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Research paper

Ordovician chitinozoans and marine phytoplankton of the Central Andean Basin, northwestern Argentina: A biostratigraphic and paleobiogeographic approach

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ABSTRACT

Ordovician deposits from the Central Andean Basin cover a vast region with thick exposed sequences in several areas, including the Sierras Subandinas, Cordillera Oriental and Puna geological provinces of northwestern Argentina. This basin was situated along the active margin of a Paleozoic foreland basin in western Gondwana. Continuous sedimentation occurred in different paleoenvironments from east to west: marginal marine settings with estuarine and deltaic deposits (Sierras Subandinas), shallow marine shelf environments with large clastic deposits in the central part (Cordillera Oriental–eastern Puna), and deep marine deposits with volcanoclastic supplies (western Puna). Limited biostratigraphic and chronostratigraphic data from these sequences are known from graptolites, conodonts and trilobites, and more recently also from palynomorphs. An analysis of Ordovician sections from the different sedimentological settings of northwestern Argentina produced 60 chitinozoan-bearing samples from which 19 genera and 45 species have been recorded. Four chitinozoan assemblages were observed in the Lower Ordovician from northwestern Argentina. Correlations with other fossil groups provide independent biostratigraphic control. A stratigraphic range chart of selected acritarch taxa throughout the Ordovician of the Central Andean Basin is developed and biostratigraphic or potential biostratigraphic markers for the basin are proposed. In northwestern Argentina, Late Ordovician chitinozoan assemblages display affinities with Polar to Subpolar faunas.

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1. Introduction

The study of Ordovician palynomorphs from Argentina began in the 1980s (Volkheimer, 1978, 1980; Bultynck and Martin, 1982), but only in the last two decades have studies really progressed in the Puna, Cordillera Oriental, Sierras Subandinas, Famatina and Precordillera geological provinces. The recent integration of palynological data with other fossil group data has allowed more accurate biostratigraphic charts and the establishment of regional correlations. It also contributed to paleogeographic and paleoenvironmental interpretations (Ottone et al., 1992, 1995, 1999, 2001; Rubinstein, 1997, 2001, 2003; Rubinstein and Toro, 1999, 2001; Rubinstein et al., 1999, 2010, 2011; Astini et al., 2003; Rubinstein and Vaccari, 2004; Achab et al., 2006).

Ordovician chitinozoa from South America is known from Brazil (Grahm, 1992, 2006; Grahm and Paris, 1992), Bolivia (Heuse et al., 1999) and Argentina (Volkheimer et al., 1980; Ottone et al., 1992, 2001; Achab et al., 2006). Chitinozoan biozones of the major Ordovician paleoplates such as North America (Achab, 1989; Achab et al., 2003), northern Gondwana (Paris, 1990), western Gondwana (Grahm, 2006), Baltoscandia (Nölvak, 1999), Avalonia (Vandenbroucke, 2008) and

China (Chen et al., 2009), demonstrate the significant contributions of this group as a biostratigraphic tool for this period.

Results of chitinozoan studies from northwestern Argentina, part of a PhD thesis (de la Puente, 2009), are presented in this paper. These chitinozoan assemblages include one of the oldest recorded chitinozoans in the world and have been calibrated with acritarchs and graptolites (de la Puente and Rubinstein, 2009). The PhD studies established a preliminary biostratigraphic scheme for the Floian, published by de la Puente (2010a, 2010b), as well as the presence of index elements that are related to the Hirnantian glaciation and its post-glacial deposits, reaching into the Silurian (Rubinstein et al., 2008; de la Puente, 2009). Here, we synthesize these data into a single biozonation. In addition, a stratigraphic range chart of selected acritarch taxa from the Ordovician of the Central Andean Basin is proposed. This chart integrates graptolite, conodont and trilobite zones (Toro and Maletz, 2007; Albanesi et al., 2008; Waisfeld and Vaccari, 2008; Vaccari et al., 2010a; Zeballo et al., 2011) as well as associated chitinozoans. Moreover, biostratigraphic or potential biostratigraphic markers for the basin have been identified. This stratigraphic range chart is the first step towards a proposed biozonation, based on marine phytoplankton, for the Ordovician of Argentina. Paleobiogeographic inferences related to the recently established distribution of chitinozoan biotopes for the Hirnantian (Vandenbroucke et al., 2010b) are discussed.

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2. Geological setting

The Central Andean Basin is one of the three main Lower Paleozoic basins of Argentina, and is characterized by its rich fauna and its proximity to the Andes Range (Cordillera de los Andes). The Famatina and Precordillera basins are the two others, located further to the south (Fig. 1A). The 5000 meter thick Central Andean Basin has a vast area of continuous sedimentation, and is extremely important in the analysis of Gondwanan margin sequences (Astini, 2003).

Geographically, the Central Andean Basin is located in northwestern Argentina, where it comprises the Salta and Jujuy provinces, as well as parts of Chile, Bolivia and Peru. Geologically, the portion of the Central Andean Basin in Argentina is known locally as the NOA basin, which is the Spanish abbreviation for northwestern Argentina. It includes the geological provinces of Puna to the west, Cordillera Oriental in the center and Sierras Subandinas and Sierras de Santa Bárbara to the east, extending to the subsurface of the Chaco plain. This physiographic division in the NOA basin is a result of the tectonic effects principally derived from the Cenozoic Andean Cycle (Ramos, 2009). The Paleozoic and Mesozoic basins, situated along the pericratonic regions are the result of a foreland basin system (Astini, 2003). In describing the depositional history of the Central Andean Basin, Astini (2008) distinguishes three depozones in the Ordovician stratigraphy (Fig. 1B).

The chitinozoans studied in this work are from the Ordovician of Puna, Cordillera Oriental and Sierras Subandinas. In the Sierras Subandinas, a complete stratigraphic and paleoenvironmental analysis has been carried out, based on sequential stratigraphy and palynological studies (Astini and Marengo, 2003, 2006; Rubinstein, 2005; Rubinstein and de la Puente, 2008; Rubinstein et al., 2010, 2011). These form the basis for the biostratigraphical studies in this work. The geological aspects and fossiliferous material of the Cordillera Oriental have been extensively studied. This central zone is characterized by clastic shelf deposits with abundant quartz-rich sandy intervals. The eastern part of the Cordillera Oriental, along with the Sierras Subandinas deposits, forms the eastern depositional zone. It is composed of strong bioturbated deltaic and estuarine units. In Puna, two different Ordovician eruptive zones, i.e., Eastern Puna and Western Puna (Méndez et al., 1973; Palma et al., 1986; Bahlburg, 1991) are distinguished. Toward the south of the Olacapato-Toro lineament is the Austral Puna segment (Alonso et al., 1984). Using the depositional zone concept, the western Puna deposits belong to the western depositional zone while those of eastern Puna belong to the central depositional zone, showing more affinity with the Cordillera Oriental deposits. The Puna section analyzed in this work is the Lari Creek section, near Salar del Rincón, within western Austral Puna.

3. Stratigraphy and biostratigraphy

Figs. 2 and 3 show the Ordovician stratigraphic units from this study and the locations of palynological sections.

3.1. Sierras Subandinas

The most complete and well-known section of this region is found along the Capillas River, where it cuts through the Sierra de Zapla, in the southern part of Sierras Subandinas (Monaldi et al., 1986). Astini and Marengo (2003, 2006) interpreted this sector of the basin (~1000 m of sediments) as a marginal marine environment. It is characterized by shallow marine deltaic systems, alternating with an estuarine environment related to relative sea-level fluctuations, which indicate frequent changes of the coast line. In this section, Lower Paleozoic outcrops range from the Middle Ordovician to the Silurian. The fossil record, however, is generally poorly represented, though it may locally be abundant (Albanesi et al., 2007). The scarcity or even absence of macrofauna in Sierras Subandinas is possibly related to the depositional environment conditions. This part of the

Ordovician–Silurian foreland basin was deposited in marginal facies less favorable to the development of most type of lifeforms.

