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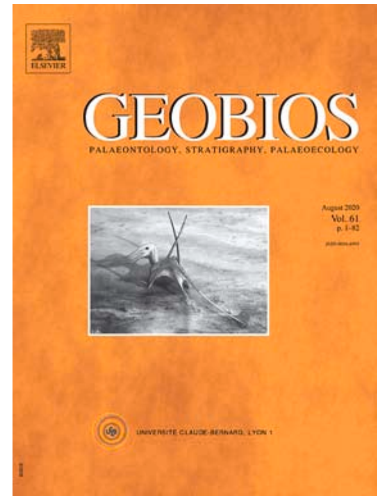

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Ordovician chitinozoans and review on basin stratigraphy, biostratigraphy and paleobiogeography of northern Argentina along the Proto-Andean margin ✡

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Abstract

Ordovician strata exposed across the Cordillera Oriental and the Sierras Subandinas in northwestern Argentina were part of a large retroarc foreland basin developed along the Proto-Andean margin within the Central Andes in South America. A revised chitinozoan biostratigraphy along and across-strike for the Tremadocian, Floian, Dapingian, Katian and Hirnantian stages, calibrated with other fossil groups in the basin, allow pinpointing the most characteristic events that affected the basin fill testing global *versus* local controls in accommodation, and suggesting comparisons with other peri-Gondwanan records. According to the chitinozoan data, the glacially-related Ordovician deposits in northwestern Argentina are restricted to the Hirnantian, and unconformably overlie late Katian deposits. In the Caspalá area (Cordillera Oriental), an interval with synsedimentary deformation and reworked chitinozoans correlate with glacially-related deposits in other sites of the eastern part of the basin (Río Capillas and Mecoyita areas). A glacial waning stage is determined by a thin interval of organic-rich black shales with sparse dropstones at the top of the Zapla Formation, containing *Spinachitina oulebsiri* associated with *Desmochitina* gr. *minor*, which together are typical latest Hirnantian components in other regions of Gondwana. Our study strengthens the foreland systems tract for the Ordovician Central Andean Basin with a volcanically fed interarc and foredeep depozone to the west (Puna region); a lower-accommodation forebulge depozone in the central area (mostly the Cordillera Oriental region); and a backbulge depozone (Sierras Subandinas and Sierras de Santa Bárbara) extending as far as the eastern Paraná Basin (reaching Paraguay and Brazil). Contemporaneous unconformities driven by global sea-level fluctuations were amplified or reduced due to deepening-narrowing or widening-shallowing, allowing contrasted accommodation, respectively associated to loading and relaxation. Ordovician chitinozoans from the Central Andean Basin indicate Northern, Western and peri-Gondwanan affinities, although locally some more cosmopolitan species described in Baltica, Avalonia and South China, are also recorded.

Keywords:

Microplankton

Stratigraphy

Lower Paleozoic

Cordillera Oriental

Sierras Subandinas

Central Andean Basin

1. Introduction

Ordovician strata structurally stacked across the Cordillera Oriental and the Sierras Subandinas reach over 5000 m thick in Argentina, being part of the sedimentary fill of a large retroarc foreland basin (Sempere, 1995; Astini, 2003), within the Palaeozoic Central Andean Basin, along the Proto-Andean margin of South America (Figs. 1, 2). This foreland basin extended between Argentina (~27° S) and Peru (~10° S), and despite Andean shortening portrays the complete foreland depozones system (De Celles and Giles 1996; Astini 2003). From west to east it includes (Fig. 3): (*i*) a volcanically fed interarc-foredeep depozone, (*ii*) a forebulge region, and (*iii*) a backbulge depozone extending as far as the Paraná Basin (reaching Paraguay and Brazil). This basin framework was strongly dynamic along the Ordovician as a response to variable subduction and related mantle flow activity, associated to the former accretionary margin (Bahlburg, 1991; Bahlburg and Furlong, 1991; Astini et al., 1995; Zimmermann and Bahlburg, 2003; Astini and Dávila 2004; Ramos, 2008, 2018a, b). For this reason, phases of contrasted accommodation, that is, deepening and narrowing as well as widening and shallowing as a result of loading and relaxation (Jordan and Flemings, 1991), had locally occurred, largely contemporaneous with global sea-level fluctuation. Chitinozoan associations from the Tremadocian, Floian, Dapingian, Katian and Hirnantian, calibrated with well-known fossil groups in the basin, such as graptolites, conodonts and trilobites (Fig. 4), allow testing global *vs*. local controls in accommodation. Our revised chitinozoan biostratigraphy along and across-strike allows to pinpoint some of the most characteristic events that affected the basin fill, and permits comparisons with other peri-Gondwanan records. A complete Ordovician section from the Caspalá and Santa Ana area is presented.

2. Geological setting

2.1. Regional context

The Central Andean Basin is one of the main lower Palaeozoic basins of South America, developed in parts of Argentina, Bolivia, Peru and Chile, recording a protracted combined detrital and partly volcaniclastic record and a well-documented fossil record (Benedetto, 2003). In Argentina, these deposits are exposed in the geological regions of Puna, Cordillera Oriental, Sierras Subandinas and Sierras de Santa Bárbara, and to the east it extends under the Chaco Plain into Paraguay and Brazil, where it is connected with the Paraná Basin (Fig. 1). These regions are the result of the development of north-south trending Andean fold and thrust belt, with an estimated west-east shortening of 600 km (DeCelles et al., 2011).

The geological cross-section across the Cordillera Oriental, such as the Humahuaca-Sierra de Zenta-Santa Ana localities (Fig. 1), constitutes one of the most important and continuous in Argentina. In this region, various Palaeozoic unconformities have been defined (Tilcárica, Irúyica, Oclóyica, Chánica, and others) and, later, extended to other subandean regions based on stratigraphic and tectonic criteria (Sempere, 1995; Starck, 1995). From a sequence stratigraphic viewpoint, the Cajas, Cardonal, Incamayo, Acoite, Los Colorados, Capillas and Ocloya supersequences have been recognized within the Ordovician of northwestern Argentina (Astini, 2003, 2008; Fig. 4).

2.2. Stratigraphic and biostratigraphic framework

Ordovician sedimentary strata within the distal foredeep, forebulge and backbulge locations in the Cordillera Oriental and the Sierras Subandinas (Fig. 3(B, C)) are largely siliciclastic, with few interbedded partly carbonate layers, and include dark gray and black shales with thin-bedded rhythmic intervals as well as greenish thickening upward sandier intervals that shallow-up into littoral and shallow-marine packages. Either yellowish cross-bedded amalgamated sandstones or purple to reddish fluvio-estuarine deposits frequently cap shallowing upward successions and greenish thoroughly bioturbated transgressive packages are also recorded. A regional, and basin-wide Hirnantian glacial record (Fig. 5(B-G)), overlays the Ordovician strata, showing partly reworked intervals and unconformities that partly truncate Middle Ordovician deposits (Buggisch and Astini, 1993; Astini, 2003, 2008; Benedetto et al., 2015) at intrabasinal highs that allow ice anchoring close to sea level and deposition of thin-bedded and massive diamictites with striated pebbles and boulders (Figs. 6, 7).

Although the glacial unconformity clearly shows an erosional component and development of striated pavements, it rarely shows angularity with the exception of what occurs in the hinterland (western Puna), where the Lower Ordovician units have been strongly folded before the glacial wasting stage (Fig. 5(A)).

Good exposure through the Cordillera Oriental allows studying field relationships with the overlying Lipeón Fm. (Turner, 1960), which overlaps in a sharp boundary the glacial beds (Fig. 5(B-G)). Onlapping of pervasively bioturbated thin-bedded fine-grained, mica-rich, silty sandstones, of proven shallow-marine environments relate to a postglacial transgression episode (Astini and Marengo, 2006). This early Silurian unit yields thin lenses of quartz pebble conglomerates in its base but sometimes directly overlaps, in a sharp and flat boundary, the glacial interval or the underlying Ordovician strata (Fig. 5(D, E)). It also contains relatively tabular thick beds of iron-rich ooids (Fig. 5(B, C, E-G)) that have been mined in the Sierras Subandinas and help interpreting development of early-stage estuaries related to the important transgression that regionally initiates the oil-bearing Cinco Picachos Supersequence (Astini, 1992; Starck, 1995). In the Sierras de Santa Bárbara, the Silurian deposits – equivalent to the Lipeón Fm. – are included within the Cachipunco Fm. (Hagerman, 1933; Fig. 5(G)).

According to Astini (2003, 2008), major transgressive-regressive intervals interpreted as Ordovician supersequences correspond to the second and third order (*sensu* Vail, 1977), whereas the younger sequences, and particularly, the Late Ordovician Ocloya Sequence was interpreted as a lower-hierarchy higher-amplitude glacially-related sea-level fluctuation (Fig. 4). The Acoite and Los Colorados supersequences are well represented in the central part of the basin, and their limits can be correlated in a wide part of the region (Astini, 2003; Vaucher et al., 2020). Intervening main unconformities indicate remarkable relative sea-level fall, truncation and overlying transgressive systems tracts, including estuarine settings developed in incisive valleys (Mángano et al., 2021). Thus some of the unconformities involve longer hiatus, favoring the development of retrograding and prograding sedimentary systems. In the Ocloya Sequence, a profound eustatic control and rapid facies variation precludes the development and preservation of complete systems tracts, increasing boundary sharpness. The Capillas Sequence probably spans less than 10 myr. The flooding surface that splits estuarine transgressive systems tracts and high-stand systems tracts is remarkable because it onlaps directly on interfluves (Astini and Marengo, 2006). During the Capillas Sequence maximum transgression is reached, and the maximum flooding surface constitutes another excellent correlation horizon between the central and eastern part of the basin.

The continued development of deltaic settings, which from the late Early Ordovician to the middle Late Ordovician (Fig. 3(B)) provided material from the cratonic Gondwanan region into the backbulge and to the foredeep toward the west, allow understanding the origin of the thick sedimentary pile that accumulated in the eastern and central parts of the basin (Figs. 3(B), 5). The relatively rapid sea level rise and low subsidence rates within the eastern side induced progradation of the deltaic systems and systematic backward changes toward estuarine systems (Boyd et al., 1992), during short time intervals.

In order to better characterize different depozones across the basin, key geological localities are stratigraphically and biostratigraphically described from the western to the eastern parts.

2.2.1. Western Cordillera Oriental: Los Colorados and Chamarra area

The Los Colorados and Chamarra localities, placed along the western part of the Cordillera Oriental (Fig. 1), are palinspastically restored within the distal foredeep belt (Fig. 3(B, C)). The upper section of the Acoite Fm. (Harrington and Leanza, 1957; Turner, 1960), together with the Alto del Cóndor and the Sepulturas Fm. (Astini et al., 2004), and the Late Ordovician Zapla Fm. (Schlagintweit, 1943), are erosively leveled by the Silurian Lipeón Fm.

underlying a thick red bedded Mesozoic succession (Astini et al., 2004; Herrera Sánchez et al., 2021).

The upper part of the Acoite Fm. is represented by a progressively more greenish shaly section with gradually increasing interbedded sandstone layers. It records the middle Floian *Baltograptus* cf. *deflexus* Zone, and dominant trilobites, including the *Famatinolithus* Fauna widespread in offshore transition-shoreface settings across the basin and better developed and more diverse in western localities than in eastern ones (Santa Victoria area), and less common brachiopods, bivalves, gastropods and crinoids (Waisfeld and Astini, 2003; Waisfeld et al., 2003; Astini et al., 2004). Chitinozoans poorly preserved from this zone include *Conochitina* sp. cf. *poumoti* Combaz and Péniguel, 1972, *Conochitina brevis* Taugourdeau and de Jekhowsky, 1960, *Clavachitina langei* (Combaz and Péniguel, 1972), *Conochitina decipiens* Taugourdeau and de Jekhowsky, 1960, and *Conochitina* sp. cf. C. sp. A of Playford and Miller, 1988 (de la Puente, 2009; de la Puente and Rubinstein, 2013a). The uppermost part of the Acoite Fm. is composed of thick (2300 m) yellowish, dominantly laminated sandstone constituting shallowing upward repetitions that record the late Floian *Didymograptellus bifidus* Zone (Toro, 1997, 1999), and, in addition, the *Baltoniodus* cf. *triangularis* Zone in the close-by Chamarra Creek (Carlorosi and Heredia, 2013). In the Chamarra Creek, associated to these biozones, the chitinozoan association contains *Conochitina* sp. cf. C. sp. A of Playford and Miller, 1988, *Conochitina decipiens* and *Eremochitina baculata brevis*? of Paris (1981) (Fig. 4). Individual cycles start with laminated shale and bioturbated interbedded siltstone (sandstones) deposited in offshore transition environments well below the influence of waves and capped by storm beds amalgamated toward the top, representing shoreface deposits with common *Cruziana* records. The upper sandstone-rich section was interpreted as part of a wave and storm dominated prograding deltaic complex, sourced to the east (Astini and Waisfeld, 1993).

The Alto del Cóndor Fm. is composed of thick-grained red and mottled sandstones, with interbedded purple and reddish silty shale layers (*sensu* Astini et al., 2004). These purple-red intervals are the result of a relative long period of subaerial exposure with notable water table seasonal fluctuations linked to sea-level withdraw, which favored redox conditions for iron state changes generating mottling and marmorization. Tidal outlets and subaerial exposure are documented by truncations and lenticular asymmetric sand bodies with sigmoidal cross-bedding, systematic reactivation surfaces, heterolithic rhythmites and countercurrent ripples, indicating pervasive tidal influence. Some shaly intervals show pervasive bioturbation, whereas *Cruziana rugosa* and *Skolithos* dominate in sandstone beds (Astini et al., 2004; Mángano et al., 2021). The unit records the *Ogyginus* assemblage (Waisfeld and Vaccari, 2003, 2008) and the *Baltoniodus triangularis* Zone, which restricts its age to the early Dapingian (Carlorosi, 2013; Fig. 4). A stressed estuarine palaeoenvironment is suggested because of the low diversity of fauna and trace fossils (Mángano et al., 2021). It is interpreted as a relictic unit during a basinwide sea-level fall, partly representing bypass and early transgressive systems tract. The reduced subsidence close to the peripheral bulge region accommodation fluvial and tidal systems and allowed regional erosive incision (Astini, 2003; Mángano et al., 2021).

The Sepulturas Fm. is composed of shale and green siltstones with gradually interbedded gray bioclastic tabular limestones overlying a 0.5 m thick sandy interval with glauconite and nodular phosphates. Laminated thin sandstones and progressive bioturbation is recorded toward the top. It records the *Hoekaspis schlagintweiti* trilobite Zone (Fig. 4), and contains brachiopods and gastropods. The limestones have diverse fossil remains, conodonts and *Sacabambaspis janvieri* in the upper levels (Albanesi and Astini, 2002). The unit is interpreted largely as an inner platform succession with condensation represented by the conodont-rich limestone beds. While the base indicates a sharp transgressive surface the upper, more bioturbated sandy section indicates progradation and includes frequent storm beds with *Skolithos*. It is erosively truncated and overlain by conglomerates of the Zapla Fm. (Fig. 5(B)).

The Zapla Fm. contains striated blocks of the Sepulturas Fm., and is composed of both massive matrix-supported diamictites and thinly stratified diamictites (Fig. 5(B)) with abundant rounded quartz clasts, and white to pink lenticular quartz-arenites, affected by soft-sediment deformation. The sandstone lenses have well-developed metric trough-cross beds. Notably rounded polished and striated clasts of sandstone, siltstone, quartz, gray and green slates, and less common granite boulders are present in a fine-grained matrix. In the area, this unit reaches a variable thickness between 9 and 20 m and is sharply covered by a meter-scale iron-rich horizon located at the base of the concordantly overlying Lipeón Fm. that embraces large part of the Silurian and records a waning stage postglacial sea-level rise (Fig. 5(B)).

The Lipeón Fm. is characterized by a notable change in the source area, indicated by abundant mica, and yields a pervasive *Zoophycos* bioturbation throughout. It starts with a 0.45-1 m thick quartz-rich fine-grained conglomerate, identifying a possible ravinement surface and immediately above, shaly siltstones contain *convolutus-sedgwicki* zones of the Lower Silurian (Middle Llandovery) (Toro, 1995). This unit was deposited in an open shelf environment, with abundant available organic material. A second, 4 m thick iron-rich horizon separates it from a purplish sandy-muddy unit with remains of Siluro-Devonian trilobite fauna (Astini et al., 2004).

2.2.2. Eastern Cordillera Oriental: Caspalá-Santa Ana and Sierra de Zenta area

The Santa Ana and Caspalá localities are placed to the south of the Sierra de Zenta, along the eastern part of the Cordillera Oriental (Figs. 1, 2(A)). The chitinozoan content of sampled levels from these localities are given in Table S1 (Appendix A). The Lower Ordovician units are composed of as much as 3000 m thick largely monotonous siliciclastic successions of black shales, greenish silty shales and more rhythmical intervals, where sandy storm layers alternate with more bioturbated siltstones. This has been mapped as pertaining to the Santa Victoria Group (Turner, 1964), which comprises the Santa Rosita (Turner, 1960) and the Acoite formations (Fig. 4). They constitute a platform setting overlain sandy levels in the base, and followed by a purple-red interval, which is covered by a thick-rhythmic and thoroughly bioturbated package. The arrangement is very similar to that observed towards the east, in the Sierra de Zapla and the Sierras de Santa Bárbara areas. Thickening coarsening upward trends develop within the Acoite Fm. and have been interpreted as progradational stacks with nearshore wave- and storm-dominated environments toward the top (Astini, 2008). Few interbedded partly carbonate layers concentrate shelly fauna.

