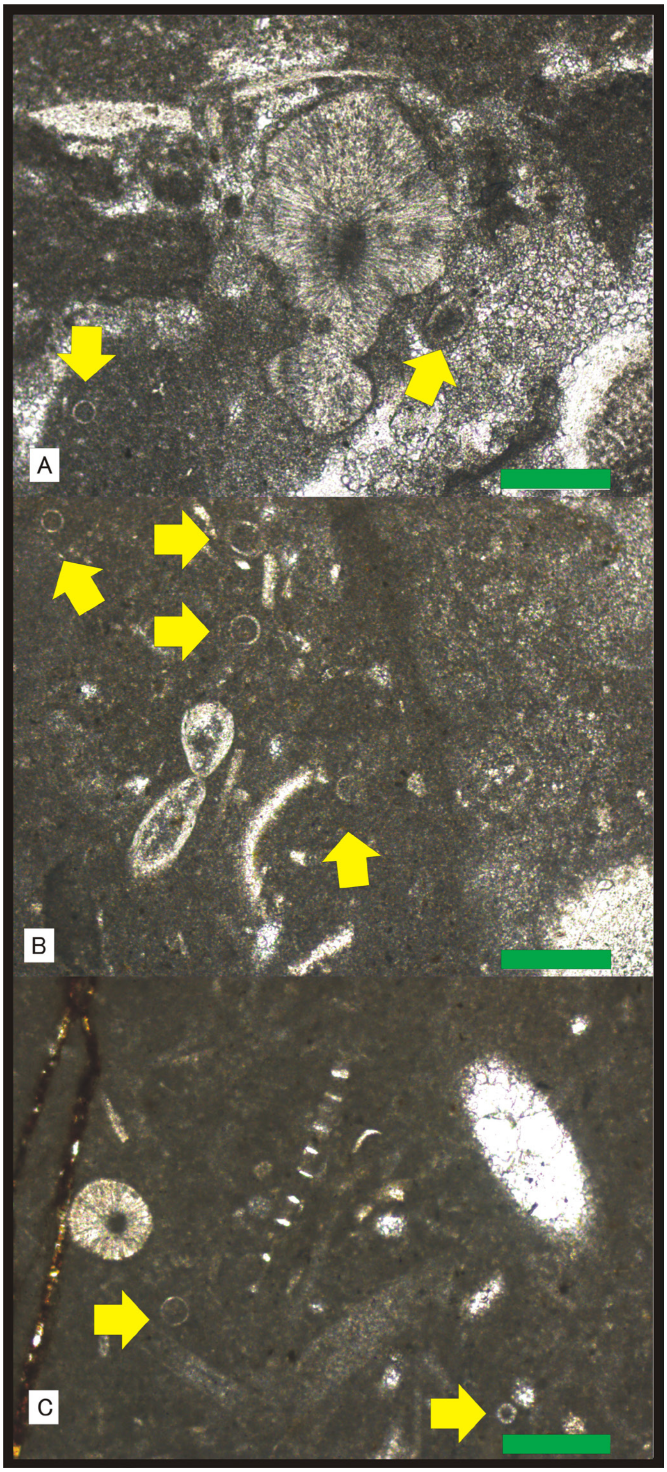


FIG. 9. Calcitarch from San Juan Formation (Precordillera), Floian Stage. **A-C.** Calcitarch type-0. The length of the scale bar is 200 µm. The samples correspond to microfacies M1.