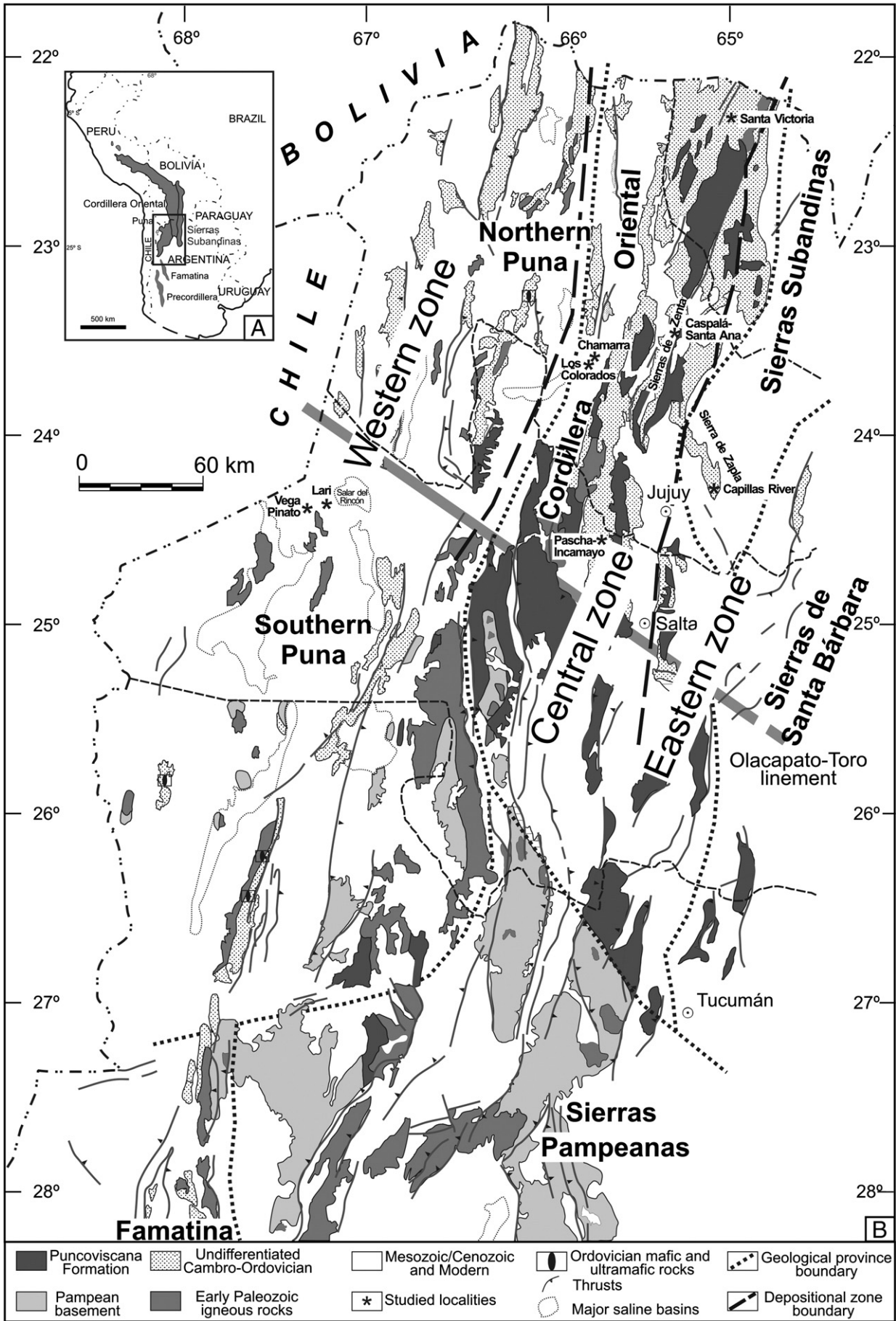
Marine palynomorphs are present in these units, although the abundance, preservation and diversity vary with the stratigraphic level and the corresponding sedimentary facies. They are mainly represented by acritarchs, chlorophyte algae, and chitinozoans, as well as terrestrially derived cryptospores (Rubinstein et al., 2010).

The basal Zanjón Formation is interpreted as a tidal plain sequence with frequent subaerial exposure. The only fossils of biostratigraphic significance are the palynomorphs in the upper part of this unit and in its transition to the Labrado Formation, indicating an early to middle Dapingian age (Rubinstein et al., 2010). The overlying unit, Labrado Formation, is transitional in nature and it is divided into two members. The lower Laja Morada Member with purplish-red colors indicates an early and extensive subaerial exposure with water table fluctuations in the interfluvies. This unit contains chlorophytes with no biostratigraphic value. The early oxidation that this unit has undergone is possibly responsible for the low fossil content. The upper Lagunillas Member represents a restricted estuarine environment not older than Dapingian in age, based on the presence of *Aremoricium*. It also contains chlorophytes and what are possibly nonmarine or brackish algae fossils (Rubinstein et al., 2011). The Capillas Formation overlays a distinct contact and it is interpreted to have been deposited in open marine environment. This formation is dated as early to late Darriwilian according to the acritarchs (*Arkonina* and *Liliosphaeridium* genera) from its lower part (Rubinstein et al., 2011). The Capillas Formation gradually transitions into the Centinela Formation. The Centinela Formation represents the progradation of a deltaic complex and contains sparse and simple acritarchs with no biostratigraphic value (Rubinstein and de la Puente, 2008).

The sequence continues with a significant change in sedimentation represented by the Zapla Formation, regionally known as the Hirnantian glacial horizon (Schlagintweit, 1943). It contains cosmopolitan trilobites of the genus *Dalmanitina* (Monaldi et al., 1986), as well as marine and terrestrial palynomorphs with a predominance of genera *Villosacapsula*, *Eupoikilofusa*, *Neoveryhachium*, *Polygonium*, *Micrhystridium* and *Multiplicisphaeridium*. There are also re-worked forms such as *Acanthodiacrodium ubui* Martin, 1969, a marker species of the Tremadocian, and a smaller number of cryptospores. This assemblage also supports a Late Ordovician age (Rubinstein and de la Puente, 2008). Some authors (Grahn and Gutiérrez, 2001; Díaz-Martínez and Grahn, 2007) suggest a Silurian age (no older than Aeronian and no younger than late Telychian) for the Zapla Formation, based on chitinozoan assemblages from this unit in the Capilla River area, composed of *Angochitina* sp. 1, *Cyathochitina* sp. B, *Cyathochitina* sp. cf. *C. campanulaeformis*, *Conochitina elongata*, and *Conochitina proboscifera*. However, this chitinozoan assemblage does not fit with other studied chitinozoan assemblages from the same formation (Rubinstein and de la Puente, 2008). It is possible that the levels assigned to the Zapla Formation by these authors actually belong to the overlying Lipeón Formation of confirmed Silurian age (Baldis et al., 1976; Benedetto, 1991; Rickards et al., 2002) and containing Silurian organic-walled phytoplankton (Rubinstein and de la Puente, 2008).

Outcrops of the Lipeón Formation in Cordillera Oriental also contain palynomorphs and graptolites, indicating a late Aeronian age in its western part (Rubinstein and Toro, 2006). There are chitinozoan and acritarch assemblages, of probably Telychian age, in its eastern part (Rubinstein et al., 2008).