The lowest Ordovician levels record *Leptoplastides marianus*, *Asaphellus catamarcensis* and *Kainella* sp., as well as the *Acodus apex* Zone and *Araneograptus murrayi* and *Hunnegraptus copiosus* zones (Tortello and Aceñolaza, 2010; Albanesi et al., 2011; Zeballos et al., 2013; Voldman et al., 2017), which restrict the age of the exposed levels of the Santa Rosita Fm. in this area to the late Tremadocian. Levels exposed near the Santa Ana locality constitute a core of an anticline (Figs. 1, 2(A), 8). They are composed of thick (0.5-1.4 m) sandy-bars with ripples and very low lamination-angle, typical of tidal plain or estuarine environment with thin shale layers containing broken chitinozoan specimens, which not allow systematic identifications, in the base below the sandy-bar deposition, indicating erosion. Discontinuous thickness inside the bars, inarticulate remains and mica-rich levels indicate high-regime flow stages. The sequence continues with gray to black massive shaly-levels interbedded with decalcified coquinas, which contain gastropods, nautiloids (in gutters), trilobites, brachiopods, and bivalves. These levels (8658, 8657, and 8656 in Fig. 8) contain *Euconochitina paschaensis* de la Puente and Rubinstein, 2009 (Fig. 9(A, B)) and *Lagenochitina* sp. cf. *longiformis* (Obut, 1995) (Fig. 9(C)) and correlates with the late Tremadocian chitinozoan association recorded in the *Kiaerograptus*, *Araneograptus murrayi*, and *Hunnegraptus copiosus* zones from the upper part of the Saladillo Fm. and the Parcha Fm. (de la Puente and Rubinstein, 2009), which are exposed toward the south in the Cordillera Oriental (Figs. 1, 4).

The overlain thick rhythmic grayish-green to olive green part of the sequence constitute the lowest Ordovician levels exposed by a series of anticline and syncline in the Caspalá section (Figs. 1, 2(A), 8), and evidence typical tidal heterolithic facies with flaser structure at the base, stratified shaly levels and sandstone layers at the top. These levels contain a relatively abundant short form of *Eremochitina brevis* Benoît and Taugourdeau, 1961 (Fig. 9(E)), with *Belonechitina* sp. (8933 and 8935 in Fig. 8) and *Lagenochitina obeligis* Paris, 1981 (8935 in Fig. 8; Fig. 9(D)). *Diplichnites* and *Rusophycus* are common in this part of the section. The sandstone interval is characterized by interference ripples at the top of the layer as well as huge *Rusophycus* (up to 10 cm width). Coquinas with inarticulate fossils and common *Skolithos* are interbedded. At the top of these levels, purple-red intervals indicate primary subaerial exposure gradually changing from the green-heterolithic facies (Fig. 8). *Eremochitina brevis* “short form” is also common in green shaly levels above a purple-red interval associated with a broken specimen of *Lagenochitina obeligis* (8938 in Fig. 8). Upper levels in this part of the section contain few remains of chitinozoans (8939 and 8941 in Fig. 8) with probably reworked *Lagenochitina* sp. cf. *longiformis* and *Desmochitina* sp. (8939 in Fig. 8). A long form of *Eremochitina brevis* form A of Paris, 1981 (Fig. 9(F)), and *Velatachitina veligera* Poumot, 1968 characterize the middle-upper part of the rhythmic greenish sequence, with *Conochitina* spp. (8942-8944 in Fig. 8; Fig. 9(H, I)). *Lagenochitina* sp. A is recorded in only one level (8949 in Fig. 8) associated to *V. veligera* and *E. brevis* form A. This association could indicate a middle early Floian age, according to its records in the base of the *Tetragraptus akzharensis* Zone of the Santa Victoria area. Upwards in the section (8990, 8991, 8951, and 8816 in Fig. 8), the grayish-green to olive green sequence is composed of silty shales interbedded with lenticular heterolithic facies of tabular thin to medium beds of fine to medium-grained sandstones with waning flow series after sharp erosive bottoms. It contains few broken specimens with *E. brevis* in its lower part (8990 in Fig. 8), and ?*Eremochitina* sp. and ?*Laufeldochitina* sp. in an overlying layer (8991 in Fig. 8). Levels in the middle part of the Sierra de Zenta contain *Cruziana rugosa*, *Babinka* and *Thysanopyge*. According to the record of the *Baltoniodus* cf. *triangularis* Zone (Fig. 4), a Floian age is suggested for the upper levels of the Ordovician sequence in the area, and correlated with the upper part of the Acoite Fm. in the western part of the Cordillera Oriental (Voldman et al., 2013). In the Caspalá area (Figs. 1, 2(A), 5(D), 8), the uppermost level of this rhythmic grayish-green to olive green section records a clearly different chitinozoan assemblage composed of *Desmochitina* gr. *minor* Eisenack, 1958, *Belonechitina robusta* (Eisenack, 1959), *Belonechitina* gr. *micracantha* (Eisenack, 1931) and *Ancyrochitina* sp. (8816 in Fig. 8). *Belonechitina robusta* has been reported from the Sandbian and Katian, and *Belonechitina* gr. *micracantha* from the Floian to the Katian although they characterize Katian associations in Gondwana (Ghavidel-Syooki and Piri-Kangarshahi, 2021).

Throughout the Sierra de Zenta (Figs. 1, 2(A), 5(E), 8) atop of the thick Ordovician siliciclastic succession, an interval of quartz-rich arenites, corresponding to the Caspalá Fm. (Starck, 1995), variously overlying laterally discontinuous massive or thin-bedded diamictites (Astini, 2008), forms a strong escarpment within the relief. The interval yields a relatively thick-bedded coarse-grained quartz-arenite package that contrasts with the underlying Ordovician and overlying Silurian sequences. Also distinct is the fact that the underlying Ordovician succession is very rhythmic, whereas the overlying Silurian seems remarkably massive due to the pervasive bioturbation that affects it and of dark gray to brownish colour, instead of the olive green to grayish green that characterizes the underlying Ordovician section.

The quartz-rich interval that reaches 25 m maximum thickness sharply overlies a thin massive diamictite and a thoroughly deformed package of 15 m thick with ductile folds and ball and pillow structures involving the uppermost part of the underlying olive-green Ordovician section (Figs. 5(D), 8). Chitinozoans from this part of the section (Rubinstein et al., 2016) are reanalysed here. This interval with synsedimentary ductile deformation (Fig. 5(D); 8817-8820 in Fig. 8) is characterized in its basal part by *Belonechitina robusta*, probably *Rhabdochitina discriminata* Martin, 1983, and *Fungochitina spinifera* (Eisenack, 1962) (Fig. 5(D); 8817 in Fig. 8). The overlying thin interval contains, in addition to *B. robusta* and *F. spinifera*, *Belonechitina* gr. *micracantha*, and probably *Hercochitina* sp. and *Conochitina rotundata* Paris et al., 2015, with a single form doubtfully assigned to the *Armoricochitina* sp. cf. *nigerica* (Bouché, 1965) (Fig. 5(D); 8818 in Fig. 8). *B.* gr. *micracantha*, *B. robusta*, *Tanuchitina* cf. *fistulosa* (Taugourdeau and de Jekhowsky, 1960) and long *Pistillachitina comma* (Eisenack, 1959; Fig. 9(J)) are present in the upper levels (Fig. 5(D); 8819-8820 in Fig. 8). The uppermost rich-chitinozoan level (Fig. 5(D); 8820 in Fig. 8) of this section probably also contains *Belonechitina llangrannogensis* Challands et al., 2014 (Fig. 9(M)) and *F. spinifera*. *Rhabdochitina* sp. is recorded throughout the interval (Fig. 5(D); 8818-8820 in Fig. 8). As it was previously noted, this Katian chitinozoan association has been frequently observed in Northern Gondwana, mixed with Darriwilian and Sandbian associations reworked by the different pulses of the Hirnantian glaciation (Paris et al., 2015, and references therein). *Belonechitina llangrannogensis* has been described in lower to middle Hirnantian deposits (underlying *persculptus* Zone) that record the glacioeustatic regression in Avalonia (Challands et al., 2014). The presence of *Ancyrochitina* genus in an underlying level immediately below to the synsedimentary deformed package could indicate that the youngest Ordovician levels underlying glacial deposits in this area can reach the Sandbian-Katian, as it occurs in the Río Capillas, in the Sierras Subandinas (Figs. 1, 2(C)).

In the Caspalá section (Figs. 1, 2(A), 5(D), 8), the massive matrix-rich diamictite (Fig. 6(C)) has 1-2 m thick and, at the top, yields a lenticular clast-supported quartz-rich conglomerate that locally reaches 1 m thick. Pebble sizes vary from 1 to 5 cm and apart from quartz common sandstone boulders from the underlying unit are present. Trough cross beds and strata with low angle features are evident indicating their derivation from low-relief transverse bars moving within channels. Within the overlying quartz-rich interval, particularly toward the top, few fine-grained (shaly-siltstone) partitions, barren of chitinozoans, are common (Fig. 5(D); 8821 in Fig. 8). Thin layers (5-10 cm thick) partitions allow separating 6 m-scale smaller cycles (Fig. 5(D, E)) that laterally amalgamate. The few sedimentary structures that can be observed within these sandstones are planar laminations cross-cut in low angles indicating their origin related with high-regime flow stages. Because in at least two beds wave reworking was detected (symmetrical ripples) some of these structures are interpreted as hummocky- and swaley-cross-stratifications common in shallow marine settings with influence of storm activity.

The overlying Lipeón Fm. covers the previous sequence in a sharp contact and with both, marked grain-size and composition differences (Fig. 5(D, E)). The lower part of this unit contains *Cyathochitina* gr. *caputoi* Da Costa, 1971, *Conochitina* cf. *proboscifera* Eisenack, 1937, *Anthochitina* cf. *primula* Nestor, 1994, *Calpichitina* cf. *densa* (Eisenack, 1962), and *Cingulochitina* cf. *serrata* (Taugourdeau and de Jekhowsky, 1960) (Fig. 5(D); 8822 in Fig. 8), which indicate a Telychian age for this level, associated with cryptospores, trilete spores and acritarchs (Rubinstein et al., 2016). At the base, the unit shows a more massive appearance related with intense bioturbation, seldom preserved as mottling, whereas toward the top more frequent and thicker beds of graded and laminated sandstones, barren of chitinozoan (8824 in Fig. 8) are present, indicating a progradational arrangement. At the fine-scale observation, delicate lamination shows important organic material contents represented like black shale partitions. One distinct characteristic apart from the strong perturbation by bioturbation is the high content in white micas, showing unroofing of a basement source.

2.2.3. Northern Cordillera Oriental and transition to Bolivia: Mecoyita and Santa Victoria area

The Mecoyita and Santa Victoria area, located in the extreme northern part of the Cordillera Oriental in Argentina (Figs. 1, 2(B)), includes the type area of the Santa Victoria Group, with the Lower Ordovician Santa Rosita and Acoite formations. Ordovician graptolite-trilobite faunas include the record of seven graptolite zones ranging from the late Tremadocian (from the *Aorograptus victoriae* Zone) to the late Floian (*Didymograptellus bifidus* Zone), and the *Thysanopyge* and *Famatinolithus* faunas (Toro et al., 2015; Fig. 4). In the type area, along the Santa Victoria River (Figs. 1, 2(B)), the Santa Rosita Fm. comprises 2300 m thick fossil-rich dark gray shales and mudstones, and interbedded greenish sandstones. In the close by La Huerta Creek (Figs. 1, 2(B)), the upper part of the Santa Rosita Fm. contains the *Notopeltis orthometopa* Zone, of the early Tremadocian, and *Aorograptus victoriae*, *Araneograptus murrayi* and *Hunnegraptus copiosus* zones record the late Tremadocian toward the top of the unit. *Thysanopyge taurinus* is recorded in the *Araneograptus murrayi* Zone. These beds are conformably overlain by 800 m thick dark gray and greenish shales of the Acoite Fm., containing *Thysanopyge victoriensis* and the *Tetragraptus phyllograptoides* Zone of the early Floian. Toward the top, increasingly bioturbated green shales and sandstones record the upper part of the *Tetragraptus akzharensis* of the early Floian, associated in its base with *Eremochitina brevis* form A and *Velatachitina veligera*, and the *Baltograptus* cf. *B. deflexus* zones of the middle Floian, with *Eremochitina brevis* form B, *Rhabdochitina* sp. cf. *R. magna* Eisenack, 1931, and *Conochitina decipiens* in its base. A short transgressive green shale interval recording *Thysanopyge clavijoi*, together with the *Famatinolithus* Fauna, and the *Didymograptellus bifidus* Zone, associated with *Conochitina decipiens*, *Cyathochitina* sp. cf. *C. dispar* Benoît and Taugourdeau, 1961, *Lagenochitina* sp. cf. *L. esthonica* Eisenack, 1955, *Siphonochitina* sp. cf. *S. Jenkinsi* Neville, 1974, *Eremochitina baculata brevis*? Paris, 1981, *Conochitina* sp. cf. *C. pervulgata* (Umnova, 1969), *Conochitina* sp. cf. *C. poumoti*, *Conochitina* sp. cf. *C. exilis* Bockelie, 1990, *Conochitina* sp. cf. *C.* sp. A de Playford and Miller, 1988, and *Eremochitina* sp. in its upper part, indicate a late Floian age (Toro et al., 2015) (Fig. 4). In the Quebrada Grande Creek (Figs. 1, 2(B), *Eremochitina brevis* form A is associated with *Lagenochitina* sp. A (de la Puente, 2010a, b). The La Huerta Creek section also contains taxa of the *messaoudensis*-

trifidum acritarch assemblage (sub-assemblages 5), which are typical in peri-Gondwanan regions, from the upper part of the *Tetragraptus phyllograptoides* Zone to the *Didymograptellus bifidus* zones, showing longer records in this basin (de la Puente and Rubinstein, 2013a; Toro et al., 2015). In the same area, the Chulpíos Creek (Figs. 1, 2(B)), records the *Acodus triangularis* Zone and *Araneograptus murrayi* Zone, in the uppermost part of the Santa Rosita Fm. and the lowermost part of the Acoite Fm. (Voldman et al., 2017). The rest of the lower part of the Acoite Fm. record the *Tetragraptus akzharensis* Zone of the early Floian. The middle and the upper parts of the Acoite Fm. records the *Baltograptus* cf. *deflexus* Zone, and the *Gothodus vetus* and *Gothodus andinus* zones. These biostratigraphic data restrict the age of this Lower Ordovician section to the early Tremadocian-middle Floian (Voldman et al., 2017).

This interval is sharply truncated by massive diamictites of the Mecoyita Fm. (Turner, 1960), herein representing northern equivalent of the Zapla Fm. (Figs. 4, 5(B-G)). This unit develops unconformably on previous Ordovician strata, usually implying a time-range hiatus that separates it from the underlying Santa Victoria Group. The Mecoyita Fm. also correlates in southern Bolivia and Peru with the Cancañiri and San Gaván formations, respectively (Astini, 2003, 2008; Schönian and Egenhoff, 2007; Díaz-Martínez and Grahn, 2007; Benedetto et al., 2015; Fig. 10). Its thickness varies from few meters up to 46 m (Astini, 2003) crossing the international boundary with Bolivia in its type section (Turner, 1960). The Mecoyita Fm. constitutes the most complete glacially-related sequence of the studied areas here. In the Mecoyita locality, it reaches 36.70 m thick and records three glacial advancing episodes (Fig. 5). The first glacial advance, at the base of the section, is characterized by an interval of a profuse glaciotectonism (Figs. 5(C), 11(E, F), 12(C, E)), with folding, dragging and big fragments from the affected previous units (Acoite Fm.?), in a diamictite matrix (Figs. 5(C), 11(C)). Polished and striated granite clasts, within this interval, reach 0.5 m (Fig. 11(F-H)). They are the result of a thin with megaclasts meltout till deposit succeeded by a gravel-sandy fluvio glacial till. Advancing and generation of an intratill pavement of striated blocks occur on the top of this interval (Figs. 5(C), 7(A-I)). The intratill pavement is overlain by a new interval of diamictites. This is a result of a new meltout and flow till deposit. Two stages of soft sedimentary deformation and a fluvioglacial stage are present in this interval. In the upper third of the section, this occurs one more time where, on top of another intratill surface, the last glacial retreating episode is developed (Fig. 5(C)). It is represented by massive till deposit succeeded by a well-stratified series of diamictites (Figs. 5(C), 6(E, F), 12(A)), in thin and graded layers with dropstones, and with more abundance of thin interbedded dark shale layers (Figs. 5(C), 6(G-I)). These massive stratified diamictites are the product of rainout deposits at the final glacial retreating episode. Each surface with striated clasts indicates a re-advance on subaqueous meltout till deposits from a previous phase (Fig. 7). These re-advances could be related to glacial pulses between interglacial pulses or warmer stages, or represent independent glaciations. There is no a remarkable angularity in the contact between this glacial unit and the overlying Lipeón Fm. (Figs. 6(E), 12(A, D)).

The Lipeón Fm. in this section is composed of, at least, two different lithofacies. The basal lithofacies is well laminated (Figs. 5(C), 12(A, B)), while the upper one is pervasively bioturbated and the stratification completely disappears. A third lithofacies is relatively sandier, contains frequent ferruginous nodules, and develops a profuse *Zoophycos* pattern of bioturbation. This latter lithofacies could also correspond to the Devonian. As in the Río Capillas section, the Lipeón Fm. is clearly transgressive and initiates with a tabular conglomerate (Figs. 5(C), 12(D, F)). Overlying this conglomerate, a mixed succession is developed with several oolitic ferriferous levels between tidal-dominated series, probably tidal rhythmites (Figs. 5(C), 12(A, B)). The overlying interval is strongly bioturbated and evidences a major transgressive surface, locating it in a deeper position in the platform. The upper levels show a gradual advance of the coastline represented by a progressive increase of the grain size, becoming silty-sandy upwards.

