LAJSBA
LATIN AMERICAN JOURNAL OF SEDIMENTOLOGY AND BASIN ANALYSIS | VOLUME 31 (1) 2024, 43-64

OLISTOLITHS OF THE GUALCAMAYO FORMATION (MIDDLE ORDOVICIAN) EMBEDDED INTO THE SILURIAN-LOWER DEVONIAN RINCONADA FORMATION, EASTERN PRECORDILLERA, ARGENTINA: PALEONTOLOGICAL, STRATIGRAPHIC, AND BASIN-MODEL IMPLICATIONS

Fernando E. Lopez[1,2], Osvaldo A. Conde[3], Alejandro R. Braeckman[4], Lautaro Estrada[4], Cintia Kaufmann[5], Juan M. Drovandi.[2], Fernando A. Pedernera[4], Ulises Abarca[4], Jonatan A. Arnol[6]*

[1] Consejo Nacional de Investigaciones Científicas
[2] Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de San Juan, Av. Ignacio de la Roza 590 (O), 5400, Rivadavia, San Juan, Argentina.
[3] CIGEOBIO - Instituto y Museo de Ciencias Naturales, Universidad Nacional de San Juan. Av. España 406 Norte, J5400, San Juan, Argentina.
[4] Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de San Juan, Av. Ignacio de la Roza 590 (O), 5400, Rivadavia, San Juan, Argentina.
[5] Instituto de Geología Dr. Emiliano Aparicio, Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de San Juan, Av. Ignacio de la Roza 590 (O), 5400, Rivadavia, San Juan.
[6] División Científica de Geología-Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata (UNLP), Paseo del Bosque s/n, 1900, La Plata, Argentina.
*Corresponding author felopez@unsj-cuim.edu.ar

ARTICLE INFO

Article history
Received April 13, 2023
Accepted October 10, 2023
Available online October 10, 2023

Handling Editor
M. Sol Raigemborn

Keywords
Precordillera basin
Graptolites
Middle Ordovician
Olistolithic mélange
Rinconada Formation

ABSTRACT

This contribution provides new paleontological and stratigraphic data for the Eastern Precordillera (San Juan province, Argentina) Ordovician basin. This is based on the description of a group of olistoliths, interpreted herein as coming from the lower beds of the Ordovician Gualcamayo Formation, found embedded within the matrix of the Silurian-early Devonian Rinconada Formation. These olistoliths are characterized by variable dimensions and uniform lithologies, composed of black shales and marlstones or following hectometric limestone blocks related to the San Juan Formation. The Gualcamayo Formation blocks show a graptolite fauna characterized by *Holmograptus spinosus*, *H. bovis*, *Cryptograptus schaeferi*, *Paraglossograptus tentaculatus*, *Archiclimacograptus* spp., *Atopograptus* sp., *Pseudophyllograptus* sp., *Tetragraptus* sp., and *Xiphograptus* sp.; whereas on the bedding plane surfaces, conodont elements of *Histiodella* sp., *Paroistodus horridus*, *Periodon macrodentatus*, and *Protopanderodus* sp. are found. In the interbedded black shales-marlstones, the trilobites *Annamitella* sp., *Mendolaspis* sp., and *Carolinites*? sp. are observed. The presence of this graptolite fauna allows recording the middle Darriwilian *H. spinosus* Zone, representing the third record in South America, and enabling a correlation with other outcrops of Precordillera and North America, Australasia, and China. These middle Darriwilian deposits at the La Rinconada section represent the youngest age ever recorded for the drowning phase of the Ordovician carbonate platform (locally referred to as *transfacies*). This is coherent with a progressive drowning model from north to south and agrees with the diachronism of the base of the Gualcamayo Formation and equivalent units. In addition, the difference between the underlying units of the Rinconada Formation in different sections, together with contrasting thickness measurements, might indicate evidence of the Alto del Tambolar tectonic activity during the Rinconada Formation accumulation in Eastern Precordillera. These processes were also previously recognized for the deposition of the Tucunuco Group in the Central Precordillera. This study expands the knowledge regarding the carbonate drowning process of the Precordillera basin that occurred during the Middle Ordovician and the effects of the Guandacol Tectonic Phase in the La Rinconada area, never mentioned until this moment.