Díaz-Martínez et al. (2011) have recently synthesized the early Paleozoic glaciation in South America. These authors consider the Zapla Formation from northwestern Argentina to be correlative with the San Gabán (Peru) and Cancañiri (Bolivia) formations, and synchronous with the glaciomarine record of adjacent intracratonic basins of South America in the Llandovery. Different deglaciation events could have taken place from the late Ordovician to the early Silurian (Grahn and Gutiérrez, 2001; Díaz-Martínez et al., 2011). More detailed studies are being carried out on the late Ordovician–



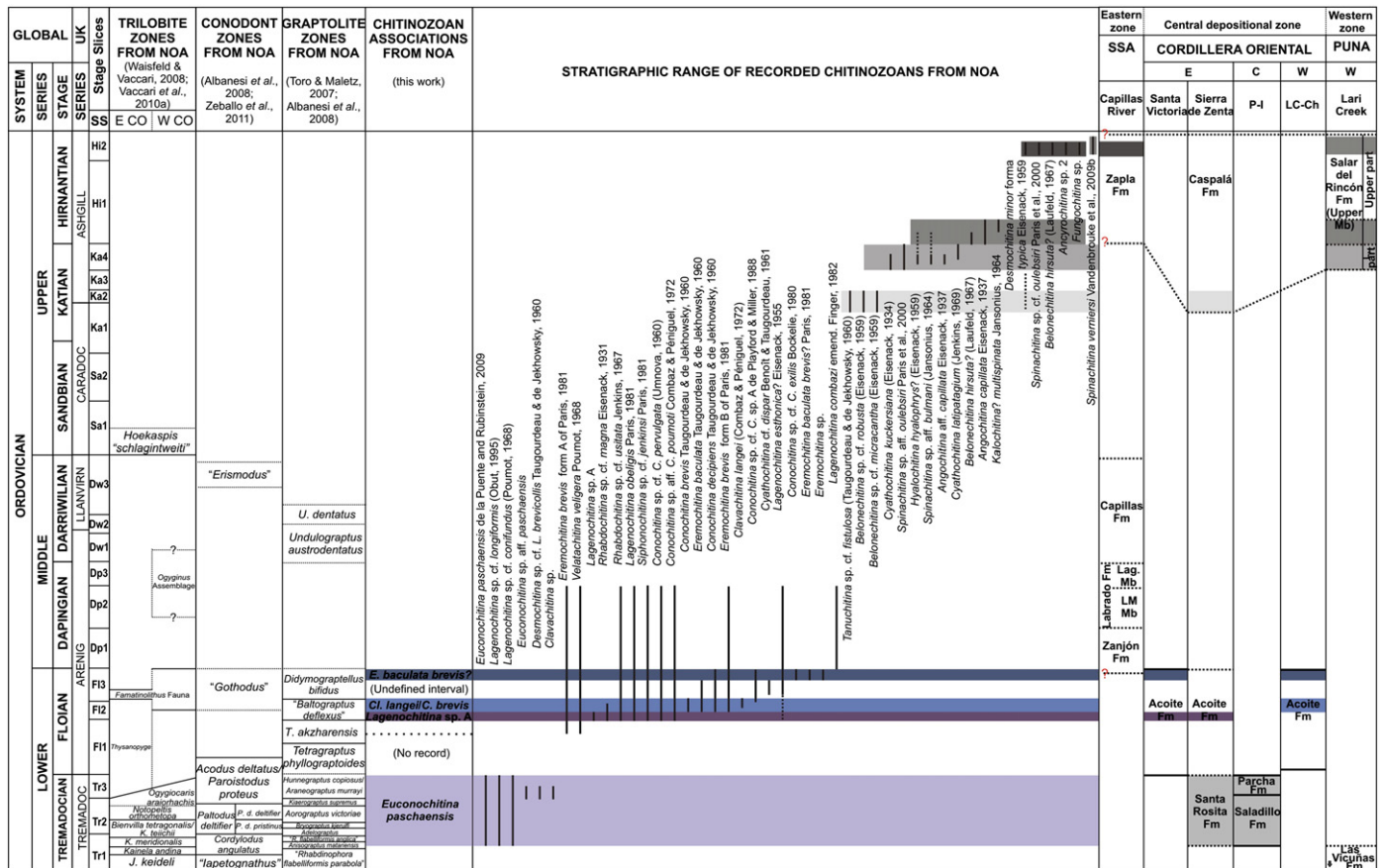


Fig. 2. Stratigraphic range and geographic distribution of the Ordovician chitinozoans from northwestern Argentina and correlation between chitinozoan assemblages, graptolite, conodont and trilobite zones from northwestern Argentina (Toro and Maletz, 2007; Albanesi et al., 2008; Waisfeld and Vaccari, 2008; Vaccari et al., 2010a; Zeballos et al., 2011) and Stage Slice (Bergström et al., 2009). Grey horizontal bars represent Hirnantian chitinozoan assemblages from the Salar del Rincón, Caspalá and Zapla formations. Stratigraphic ranges of chitinozoans are based on: de la Puente and Rubinstein (2009) (Pascha-Incamayo area); de la Puente (2010a, 2010b) (Santa Victoria area); Rubinstein et al. (2010) (Capillas area); de la Puente (unpublished data) (Sierras de Zenta, Los Colorados-Chamarra and Lari Creek areas). SSA: Sierras Subandinas; E: Eastern; C: Central; W: Western; CO: Cordillera Oriental; P-I: Pascha-Incamayo; LC-Ch: Los Colorados-Chamarra; Lag.: Lagunillas; LM: Laja Morada.

early Silurian levels from northwestern Argentina in order to constrain the ages of the units (Zapla and Lipeón formations) in this part of the Central Andean Basin.

3.2. Cordillera Oriental

The Ordovician stratigraphy of Cordillera Oriental is complex with strong lateral variations in lithology. This has caused a proliferation of nomenclature. A synthesized diagram of the Ordovician units of Cordillera Oriental is presented by Astini (2008). Figs. 2 and 3 outline the stratigraphic units of Cordillera Oriental studied in this work.

The Lower Ordovician in the Cordillera Oriental is traditionally included within the Santa Victoria Group. It is composed of the Santa Rosita (late Cambrian-Tremadocian) and Acoite (Floian) formations (Turner, 1964), and commences deposition on the Iruyica discordance. The sedimentation is predominantly clastic (~3700 m thick). Graptolite, conodont and trilobite records have been used to establish a chronostratigraphic global correlation for this group (Rao et al., 1994; Toro and Maletz, 2007; Albanesi et al., 2008; Waisfeld and Vaccari, 2008; Zeballos and Albanesi, 2009; Albanesi et al., 2010; Vaccari et al., 2010a; Zeballos et al., 2011). The oldest palynological data from the Argentinian Paleozoic are from the late Cambrian of the Casa Colorada Member in the Santa Rosita Formation (Rubinstein et al., 2003; Vergel et al., 2007).

The Middle Ordovician is less widely represented. In some areas, such as in the Los Colorados-Chamarra area, the Santa Victoria Group is followed by the Alto del Cóndor Formation (possibly Darrivilian; 43 m thick) and the Sepulturas Formation (late Darrivilian and probably to the basal Sandbian; 66 m thick) (Astini et al., 2004). The Alto del Cóndor Formation yields sparse fossil content. The Sepulturas Formation records *Sacabambaspis janvieri* and stratigraphically significant conodonts and trilobites (Astini et al., 2004, and references therein).

The Upper Ordovician is generally recognized as the Zapla glacial horizon of the late Hirnantian, which is locally named Mecoyita Formation (Turner, 1960; Santa Victoria-Mecoyita area) or Caspalá Formation (Starck, 1995; Sierras de Zenta). This unit (10–60 m thick) is deposited over Lower and Middle Ordovician levels on the Oclóyic unconformity, and it is overlain by the transgressive Silurian Lipeón Formation deposits (Turner, 1960).

3.3. Puna

The palynological material from Lari Creek in the western part of Austral Puna has been mentioned in preliminary studies (Vaccari et al., 2010b), and a detailed taxonomic study of the material is currently being prepared for publication. In this area, the Las Vicuñas Formation is the oldest outcrop. It is composed of an intrusive-sedimentary

Fig. 1. (A). Geographic map of northern Argentina indicating Ordovician basins. (B). Geological map of the Central Andean Basin, in northwestern Argentina, showing studied localities, geological provinces and depositional zones. Modified from Astini (2008) and Rubinstein et al. (2011).