2.2.4. Sierras Subandinas and Sierras de Santa Bárbara: Río Capillas area

Probably one of the most complete and continuous Middle-Upper Ordovician deposits of Argentina are those exposed in the Sierras Subandinas and Sierras de Santa Bárbara (Fig. 1). In the Río Capillas area, within the Sierra de Zapla anticline (Figs. 1, 2(C)), they reach over 500 m thick and comprise the Zanjón, Labrado, Capillas and Centinela formations (Harrington and Leanza, 1957; Monaldi et al., 1986; Figs. 4, 12(A-E)). The succession is represented by shallow-marine wave and storm dominated deltaic systems switching into estuarine environments, due to frequent relative sea-level fluctuations. Because of the dominantly nearshore to marginal marine settings that explain the scarcity of invertebrates throughout the section, trace fossils are important aids in paleoenvironmental analysis and palynomorphs are the main tool in stratigraphic studies (Astini and Marengo, 2006; Rubinstein et al., 2010, 2011; de la Puente et al., 2012; de la Puente and Rubinstein, 2013a). However, abundance, preservation and diversity vary with the stratigraphic level and the corresponding sedimentary facies. Based on detailed geometry and facies analysis, paleocurrent data, and recognition of key surfaces, four depositional sequences with different internal arrangements, and compatible with third order cycles, have been identified (Astini, 2003; Astini and Marengo, 2006).

The Zanjón Fm., the oldest Ordovician unit, outcrops in the anticline core and its base is unexposed (Figs. 1, 2(C), 13(A)). It is composed of a heterolithic facies association with subordinate storm layers, thin-bedded phosphate-rich micro-conglomerates and inarticulate-rich shell beds. Tidal flat environments are suggested for this unit according to common subaerial exposure features (truncated ripple tops and mud cracks). This interval yields a mixed *Skolithos-Cruziana* ichnofacies. The Labrado Fm. is composed of the Laja Morada and Lagunillas members (Fig. 11(B, D, E)). The Laja Morada Mb. has a transitional contact with the underlying Zanjón Fm. showing an increase in mottling and a gradual change into dominant purplish-red colours. This was interpreted as a protracted subaerial emergence during a relative sea-level drop, and a fluctuating water table in interfluves, and correlated with the Alto del Cóndor Fm. from the Los Colorados area (Fig. 1), according to sedimentological criteria (Astini and Marengo, 2006). The Zanjón Fm.-Laja Morada Mb. transition contains *Eremochitina brevis* morphotypes A and B and *Lagenochitina combazi* (Finger, 1982), suggesting an early to middle Dapingian age which is in agreement with the age assigned to the Alto del Cóndor Fm. in the Los Colorados area (Fig. 4). It is associated with cf. *Aremoricanium*, a genus common in the Middle to Upper Ordovician (Vecoli and Le Hérissé, 2004), a moderately diverse cryptospore assemblage (Rubinstein et al., 2010), and the polychaete *Andiprion paxtonae* (Hints et al., 2017). The Laja Morada Mb. shows a profuse bioturbation pattern and is covered in a sharp erosive contact by the Lagunilla Mb., as the development of composite fluvial incisions (Fig. 11(B, D, E)). Sandy fluvial to tide-dominated estuarine fills and thoroughly bioturbated subtidal heterolithic beds overlie the sequence boundary representing a transgressive system tract (Fig. 11(E)). *Glossifungites* ichnofacies surfaces, with dominant *Skolithos* forms, indicate bypass erosion and firm-ground development previous to reworking of interfluves by advancing ravinement surface (Astini and Marengo, 2006). A probably Dapingian age is interpreted for the upper Lagunillas Mb. according to palynological assemblage (Rubinstein et al., 2011).

The Capillas Fm. sharply levels the previous estuarine complexes and represents a fine-grained wedge that gradually coarsens up (Astini and Marengo, 2006). The lower part of the Capillas Fm. has been assigned to the Darriwilian, even though marker palynomorphs are absent, based on the presence of typical peri-Gondwana taxa mainly the genus *Arkonia* (Rubinstein et al., 2011). However, the global FAD of *Arkonia* is placed at the base of upper Floian (Servais et al., 2018), according to its record in South China (Yan and Li, 2005; Yan et al., 2011). It has been also recorded in the Floian of the Arabian margin of Gondwana, as well as *Cymatiogalea granulata* Vavrdová, 1966 (Ghavidel-Syooki et al., 2014) also present in the Capillas Fm. It also contains *Ericanthea pollicipes*, whose FAD is in the Dapingian (Vecoli and Le Hérissé, 2004). This unit contains the only truly marine shelly fauna concentrated in few storm beds, which contains a limited number of thin calcareous levels with bioclastic accumulations, in the lower part above the fine-grained interval that characterizes a maximum flooding stage. Shelly fauna, mostly composed of well-preserved bivalves, brachiopods, few trilobite remains and large cephalopods, contain the bivalves *Zaplaella capillaensis* Sánchez et al., 2003, *Cadomia typa* de Tromelin (Sánchez, 1986) and *Cardiolaria benicioi* Sánchez and Astini, 2011, as well as the trilobite *Huemacaspis gallinatoensis* Waisfeld and Henry, 2003. Bivalves show strong paleobiogeographic affinities with those from Gondwanan and peri-Gondwanan basins (Sánchez et al., 2003; Sánchez and Astini, 2011). In equivalent levels to the SE of this area (Santa Gertrudis Fm., in the Sierra de Mojotoro), this fauna is associated with conodonts corresponding to the upper part of the *Pygodus anserinus* and lower part of the *Amorphognathus tvaerensis* zones of the early Sandbian (Albanesi and Rao, 1996; Fig. 4). According to this record, this is the only interval that can be positively correlated, using open marine taxa, with other sections in the basin, in Argentina and Bolivia. This unit shows a shallowing-upward section evidenced by a gradual coarsening to silty sandstones and the *Skolithos* dominated ichnofacies replacing the *Cruziana* ones. In the Tutimayo Creek, few kilometres to the south of the Capillas River section, the upper part of the Capillas Fm. contains a conodont association, which not allow specific biozonal assignment. However, an age no younger than late Darriwilian for the unit, based on biostratigraphic interpretations, has been assigned (Albanesi et al., 2007).

The Centinela Fm. caps the previous layers characterized by thick-bedded, high-energy quartz sandstones with pipe-rock structures (Fig. 11(B, C)). Progradation of deltaic complexes are interpreted by the shallowing-upward trend (Astini and Marengo, 2006). This unit has been assigned tentatively to the early Katian according to the *Calymenella*? *zaplensis* Zone Harrington and Leanza, 1957 (= *Eohomalonotus*? *zaplensis sensu* Waisfeld and Vaccari, 2003, 2008) (Fig. 4).

The sequence is erosively truncated by the waxing stage of the ice-cap represented by the Zapla Fm. (Figs. 5(F), 13(F)). The unit contain microphytoplankton, including *Villosacapsula*, *Eupoikilofusa*, *Neoveryhachium*, *Polygonium*, *Micrhystridium*, and *Multiplicisphaeridium*, with reworked forms and few cryptospores (de la Puente and Rubinstein, 2013a). The detailed study of chitinozoan assemblages carried out throughout the Zapla Fm. and the lowermost Lipeón Fm. (Fig. 5(F)), in outcrops on both flanks of the Zapla Anticline (the Arroyo Los Matos section in the western flank and the Río Capillas section in the eastern flank; Figs. 1, 2), constrain the ages of these units, and contribute to the knowledge of the glacial and post-glacial depositional events.

At detail, massive diamictites contain meter-scale ball and pillows and dispersed granite and sandstone boulders that frequently reach 0.5 m (Figs. 5(F), 13(F)). This interval is overlain by thick-bedded quartz-rich sandstones, comprising an overall lenticular facies association at a kilometre scale. Thin shale partitions that laterally pinch out are seldom present between the sandy beds that individually show erosive bases, internal gradation and floating oversized pebbles (Figs. 5(F), 13(F)). To their top asymmetric ripple-lamination occurs. Thinning and thickening upwards cycles are differentiated. This sandy interval also varies its thickness and its position within the unit in separate sections.

In this area, chitinozoan assemblages from the Zapla Fm. are diverse but poorly preserved. A massive but a slightly stratified diamictite layer placed 8 m above its contact with the underlying Centinela Fm. (10123 in Fig. 5(F)) contains *Desmochitina* gr. *minor*, *Fungochitina spinifera*, *Tanuchitina* sp., *Ordochitina* sp., *Hercochitina* sp., and *Rhabdochitina* sp. Thin intervals of dark green to black shales (10014, 7590/9676/9677, 10124 in Fig. 5(F)) present between graded sandy beds above the massive glacially derived diamictite are characterized by *Desmochitina* gr. *minor*, *Desmochitina erinacea* (Fig. 9(P)), *Belonechitina robusta*, *Fungochitina spinifera*, *Ramochitina deynouxi* de la Puente et al., 2020, *Tanuchitina elongata* Bouché, 1965 (Fig. 9(K)), *Spinachitina* cf. *oulebsiri* Paris et al., 2000, *Ancyrochitina* spp. (Fig. 9(Q)), relatively abundant *Belonechitina* spp., and probably *Conochitina rotundata* and *Pistillachitina pistillifrons* Eisenack, 1939. A highly organic-rich black shale at the very top of the unit (10125, 10015/10126, 10127, and 10128 in Fig. 5(F)) registers *Desmochitina* gr. *minor*, *R. deynouxi* (Fig. 9(N)), *Tanuchitina ontariensis* Jansonius, 1964 (Fig. 9(L)), *Rhabdochitina* sp., and probably *T. elongata*, *S. oulebsiri*, *C. rotundata*, *F. spinifera*, and *Ordochitina* sp. The uppermost sample (10128 in Fig. 5(F)) from these levels (0.10 m below the contact with the overlying Lipeón Fm.) yield few broken specimens containing *R. deynouxi*, *Ancyrochitina* sp., and probably *Fungochitina* sp. *Belonechitina* spp., *Ancyrochitina* spp., and *Angochitina* spp. are common components throughout this part of the section. Although *Ancyrochitina* specimens present broken processes, and therefore it is not possible to determinate the species levels, several of them show similar shapes, sizes and ornamentation than *Ancyrochitina merga* (1.50 m below the contact with the overlying Lipeón Fm.; 10125 in Fig. 5(F)).

Indicative early Hirnantian species (e.g., *T. elongata*) and latest Hirnantian-earliest Rhuddanian species (e.g., *S. oulebsiri*, *R. deynouxi*) with common Hirnantian component (e.g., *D.* gr. *minor*) allow constraining the age of the Zapla Fm. to the late Hirnantian. The mixture of typical Katian chitinozoans (e.g., *B. robusta*, *D. erinacea*, *Ancyrochitina* cf. *merga*, *F. spinifera*, *P. Pistillifrons*, and *T. ontariensis*) with Hirnantian components indicates reworking of previous deposits associated to the glacial dynamics, as it is observed in Caspalá section and frequently in Northern Gondwana records (Paris et al., 2015). It also suggests a late Katian age for the underlying glacial deposits in the area, which is in agreement with the age of the underlying Centinela Fm.

The Lipeón Fm. begins with a 1 m thick transgressive conglomerate, which truncates the underlying unit (Figs. 5(F), 13(G)). In this area, 0.3-0.5 m of greenish silty-shales gradationally overlie the basal conglomerate of the Lipeón Fm., containing a diverse and better preserved assemblages (Fig. 5(F)). The lowest analysed level (0.2 m above the contact with the underlying conglomerate; 10016 in Fig. 5(F)) contains dominant *Cyathochitina lariensis* de la Puente et al., 2020, and less common *Cyathochitina brussai* de la Puente et al., 2020 and *Calpichitina* sp. with singles specimens of probably *Ancyrochitina* cf. *laevaensis* Nestor, 1980, and *Conochitina* sp. Ten centimetres above this level (0.3 m above the contact with the underlying conglomerate; 10017 in Fig. 5(F)), the assemblage additionally contains

Spinachitina fragilis Nestor, 1980, with abundant *Cyathochitina lariensis*, *Cyathochitina brussai*, *Ancyrochitina* sp., and *Conochitina* sp. It also contains *Ancyrochitina laevaensis*, *Calpichitina* sp., *Plectochitina* cf. *nodifera* (Nestor, 1980), *Belonechitina* cf. *postrobusta* (Nestor, 1980), and *Sphaerochitina* sp. *Spinachitina fragilis* is the index species of the Rhuddanian and indicative of the early Rhuddanian recorded in the *acuminatus* Zone in most of the northern Gondwana regions. *Ancyrochitina laevaensis* has been recorded from Baltica, Laurentia and northern Gondwana as having a range restricted to the *ascensus-acuminatus* Zone (Butcher, 2009). Detailed studies in Late Ordovician-earliest Silurian chitinozoan associations in Northern Gondwana indicate a common proliferation of *Cyathochitina* spp., as *Cyathochitina caputoi* da Costa, 1971 and related *Cyathochitina* forms with large carina, preceding the FAD of *S. fragilis* and therefore assigned to the earliest Rhuddanian (Thusu et al., 2013; Le Hérissé et al., 2013; Paris et al., 2015). According to this, the same characteristic assemblages recorded in the lowermost Lipeón Fm. allow to determinate the record of the earliest Rhuddanian in the basalmost interval (0.2 m from the base of the unit; 10016 in Fig. 5(F)), succeeded by the record of the early Rhuddanian (0.3 m from the base of the unit; 10017 in Fig. 5(F)). This succession continues with regionally and laterally continuous oolitic ironstone beds (~2.2 m, 1.2 m and 0.3 m) overlain by greenish to yellowish silty-sandy pervasively bioturbated shales. Thin finer-grained partitions between the major two lower beds (2.7 m above the contact, from the base of the unit; Figs. 5(F), 13(H)) contain in addition abundant *Spinachitina maennili* (Nestor, 1980), *Pogonochitina djalmai* (Sommer and van Boekel, 1965), *Conochitina* sp., and *Sphaerochitina silurica* Grahn et al., 2000. It also contains less common *Ancyrochitina udayanensis* Paris and Al-Hajri, 1995 and *Calpichitina* sp. Interestingly, *Cyathochitina* spp. are absent in this interval. Silty-sandy beds above the ironstone horizons (5 m above the contact) contain predominant *C. lariensis*, *C. brussai* and *Ancyrochitina* sp., with *P. djalmai*. This assemblage is considered Aeronian in age. The rest of the pervasively bioturbated silty-sandy shales (~340 m thick), exposed above and along the Los Matos Creek (Figs. 1, 2(C)), contain Telychian-Sheinwoodian chitinozoan assemblages. This part of the sequence is characterized by the development of a *Zoophycos* dominated muddy shelf (Astini, 2003; Astini and Marengo, 2006). The age for the lower part of the Lipeón Fm. largely agrees with the *acuminatus-atavus* zones recorded from this unit in the region (Rickards et al., 2002). The presence of *Talacastograptus* genus allows correlating the Lipeón Fm. with similar levels to the north, in Bolivia, and to the south, in the Precordillera region of Argentina (Benedetto et al., 2015).

Angochitina sp. 1, *Cyathochitina* sp. B, *Conochitina elongata* and *Cyathochitina* cf. *campanulaeformis* reported and interpreted as Aeronian to Telychian in age for levels assigned to the Zapla Fm. (Grahn and Gutiérrez, 2001) probably belong, instead, to Lipeón Fm. levels.

In the Arroyo Pedregoso Creek, in the southern part of the Sierras de Santa Bárbara, ca. 40 km to the east of the Río Capillas area (Figs. 1, 2(C)), the glacially-related Zapla Fm. contains *in situ* in its uppermost part the widespread latest Ordovician *Hirnantia-Dalmanitina* Fauna (*Normalograptus persculptus* Zone), which include the trilobite *Dalmanitina subandina* (Benedetto et al., 2015; Figs. 4, 5(G)). The low diversity of this assemblage in the Zapla Fm. is interpreted as related to slightly dysoxic bottom conditions, episodic input of coarse sediments, and/or salinity fluctuations (Benedetto et al., 2015). A recent global review on marine benthic organisms across the Ordovician and Silurian transition recognizes this fauna as related to the postglacial middle Hirnantian (Transitional Benthic Faunas–TBF 2 of Wang et al., 2019). On the other hand, a revision on the *Hirnantia* Fauna established it as a widespread and diachronous assemblage related to the glacial acme in the early−mid

Hirnantian associated to a global low stand, which is replaced in the postglacial stage by the Edgewood-Cathay Fauna (Rong et al., 2020). In this area, the equivalent Cachipunco Fm. records, from the middle part of the section to the upper part of the unit, chitinozoans assemblages interpreted as late Telychian to early Pridoli in age (Grahn and Gutiérrez, 2001).

In the subsurface, toward the east of the Central Andean Basin, the Ramos Fm. (Fernandez Garrasino, 1980; Fig. 10) with a minimum thickness of 560 m has been defined and described based on cuttings. It has been correlated with the Ordovician units exposed in the Sierra de Zapla according to its stratigraphic position directly underlying the Zapla Fm. because no fossils have been recovered. Cutting descriptions allow gross correlation with the exposed Ordovician stratigraphy, and gamma-ray logs evidence the characteristic alternating sandstone packages and shales successions. The importance of this unit resides on its hydrocarbon content, being an interesting target in subsurface and taken to be extended toward the Chaco Plain (Astini, 2003).