INTRODUCTION

Olistostromes are complex sedimentary bodies made up of a chaotic mixture of blocks (=olistoliths) of different ages and origins, immersed in a sedimentary matrix (Festa *et al.*, 2010). These deposits result from mass transport processes such as slumps, slides, rock falls, and debris flows, which accumulate downslope in a sedimentary basin under different conditions and tectonic environments (Festa *et al.*, 2016). Studying the olistoliths contained in a younger formation may allow recognizing absent units due to erosion processes and correlating them with other sections, unknown units (=ghost formations) in the stratigraphy of the basin, and the constituents of the olistostrome basement. Given this, olistostromes represent a crucial tool in the reconstruction of the tecto-sedimentary history of basins.

In the Precordillera Geological Province of western Argentina, the Rinconada Formation (Wenlockian-early Devonian) presents vast and thick olistostrome deposits, with olistoliths of different lithologies and ages. This unit is underlaid by Ordovician-Silurian units that in turn can be found as olistoliths in different sections of the Rinconada Formation. For example, the Gualcamayo Formation is present as basement in the northern outcrops (Villicum Range; Peralta, 1993; Kaufmann, 2019), and as olistoliths in the centre of the Eastern Precordillera (Chica de Zonda Range, La Rinconada section; Ramos *et al.*, 2000; this study).

The Gualcamayo Formation is characterized by interbedded black shales and marlstones at its lower part and a strong diachronism was interpreted for its base (Baldis and Beresi, 1981; Astini, 1992; Carrera, 1997; and cites therein). These aspects represent stratigraphic evidence of the beginning of the Cuyania terrane collision during the Middle Ordovician, referred to as the Guandacol Tectonic Phase (Ramos *et al.*, 1986; Astini, 1992; Ramos, 2004; among others). This collision event initially produced a progressive drowning of the previous carbonate platform successions and the subsequent deposition of marine black shales.

Despite several studies have been performed in different areas of the Precordillera, the Gualcamayo Formation has not been analyzed at the La Rinconada section (central Eastern Precordillera). Given this, the present study reports the finding and describe fossiliferous olistoliths constituted of black shales and interbedded marlstones, related herein to the lower meters of the Gualcamayo Formation, included in the matrix of the younger Rinconada Formation. This allows enunciating important conclusions about the diachronic character of the base of the Gualcamayo Formation, and support new evidence about the tectono-sedimentary activity during the Ordovician and Silurian times at the La Rinconada section, an aspect barely studied so far.

GEOLOGIC AND STRATIGRAPHIC CONTEXT

In western Argentina, the Precordillera Geological Province (Furque and Cuerda, 1979) has been divided into four subprovinces: Western, Central, South, and Eastern (Baldis and Chebli, 1969; Ortiz and Zambrano, 1981; Baldis et al., 1982; Cortéz et al., 2005). Olistostromic deposits have been recognized in all of them: at Western Precordillera, in the early to late Ordovician Los Sombreros Formation (Cuerda et al., 1983); at Central Precordillera, in the Silurian-early Devonian Corralito Formation (Furque et al., 1990); at South Precordillera, in the middle Ordovician Estancia San Isidro Formation and the late Ordovician Empozada Formation (Heredia and Beresi, 2004); and at Eastern Precordillera, in the Wenlockian-early Devonian Rinconada Formation (Amos, 1954).