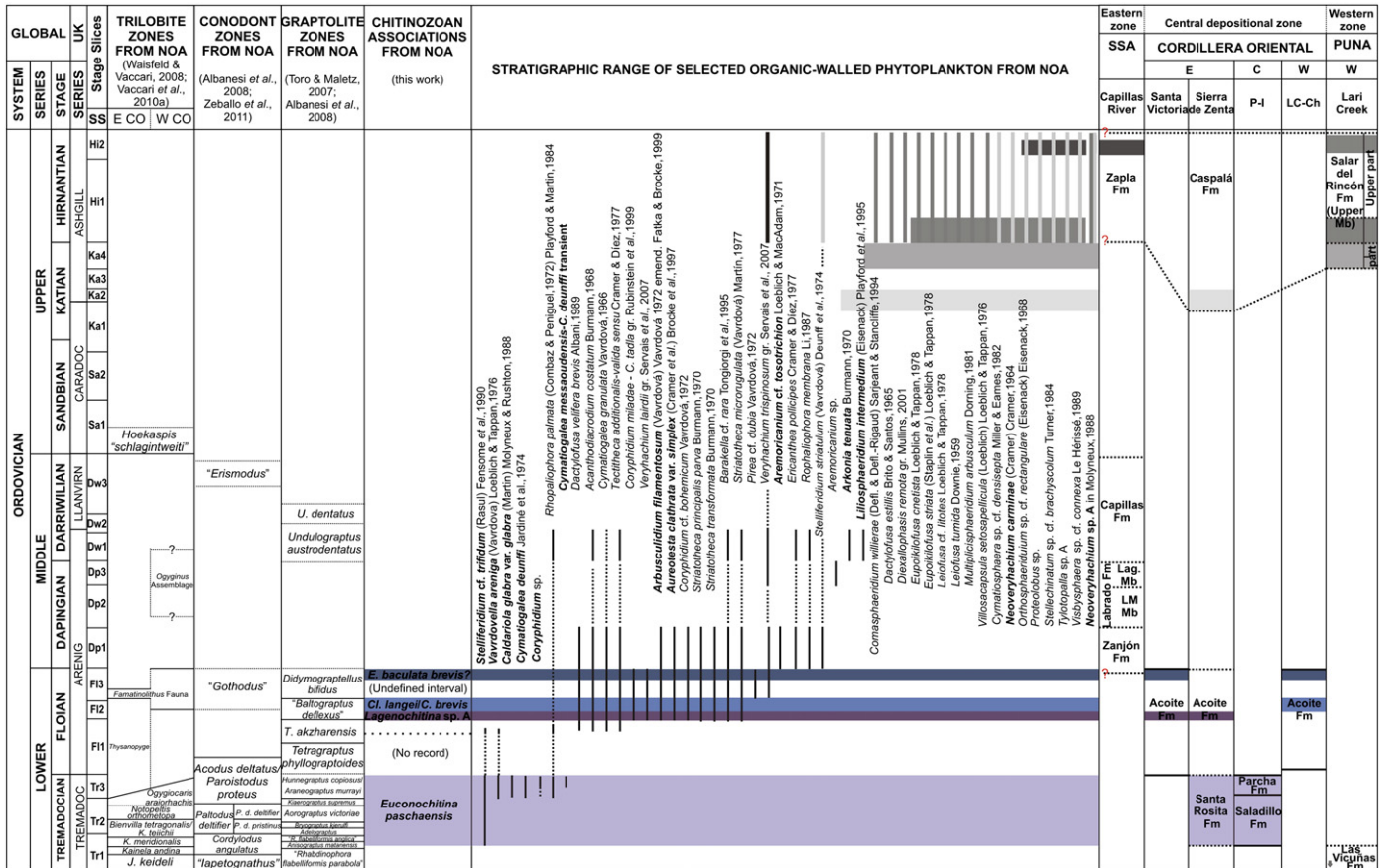


Fig. 3. Stratigraphic distribution of selected organic-walled phytoplankton taxa throughout the Ordovician of the Central Andean Basin (NOA) by stratigraphic units, sections and areas. Correlation with graptolite, conodont and trilobite zones and chitinozoan assemblages of the NOA. Grey horizontal bars represent chitinozoan assemblages from the Salar del Rincón, Caspalá and Zapla formations, of late Hirnantian–early Rhuddanian? age. Stratigraphic range lines: light grey corresponds to the Caspalá Formation; dark grey corresponds to the Salar del Rincón Formation; black corresponds to the three Hirnantian units. Taxa in bold letters are considered to be stratigraphic markers according to their first appearance datum (FAD) in different paleoplates. Based on: Toro and Maletz (2007); Albanesi et al. (2008); Waisfeld and Vaccari (2008); Vaccari et al. (2010a); Zeballo et al. (2011); de la Puente and Rubinstein (2009); Rubinstein and Toro (2001); Rubinstein and Vaccari (2004); Rubinstein (2005); Rubinstein et al. (2007, 2008, 2011); Rubinstein and de la Puente (2008); Rubinstein (unpublished data).

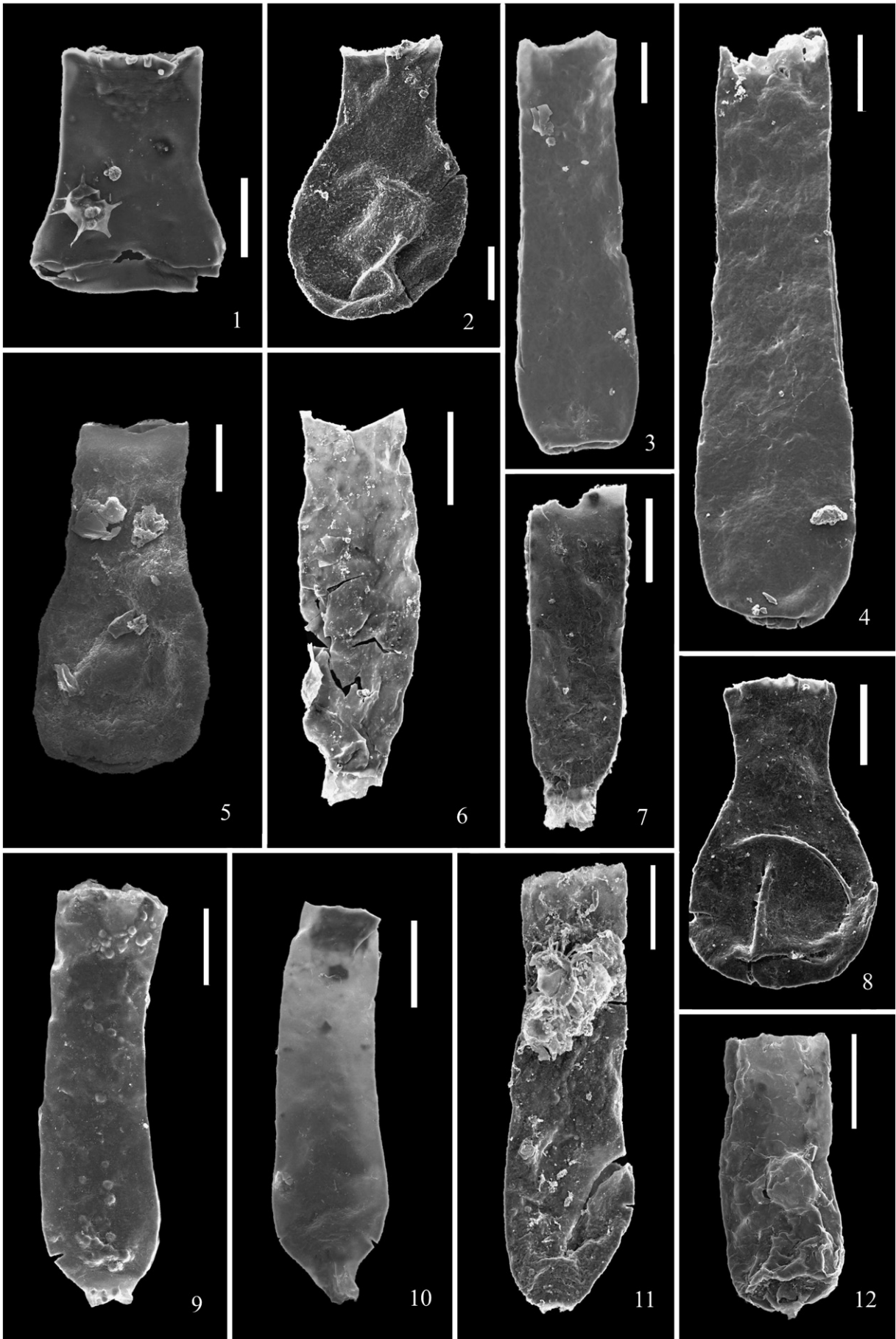
complex (Donato and Vergani, 1985), assigned to the Furongian–early Tremadocian based on its paleontological content (Rao et al., 2000).