2.3. The Ocloyic record in neighbor basins

2.3.1. Chacoparanaense Basin (subsurface)

In the subsurface of the Chaco Plain in Argentina, Palaeozoic deposits of the Chacoparanaense Basin are connected with the Central Andean Basin to the west (Fig. 1) and the Paraná Basin to the east. In the northern part, this basin records the Cambrian-Ordovician Las Breñas depocentre (Pezzi and Mozetic, 1989), a NE-SW trend hemigraben. Cambrian-Ordovician deposits have been correlated with equivalent levels of the Central Andean Basin, based on lithological criteria (Russo et al., 1979, 1986). Ordovician marine sequences composed of quartz-rich medium to thick grained sandstone are included in the upper part of the Las Breñas Fm. (Las Breñas 1 YPF well, Chaco Province; Fernández Garrasino et al., 2005; Fig. 10). A 71 m thick diamictite package, interpreted as a possibly glacial, glacimarine or gravity flows in deep deposition origin, has been reached (Árbol Blanco 1 YPF well, Santiago del Estero Province). It is overlain by 398 m thick marine dark shales of the Copo Fm. (El Caburé 1 YPF well, Santiago del Estero Province), which has been correlated with the Vargas Peña Fm. of eastern Paraguay and Vila Maria Fm. of Brazil based on Silurian microfossils reported in its lower part (Fig. 10). According to this age, the diamictites have been correlated with the Hirnantian Zapla Fm. of the Central Andean Basin, and its basal contact interpreted as the record of the Ocloyic unconformity (Russo et al., 1979, 1986; Fernández Garrasino et al., 2005; Fig. 10). The upper part of the Copo Fm. records lower Devonian trilobites and brachiopods (Chebli et al., 1999). The lower Palaeozoic deposits of the Chacoparanaense Basin reach over 700 m thick and constitute a probably continue westward-thickening wedge depocentre extended from the eastern part of the Sierras Subandinas and Sierras de Santa Bárbara to ca. 400 km to the east in the subsurface of the Chaco Plain (Chebli et al., 1999).

2.3.2. Paraná Basin

The Paraná Basin is a wide region with a N-S trend and ca. 1,500,000 km^2 in extension, developed mainly in southern to central Brazil, eastern Paraguay, northern Uruguay, and northeastern Argentina. Its western border superposes with the Present-day wide flexural bulge linked to the Andean Orogeny (Horton and DeCelles, 1997; Ussami et al., 1999). It continues to the south toward Uruguay and Argentina (Milani et al., 2007). Although it is an intracratonic basin, its tectono-stratigraphic evolution has been related to active collisional orogenies and associated foreland depozones developed along the southwestern margin of Gondwana during the Phanerozoic (Ramos et al., 1996). The orogenic episodes are related to the generation of the depositional space in the cratonic area with an important subsidence related to the tectonic overload due to the lithospheric flexure (Milani, 1997; Milani et al., 2007). The oldest records in the basin include the Ordovician-Silurian Rio Itaví Supersequence (*sensu* Vail, 1977), which represents a sedimentary succession that records the first transgressive-regressive cycle linked to relative sea level fluctuations in the basin (Milani, 1997). The Upper Ordovician-Silurian deposits are included in the Rio Ivaí Group composed of the Alto Garças, Iapó and Vila Maria formations (Assine et al., 1994; Fig. 10).

The Alto Garças Fm. is composed of a 300 m thick, mostly sandy to conglomeradic sandstone package characterized by *Skolithos*, with a basal quartz-rich conglomerate and finer-grain clastics towards the top. The detrital source of the basal fluvial sediments points to the SW. The Iapó Fm. is composed of glaciogenic diamictites with silty-sandy matrix and diverse clasts, shale with dropstones and siltstone lenses. This widespread unit in the basin of ca. 60 m thick is recognised in outcrops and subsurface as a regional correlation horizon. Its lower contact is sharp indicating a discontinuity in the sedimentation of the basin. The Vila Maria Fm. overlaps the diamictites and it is characterised by fossil and organic matter-rich micaceous and ferruginous marine black shale in a coarsening upwards setting, with an eventual aerial exposure. The transitional contact between these units is a 0.5 m thick pebbly shale layer with dropstones that become scarcer toward the fossiliferous shale. It has been considered to interpret the basal shaly part of the Vila Maria Fm. as a periglacial marine environment from mid to outer continental shelf (Assine et al., 1998; Adorno et al., 2016). According to the fossil record of the Vila Maria Fm. and the correlative Vargas Peña Fm. in Paraguay (Fig. 10), based mainly on graptolites, chitinozoans and cryptospores, as well as a Rb-Sr dating, which indicates a 435.9 ± 7.8 Ma age (Mizusaki et al., 2002), it is considered as lower Silurian (Llandovery) in age (Milani et al., 2007). New data based on first records of Hirnantian ostracods from the uppermost part of the Iapó Fm. and the basal part of the Vila Maria Fm. constrain the ages around the limits of the units (Fig. 10). A Hirnantian age is in agreement with Rhuddanian palynological data, including chitinozoans, reported from above the lower levels of the Vila Maria Fm. (Gonçalves et al., 2022). The Hirnantian-Rhuddanian interval is inferred in the lower portion of the basal shales of the Vila Maria Fm. according to the record of *Spinachitina* cf. *S. oulebsiri, Spinachitina* cf. *S. verniersi* Vandenbroucke et al., 2009 and *Plectochitina* cf. *P. longispina* (Achab, 1978). The Hirnantian-Rhuddanian boundary is assigned according to the presence of *Spinachitina debbajae*, and the base of the Aeronian to the records of *Sphaerochitina silurica* and *Sphaerochitina* sp. A (Rodrigues et al., 2021).

This dominant marine sedimentation represents the transgressive event from the base of the Rio Ivaí Group to the shaly levels of the Vila Maria Fm., which indicate the maximum flooding of the cycle. The regression event is represented from the shaly levels to the top of the unit (Milani, 1997; Milani et al., 2007). Local maximum flooding levels developed in second order transgressive cycles, as that during the early Silurian, defining the particular subsidence history of this interior basin as an intraplate response to geodynamic processes affecting the southwestern Gondwanan margin (Assine, 1996; Milani and Ramos, 1998). Subsidence and sediment accumulation in the Paraná Basin started during Middle to Late Ordovician times and it has been related to the Cuyania (Precordillera) terrane collision against the pre-Andean margin of Gondwana, which has produced the different contractional phases of the Ocloyic Orogeny in Argentina (Ramos et al., 1986; Astini et al., 1995; Assine, 1996). The intraplate response to the compressional stress related to this orogenic cycle was interpreted as a transtensional reactivation of NE-SW trend weakness zones through Paraguay to the Eastern Pampean Orogen in Argentina, providing the initial subsidence for the basin (Milani and Ramos, 1998). According to the wedge-like geometry of the Ordovician-Silurian, a wide continental open shelf to an ocean situated to the SW has been inferred. The Paraná Basin was located in a stable area inside the continent, far away from the major depositional centres, accumulating a thin Ordovician-Silurian package (Milani et al., 1995).

The sequence is distributed over almost the entire Paraná Basin, with a general geometry of a westward-thickening wedge, in eastern Paraguay (western margin of the Paraná Basin), where it is correlated with the 1000 m thick Caacupé (Harrington, 1950) and Itacurubí (Harrington, 1972) groups (Fig. 10), representing the connection with the Central Andean Basin (Milani et al., 1995; Milani and Ramos, 1998; Benedetto et al., 2015). Some local depocentres exist probably related to extensional stress during the inception of the basin (Milani et al., 1995; Milani and Ramos, 1998). The inferred Ordovician deposits of the Caacupé Group are composed of probably estuarine or fluviodeltaic conglomerates and massive to cross-stratified yellowish feldspathic sandstones. It is conformably overlain by the Itacuribí Group, which is composed of the Eusebio Ayala, Vargas Peña and Cariy formations (Harrington, 1972; Fig. 10). The Eusebio Ayala Fm. (Fig. 10) is a 200 m thick deposit characterized by reddish micaceous sandstone grading to fine-grained fossiliferous sandstone and siltstone (Benedetto et al., 2013). Abundant *Skolithos* suggest lower intertidal-shallow subtidal depositional settings. The upper part of the unit contains interbedded iron-rich levels and records the *Normalograptus persculptus* Zone indicating a Hirnantian age for these layers (Alfaro et al., 2012), which is in agreement with the *Arenorthis* component of the associated *Hirnantia* Fauna (Benedetto et al., 2013). The *Hirnantian* Fauna includes a common component with the Salar del Rincón Fm. in Argentina (Benedetto et al., 2013), which is assigned to the latest Hirnantian-lowermost Ruddanian based on chitinozoan assemblages (de la Puente et al., 2020). Glacial deposits probably older than this unit are recorded in the subsurface of the basin (Benedetto et al., 2013). The Eusebio Ayala and Vargas Peña formations (Fig. 10) record the transition from shoreface to platform deposits. The Vargas Peña Fm. is characterized by pale-gray fossiliferous claystones, which are interpreted as representing the maximum flooding. The Cariy Fm. (Fig. 10) consists of sparsely fossiliferous massive to cross-bedded quartz and feldspathic sandstone interpreted as a shoreline progradation (Benedetto et al., 2013). The lower part of the Vargas Peña Fm. has been assigned to the late Rhuddanian according to chitinozoan (Grahn et al., 2000) and graptolite (Tortello et al., 2008) records. The middle part of this formation has been considered as Aeronian and its uppermost part as early Telychian (Grahn et al., 2000) or late Aeronian-early Telychian (*sedwickii-turriculatus* zones) in age (Uriz et al., 2008; Fig. 10).

2.3.3. Precordillera Region

In the Precordillera region of western Argentina, the Middle to Late Ordovician Ocloyic Orogeny is related to the collision of the Cuyania (Precordillera) microplate with the western Gondwanan margin (Ramos et al., 1986; Astini et al., 1995). In the eastern Precordillera, the west-directed Ocloyic thrusting was coeval with the deposition of the Las Vacas Conglomerate (Thomas and Astini, 2007). The Las Vacas Fm. (Fig. 10), from Los Piojos Creek, records in its Basal Mb. late Darriwilian *Lagenochitina* sp. cf. *L. baltica*

Eisenack 1931 and *Lagenochitina* spp. The Lower Mb., the overlying Las Plantas Mb. and the lower part of the Upper Mb. register the Sandbian *gracilis-bicornis* zones. The uppermost part of the Upper Mb. records a Katian association composed of *Kalochitina multispinata* Jansonius 1964, *Cyathochitina* sp. cf. *C. kuckersiana* (Eisenack 1934), *Spinachitina bulmani* (Jansonius 1964), *Desmochitina minor* form *typica*, *Belonechitina* sp., and *Cyathochitina* sp. aff. *C. macastyensis* Achab, 1978 (de la Puente and Rubinstein, 2013b).

The La Pola Fm. (Astini, 2001; Fig. 10) has been defined as an erosive relict of the Hirnantian glaciation in the easternmost part of the Precordillera. It is composed of a succession of thick-bedded coarse-grained debris flows with interbedded pebbly mudstone, quartz-bioclastic-rich sandstone, and few turbidites and silty shale. It was deposited in a proximal deep-marine through with directed toward the W-NW palaeocurrents (Astini, 2001). Its age is assigned to the Sandbian according to the *Baltoniodus variabilis* subzone (Heredia and Milana, 2010). It is succeded by the Don Braulio Fm. (Fig. 10) characterized by a Hirnantian glacial diamictite, which ends with dark gray bioturbated mudstones, interbedded fine sandstone and thin sharp-based oolitic ironstones (Astini, 1992). The Don Braulio Fm. records three separate ice advances and a striated pavement that indicates an ESE to NWN transport direction (Astini, 1999).

The ironstones contain Rhuddanian graptolites, chitinozoans and acritarchs (Volkheimer et al., 1980; Peralta, 1985; Pothe de Baldis, 1997). The La Chilca Fm. (Fig. 10) registers bioturbated mudstones, in addition to *Hirnantia* Fauna, ferruginous layers and Rhuddanian graptolites, including *Talacastograptus* in the basal part also present in the Lipeón Fm. of the Sierras de Santa Bárbara and Sierras Subandinas in Argentina (Fig. 1) and Bolivia (Astini and Benedetto, 1992; Benedetto et al., 2015). In the Precordillera region, the flooding surface is considered slightly diachronous ranging from the late Hirnantian (*persculptus* Zone) to the early Rhuddanian (*acuminatus-atavus* zones) (Cuerda et al., 1988; Rickards et al., 1996; Benedetto et al., 2015). It has been attributed to the complex topography inherited from the collision of the Cuyania (Precordillera) terrane against the Gondwanan margin (Astini et al., 1995; Benedetto, 2004).

3. Chitinozoan biostratigraphy

A biostratigraphic analysis of chitinozoan records from the Central Andean Basin in Argentina, calibrated with updated biostratigraphic data based on key fossil groups is synthesized in Fig. 3.

The lowest Ordovician chitinozoan association is recorded in the eastern (Caspalá-Santa Ana area) and central (Pascha-Incamayo) part of the Cordillera Oriental (Fig. 1). It is included in the *Euconochitina paschaensis* Assemblage (Fig. 4) composed of *Euconochitina paschaensis* and *Lagenochitina* sp. cf. *longiformis*. It is registered in the late upper Tremadocian associated with the *Kiaerograptus supremus*, *Araneograptus murrayi* and *Hunnegraptus copiosus* zones, and the *Acodus apex* Zone. *Euconochitina paschaensis* has recently been considered as a synonym of *Euconochitina symmetrica* and *Euconochitina fenxiangensis* (Achab and Maletz, 2021). However, its local denomination is maintained here according to the restricted age of *Euconochitina paschaensis* to the late upper Tremadocian having no records in younger deposits.

Eremochitina brevis is a common component in the late Floian of Gondwana although its records reach the Darriwilian (Paris, 1981). *Eremochitina brevis* have been also reported in the *Oeplkodus evae* Zone (late Floian) of the Suri Fm. from the Famatina region (Achab et al., 2006), to the south of the Central Andean Basin in Argentina (Fig. 1). In the studied deposits of the Cordillera Oriental (western, eastern and northern part), different forms of *Eremochitina brevis* are represented. *Eremochitina brevis* form A de Paris, 1981, was observed in older (Arenig) Armorican (France and Portugal) specimens with a tubular and narrow copula which clearly separate from the chamber (Paris, 1981). *Eremochitina brevis* form B of Paris, 1981, was observed in younger (Arenigian to basal Llanvirn) Armorican specimens with a wider and longer copula, which progressively separate from the bottom of the chamber (Paris, 1981). *Eremochitina baculata brevis*? of Paris, 1981 has been described in the middle Arenig of the Pissot Fm. in France. This short form has an ovoid chamber with a truncated oral end and a wide and rounded margin. The flexure and neck are not developed. According to the copula, which is described as shorter, narrow and separate from the base of the chamber, it is interpreted as a last evolutionary stage of *Eremochitina baculata* and a close form to *Velatachitina* genus.

In the Santa Victoria and Los Colorados areas (Figs. 1, 2(B)), *Eremochitina* related forms are calibrated with Floian graptolite and conodont zones. *Eremochitina brevis* form A Assemblage (Fig. 4) includes *Eremochitina brevis* form A, which is commonly associated with *Velatachitina veligera* and *Lagenochitina* sp. A, and is reported in the middle early Floian (the base of the *Tetragraptus akzharensis* Zone); *Eremochitina brevis* form B Assemblage (Fig. 4) is characterized by *Eremochitina brevis* form B, which is recorded in the early middle Floain (the base of the *Baltograptus* cf. *deflexus* Zone), associated with *Rhabdochitina* sp. cf. *R. magna* and *Conochitina decipiens* in the eastern part of the Cordillera Oriental (Santa Victoria area) (Figs. 1, 2(B)); while the *Clavachitina langei* and *Conochitina brevis* Assemblage, containing *V. veligera*, *C. decipiens*, *Conochitina* sp. cf. *C. poumoti* and *Conochitina* sp. cf. *Conochitina* sp. A of Playford and Miller, 1988, characterizes the late middle Floian (the upper part of the *Baltograptus* cf. *deflexus* Zone) in the western part of the Cordillera Oriental (Los Colorados area; Fig. 1). *Eremochitina baculata brevis*? Assemblage (Fig. 4) contains *Eremochitina baculata brevis*? in the late Floain (*Didymograptus bifidus* Zone and *Baltoniodus* cf. *triangularis* Zone), associated with *Eremochitina* sp., *Thysanopyge clavijoi* and *Famatinolithus* Fauna in the eastern part of the Cordillera Oriental, and with *Conochitina decipiens* and *Conochitina* sp. cf. C. sp. A of Playford and Miller, 1988, in its western part. In the Caspalá-Santa Ana area (Figs. 1, 2(A)), only *Eremochitina brevis* form A is recorded although a “short form” in lower levels, and a “long form” in upper levels are distinguished. A Floian age for these levels is supported by the record of the *Baltoniodus* cf. *triangularis* Zone in the upper levels of the Ordovician sequence in the Sierra de Zenta area (Figs. 1, 2(A)). In the eastern part of the basin, in the Río Capillas area from the Sierras Subandinas (Figs. 1, 2(C)), however, *E. brevis* forms A and B are associated. Additional detailed studies are needed to better understand the distribution of different forms of *E. brevis* and its potential stratigraphic usefulness.