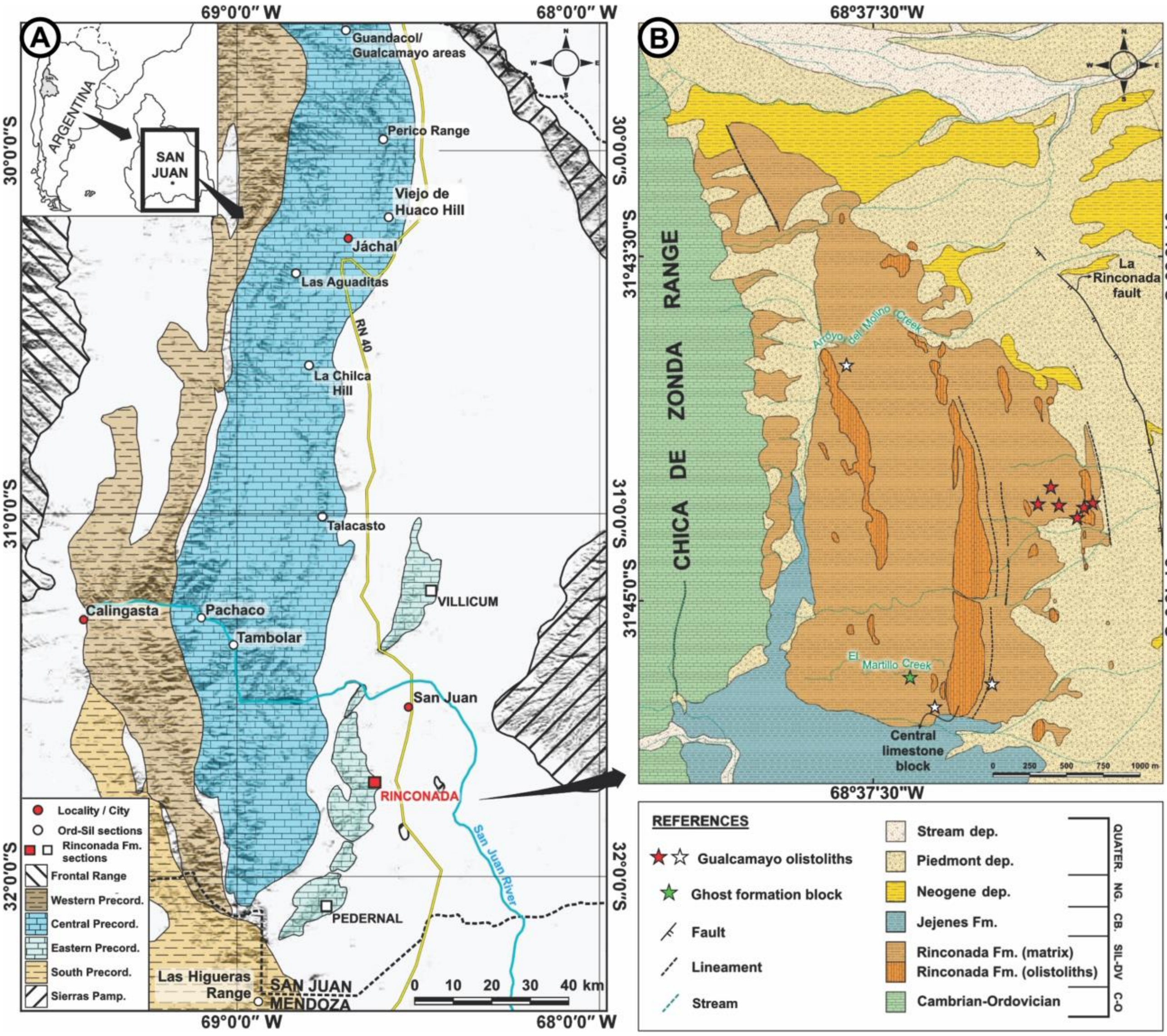

Figure 1. Location maps. **a)** Regional map of the Precordillera Geological Province showing its four subprovinces and surrounding geological units (Baldis and Chebli 1969; Ortiz and Zambrano, 1981; Baldis *et al.* 1982; Cortés *et al.* 2005). The La Rinconada section is pointed by the black-red square. **b)** Geological map of the La Rinconada area. The Ordovician graptolitic olistoliths are shown in black-red (this study), black-white (Peralta, 1986), and black-green (Voldman *et al.*, 2018) stars. Modified from Lopez *et al.* (2023a).