The Las Vicuñas Formation is separated by an angular discordance from the Salar del Rincón Formation in Lari Creek. The age of the Salar del Rincón Formation, which is based on the macrofauna, has been extensively discussed and is variously interpreted as Early Devonian (Aceñolaza et al., 1972), early Llandovery–Pre-late Llandovery (Isacson et al., 1976), late Hirnantian–early Llandovery (Benedetto and Sánchez, 1990), and not younger than Ashgill, using

cf. *Eohomalonotus* (Malanca and Moya, 1998). Based on palynological data, Rubinstein and Vaccari (2004) suggested a late Hirnantian or early Llandovery age for the Upper Member of this formation. The Salar del Rincón Formation ends with an erosive discordance and is overlain by Late Carboniferous beds of the Cerro Oscuro Formation. The Lower Member (38 m thick) of the Salar del Rincón Formation is interpreted as a proximal anastomosed fluvial depositional system with a supply area situated very close to the east (Donato and Vergani, 1985). This member transitions in to the Upper Member

Plate 1. Lower and Middle Ordovician chitinozoans from northwestern Argentina. Scale bars represent 50 µm.

- Euconochitina paschaensis* de la Puente and Rubinstein, 2009. Sample 8656, late Tremadocian levels of the Santa Rosita Fm from the Sierras de Zenta area.
- Lagenochitina* sp. A. Sample 8949, early middle Floian of the upper part of the Acoite Fm from the Sierras de Zenta area.
- Conochitina decipiens* Taugourdeau and de Jekhowsky, 1960. Sample 8395, late middle Floian of the upper part of the Acoite Fm from the Los Colorados–Chamarra area.
- Clavachitina langei* (Combaz and Péniguel, 1972). Sample 8395, late middle Floian of the upper part of the Acoite Fm from the Los Colorados–Chamarra area.
- Conochitina* sp. cf. *Conochitina* sp. A. Playford and Miller, 1988. Sample 8495, late Floian of the upper part of the Acoite Fm from the Los Colorados–Chamarra area.
- Eremochitina baculata* Taugourdeau and de Jekhowsky, 1960. Sample 8991, late middle Floian of the upper part of the Acoite Fm from the Sierras de Zenta area.
- Velatachitina veligera* Poumot, 1968. Sample 7999, Dapingian of the upper part of the Zanjón Fm and its transition to Laja Morada Mb of the Labrado Fm from the Río Capillas area.
- Lagenochitina combazi* Finger, 1982. Sample 7999, Dapingian of the upper part of the Zanjón Fm and its transition to Laja Morada Mb of the Labrado Fm from the Río Capillas area.
- Eremochitina brevis* Benoît and Taugourdeau, 1961. Sample 8000, Dapingian of the upper part of the Zanjón Fm and its transition to Laja Morada Mb of the Labrado Fm from the Río Capillas area.
- Eremochitina brevis* morphotype A of Paris, 1981.
- Eremochitina brevis* morphotype B of Paris, 1981.
- Eremochitina* sp. Sample 6289, late Floian of the upper part of the Acoite Fm from Santa Victoria area.
- Eremochitina baculata brevis*? Paris, 1981. Sample 6764, late middle Floian of the middle part of the Acoite Fm from Santa Victoria area.



(78 m thick) and is interpreted as a silicoclastic coastal marine to a transitional environment, with abundant invertebrate fauna (Donato and Vergani, 1985).

4. Material and methods

The material is fully described in the author's PhD studies (de la Puente, 2009). The systematic paleontology was partially published (Rubinstein et al., 2008; de la Puente and Rubinstein, 2009; de la Puente, 2010a, 2010b; Vaccari et al., 2010b) and a paper with additional descriptions is forthcoming. This material is stored in the collections of the Paleopalynology Unit, IANIGLA, CCT, Mendoza, labeled MPLP (Mendoza-Paleopalintoteca-Laboratorio de Paleopalinoología).

The chitinozoans have been extracted from 60 samples from the localities shown in Fig. 1B. The sampled stratigraphic units are outlined in Fig. 2 and detailed below:

- Capillas River area: The sampled levels are from the Middle Ordovician Zanjón Formation and transitions to the Laja Morada Member of the Labrado Formation (repository code numbers: 7586–7587, 7999–8000), and the Upper Ordovician Zapla Formation (repository code number: 7590).
- Santa Victoria area: The Lower Ordovician samples are from the La Huerta (repository code numbers: 6455, 6458, 6462, 6289) and Grande (repository code numbers: 6444, 6765, 6764, 6447) creeks, both tributaries of the Santa Victoria River.
- Sierras de Zenta area: The Tremadocian samples are from the Santa Rosita Formation exposed near the Santa Ana locality (repository code numbers: 8656–8658). The Floian samples are from the Acoite Formation (repository code numbers: 8942–8944, 8949–8950, 8990–8991) and the uppermost Ordovician samples are from the Caspalá Formation exposed near the Caspalá locality (repository code numbers: 8816–8820).
- Pascha-Incamayo area: The palynomorphs are recovered from paleontological sampling carried out in the Tremadocian Saladillo and Parcha formations from the Aguada del Attillo and Barranco creeks, which are both tributaries of the Incamayo River (repository code numbers: 7289–7290, 6129, 6131, 9313, 7292, 7291).
- Los Colorados–Chamarra area: In the Los Colorados Creek, the palynological samples are from the paleontological sampling carried out in the Floian Acoite Formation (repository code numbers: 8396, 8392–8393, 8395). In the Chamarra Creek, the samples are also from the Floian Acoite Formation (repository code numbers: 8512–8514, 8495, 8500).

- Lari Creek area: The Upper Ordovician–Lower Silurian? samples are from the Upper Member of the Salar del Rincón Formation (repository code numbers: 9407–9413, 9415–9416, 9420, 9423).