Middle Ordovician deposits are less known regarding their characteristic low fossil content related to restricted estuarine facies and low stand system stage (Mángano et al., 2021). A single chitinozoan report is from the transition between the Zanjón Fm. and the Laja Morada Mb. of the Labrado Fm. in the Río Capillas area (Figs. 1, 2(C)). This interval was related to a Darriwilian relative sea-level drop according to sedimentological criteria and previous biostratigraphic data from equivalents levels of the Alto del Cóndor Fm. in the Los Colorados area (Fig. 1). The presence of *Lagenochitina combazi*, indicative of the

Lagenochitina combazi Assemblage (Fig. 4), in the Zanjón Fm.-Laja Morada Mb. transition suggests an early to middle Dapingian age in agreement with the early Dapingian *Baltoniodus triangularis* Zone recorded in the Alto del Cóndor Fm.

In the eastern part of the basin (Caspalá-Santa Ana area; Figs. 1, 2(A)), chitinozoan associations from the Lower Mb. of the Caspalá Fm., preliminarily proposed here, allow constraining the age of the uppermost level of the characteristic rhythmic grayish-green to olive green Ordovician sequence in the area to the Sandbian-Katian, according to the presence of *Belonechitina robusta* and *Ancyrochitina* sp., associated with *Desmochitina* gr. *minor* and *Belonechitina* gr. *micracantha*. *Desmochitina* gr. *minor* is reported from the Floian to the Hirnantian but it is a common component in the Katian and glacial Hirnantian deposits of northern Gondwana regions, which record the Ordovician/Silurian boundary (Paris et al., 2012). *Ancyrochitina* genus appears in the Upper Ordovician (Paris et al., 1999). They constitute the *Belonechitina robusta* Assemblage (Fig. 4) according to Northern and peri-Gondwanan chitinozoan zones. Older chitinozoans with a common late Katian association, as *Belonechitina* gr. *micracantha*, *Belonechitina robusta*, *Fungochitina spinifera*, *Tanuchitina* cf. *fistulosa*, and *Pistillachitina comma*, and Hirnantian species, as *Belonechitina llangrannogensis* (Challands et al., 2014; Fig. 9(M)) from the overlying thoroughly synsedimentary deformed package (Figs. 5(D), 8), have been interpreted as reworked deposits originated by glacial dynamic, as it is observed in Northern Gondwana (Paris et al., 2015). Therefore, the youngest deposits underlying the glacial processes in the area are restricted to the late Katian (Figs. 5(D), 8). Similar results are provided by chitinozoan assemblages from the Zapla Fm. in the easternmost studied part of the basin (Figs. 1, 2(C)). Relatively more diverse chitinozoan associations recovered throughout the glacially related unit include, in addition to the Caspalá area records, key stratigraphic species such as *Tanuchitina elongata*, *Spinachitina* cf. *oulebsiri*, *Ramochitina deynouxi*, *Conochitina rotundata*, *Tanuchitina ontariensis*, and *Ordochitina* sp., restricting the age of the glacial deposits to the Hirnantian (Figs. 5(F), 9(K, L, N)). A glacial waning stage is represented by highly organic-rich black shale with sparse dropstones at the top of the Zapla Fm. in this area (Figs. 1, 2(C)), which contains typical latest Hirnantian component in other regions of Gondwana, as *Spinachitina oulebsiri* associated with Ordovician species as *Desmochitina* gr. *minor* (Figs. 5(F), 9(O)).

The studied chitinozoan assemblages corroborate a Hirnantian age for the complete Zapla Fm. up to its very top, including an interval immediately above the glacially derived diamictites (Fig. 5(F)). Genera as *Rhabdochitina*, *Hercochitina*, *Pistillachitina*, and *Ordochitina* are characteristic of the Ordovician. *Ancyrochitina*, *Angochitina*, and *Fungochitina* are reported from the Upper Ordovician. *Spinachitina oulebsiri* is a common component in the latest Hirnantian-earliest Rhuddanian postglacial stage of Gondwana. It is associated to *Ramochitina deynouxi* in the latest Hirnantian-earliest Rhuddanian of the middle to upper part of the Upper Mb. of the Salar del Rincón Fm. in Puna, with common *Cyathochitina* spp. and *Spinachitina* spp. *Ramochitina deynouxi* has been also reported in the *persculptus* Zone of the lowermost part of Nseirat section of Mauritania (Paris et al., 1998; Underwood et al., 1998; de la Puente et al., 2020).

The chitinozoan assemblages, according to the presence of *Spinachitina fragilis*, *Ancyrochitina laevaensis* and abundant *Cyathochitina* spp., which proliferation is common before the FAD of *S. fragilis* in Northern Gondwana (Thusu et al., 2013; Le Hérissé et al., 2013; Paris et al., 2015; de la Puente et al., 2020), constrain an earliest Rhuddanian age for the base of the Lipeón Fm., hence the unconformity below the ravinement conglomerate may be under chitinozoan biostratigraphic resolution (Figs. 5(F), 13(G)). An early Rhuddanian age is interpreted for the shale atop the conglomerate (Fig. 5(F)), representing a condensed interval coeval with the flooding surface that occurred after the Hirnantian glacial waning stage. The shale intervals within and immediately above the major ironstone bed (Figs. 5(F), 13(H)) are interpreted to be an Aeronian age, though for the rest of the Lipeón Fm. cropping in this region a Telychian-Sheinwoodian age is suggested. This biostratigraphic constraint indicates that the ironstones are also quite condensed, along with the peculiar oolite-rich ironstones that need an extremely low sedimentation rate, which is compatible with maximum flooding surfaces. The age for the lower part of the Lipeón Fm. is supported by the record of the *acuminatus-atavus* zones in this region, however the detailed sampling herein allows constraining gaps and condensed intervals as represented by postglacial omission, flooding and maximum flooding surfaces.

4. Discussion

Since the Caspalá Fm. was defined in the Cordillera Oriental as "composed of sandstones and conglomerates that vary their thickness from few cm to >30 m thick that erosively truncate the underlying succession allowing to interpret a prominent unconformity with a clear regional expression" (Starck, 1995), new consideration related to this unit can be made. The underlying synsedimentary deformed package is tentatively considered here as a lower member of the unit (Figs. 5(D), 8). The distinct coarse-grained interval is, in turn, overlain by well-known Silurian and Devonian units (de la Puente and Rubinstein, 2013a; Rubinstein et al., 2016). Glacially-related features, equivalent to those of the Zapla Fm., are now recognised in the area (Astini, 2008), thus considered to represent the Hirnantian glacial interval. While the basal unconformity represents the glacial waxing stage, associated to sea-level fall and exposure, the Caspalá Fm. represents proglacial waning stage deposits and are sharply overlain by transgressive Silurian shales, with no iron-rich beds like in other parts of the basin (Fig. 5(B, C, E-G)). Along the Sierra de Zenta (Figs. 1, 2(A), 5(E)), the diamictite reaches a maximum of 20 m thick, and it is overlain by 34 m of amalgamated coarse sandstones (Figs. 5(D, E), 6(A-C), 8) with lenses of quartz-rich pebble conglomerates and frequent development of cross-bedding with high angle of repose. In some outcrops, the "glacial horizon" seems to overlie in slight angular unconformity (~5°), although the angularity may be enhanced by rheological contrasts related to Andean tectonics affecting the whole stratigraphy in the Cordillera Oriental ranges. In other views, as that to the south of the Caspalá River section (Figs. 1, 2(C)), a clear onlap relationships of the Lipeón Fm. onto the diamictites or directly onto the earlier Ordovician units are recorded. This fact indicates that, between both intervals, major sea-level drops have incised into the previous stratigraphy, related to influence of the Hirnantian glaciation, and thus it can be taken as a global signature. However, the local expression in different sections along the Cordillera Oriental and particularly across indicates slightly different attitudes owing to enhancement of a broad paleorelief, associated to relatively passive uplifting (forebulge tectonics; Fig. 3(B, C)).

Detailed sedimentological studies carried out in the glacially-related sequence of the Mecoyita Fm. (Fig. 5(C)) allow recognition of three glacial advancing episodes characterized by profuse glaciotectonism, in a diamictite matrix deposit with polished and striated clasts, which reach a half meter, and intratill pavements of striated blocks, with the record of a fluvioglacial stage (Figs. 6(E-I), 7(A-I), 11(A-I), 13(A, C-F)). Massive stratified diamictites indicate rainout deposits at the final glacial retreating episode. The re-advances are interpreted to be related to glacial pulses between interglacial pulses or warmer stages, rather than to represent independent glaciations according to the biostratigraphic data analysed here from equivalent levels of the Zapla and Caspalá formations. New data suggest a shorter duration of

0.47 ± 0.34 myr for the Hirnantian Stage, constraining the Hirnantian glacial maximum to ~0.2 myr, based on high-precision zircon U-Pb dates well-constrained biostratigraphically by graptolites, and sedimentation rates of a continuous Ordovician-Silurian boundary section in southwestern China (Ling et al., 2019).

Hirnantian glacially-related deposits in the Argentine part of the Central Andean Basin reach 20 m thick in the western part of the Cordillera Oriental (Fig. 5(B)) and its thickness progressively increases toward the east, reaching over 36 m in the Mecoyita area (Fig. 5(C)), over 50 m in the Caspalá and Sierra de Zenta areas (Fig. 5(D, E)), the eastern part of the Cordillera Oriental, and over 70 m in the Sierras Subandinas and Sierras de Santa Bárbara (Fig. 5(F, G)). The thickness of the glacially-related deposits also increases to the NW, in equivalent levels of the Cancañiri Fm., in southern Bolivia, where they indicate an SSE to NNW transport direction (Schönian and Egenhoff, 2007). Sedimentological analysis carried out in the Mecoyita Fm., confirms the relative continuity of the glacial record, showing three ice advances overlain by a waning stage with iron-rich intervals as also was observed in equivalent levels of the Cancañiri Fm. to the north of the studied area (Schönian and Egenhoff, 2007). Three separate ice advances are reported with an ESE to NWN transport direction also characterize the Don Braulio Fm. from the Argentine Precordillera region (Astini, 1999), to the south of the studied area (Fig. 1). To the east of the Central Andean Basin, the glacially-related deposits continue as well in subsurface (Russo et al., 1979; 1986; Fernandez Garrasino, 1980; Fig. 10), where they reach over 70 m as part of a westward-thickening wedge depocentre, which extends ca. 400 km in W-E direction and represent the connection with the Paraná Basin in eastern Paraguay. In this basin, the glaciogenic deposits are part of the Iapó Fm. and reach 60 m thick in outcrops and subsurface (Assine et al., 1998). Within this eastern part of the Paraná Basin, the Hirnantian-Rhuddanian interval is reported in the overlying Vila Maria Fm., correlated with the Vargas Peñas Fm. in Paraguay (Fig. 10), interpreted as a periglacial marine environment from mid to outer continental shelf (Assine et al., 1998; Adorno et al., 2016). Biostratigraphic data, based mainly on graptolites and chitinozoans records (Milani et al., 2007; Adorno et al., 2016; Rodrigues et al., 2021; Gonçalves et al., 2022), allow confirming the correlation of these levels with the Zapla and Lipeón formations of the Central Andean Basin in Argentina (Fig. 10).

The Ocloyic unconformity characterized by a subtle very low angle, except in the Puna region (Figs. 1, 5(A)) where it yields the maximum time-gap and strong angularity, has been recognized throughout the Central Andean Basin in Argentina and southern Bolivia, subsurface of the Chacoparanaense Basin, and the eastern Paraná Basin. Subsidence and sediment accumulation in the Paraná Basin have been related to the Ocloyic Orogeny in Argentina (Ramos et al., 1986; Astini et al., 1995; Assine, 1996), which represent the collision of Cuyania (Precordillera) microplate against the pre-Andean margin of Gondwana in western Argentina during the Middle to Late Ordovician and active subduction along the Central Andean Basin (Astini et al., 1995; Astini and Dávila, 2004; Ramos, 2018a, 2018b). As it is indicated by sequence stratigraphy analyses throughout W-E sections of the Central Andean Basin, development of deltaic settings alternating with estuarine systems from the late Early Ordovician to the middle Late Ordovician, carried material from the Gondwanan craton, placed to the east, toward deeper depozones of the foreland basin to the west (Astini, 2003, 2008; Astini and Marengo, 2006; Fig. 3(B, C)). This geological context allows explaining the provenance and preservation of thick Ordovician sedimentary packages in the eastern and central part of the broad basin track. This is in agreement with deposits in the eastern Paraná Basin, whereas the easternmost expressions of the Paraná Basin may relate to intracratonic contexts (Milani et al., 1995; Assine, 1996; Milani and Ramos, 1998).

Detailed stratigraphic and biostratigraphic studies allow constraining the ages of key correlatable discontinuity surfaces related to different order transgressive-regressive sequences, as those indicating intervals with remarkable relative see-level falls and associated estuarine settings developed in incisive valleys (Astini, 2003, 2008; Astini and Marengo, 2006; Mángano et al., 2021). In particular, the hiatus involved in the Ocloyic unconformity can be inferred as close to the duration of the Hirnantian glacial (constraining to ~0.2 myr in SW China) in the eastern part of the basin (Caspalá and Zapla formations from the Caspalá-Santa Ana and Río Capillas areas, respectively) where the Ordovician strata are interpreted to be less affected by the Ocloyic tectonic phase.

Because of the time gap involved in the different sections throughout the basin and the erosive nature at its base, with local development of striated pavements and strong lithological contrasts to both sides of this regional unconformity, it has previously been linked to the Ocloyic tectonic phase (Ramos et al., 1986; Astini et al., 1995). However, this tectonic event related to the accretionary margin of Gondwana (Cawood and Buchan, 2007) represents tectonic thickening and folding within the hinterland (in Puna), but may have only been represented by regional upwarping within the peripheral bulge region, implying both a possibility for anchorage of a Late Ordovician ice cap and amplification of the relative sea-level drop in the region. Thus, explaining the topography and facies diversity associated to the Hirnantian glacial horizon at various localities along and across northwest Argentina.

In the northern Argentine part of the Cordillera Oriental (i.e., in the Puestos Creek of the Sierra de Santa Victoria, in the Santa Victoria area; Figs. 1, 2(B)), a glacially striated surface suggests an SE to NW transport direction (Martínez, 1998). Considering the equivalent outcrops in Bolivia and Peru, the glacially related interval extends for ca. 1200 km in an N-S trend, and a maximum E-W extent of as much as 600 km has been suggested (Schönian and Egenhoff, 2007). In southern Bolivia, the Cancañiri Fm. (Fig. 10) reports correlatable three ice advances and glacial waning stage iron-rich deposits, which are interpreted to be associated to low-latitude, temperate, ice sheet centered on the Argentine Neoproterozoic to Lower Cambrian Pampean orogen (Schönian and Egenhoff, 2007). The provenance of the clasts indicates erosion from the immediately underlying shallow-marine Ordovician deposits, the Precambrian-Lower Cambrian forming the local basement (Puncoviscana Fm.), and the Pampean basement, further south in central Argentina (Schönian and Egenhoff, 2007).

The Mecoyita Fm. is unconformably overlain by Silurian deposits of the Lipeón Fm. (Figs. 5(C), 6(E), 12(A, D, F)), correlated with the Kirusillas Fm. (Fig. 10) in southern Bolivia (Benedetto et al., 1992; Schönian and Egenhoff, 2007). Northern Bolivia and southern Peru diamictites containing younger lower Silurian palynomorphs are interpreted as resedimentation of the striated and faceted boulders into the deep basin, which were reworked and redistributed by high-energy marine processes along the shore during the postglacial transgression. Gravity flow deposits including olistostromic successions and interbedded turbiditic deposits support accumulation in a tectonically active deep-marine trough (Benedetto et al., 2015) or alternatively, within intrabulge basins (Fig. 3(C)).

5. Conclusions

Lower Ordovician chitinozoan associations recorded from the Central Andean Basin in Argentina, are well constrained in the Cordillera Oriental, the central-eastern part of the basin, by graptolite and conodont zones as well as well-known trilobite associations. The *Euconochitina paschaensis* Assemblage is recorded in the late upper Tremadocian together with the *Kiaerograptus supremus*, *Araneograptus murrayi* and *Hunnegraptus copiosus* zones, and the *Acodus apex* Zone. Different forms related to *Eremochitina brevis* are tentatively differentiated in this region: *Eremochitina brevis* form A Assemblage is reported in the middle early Floian at the base of the *Tetragraptus akzharensis* Zone; *Eremochitina brevis* form B Assemblage is recorded in the early middle Floain at the base of the *Baltograptus* cf. *deflexus* Zone; and *Eremochitina baculata brevis*? Assemblage is reported in the late Floain according to its presence in the *Didymograptus bifidus* Zone and *Baltoniodus* cf. *triangularis* Zone, associated with *Thysanopyge clavijoi* and *Famatinolithus* Fauna. In Sierras Subandinas, the easternmost part of the basin, different forms of *Eremochitina brevis* occur. Therefore, additional detailed studies are needed to better understand the distribution of the *Eremochitina* genus and its potential stratigraphic usefulness.