Rinconada Formation

The Rinconada Formation is an olistolithic mélange, which crops out all over the Eastern Precordillera of the San Juan Province (Fig. 1). The allochthonous blocks immersed in its matrix are composed of limestones associated with the early to middle Ordovician San Juan Formation (and possibly older units), Ordovician black shales and marlstones from the middle Ordovician Gualcamayo Formation (studied herein), middle Ordovician quartz-arenites from an unknown formation (=ghost formation; Ortega *et al.*, 2016; Voldman *et al.*, 2018), allochthonous conglomerates that might be related to the middle to late Ordovician La Cantera or the late Ordovician to Llandoverian Don Braulio formations, and claystones and sandstones related to the Don Braulio Formation or a lateral equivalent unit (Cuerda, 1981) (Fig. 2). It is worth mentioning the presence of autochthonous conglomerates and blocks as the result of the reworking of previous deposits of the Rinconada Formation.

At the La Rinconada section, the most common composition for the olistoliths found in the

Rinconada Formation is limestone with few km long (*e.g.*, the central limestone block, Fig. 1b), followed in abundance by conglomerates and sandstones. Olistoliths from the Gualcamayo Formation are found throughout the unit, bonded to large limestone olistoliths, or as isolated (surrounded by the matrix) black shale allochthonous blocks (black-red stars, Fig. 1b). The boundaries of the olistoliths are sharp, showing a lithological contrast with the greenish-yellowish matrix claystones and sandstones of the Rinconada Formation. Recently, Lopez *et al.* (2023a) modelled a stratigraphic column of 550 m-thick, encompassing the levels of the Rinconada Formation east side of the central limestone block, at the eponymous section. This column starts with a faulted zone a few meters above the central limestone block, and finishes with the overlying Quaternary piedmont deposits (Fig. 3). The base and top of the unit are not exposed in the studied section, thus the real thickness is unknown.

The most complete and studied underlying stratigraphy of the Rinconada Formation is located in the Villicum Range (Fig. 1) in the northern part of the Eastern Precordillera. There, the early to middle Ordovician San Juan Formation (Kobayashi, 1937) is followed by the middle Ordovician Gualcamayo Formation (Furque, 1963), the middle to late Ordovician La Cantera Formation (Baldis *et al.*, 1982), the late Ordovician La Pola Formation (Astini, 2001), and the late Ordovician to Llandoverian Don Braulio Formation (Baldis *et al.*, 1982). At the La Rinconada section, the underlying units of the Rinconada Formation is only composed of the San Juan Formation. Finally, in the Pedernal Range, the Rinconada Formation lies on top of the Los Azules (Harrington in: Harrington and Leanza, 1957) and Don Braulio formations (Mestre and Heredia, 2014), both units with no age data until now.

Gualcamayo Formation

The Gualcamayo Formation, objective of this study, is composed mainly of graptolitic black shales that crop out in the Eastern and Central Precordillera of western Argentina. Its type area is located between the Guandacol and Gualcamayo rivers (northeast of Precordillera; Fig. 1), with extensive exposures. In that area, Astini (1986) divided the formation into three members: the lower member initiates with an alternation of fossiliferous black shales and marlstones, followed by continuous black shales; the middle member is represented by claystones and siltstones; and finally, the upper member includes black shales with interbedded sandstones and conglomerates (Astini, 1994). The basal black shale and marlstone interbedded in the lower member of the Gualcamayo Formation was firstly denominated as *transfacies* by Baldis and Beresi (1981), term used in the present study.