5. Chitinozoan biostratigraphy

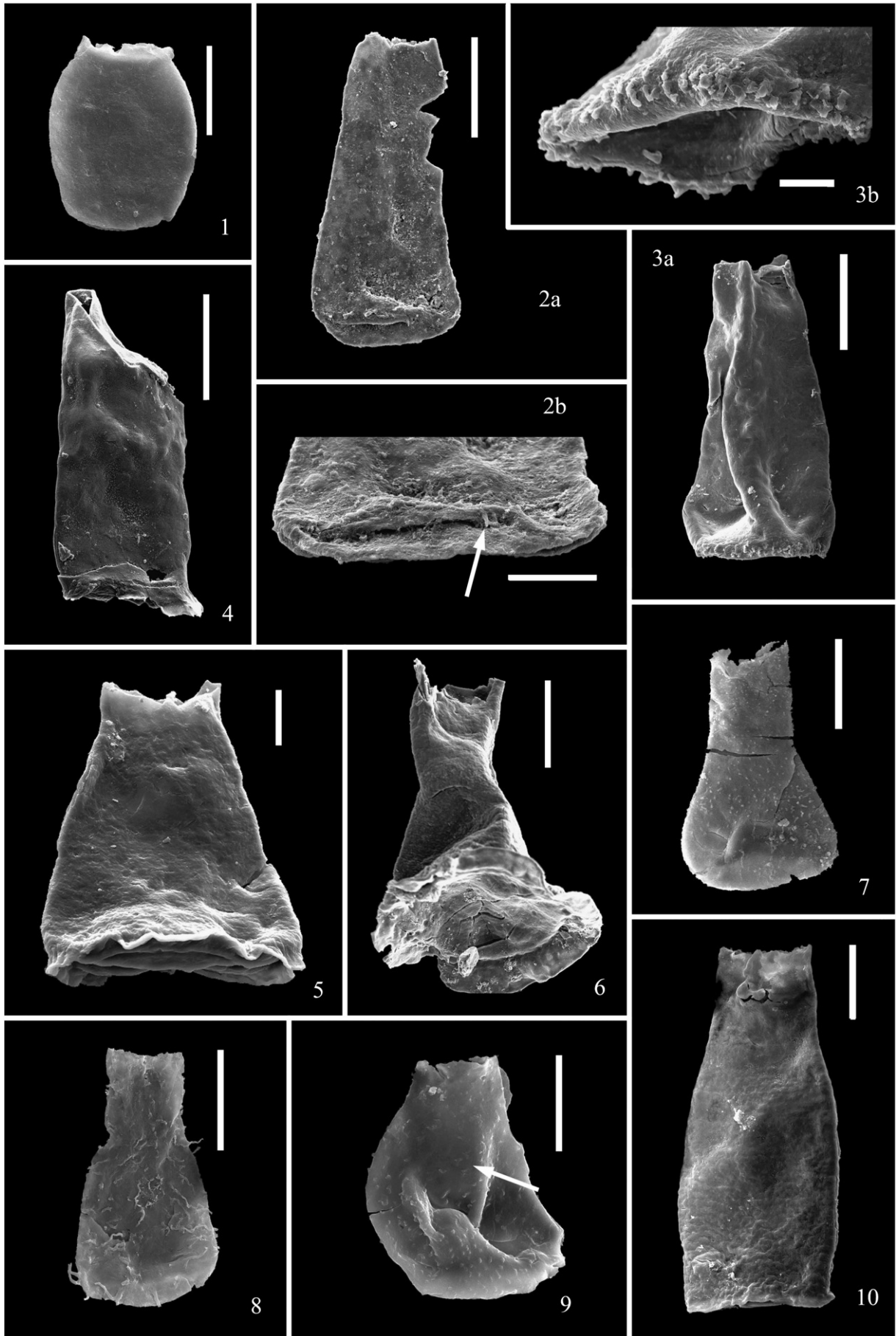
It is difficult to establish a biostratigraphic scheme, based on chitinozoans, for Ordovician deposits from northwestern Argentina due to the heterogeneity of lateral facies and their peculiar paleoenvironments related to the geodynamics of the basin. In addition, studies of this group are still limited in the region. Some Ordovician chitinozoan assemblages from northwestern Argentina (Fig. 2), however, are useful due to the biostratigraphic control given by the graptolite, conodont and trilobite zones in the Lower Ordovician (Toro and Maletz, 2007; Albanesi et al., 2008; Waisfeld and Vaccari, 2008; Vaccari et al., 2010a; Zeballo et al., 2011), which confirm the determined ages. Some chitinozoan assemblages have already been defined (de la Puente, 2010b). The Middle Ordovician from northwestern Argentina is poorly represented but there are some records of early to middle Dapingian chitinozoans (Rubinstein et al., 2010). The age of Upper Ordovician chitinozoan bearing deposits is controversial and their chitinozoan assemblages are difficult to define due to their poor preservation.

The oldest chitinozoans observed in northwestern Argentina are from the *Euconochitina paschaensis* assemblage, which includes *Lagenochitina* sp. cf. *longiformis*, *Lagenochitina* sp. cf. *conifundus*, *Desmochitina* sp. cf. *L. brevicollis*, *Euconochitina* sp. aff. *paschaensis* and *Clavachitina* sp. Presently, *Eu. paschaensis* (Plate 1, 1) has only been observed in late Tremadocian deposits from the Argentinian Cordillera Oriental, in the Saladillo and Parcha formations from the Pascha-Incamayo area, and equivalent levels assigned to the Santa Rosita Formation from the Sierras de Zenta area. In the Pascha-Incamayo area, *Eu. paschaensis* is present in the *Kiaerograptus supremus* Zone of early late Tremadocian age, and *Araneograptus murrayi* and *Hunnegraptus copiosus* zones of the late Tremadocian, which are probably equivalents of the Tr 2–Tr 3 Stage Slices (SS) of Bergström et al. (2009). Specimens considered to be *Desmochitina* sp. cf. *L. brevicollis* (de la Puente and Rubinstein, 2009) have been described from the *A. murrayi* and *H. copiosus* zones of Cordillera Oriental from south Bolivia (Heuse et al., 1999).

The assemblage characterized by the presence of *Lagenochitina* sp. A (Plate 1, 2) contains *Eremochitina brevis* (*E. brevis* morphotype A of Paris, 1981) and *Velatachitina veligera* (Plate 1, 7). It is from the lower part of the Acoite Formation exposed in the Grande Creek from the Santa Victoria area, and probably from equivalent levels in the Sierras de Zenta area. An assemblage from Grande Creek is assigned to an early middle Floian age based on acritarchs (Rubinstein and Toro, 2001), which are

Plate 2. Upper Ordovician chitinozoans from northwestern Argentina. Scale bars represent 50 µm.

1. *Desmochitina minor* form *typica* Eisenack, 1958. Sample 7590, late Hirnantian–early Rhuddanian? of the Zapla Fm from the Río Capillas area.
- 2a–b. *Spinachitina* sp. cf. *oulebsiri* Paris et al., 2000. Sample 7590, late Hirnantian–early Rhuddanian? of the Zapla Fm from the Río Capillas area; 2b. Detail of the base of 2a indicating the aboral orientation of the spine; scale bar detail: 20 µm.
- 3a–b. *Spinachitina verniersi* Vandenbroucke et al., 2009a. Sample 9407, late Hirnantian–early Rhuddanian? of the lower part of the Upper Mb of the Salar del Rincón Fm from the Lari Creek area; 3b. Detail of the base of 3a; scale bar detail: 10 µm.
4. *Tanuchitina* sp. cf. *fistulosa* Taugourdeau and de Jekhowsky, 1960. Sample 8819, re-worked deposits of the late Hirnantian of the Caspalá Fm from the Sierras de Zenta area.
5. *Cyathochitina kuckersiana* (Eisenack, 1934). Sample 9411, late Hirnantian–early Rhuddanian? of the lower part of the Upper Mb of the Salar del Rincón Fm from the Lari Creek area.
6. *Cyathochitina latipatagium* (Jenkins, 1969). Sample 9412, late Hirnantian–early Rhuddanian? of the lower part of the Upper Mb of the Salar del Rincón Fm from the Lari Creek area.
7. *Angochitina capillata* Eisenack, 1937. Sample 9420, late Hirnantian–early Rhuddanian? of the upper part of the Upper Mb of the Salar del Rincón Fm from the Lari Creek area.
8. *Belonechitina hirsuta?* (Laufeld, 1967). Sample 7590, late Hirnantian–early Rhuddanian? of the Zapla Fm from the Río Capillas area.
9. *Kalochitina? multispinata* Jansonius, 1964. Sample 9423, late Hirnantian–early Rhuddanian? of the upper part of the Upper Mb of the Salar del Rincón Fm from the Lari Creek area. The arrow indicates the spine ornamentation (multiple base spines).
10. *Cyathochitina jenkinsi* Neville, 1974. Sample 9420, re-worked deposits of the late Hirnantian–early Rhuddanian? of the upper part of the Upper Mb of the Salar del Rincón Fm from the Lari Creek area.



probably equivalent to the lower part of the SS Fl 2 (Bergström et al., 2009). *Lagenochitina* sp. A has only been observed in northwestern Argentina, however it is similar to specimens described as *Lagenochitina* sp. 2 in the late Floian of West Hubei (China) by Chen et al. (2009). *E. brevis* is typically associated with *Lagenochitina* sp. A, and is the index species of the late middle Floian in North Gondwana, indicating the Time Slice (TS) 2.c of Webby et al. (2004), which is approximately equivalent to the SS Fl 2–SS Fl 3 of Bergström et al. (2009). In South China, it is equivalent to the *suecicus* Zone (Wang and Chen, 2004). *E. brevis* is also the index species of the homonymous biozone of the Middle Arenig (upper Floian) from western Gondwana (Grahm, 2006). In northwestern Argentina, this species appears in the *Tetragraptus akzharensis* Zone (Toro and Maletz, 2007), in the late early Floian, equivalent to the upper part of the SS Fl 1 (Bergström et al., 2009). In the upper part of the Zanjón Formation and its transition to the Labrado Formation, *E. brevis* (*E. brevis* morphotypes A and B of Paris, 1981) (Plate 1, 9, 10) is associated with *Lagenochitina combazi* (Plate 1, 8), which is described from the Dapingian of China (Chen et al., 2009). Therefore, the oldest documented stratigraphic record of *E. brevis*, from the lower Floian (*T. akzharensis* Zone), occurs in the Central Andean Basin and its upper limit possibly reaches the Dapingian.