Detailed studies carried out throughout the glacially related deposits of the uppermost Ordovician Zapla, Caspalá, and Mecoyita formations contribute to the knowledge of the Hirnantian glaciation and its glacial waning stage in the western margin of Gondwana, and its relation with neighboring basins. According to the chitinozoan data, the glacially related Ordovician deposits in the Central Andean Basin of Argentina are restricted to the Hirnantian, and the youngest underlying deposits to the late Katian. In the Caspalá-Santa Ana area (eastern Cordillera Oriental), in addition, a synsedimentary deformed package considered here as the Lower Mb. of the Caspalá Fm., characterized by reworked chitinozoans, is described and correlated with glacially-related deposits in the other sites of the eastern part of the basin (Río Capillas and Mecoyita areas, in Sierras Subandinas and eastern Cordillera Oriental respectively). Chitinozoan assemblages of the complete Zapla Fm., up to its very top, in the eastern part of the basin (Río Capillas area) corroborate a Hirnantian age for this unit, including an interval immediately above the glacially derived diamictites. A glacial waning stage is determined in the highly organic-rich black shale with sparse dropstones at the top of the Zapla Fm., based on the presence of *Spinachitina oulebsiri* associated with *Desmochitina* gr. *minor*, which together are typical latest Hirnantian components in other regions of Gondwana. An earliest Rhuddanian age for the base of the Lipeón Fm. in this area is constrained by chitinozoan assemblages, hence the unconformity below the ravinement conglomerate at its base may be under chitinozoan biostratigraphic resolution. The flooding surface that occurred after the Hirnantian glacial waning stage is interpreted by the shale atop the conglomerate, representing a condensed interval in the early Rhuddanian according to the chitinozoan records. The shale intervals within and immediately above the major ironstone beds are interpreted to be an Aeronian age. This biostratigraphic constraint indicates an extremely low sedimentation rate, which is compatible with maximum flooding surfaces.

Integration of high-resolution palynological and sedimentary studies contributes to the unraveling of key surface hierarchy and intervening hiatuses in stratigraphy. The proposal of deposition related to different depozones of a retroarc foreland basin system with a contractional tectonic phase during the Middle to Upper Ordovician is in agreement with the thickness and facies variations of different stratigraphic sections analysed here across the Central Andean Basin in Argentina, with a volcanically fed interarc and foredeep depozone in the west (Puna region); a lower-accommodation forebulge depozone in the central area (mostly the Cordillera Oriental region); and a backbulge depozone (Sierras Subandinas and Sierras de Santa Bárbara) extending as far as the eastern Paraná Basin (reaching Paraguay and Brazil). Ordovician chitinozoan assemblages from the Central Andean Basin indicate Northern, Western and peri-Gondwanan affinities, although locally some more cosmopolitan species described in different plates, such as Baltica, Avalonia and South China, are also recorded.

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Appendix A. Supplementary information

Supplementary information (including material and methods and Table S1) associated with this article cand be found, in the online version, at:

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Figure captions

Figure 1. Studied areas of the Central Andean Basin in Argentina. Depositional bands: WZ, Western Zone; CZ, Central Zone; EZ, Eastern Zone. Location of the studied Ordovician stratigraphic sections of Fig. 5(A-G) are placed.

Figure 2. A. Detail of the Caspalá-Santa Ana area. **B.** Detail of the Santa Victoria and Mecoyita area. **C.** Detail of the Río Capillas area. Location of the studied Ordovician stratigraphic sections of Fig. 5(C-F) are placed.

Figure 3. Threefold schematic W-E cross sections of northwestern Argentina showing the tectonic setting and distribution of the adjacent regions treated in the text as part of an Ordovician retroarc foreland basin system (modified from Astini, 2003, 2008). **A.** Oceanic plate steepening, with extension in the back-arc position, inferred for the lowest Ordovician. **B.** Shallowing of the subduction, with the development of foredeep and back-bulge depozones, and fold and thrust belt and forebulge related, inferred for the Lower-Middle to Upper Ordovician. **C.** Hirnantian glaciation effects in the Uppermost Ordovician.

Figure 4. Stratigraphic distribution of chitinozoan assemblages correlated with graptolite (Toro and Herrera Sánchez, 2019), conodont (Albanesi and Rao, 1996; Voldman et al., 2017; Toro et al., 2020) and trilobite (Harrington and Leanza, 1957; Monaldi and Boso, 1987; Waisfeld and Vaccari, 2008; Vaccari et al., 2010; Toro et al., 2015; Vaucher et al., 2020) zones in different regions within the Central Andean Basin of Argentina. International Chronostratigraphic Chart by Cohen et al. (2022). Ordovician Stage Slice by Bergström et al.

(2009). LC: Los Colorados; Ch: Chamarra; P/I: Parcha/Incamayo; SZ: Sierra de Zenta; SV/M: Santa Victoria/Mecoyita. Main supersequences to the right (Acoite Supersequence includes Cardonal and Incamayo supersequences).

Figure 5. Studied Ordovician stratigraphic sections across Puna (Salar del Rincón section from de la Puente et al., 2020), Cordillera Oriental (Los Colorados section after Astini et al., 2004, and Mecoyita, Caspalá and Sierra del Zenta sections, this paper), and the Sierras Subandinas (Río Capillas, this paper) and Sierras de Santa Bárbara (Arroyo Pedregoso section by Benedetto et al., 2015) regions of the Central Andean Basin in Argentina.

Figure 6. Glacigenic deposits in the studied areas of eastern Cordillera Oriental. **A-D.** Caspalá area. A: view of the upper Ordovician "glacial horizon" of the Caspalá Formation, sharply overlaying early Ordovician rocks at the Caspalá section; B: detail of the Ordovician/Silurian contact (indicated with an arrow) at the Caspalá section; C: detail of the Ordovician/Silurian contact (indicated with an arrow) in the Sierras de Zenta; D: contrasting grain sizes within the diamictite of the Caspalá Formation in the Sierras de Zenta. Diameter of the coin is 18 mm. **E-I**. Mecoyita area. E: massive matrix-supported (Dmm) and thin-bedded stratified matrix-supported (Dms) diamictites of the Mecoyita Formation and its contact with the Lipeón Formation; F: detail of the contact between the massive matrix-supported (Dmm) and thin-bedded stratified matrix-supported (Dms) diamictites of the Mecoyita Formation; G-I: details of the thin-bedded diamictite texture of F, with thin and graded layers with dropstones, and relatively more abundance of thin interbedded dark shale layers.

Figure 7. Glacigenic deposits of the northeastern Cordillera Oriental of Argentina in the Mecoyita area. **A, B**. Intratill pavement of striated blocks. **C, D**. Striated block of the intratill pavement composed of conglomerate and sandstone. **E, F**. Details of striated crossed sets diamictite and faceted blocks. **G.** Striated and faceted volcanic clast. **H, I.** Striated and faceted sandstone clast.

Figure 8. Stratigraphic sections of the Caspalá, Santa Ana and Sierra de Zenta (eastern Cordillera Oriental) areas with Ordovician chitinozoan records and photographs of the outcrops (Table S1, Appendix A).

Figure 9. Ordovician chitinozoans from the Caspalá and Santa Ana areas (A-J, M) (Cordillera Oriental) and Río Capillas area (K-L, O-Q) (Sierras Subandinas). **A.** *Euconochitina paschaensis* de la Puente and Rubinstein, 2009 (sample 8656). **B.** *Euconochitina paschaensis* specimens in a chain (sample 8656). **C.** Broken specimen of *Lagenochitina* sp. cf. *longiformis* (Obut, 1995) (sample 8658). **D.** *Lagenochitina obeligis* Paris, 1981 (sample 8935). **E.** *Eremochitina brevis* Benoît and Taugourdeau, 1961 "short form" (sample 8935). **F, G.** *Eremochitina brevis* form A de Paris, 1981 "long form" (F from sample 8942; G from sample 8949). **H, I.** *Conochitina* spp. (sample 8943). **J.** *Pistillachitina comma* (Eisenack, 1959) (sample 8820). **K.** *Tanuchitina elongata* Bouché, 1965 (sample 7590). **L.** *Tanuchitina*

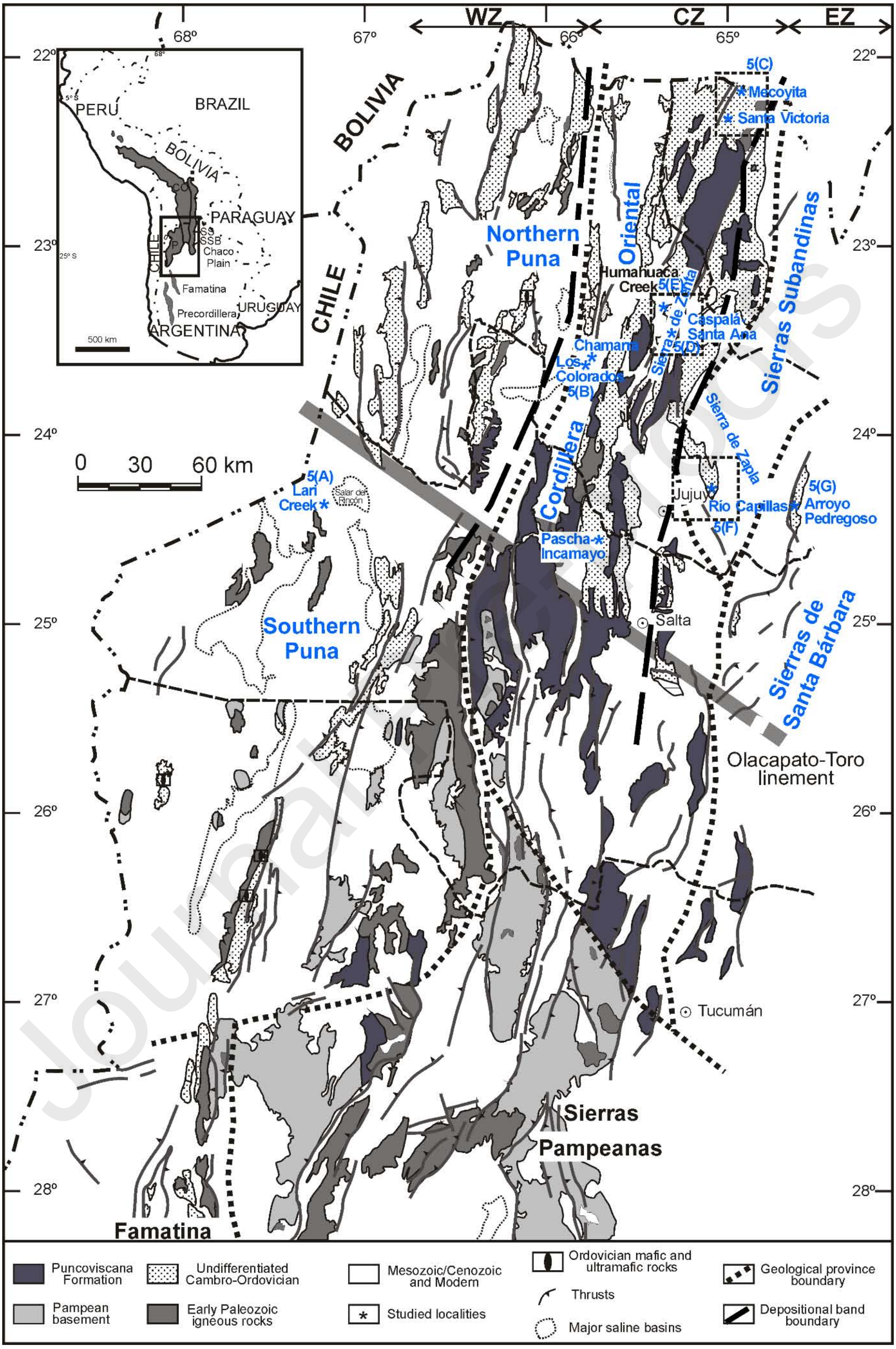
ontariensis Jansonius, 1964 (sample 10127). **M.** *Belonechitina llangrannogensis* Challands et al., 2014 (sample 8820). **N.** *Ramochitina deynouxi* de la Puente et al., 2020. Small Ramochitina with an ornamentation of simple, bi- or multirooted spines arranged in longitudinal rows (sample 10127). **O.** *Desmochitina* gr. *minor* Eisenack, 1958 (sample 10127). **P.** *Desmochitina erinacea* Eisenack, 1931 (sample 7590). **Q.** *Ancyrochitina* sp. (sample 10124). Scale bars: 50 µm.

Figure 10. Stratigraphic diagram of the Central Andean Basin in Argentina and adjacent regions treated in the text as related to the Middle-Upper Ordovician retroarc foreland basin system. R: Rhuddanian; A: Aeronian; T: Telychian. International Chronostratigraphic Chart by Cohen et al. (2022). Ordovician Stage Slice by Bergström et al. (2009).

Figure 11. The Mecoyita Formation in the Mecoyita area (northeastern Cordillera Oriental of Argentina). **A**. Details of the thin-bedded diamictites. **B**. Detail of a polished granite clast. **C**. Block of sandstone of previous rocks (Acoite Formation?) within the diamictite. **D**. Detail of the diamictite matrix. **E, F**. Views of the diamictite interval with a profuse glaciotectonism. **G-I**. Views and details of polished granite clasts.

Figure 12. Lower and upper contacts of the Mecoyita Formation in the Mecoyita area (northeastern Cordillera Oriental of Argentina). **A**. View of the contact of the Mecoyita Formation and the overlying Lipeón Formation. **B**. Detail of the ironstone beds of the Lipéon Formation. **C**. View of contact of the Mecoyita Formation and the underlying Acoite Formation? **D**. Detail of the contact of the Mecoyita Formation and the overlying Lipeón Formation, which starts with a basal conglomerate and a first ironstone bed. **E**. Detail of the profuse glaciotectonism affecting the upper part of the underlying formation. **F**. Detail of the basal conglomerate of the Lipeón Formation overlain the thin-bedded (Dms) diamictites.