The Gualcamayo Formation possesses a vast and rich fossiliferous content, composed mainly of graptolites, conodonts, trilobites, brachiopods, and scolecodonts. Graptolites are, followed by conodonts, the most important biostratigraphic fossils for the Gualcamayo Formation. Thus, the *Isograptus maximus*, *Oncograptus upsilon*, *Cardiograptus morsus*, *Levisograptus austrodentatus*, *Levisograptus dentatus*, *Holmograptus lentus*, *Holmograptus spinosus*, *Pterograptus elegans*, and *Hustedograptus teretiusculus* graptolite zones were recognized in the unit, encompassing a time span from the middle Dapingian to the upper Darriwilian (Cuerda and Furque, 1975; Ortega *et al.*, 1993; Brussa and Astini, 1996; Ortega and Albanesi, 2000; Ortega and Máspero Castro, 2002; Kaufmann and Ortega, 2016; Kaufmann, 2019).

A particular feature of the Gualcamayo Formation is the marked diachronism of its base, evidenced by graptolite and conodont biozones in different areas, and associated to diverse rates of subsidence in the basin (Astini *et al.*, 1995). In the Potrerillos Creek section (hereafter included in the Gualcamayo-Guandacol area, northern San Juan), the base of the unit has been dated by the presence of the middle Dapingian *Isograptus maximus* and the *Baltoniodus navis* graptolite a conodont zones (Ortega *et al.*, 1993; Mango and Albanesi, 2023); whereas, in the Villicum area, the lower levels show the lower Darriwilian *Levisograptus dentatus* graptolites Zone (Kaufmann, 2019). On the other hand, the upper beds of the Gualcamayo Formation are characterised by the late Darriwilian *P. elegans* and *H. teretiusculus* graptolite zones in the mentioned sections (Ortega *et al.*, 1993; Ortega and Albanesi, 2000; Máspero Castro *et al.*, 2003; Kaufmann, 2019).