The interval between the *E. paschaensis* and *Lagenochitina* sp. A assemblages has not yielded any chitinozoans, except in the upper part of the *T. akzharensis* Zone of the late early Floian where *E. brevis* and *V. veligera* are observed. This interval corresponds to the *Tetragraptus phyllograptoides* and the lower part of the *T. akzharensis* zones of the late Floian, which is approximately equivalent to the SS Fl 1 (Bergström et al., 2009).

In the middle and upper parts of the Acoite Formation from the Chamarra and Los Colorados creeks in the western Cordillera Oriental, an interval assemblage is characterized by the presence of both *Clavachitina langei* (Plate 1, 4) and *Conochitina brevis* Taugourdeau and de Jekhowsky, 1960. *Eremochitina baculata* Taugourdeau and de Jekhowsky, 1960 (Plate 1, 6) is an important component of this assemblage; it is not present in either of the previous and following assemblages. *V. veligera*, *Conochitina decipiens* (Plate 1, 3), *Conochitina* sp. cf. *C. poumoti* and *Conochitina* sp. cf. *Conochitina* sp. A of Playford and Miller, 1988 (Plate 1, 5) are also present. The age of the assemblage is considered to be late middle Floian, corresponding to the upper part of the “*Baltograptus deflexus*” Zone, which is probably equivalent to the upper part of the SS Fl 2 (Bergström et al., 2009).

An assemblage characterized by the presence of *Eremochitina baculata brevis?* (Plate 1, 12) has been recovered from the upper part of the Acoite Formation from La Huerta Creek in the Santa Victoria area, and from Chamarra Creek in the Los Colorados–Chamarra area, respectively from the northeastern and western Argentinian Cordillera Oriental. *E. baculata brevis?* is also present in the middle part of the same formation from Grande Creek in the Santa Victoria area. This assemblage also contains *V. veligera*, *C. decipiens*, *Conochitina* sp. cf. *C. poumoti*, *Conochitina* sp. cf. *C. sp. A* Playford and Miller, 1988, *Conochitina* sp. cf. *C. pervulgata*, *Conochitina* sp. cf. *C. exilis*, and *Eremochitina* sp. (Plate 1, 11). It is assigned to the late Floian, corresponding to the upper part of the *Didymograptellus bifidus* Zone, which is probably equivalent to the upper part of the SS Fl 3 (Bergström et al., 2009). Paris (1981) considered *E. baculata brevis?* as a final evolutionary stage of *E. baculata* in the Middle Arenig levels of the Pissot Formation from the Armorican Massif in France (de la Puente, 2010a). The specimens of *E. baculata brevis?* are observed in stratigraphically higher levels than those that contain *E. brevis*, thus supporting the evolutionary stages proposed by Paris (1981). The lower limit of this assemblage may be confirmed by the revision of the graptolite biostratigraphy of the Grande Creek section.

In the interval between *Cl. langei*/*C. brevis* and *E. baculata brevis?*, chitinozoans recovered for this study are insufficient to establish assemblages. There are no common elements between the sections

or, as in the case of the lower limit of *E. baculata brevis?*, some species are still under revision. Future studies with additional sections of the middle-upper part of the Acoite Formation, may extend the *Cl. langei*/*C. brevis* assemblage into higher stratigraphic levels covering such an interval. It is significant that in northwestern Argentina, the *Cl. langei*/*C. brevis* has only been observed in the Los Colorados area. *E. brevis* is also present in this area (Ottone et al., 1992).

In the Upper Ordovician levels, poorly preserved specimens, such as those assigned to *Tanuchitina* sp. cf. *fistulosa* (Plate 2, 4), were recovered from the Caspalá Formation in eastern Cordillera Oriental. Similarly, *Spinachitina* sp. cf. *oulebsiri* (Plate 2, 2a–b) was recovered from levels equivalent to the Zapla Formation in the Sierras Subandinas. The imprecise taxonomic assignment of the chitinozoans is due to poor preservation of individual specimens, probably related to re-working of the palynological material during the glacial Hirnantian stage. This may have produced a mixture of taxa of different ages. *T. fistulosa* is the index species of the homonymous biozone of the middle part of the TS.5d of North Gondwana (Webby et al., 2004), equivalent to the middle Katian, SS Ka 2 (Bergström et al., 2009). *Spinachitina* sp. cf. *oulebsiri* from the Zapla Formation is associated with common Darriwilian, Sandbian and Katian chitinozoans, such as *Desmochitina minor form typica* (Plate 2, 1), that suggest re-working. *S. oulebsiri*, from the *Spinachitina oulebsiri-fragilis* group (Vandenbroucke et al., 2009a), one of the first chitinozoans with Silurian affinity, occurred in the latest Hirnantian (upper *Normalograptus persculptus* Zone) (Grahm and Paris, 2011). If the assignment to *S. oulebsiri* could be proven in the Zapla Formation, it would indicate a latest Hirnantian–early Silurian age for the assemblage since it is the youngest element documented herein. *Spinachitina* species are common, on the other hand, in the lower part of the Upper Member of the Salar del Rincón Formation in southwestern Puna. They have been attributed to *Spinachitina verniersi* (Plate 2, 3a–b) with an age which is suggested to be “latest Ordovician (late Hirnantian) and sporadically observed in earliest Silurian strata (early Rhuddanian, Butcher, 2009)” by Vandenbroucke et al. (2009a). In the uppermost Salar del Rincón Formation, specimens of *Angochitina capillata* (Plate 2, 7), *Kalochitina? multispinata* (Plate 2, 9), and *Cyathochitina jenkinsi* (Plate 2, 10) are observed higher in the stratigraphy than *S. verniersi*. *K. multispinata* has been described from the Upper Member of the Los Azules Formation from the Central Precordillera of Argentina (Ottone et al., 2001), and has been dated as early Caradoc based on chitinozoan, graptolite and conodont zones. *Cyathochitina* sp. cf. *C. jenkinsi* is recorded in the Los Azules Formation from the Central Precordillera (Ottone et al., 2001). It is present in the Lower Member (late Darriwilian) and in the Upper Member (early Caradoc) of this formation, where it is associated with *K. multispinata*. Although there is no stratigraphic feature that provides direct evidence of glaciation in the section from Puna, chitinozoan assemblages from the Upper Member of the Salar del Rincón Formation correlate with other parts of the Gondwanan paleocontinent, which would indicate a post-glacial stage of the late Hirnantian. This could reach the early Rhuddanian, in this sector of western Gondwana. The uppermost formation contains re-worked material from older levels. Therefore, these levels from Puna are considered, at least partially, to be stratigraphically equivalent to the Zapla and Caspalá formations from Sierras Subandinas and Cordillera Oriental respectively.

5.1. Correlations with other chitinozoan biozonations

The Lower Ordovician from Northern Gondwana is represented by the *destombesi* and *confundus* biozones in the Tremadocian and *symmetrica*, *baculata* and *E. brevis* biozones in the Floian. The presence of the *Lagenochitina confundus* species indicates the homonymous biozone for Baltoscandia in the late early Tremadocian. In Northern Gondwana, the *confundus*/*brevicollis* Biozone is assigned to the late Tremadocian, preceding the *symmetrica* Biozone. The *symmetrica*

Biozone is the index biozone of the early Floian (Webby et al., 2004). The range of *Eu. paschaensis* can be considered of equivalent age to *conifundus*/*brevicollis* Biozone. In North America, the Tremadocian is not represented and the Floian contains the broad biozone of *Cl. langei*/*C. brevis* (Webby et al., 2004).

Euconochitina symmetrica (Taugourdeau and de Jekhowsky, 1960) has not yet been recorded in western Gondwana. However, the late Tremadocian from northwestern Argentina is characterized by *Eu. paschaensis*, a species whose local records could represent a previous evolutionary stage of the *Eu. symmetrica* (de la Puente and Rubinstein, 2009).