Figure 13. Ordovician outcrops at the Río Capillas section in the Sierra de Zapla (Sierras Subandinas). **A**. View of the anticline showing the oldest Ordovician deposits in the core area corresponding to the Zanjón Formation. **B**. Views of the Laja Morada (purplish-red colours) and Lagunillas (sandy package) members of the Labrado Formation, and partially the Centinela Formation; the Capillas Formation is covered by vegetation. The sharp erosive contact between the Laja Morada and the Lagunillas members (indicated with an arrow) represents the development of composite fluvial incisions. **C**. View of the Centinela Formation outcrop. **D**. Detail of the Lagunillas Member characterized by sandy fluvial to tide-dominated estuarine fills. **E**. Detail of the sharp erosive contact between the Laja Morada and the Lagunillas members (indicated with an arrow). **F**. View of the thick-bedded quartz-rich sandstones which individually show erosive bases, internal gradation and floating oversized pebbles with seldom interbedded thin shale partitions, covering the massive diamictite of the Zapla Formation. **G**. Detail of the basal conglomerate of Lipeón Formation. **H**. View of the greenish silty-shales between the two lowermost ironstone beds of the Lipeón Formation. Fe (1) indicates the main (first) ironstone bed.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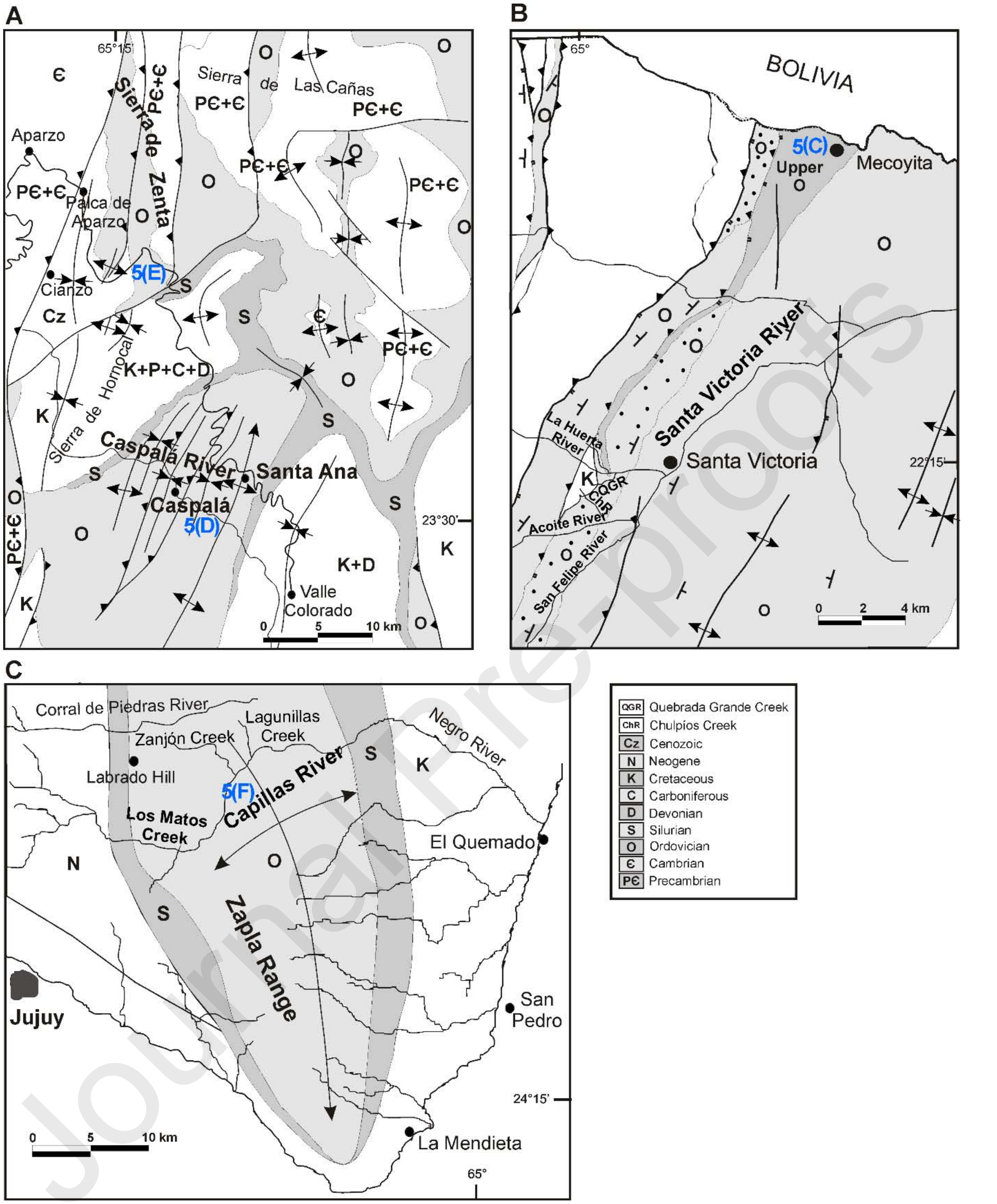
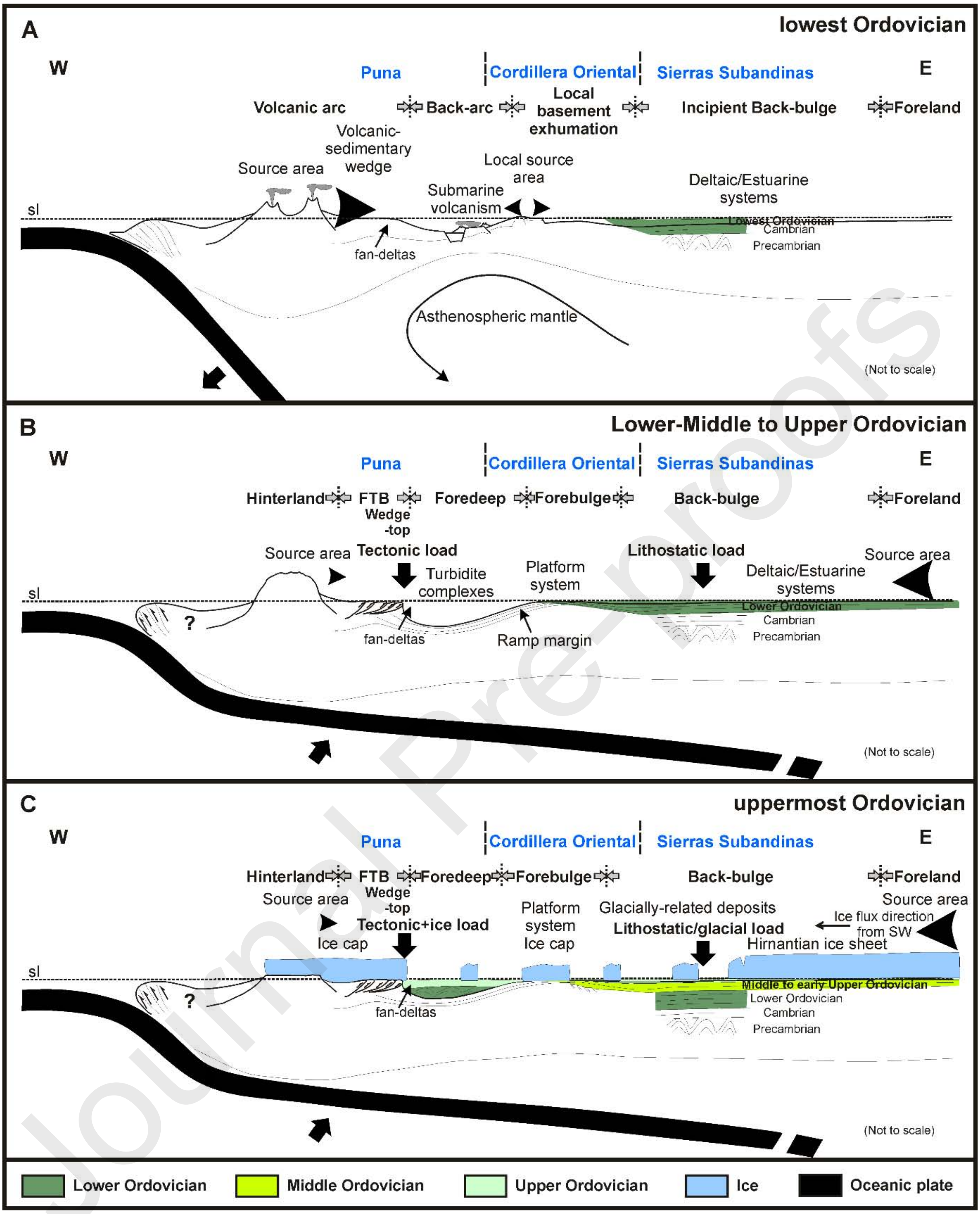
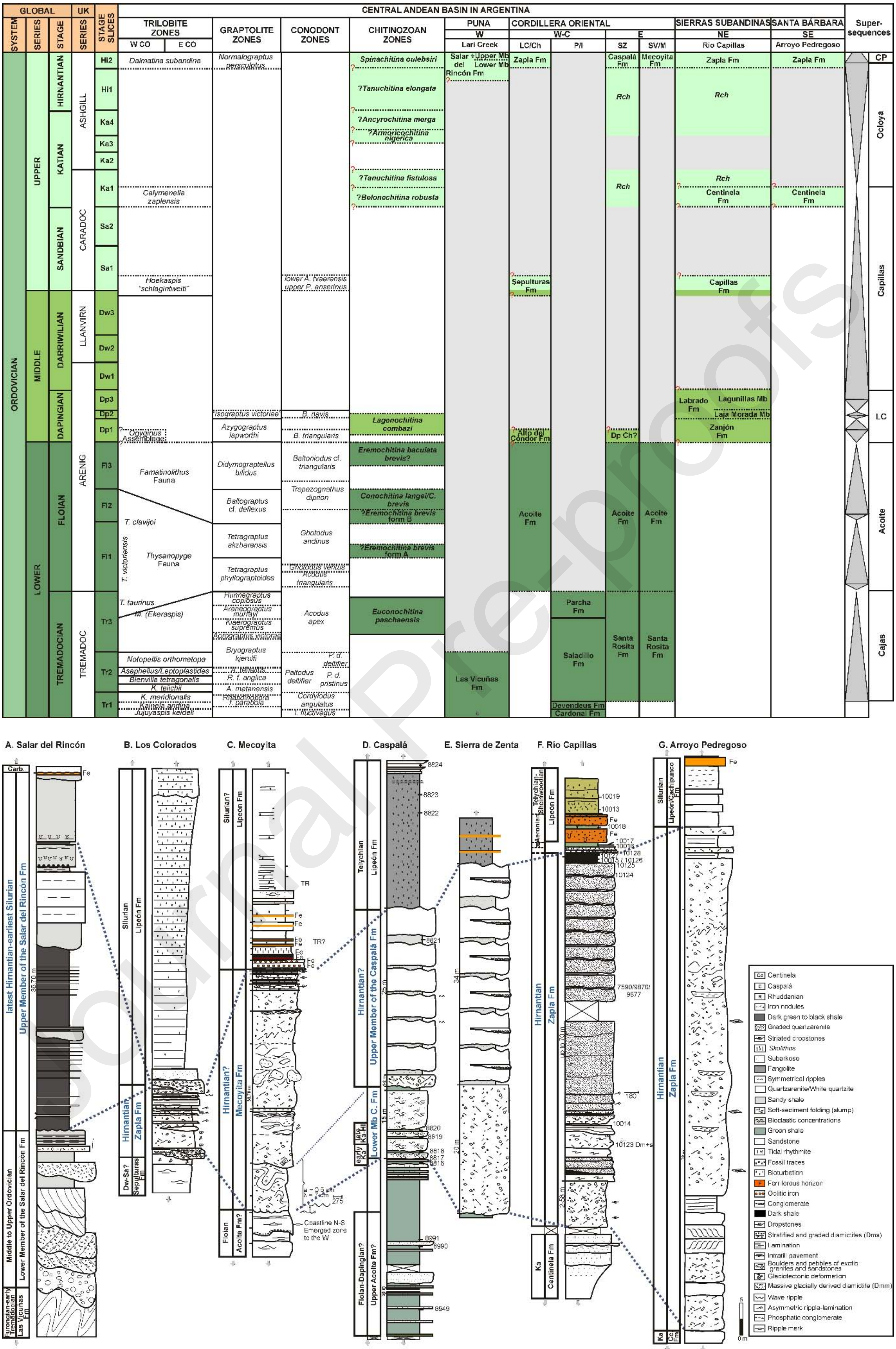
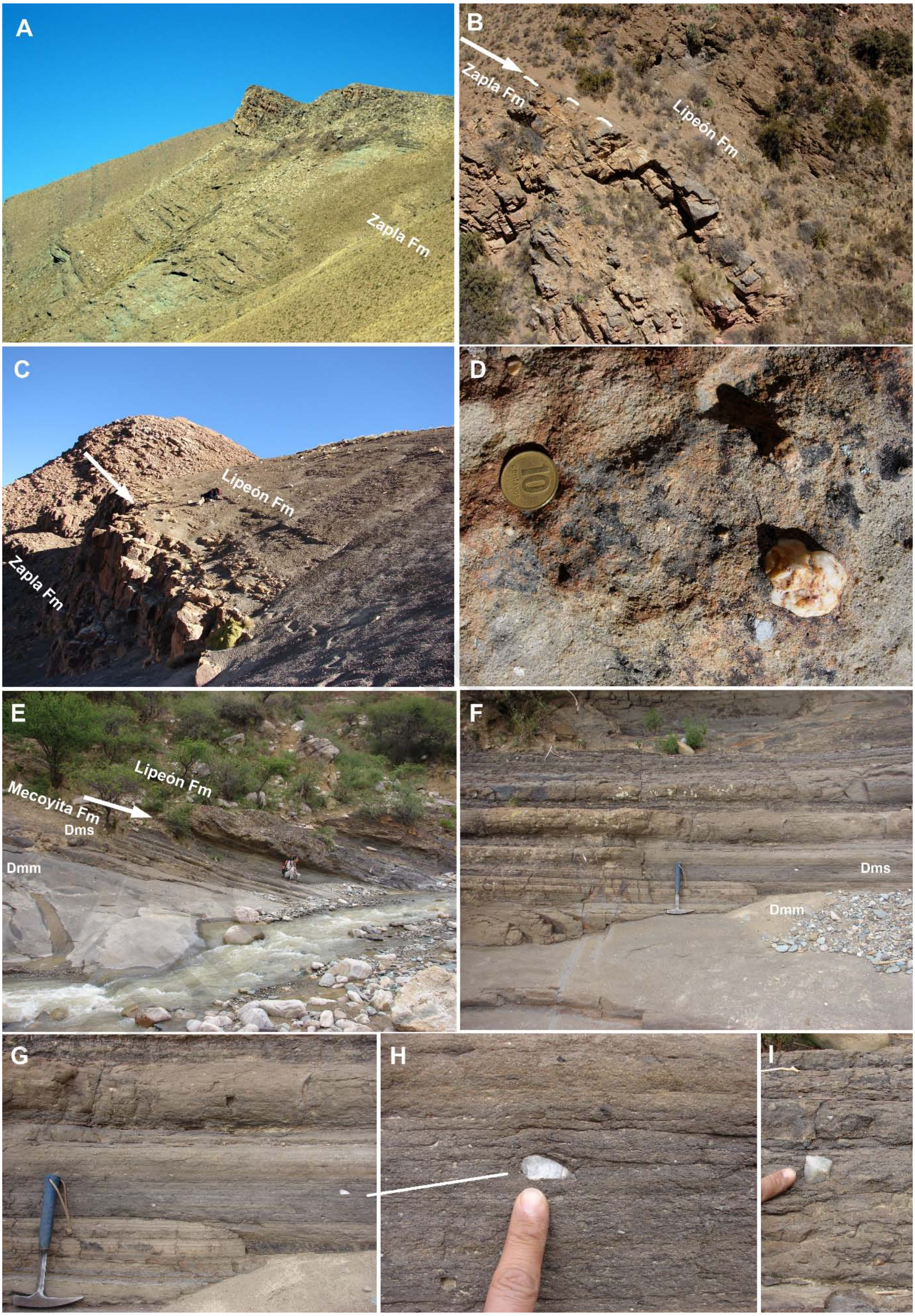
PARAGUAY
CHILE
Chaco Plain
Famatina
Precordillera
URUGUAY
ARGENTINA
500 km
BOLIVIA
CHILE
Northern Puna
Oriental
Cordillera
Sierras Subandinas
5(C)
Mecoyita
Santa Victoria
Humahuaca Creek
5(E)
Sierra de Zenta
Caspalá
Santa Ana
5(D)
Chamarra
Los Colorados
5(B)
Sierra de Zapla
0 30 60 km
5(A)
Lari Creek
Salar de Rincón
Jujuy
Río Capillas
5(F)
5(G)
Arroyo Pedregoso
Pascha-Incamayo
Southern Puna
Salta
Sierras de Santa Bárbara
Olacapato-Toro lineament
Tucumán
Sierras Pampeanas
Famatina
Puncoviscana Formation
Undifferentiated Cambro-Ordovician
Mesozoic/Cenozoic and Modern
Ordovician mafic and ultramafic rocks
Geological province boundary
Thrusts
Pampean basement
Early Paleozoic igneous rocks
Studied localities
Major saline basins
Depositional band boundary

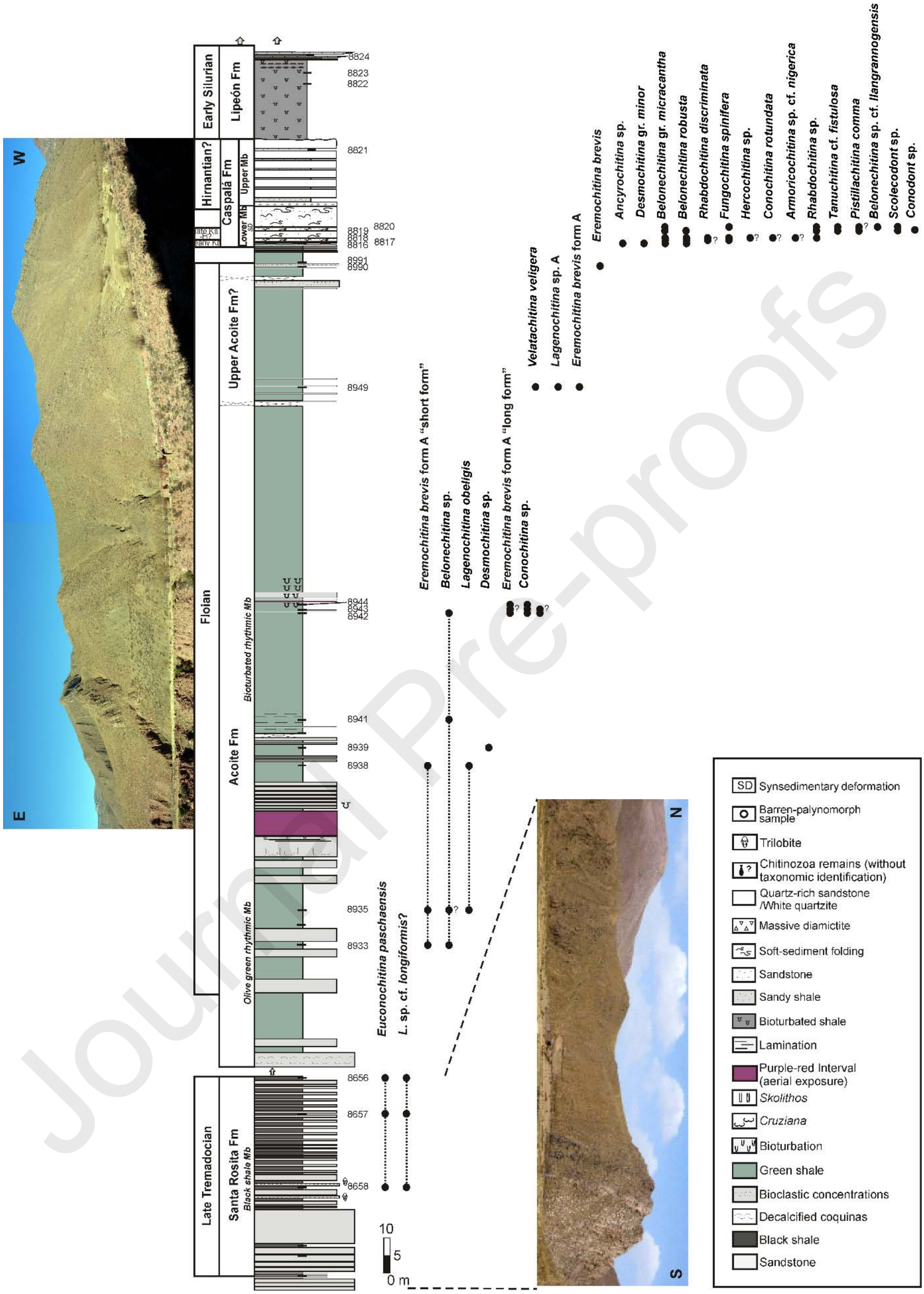

A
65°15'
Sierra de Zenta
Sierra de Las Cañas
Aparzo
Palca de Aparzo
Cianzo
5(E)
Sierra de Hornocal
K+P+C+D
Caspalá River
Santa Ana
Caspalá
5(D)
Valle Colorado
K+D
23°30'
0 5 10 km
B
65°
BOLIVIA
5(C)
Upper
Mecoyita
Santa Victoria River
La Huerta River
Santa Victoria
QGR
ChR
Acoite River
San Felipe River
22°15'
0 2 4 km
C
Corral de Piedras River
Zanjón Creek
Lagunillas Creek
Negro River
Labrado Hill
5(F)
Capillas River
Los Matos Creek
El Quemado
Zapla Range
Jujuy
San Pedro
24°15'
La Mendieta
65°
0 5 10 km
QGR Quebrada Grande Creek
ChR Chulpíos Creek
Cz Cenozoic
N Neogene
K Cretaceous
C Carboniferous
D Devonian
S Silurian
O Ordovician
Є Cambrian
PЄ Precambrian