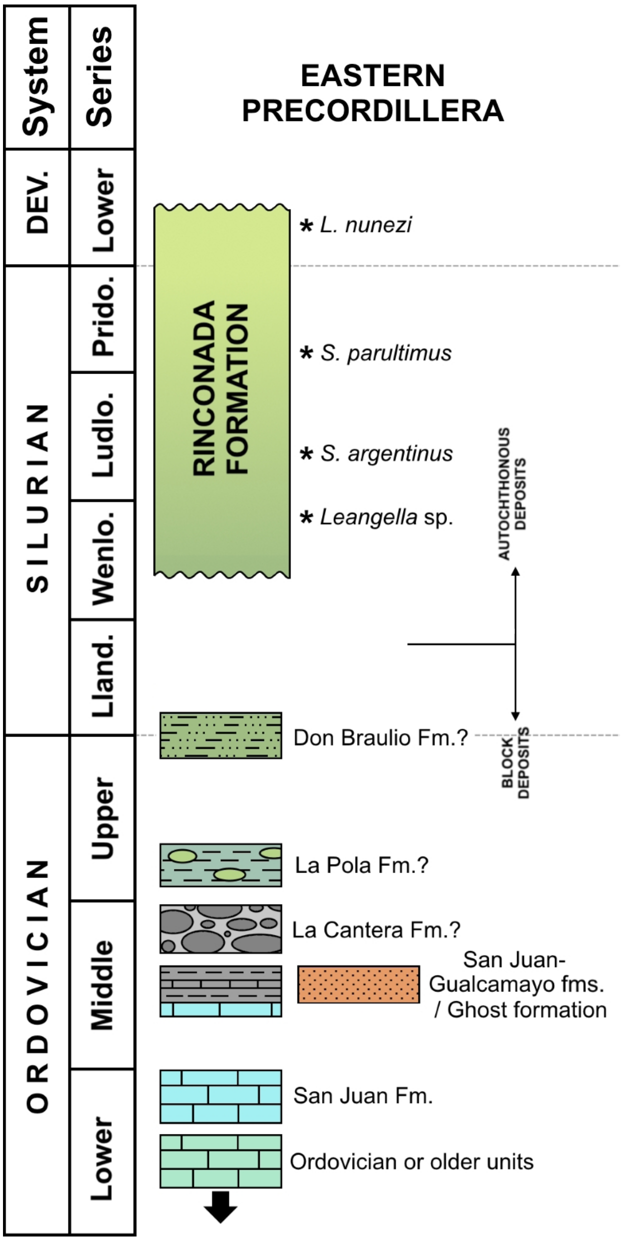

Figure 2. Olistolith ages, lithologies, and time span of the Rinconada Formation in its type area. Paleontological and stratigraphic data from Amos and Fernandez (1977), Peralta (1986), Benedetto and Franciosi (1998) and Lopez *et al.* (2023a).

Precordillera tectono-sedimentary features during the early Paleozoic

The Cambrian and Ordovician stratigraphic record of the Precordillera Geological Province is the result of a complex geological history, induced by the accretion of the exotic Cuyania terrane to the west of the Gondwanic margin in the Middle Ordovician during the Guandacol Tectonic Phase or the Ocloyic Orogeny (Turner and Méndez, 1975; Furque and Cuerda, 1979; Ramos *et al.*, 1986; Astini, 1998; Astini *et al.*, 1995; Ramos, 2004; Ariza *et al.*, 2018). This annexation process would have started in the north-east area of the Precordillera (Gualcamayo-Guandacol area), causing the reconfiguration of the previous extensional Ordovician basin into a foreland basin (Astini, 1992; Ramos, 2004; and studies cited therein). The above mentioned controlled the sedimentation during the Silurian and Devonian with the uplifting of structural highs, which caused the omission/erosion of previous or contemporaneous deposits. During the accretion, the San Juan Formation carbonate platform was drowned by a progressive subsidence and sea level rise, giving place to mixed carbonate-siliciclastic and/or siliciclastic deposits (Baldis and Beresi, 1981; Furque and Cuerda, 1982; Peralta, 1995; Astini, 1998; Cuerda *et al.*, 2004). The contacts between the San Juan and the Gualcamayo, Los Azules, Las Aguaditas, and Las Chacritas formations have been related to this drowning process.

A particular case is the Alto del Tambolar (or Arco Talacasto-Tambolar), an intrabasinal and folded structural high disposed north-south, whose effects have been studied in detail in the Central Precordillera (see Astini, 1992; Astini and Maretto, 1996). This would lead to the omission of a large part of the Middle-Upper Ordovician in the Talacasto, La Dehesa, and surrounded areas; the Middle Ordovician-lower Silurian (Llandovery) in the San Juan River area; and the Lower Devonian in the La Invernada Range and Tambolar area (Astini, 1992; Astini and Maretto, 1996; Peralta, 2013).

Diachronism in the Ordovician of Precordillera

Astini (1992) modelled two regional sections, north-south and west-east, for the Ordovician-Silurian-Devonian marine deposits of Precordillera. The first shows a lateral flexion and an upwards convexity of the basin, with the apex located in the Alto del Tambolar (San Juan River area). Northward, this structure evolved into the Arco Talacasto-Tambolar (Astini and Maretto, 1996). In the Tambolar area, a strong erosive process is evidenced on top of the Ordovician carbonate deposits of the San Juan Formation, which omitted the Ordovician units, La Chilca, Los Espejos, and Talacasto formations. On the other hand, in both southward and northward from the Tambolar area, an increment in the thickness of the Paleozoic deposits, onlap and downlap terminations, and higher depths in the edges of the basin are observed. This also suggests different ages at the beginning of each unit: i.e. the closer to the basin boundary, the older the base of the formation. This diachronism was already mentioned by several authors (Hünicken, 1985; Beresi, 1988; Astini, 1992; 1994: Ortega *et al.*, 1995; Peralta, 1995; Carrera, 1997) for deposits of the Gualcamayo Formation in the northern Precordillera.