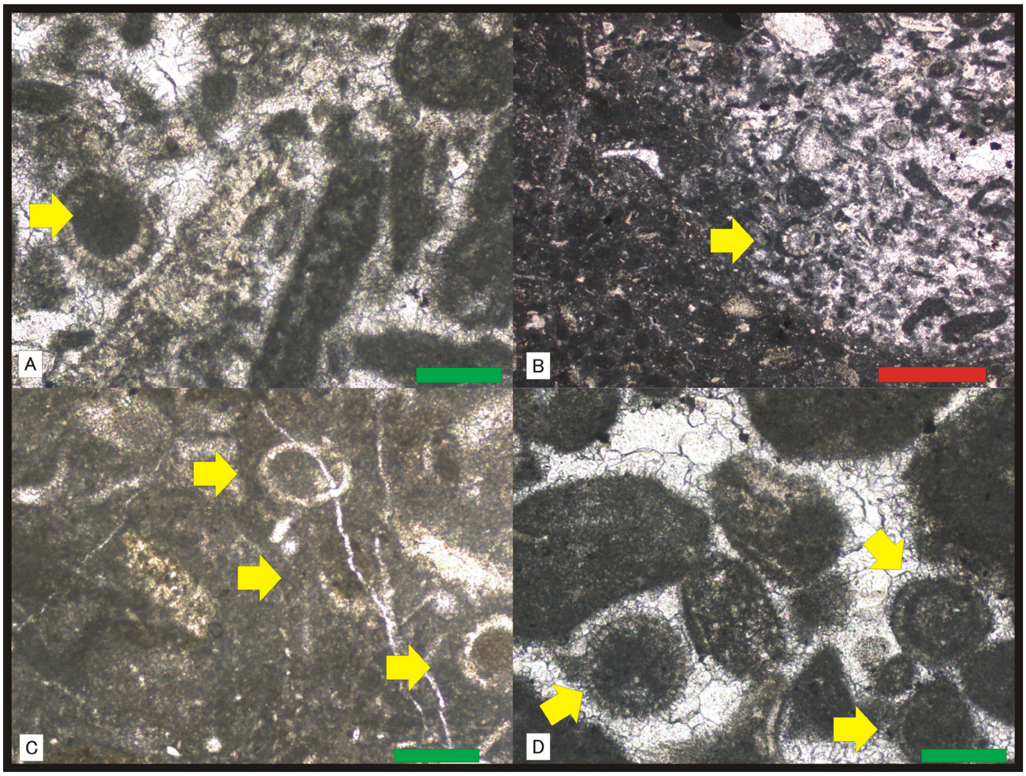


FIG. 10. Calcitarch from San Juan Formation (Precordillera), Floian Stage. **A-D.** Calcitarch type-III. The length of the scale bar in B is 1 mm and the length of the scale bar in A, C, D is 200 µm. The samples correspond to microfacies M2.

Palaeozoic calcispheres occurred in a shallow-marine platform and ramp carbonates, while most of the Jurassic and Cretaceous calcispheres occurred in pelagic limestones represented by calcareous dinoflagellate cysts.

The different types of calcitarchs appear associated with green calcified algae as the main skeletal component of the Baltica Limestone facies (Late Ordovician) and its associated reefs (Kröger *et al.,* 2019). They indicate environment deposition within the shallow euphotic and euryhaline zone under low-latitude climatic conditions. The Baltic limestone facies are interpreted as representing the shallower part of an open-marine carbonate platform, which underwent high temperatures and extremely low terrigenous sediment input (Kröger *et al*., 2019). Moreover, the Silurian calcitarchs from Gotland (Sweden) were found in different facies associated with the ancestors of the foraminifera (*Parathurammina, Caligella,* etc.), *Girvanella* and *Halysis*. However, the well-preserved calcitarchs specimens were recovered only from so-called limestone-marl alternations deposit in shallow platform facies (Munnecke and Servais, 2008).

The facies and carbonate component features present in the deposits that enclose the type-0 and type-III calcitarchs in the Cerro La Chilca section indicate from shallow subtidal environment in low energy conditions to shoal deposits with an increase of energy in the carbonate platform (Fig. 11). Furthermore, the facies analyzed herein is composed of *Nuia sibírica*, *Girvanella* and other calcareous algae which allow interpreting a shallow subtidal environment within the photic zone in a tropical to subtropical climate (Flügel, 2010; Rong *et al.*, 2014; Vachard *et al.,* 2017; Pandey and Parcha, 2018).