Cl. langei and *C. brevis* are common in Northern Gondwana and Laurentia. In North America, the association of these species determines the *langei*/*C. brevis* Biozone which ranges from the late Floian to the early Dapingian, ranging from the TS.2c to the TS.3a (Webby et al., 2004), equivalent to SS Fl 3–SS Dp 1 (Bergström et al., 2009). However, in northwestern Argentina this assemblage is observed in the late middle Floian ("*Baltograptus deflexus*" Zone) which is equivalent to the upper part of the SS Fl 2 (Bergström et al., 2009). *Cl. langei* indicates the late Floian from eastern Gondwana in Australia. The *Cl. langei* Biozone is defined in the late Floian from Yichang area of China. It is present in the *Oepikodus evae* conodont zone, as well as *Didymograptellus bifidus* and part of the *Azygograptus suecicus* zones (Chen et al., 2009). An undefined interval is observed immediately above this assemblage in northwestern Argentina, therefore it may extend stratigraphically upwards.

Tanuchitina anticostiensis (Achab, 1977) is recorded in the Autás-Mirim Formation of the subsurface of Brazil and indicates its Rawtheyan biozone in the biozonation for western Gondwana by Grahn (2006). *Armoricochitina nigerica* (Bouché, 1965) appears in the middle late Katian (approximately the SS Ka 4 of Bergström et al., 2009) and constitutes a partial range biozone for that age in Northern Gondwana (Webby et al., 2004). *A. nigerica* has also been observed in the subsurface of Brazil (Grahn, 2006). However, *T. anticostiensis* and *A. nigerica* have not been recorded in the levels studied from northwestern Argentina. Paleocological studies may indicate if the absence of these species in northwestern Argentina is related to local paleoenvironmental conditions.

A recent revision of the *Spinachitina* genus, typical of the latest Ordovician–earliest Silurian, establishes that *S. oulebsiri* and *S. verniersi* reach into the early Rhuddanian (Butcher, 2009; Vandenbroucke et al., 2009a). Grahn and Paris (2011) conclude that during the deglaciation of the Hirnantian ice sheet, most Ordovician genera and species became extinct and the first chitinozoans with Silurian affinity, *S. oulebsiri* or *Spinachitina oulebsiri-fragilis* group (Vandenbroucke et al., 2009a), occurred in the latest Hirnantian (upper *Normalograptus persculptus* Zone). Further studies on the *Spinachitina* genus from additional latest Ordovician–earliest Silurian sections in this sector of western Gondwana, such as the Central Andean Basin in Bolivia and the Precordillera Argentina, could contribute to knowledge of the paleocological significance of the various species and a reliable stratigraphic range for these particular species.

6. Marine phytoplankton biostratigraphy

The oldest Argentinian phytoplankton assemblage occurs in the late Cambrian of Cordillera Oriental (Rubinstein et al., 2003), followed by early to middle Tremadocian assemblages (Rubinstein, 1997; Vergel et al., 2007), both without independent age-control. Following the late Tremadocian acritarch assemblage, independently dated by graptolites and chitinozoans, phytoplankton assemblages occur throughout all of the Ordovician, with the exception of the earliest Floian *phyllograptoides* graptolite Zone. Data has not been recorded from either the middle–late Darriwilian, or from the Katian; while the Sandbian yields sparse acritarchs with a low diversity and with no real stratigraphic value. Fig. 3 displays the occurrence of selected phytoplankton taxa from the late

Tremadocian to the latest Ordovician. The biostratigraphic and paleogeographic relevance of these taxa has already been discussed in several papers (Rubinstein and Toro, 1999, 2002; Rubinstein et al., 1999, 2007, 2008, 2010, 2011; Rubinstein, 2003, 2005; de la Puente and Rubinstein, 2009).

7. Paleobiogeographic remarks

The Central Andean Basin has generally been regarded as being related to the western margin of the Gondwanan paleocontinent, which was the active margin of a large foreland basin situated in intermediate paleolatitudes, approximately between 30° and 40° in the south hemisphere during the Early Ordovician (Astini, 1998; Webby et al., 2004; Grahn, 2006). Acritarch and graptolite data have supported this paleoposition (Rubinstein and Toro, 2001).

The peri-Gondwanan relationship and the intermediate paleolatitudinal position continue into the late Floian. Typical taxa of the *messauoudensis-trifidum* assemblage exceptionally show wider records in northwestern Argentina (see synthesis in Rubinstein et al., 2007).

Biotores of planktonic graptolites and epipelagic chitinozoans have been mapped for the Late Ordovician (Vandenbroucke et al., 2009b, 2010a, 2010b) based on new Early Paleozoic climate concepts (Herrmann et al., 2004; Saltzman and Young, 2005; Page et al., 2007). Despite late Ordovician chitinozoan assemblages from northwestern Argentina still being under study, and even if our assemblages have not been subjected to the multivariate analyses, some preliminary paleogeographic inferences can be highlighted. According to the chitinozoan biotores established for the Hirnantian (Vandenbroucke et al., 2010b), the assemblage including *Cyathochitina latipatagium* from western Puna indicates a Polar Biotope (35°/40°–80° south) for the area, although it also contains *Cyathochitina kuckersiana*, which is one of the species of the Subtropical Biotope (20°–25° south). Meanwhile *Spinachitina verniersi* from western Puna and *S. oulebsiri* from Sierras Subandinas indicate Polar (35°/40°–80° south) to Subpolar (30°–35°/40° south) faunas. The wider distribution for these last species, in northwestern Argentina, may be related to transport by oceanic currents, or to (slightly) wider environmental tolerances, or suggest incursions of the Polar Front that reach even further equatorward than suggested by Vandenbroucke et al. (2010b). Alternatively, the position of the Central Andean Basin may have slightly shifted southwards by the end of the Ordovician.

Taken at face value, the new chitinozoan data does not contradict intermediate paleolatitudes for northwestern Argentina (with widespread elements of the Polar to Subpolar faunas). Elements from lower latitudes (Subtropical Biotope), which are less reliable than the (sub)polar species we recorded, may indicate the influence of warmer water masses as a result of the ocean surface circulation (such as the south Panthalassic convergence or the south Paleo-Tethys convergence major ocean gyre systems) proposed for the Hirnantian (Herrmann et al., 2004). It may also support the proposal of sea-way connections with the Rheic Ocean sharing the fauna and phytoplankton during the early Silurian (Llandovery) (Grahn and Paris, 2011, and references therein).

8. Conclusions

Although the chitinozoan records are still sparse in relation to the extensive deposits and different deposition facies studied in the Central Andean Basin, it is possible to propose four chitinozoan assemblages for the Lower Ordovician of northwestern Argentina: *Euconochitina paschaensis*, early late Tremadocian–late Tremadocian (SS Tr 2–Tr 3); *Lagenochitina* sp. A, early middle Floian (the lower part of the SS Fl 2); *Clavachitina langei/Conochitina brevis*, late middle Floian (the upper part of the SS Fl 2); *Eremochitina baculata brevis?*, late Floian (the upper part of the SS Fl 3). The *Cl. langei/C. brevis*

assemblage has only been observed in the western Cordillera Oriental, and its exact stratigraphic range is unknown.

A stratigraphic range of selected taxa, calibrated with graptolite, conodont, and trilobite zones and chitinozoan assemblages for Ordovician marine phytoplankton from the Central Andean Basin is proposed for the first time. Therefore, this is a step towards the establishment of a marine phytoplankton biozonation for the region.

In northwestern Argentina, chitinozoan assemblages and marine phytoplankton suggest a high to intermediate Early Ordovician paleolatitude position. At the Tremadocian-Floian boundary, the *messauoudensis-trifidum* acritarch assemblage indicates a strong connection of this region with the peri-Gondwanan province. In the Hirnantian, the recent chitinozoan biotope definition indicates Polar to Subpolar latitudes for northwestern Argentina potentially with some influence of warmer currents as a result of the ocean surface circulation.

This contribution demonstrates that chitinozoan assemblages are a useful addition to biostratigraphic tools used for studies of Ordovician deposits from Argentina. In some sections other groups such as graptolites, conodonts and, locally, trilobites provide independent biostratigraphic controls that facilitate the establishment of correlations and calibration of ages. In other sections with no independent biostratigraphic control, such as the Late Ordovician from northwestern Argentina, the presence of chitinozoans, acritarchs and cryptospores assist the development of biostratigraphic, paleogeographic and, even paleoenvironmental inferences.

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