On the other hand, the influence of the Guandacol Tectonic Phase would have started in the north-east zone of the Precordillera in the middle Dapingian (*I. maximus* and *B. navis* graptolite and conodont zones; Gualcamayo-Guandacol area; Ortega *et al.*, 1993; Mango and Albanesi, 2023) and spread later westward and southward (Astini *et al.*, 1995; Astini, 1998). In this way, the Gualcamayo-Guandacol area should have the oldest ages for the *transfacies* beds, whereas the austral area of the Ordovician carbonate deposits should show the earliest limestones of the San Juan Formation (*E. suecicus* conodont Zone, middle Darriwilian; Lehnert, 1995).

PALEONTOLOGICAL BACKGROUND

Matrix fossils of the Rinconada Formation

Fossils from the Rinconada Formation have been studied in three different areas of the Precordillera. In the Villicum Range (Fig. 1a), specimens of graptolites, brachiopods, tentaculitoids, trilobites, corals, gastropods and crinoids were recognized, and an early Ludlovian (Gorstian) age was stimated (Peralta, 1984).

At the La Rinconada section, in the Chica de Zonda Range (Fig. 1b), brachiopods, graptolites, conodonts and plant remains were described, and a Wenlockian to early Pridolian age was given for these levels (Keidel, 1938; Peralta, 1986; Lucena, 1988; Benedetto and Franciosi, 1998; Voldman *et al.*, 2015; 2017; Lopez *et al.*, 2023a).

Finally, few paleontologic studies are available for the Rinconada Formation at the Pedernal Range (Fig. 1a). There, specimens of brachiopods, trilobites and cnidarians were recognized and dated the carrier levels as late Silurian to early Devonian (Amos and Boucot; Amos and Fernandez, 1977; Peralta and Medina, 1985).

Summarizing, the Rinconada Formation ranges from the Wenlock to the early Devonian, dated on the basis of the presence of brachiopods (Amos and Boucot, 1963; Benedetto and Franciosi, 1998).

Fossils from the allochthonous blocks of the Rinconada Formation

At the La Rinconada section, the first reference to fauna from the olistoliths was made by Cuerda (1981), who described graptolites assigned to *Climacograptus* sp., *Climacograptus minutus*, *Diplograptus* sp., and *Monograptus* sp., interpreting a Llandoverian age for this assemblage. Later, Peralta (1986), Peralta and Uliarte (1986), and Lucena (1988) detailed a graptolite association found in black shales, composed by *Paraglossograptus tentaculatus*, *Dichograptus* cf. *D. octobrachiatus*, *Levisograptus austrodentatus* aff. *L a. austrodentatus*, *Tetragraptus*