The studied stratigraphic range begins with fine facies represented by burrowed bioclastic wackestone (M1) that has been deposited in low-energy conditions. In this facies only the type-0 calcitarch is present. The presence of carbonate mud indicates low energy conditions below fair weather waves within a shallow inner platform setting. Then, the peloidal intraclastic

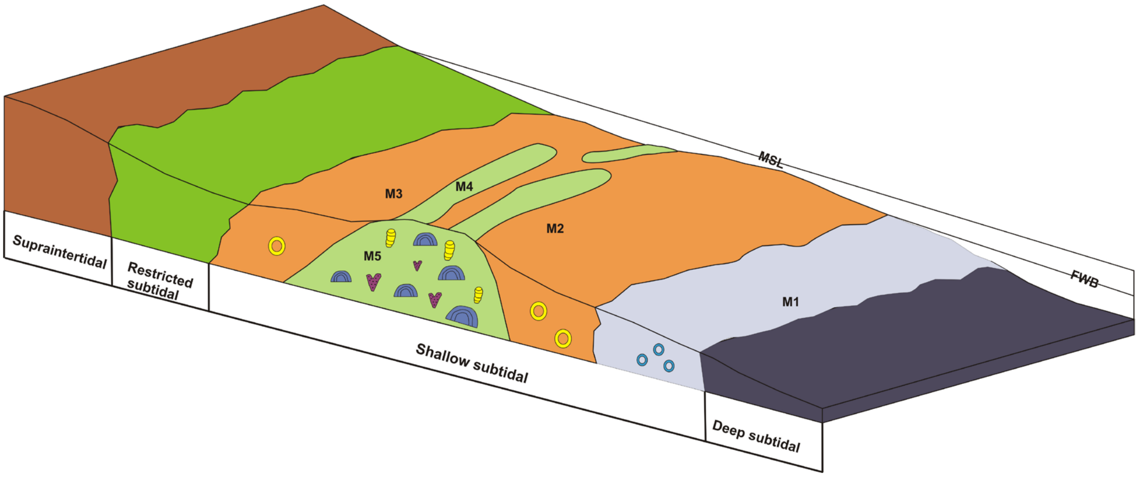


FIG. 11. Carbonate platform depositional model for the San Juan Formation in the study area. The platform displays a gentle transition from shallow to deeper depositional environments. The subdivision of the carbonate platform is based on Pomar (2001). **FWB:** fair-weather wave base; **MSL:** medium sea level; **M1:** Burrowed bioclastic wackestone; **M2:** Peloidal intraclastic packstone-grainstone; **M3:** Intraclastic floatstone; **M4:** Intraclastic wackestone-packstone; **M5:** Bioclastic boundstone; **white circle:** calcitarch type-III; **grey circle:** calcitarch type-0.

packstone-grainstone (M2), intraclastic floatstone (M3), intraclastic wackestone-packstone (M4) and bioclastic boundstone (M5) facies indicate high energy conditions, suggesting a shallow subtidal environment within the inner high-energy platform associated with shoal and reef facies. In these beds the type-III calcitarch is recorded. The variation in the size of the calcitarch recognized along the studied sections could be related to a gradual increase of energy within a shallow subtidal environment, from distal to proximal, including from shallow subtidal facies below wave action to shoal and reef facies. This could be interpreted as a reflect a gradual shallowing-upward evolution as it was proposed by Soria *et al.* (2017) and Mestre *et al.* (2020) for coeval levels of San Juan Formation from the Niquivil and Talacasto sections.

8. Conclusion

Based on the investigation of calcareous microfossils and their depositional facies, as well as a microfacies analysis of the lower-middle part of the San Juan Formation in the La Chilca section (Central Precordillera), conclusions are drawn as follows:

- In this study we consider the classification proposed by Kröger *et al.* (2019) for describing our calcareous microfossils. We suggest that the largest microfossils correspond to type-III calcitarch, and we propose a new group, type-0 calcitarch, for calcareous microfossils smaller than 100 µm.
- The calcitarchs recognized in wackestone facies are the Type-0 calcitarch and those recovered from the packstone-grainstone facies are the Type-III calcitarch. This distribution pattern is recognized for the first time in the Paleozoic, showing great potential for evaluating the possible paleoenvironment preferences of these microfossils.
- The size variations of the calcitarch recognized along the studied section probably related to a gradual increase of energy within a shallow subtidal environment, from distal to proximal, including from shallow subtidal facies below wave action to shoal and reef facies.
- The occurrence of the calcitarchs in the Floian *O. evae* and *O. intermedius* conodont zones of the San Juan Formation represents the oldest worldwide records, extending the first appearance of this type calcareous microfossil down into the Early Ordovician.

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