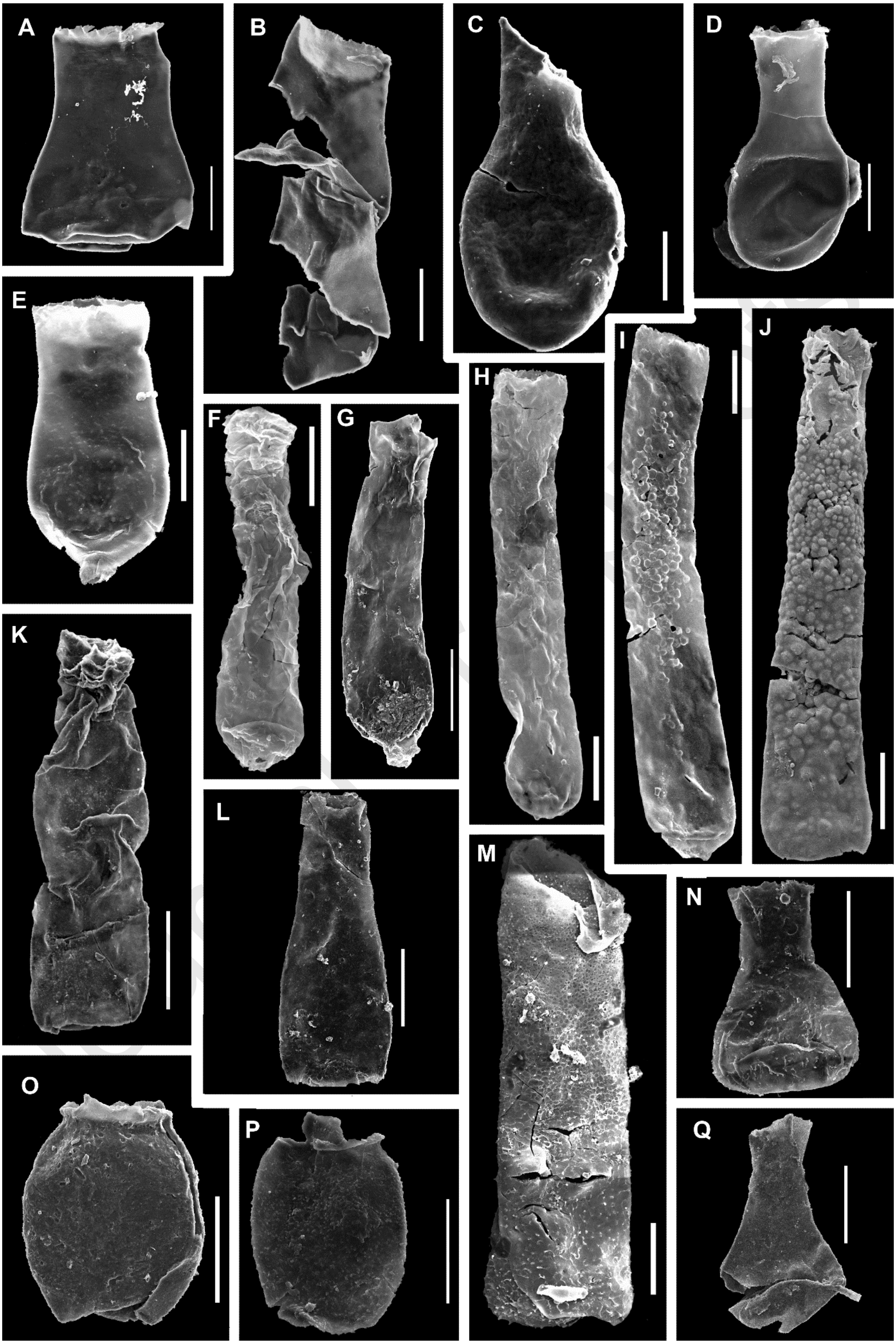

A
lowest Ordovician
W
Puna
Cordillera Oriental
Sierras Subandinas
E
Volcanic arc
Back-arc
Local basement exhumation
Incipient Back-bulge
Foreland
Volcanic-sedimentary wedge
Source area
Local source area
Submarine volcanism
Deltaic/Estuarine systems
sl
Lowest Ordovician
Cambrian
Precambrian
fan-deltas
Asthenospheric mantle
(Not to scale)
B
Lower-Middle to Upper Ordovician
W
Puna
Cordillera Oriental
Sierras Subandinas
E
Hinterland
FTB
Wedge-top
Foredeep
Forebulge
Back-bulge
Foreland
Source area
Tectonic load
Lithostatic load
Source area
Turbidite complexes
Platform system
Deltaic/Estuarine systems
sl
?
fan-deltas
Ramp margin
Lower Ordovician
Cambrian
Precambrian
(Not to scale)
C
uppermost Ordovician
W
Puna
Cordillera Oriental
Sierras Subandinas
E
Hinterland
FTB
Foredeep
Forebulge
Back-bulge
Foreland
Source area
Wedge-top
Platform system
Glacially-related deposits
Source area
Tectonic+ice load
Lithostatic/glacial load
Ice flux direction from SW
Ice cap
Ice cap
Hirnantian ice sheet
sl
?
fan-deltas
Middle to early Upper Ordovician
Lower Ordovician
Cambrian
Precambrian
(Not to scale)
Lower Ordovician
Middle Ordovician
Upper Ordovician
Ice
Oceanic plate

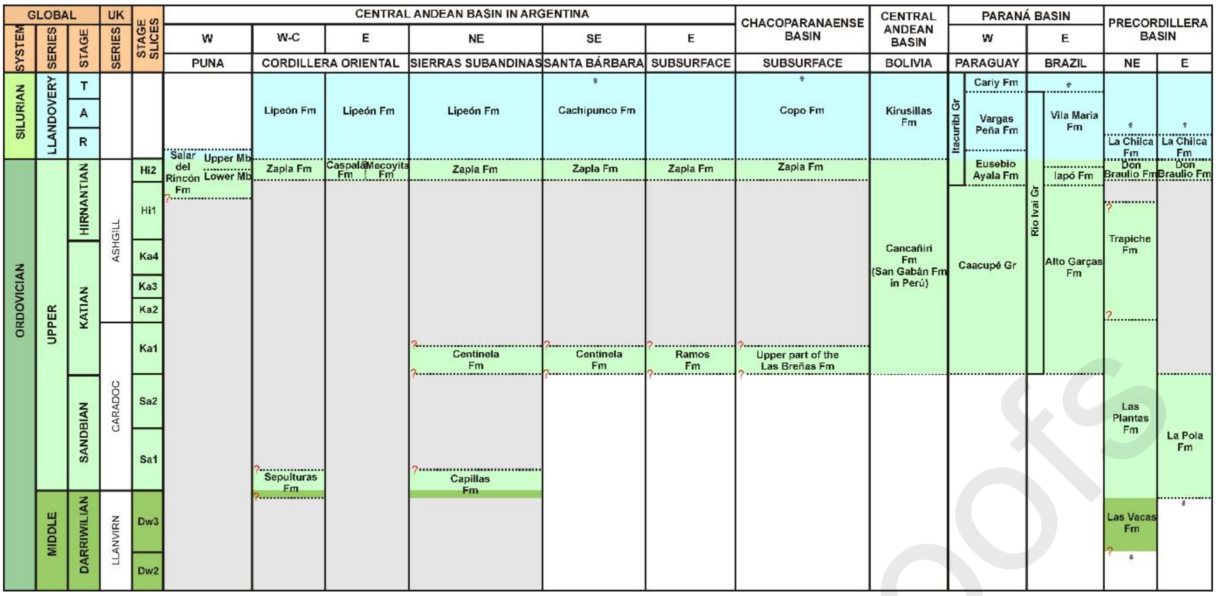

GLOBAL
UK
SYSTEM
SERIES
STAGE
STAGE SLICES
CENTRAL ANDEAN BASIN IN ARGENTINA
TRILOBITE ZONES
W CO
E CO
GRAPTOLITE ZONES
CONODONT ZONES
CHITINOZOAN ZONES
PUNA
W
Lari Creek
CORDILLERA ORIENTAL
W-C
E
LC/Ch
P/I
SZ
SV/M
SIERRAS SUBANDINAS
NE
Rio Capillas
SANTA BÁRBARA
SE
Arroyo Pedregoso
Super-sequences
ORDOVICIAN
UPPER
MIDDLE
LOWER
HIRNANTIAN
KATIAN
SANDBIAN
DARRIWILIAN
DAPINGIAN
FLOIAN
TREMADOCIAN
ASHGILL
CARADOC
LLANVIRN
ARENIG
TREMADOC
Hi2
Hi1
Ka4
Ka3
Ka2
Ka1
Sa2
Sa1
Dw3
Dw2
Dw1
Dp3
Dp2
Dp1
Fl3
Fl2
Fl1
Tr3
Tr2
Tr1
Dalmatina subandina
Calymenella zaplensis
Hoekaspis "schlagintweiti"
Famatinolithus Fauna
T. clavijoi
Thysanopyge Fauna
T. victoriensis
T. taurinus
M. (Ekeraspis)
Notopeltis orthometopa
Asaphellus/Leptoplastides
Bienvilla tetragonalis
K. teiichii
K. meridionalis
Kainella andina
Jujuyaspis keideli
Normalograptus persculptus
Isograptus victoriae
Azygograptus lapworthi
Didymograptellus bifidus
Baltograptus cf. deflexus
Tetragraptus akzharensis
Tetragraptus phyllograptoides
Bryograptus kjerulfi
R. f. anglica
A. matanensis
Spinachitina oulebsiri
?Tanuchitina elongata
?Ancyrochitina merga
?Armoricochitina nigerica
?Tanuchitina fistulosa
?Belonechitina robusta
Lagenochitina combazi
Eremochitina baculata brevis?
Conochitina langei/C. brevis
?Eremochitina brevis form B
?Eremochitina brevis form A
Euconochitina paschaensis
lower A. tvaerensis
upper P. anserinus
B. navis
B. triangularis
Baltoniodus cf. triangularis
Trapezognathus diprion
Gothodus andinus
Acodus triangularis
Acodus apex
P. d. deltifier
Paltodus deltifier
P. d. pristinus
Cordylodus angulatus
I. fluctivagus
Salar del Rincón Fm
Upper Mb
Lower Mb
Las Vicuñas Fm
Zapla Fm
Sepulturas Fm
Alto del Cóndor Fm
Acoite Fm
Parcha Fm
Saladillo Fm
Devendeus Fm
Cardonal Fm
Caspalá Fm
Mecoyita Fm
Rch
Dp Ch?
Santa Rosita Fm
Centinela Fm
Capillas Fm
Labrado Fm
Lagunillas Mb
Laja Morada Mb
Zanjón Fm
CP
Ocloya
Capillas
LC
Acoite
Cajas
A. Salar del Rincón
B. Los Colorados
C. Mecoyita
D. Caspalá
E. Sierra de Zenta
F. Rio Capillas
G. Arroyo Pedregoso
Carb.
latest Hirnantian-earliest Silurian
Upper Member of the Salar del Rincón Fm
Middle to Upper Ordovician
Lower Member of the Salar del Rincón Fm
Furongian-early Tremadocian
Las Vicuñas Fm
Silurian
Lipeón Fm
Hirnantian
Zapla Fm
Dw-Sa?
Sepulturas Fm
Silurian?
Hirnantian?
Mecoyita Fm
Floian
Acoite Fm?
TR
TR?
Coastline N-S
Emerged zone to the W
Telychian
Hirnantian?
Upper Member of the Caspalá Fm
Lower Mb C. Fm
Floian-Dapingian?
Upper Acoite Fm?
Telychian-Sheinwoodian
Ka
Centinela Fm
Fe
Centinela
Caspalá
Rhuddanian
Iron nodules
Dark green to black shale
Graded quartzarenite
Striated clcostones
Skolithos
Subarkose
Fangolite
Symmetrical ripples
Quartzarenite/White quartzite
Sandy shale
Soft-sediment folding (slump)
Bioclastic concentrations
Green shale
Sandstone
Tidal rhythmite
Fossil traces
Bioturbation
Ferruginous horizon
Oolitic iron
Conglomerate
Dark shale
Dropstones
Stratified and graded diamictites (Dms)
Lamination
Intratill pavement
Boulders and pebbles of exotic granites and sandstones
Glaciotectonic deformation
Massive glacially derived diamictite (Dmm)
Wave ripple
Asymmetric ripple-lamination
Phosphatic conglomerate
Ripple mark


A
Zapla Fm
B
Zapla Fm
Lipeón Fm
C
Lipeón Fm
Zapla Fm
D
E
Lipeón Fm
Mecoyita Fm
Dms
Dmm
F
Dms
Dmm
G
H
I


A
B
C
D
E
F
G
H
I


W
E
N
S
Early Silurian
Lipeón Fm
Hirnantian?
Caspalá Fm
Upper Mb
Lower Mb
Floian
Upper Acoite Fm?
Acoite Fm
Bioturbated rhythmic Mb
Olive green rhythmic Mb
Late Tremadocian
Santa Rosita Fm
Black shale Mb
8824
8823
8822
8821
8820
8819
8818
8817
8816
8991
8990
8949
8944
8943
8942
8941
8939
8938
8935
8933
8656
8657
8658
10
5
0 m
Euconochitina paschaensis
L. sp. cf. longiformis?
Eremochitina brevis form A "short form"
Belonechitina sp.
Lagenochitina obeligis
Desmochitina sp.
Eremochitina brevis form A "long form"
Conochitina sp.
Velatachitina veligera
Lagenochitina sp. A
Eremochitina brevis form A
Eremochitina brevis
Ancyrochitina sp.
Desmochitina gr. minor
Belonechitina gr. micracantha
Belonechitina robusta
Rhabdochitina discriminata
Fungochitina spinifera
Hercochitina sp.
Conochitina rotundata
Armoricochitina sp. cf. nigerica
Rhabdochitina sp.
Tanuchitina cf. fistulosa
Pistillachitina comma
Belonechitina sp. cf. llangrannogensis
Scolecodont sp.
Conodont sp.
SD Synsedimentary deformation
Barren-palynomorph sample
Trilobite
Chitinozoa remains (without taxonomic identification)
Quartz-rich sandstone /White quartzite
Massive diamictite
Soft-sediment folding
Sandstone
Sandy shale
Bioturbated shale
Lamination
Purple-red Interval (aerial exposure)
Skolithos
Cruziana
Bioturbation
Green shale
Bioclastic concentrations
Decalcified coquinas
Black shale
Sandstone


A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q


GLOBAL
UK
SYSTEM
SERIES
STAGE
SERIES
STAGE SLICES
CENTRAL ANDEAN BASIN IN ARGENTINA
W
W-C
E
NE
SE
E
PUNA
CORDILLERA ORIENTAL
SIERRAS SUBANDINAS
SANTA BÁRBARA
SUBSURFACE
CHACOPARANAENSE BASIN
SUBSURFACE
CENTRAL ANDEAN BASIN
BOLIVIA
PARANÁ BASIN
W
E
PARAGUAY
BRAZIL
PRECORDILLERA BASIN
NE
E
SILURIAN
LLANDOVERY
T
A
R
ORDOVICIAN
UPPER
MIDDLE
HIRNANTIAN
KATIAN
SANDBIAN
DARRIWILIAN
ASHGILL
CARADOC
LLANVIRN
Hi2
Hi1
Ka4
Ka3
Ka2
Ka1
Sa2
Sa1
Dw3
Dw2
Salar del Rincón Fm
Upper Mb
Lower Mb
Lipeón Fm
Lipeón Fm
Lipeón Fm
Cachipunco Fm
Copo Fm
Kirusillas Fm
Itacurubí Gr
Cariy Fm
Vargas Peña Fm
Vila Maria Fm
La Chilca Fm
La Chilca Fm
Zapla Fm
Caspalá Fm
Mecoyita Fm
Zapla Fm
Zapla Fm
Zapla Fm
Zapla Fm
Eusebio Ayala Fm
Iapó Fm
Don Braulio Fm
Don Braulio Fm
Rio Ivaí Gr
Cancañiri Fm (San Gabán Fm in Perú)
Caacupé Gr
Alto Garças Fm
Trapiche Fm
Centinela Fm
Centinela Fm
Ramos Fm
Upper part of the Las Breñas Fm
Las Plantas Fm
La Pola Fm
Sepulturas Fm
Capillas Fm
Las Vacas Fm


A
B
C
D
E
F
G
H
I


A
Lipeón Fm
Mecoyita Fm
Fe
Fe
B
Lipeón Fm
Fe
Fe
C
D
Lipeón Fm
Mecoyita Fm
E
F
Cgl
Dms


A
Zanjón Fm
B
Labrado Fm
C
Centinela Fm
D
Lagunillas Mb
Laja Morada Mb
E
Lagunillas Mb
Laja Morada Mb
F
Zapla Fm
Dm
Sg
G
Cgl
H
Lipeón Fm
Fe (2)
Fe (1)