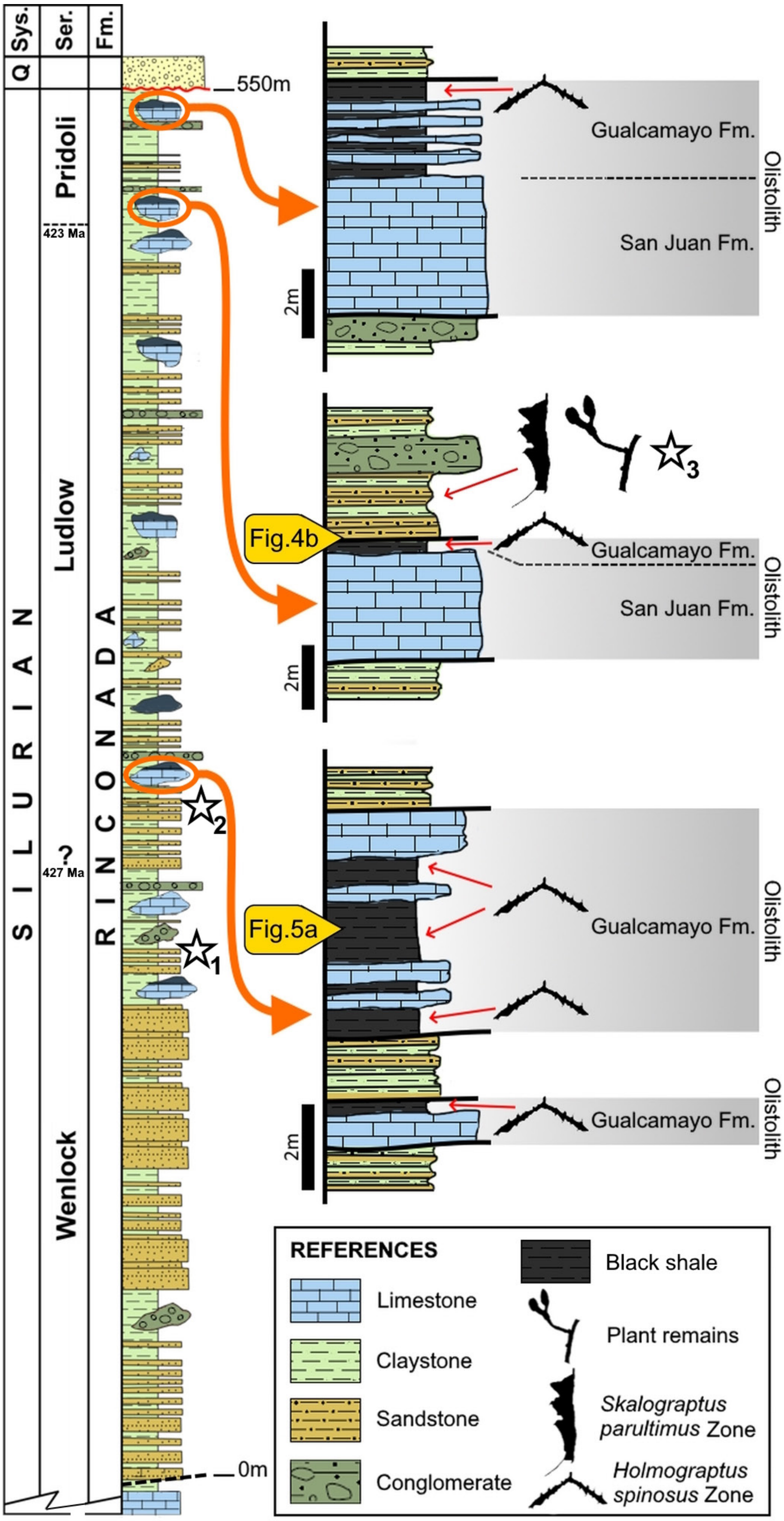

Figure 3. Details of the graptolitic Gualcamayo Formation olistoliths. The stars represent: 1-Wenlockian datum (*Leangella sp.*) from Benedetto and Franciosi (1998); 2-Ludlovian datum (*S. argentinus*) from Peralta (1986); 3-Pridolian datum (*S. parultimus*) from Lopez *et al.* (2023a). Stratigraphic column modified from Lopez *et al.* (2023a).

aff. *T. bigsbyi*, *T. quadribrachiatus*, *Tetragraptus* sp., *Isograptus forcipiformis*, *I. caduceus*, *Isograptus* sp., and *Glossograptus* sp. An early Llanvirnian (middle Darriwilian) age was assigned to these levels. In the same allochthonous blocks, Sarmiento *et al.* (1986) described an Ordovician conodont fauna characterized by *Periodon macrodentatus*, *Cordylodus*? *horridus*, *Staufferrella*? sp., *Histiodella holodentata*, and *Amorphognathus*? sp. with no biostratigraphic affinity (black-white stars, Fig. 1a).

Later, in the same section, Dorn (1993) detailed a conodont and graptolite fauna, recording the *Paraglossograptus tentaculatus* Zone (early to middle Darriwilian). This author included *Periodon macrodentatus*, *Pteracontiodus cryptodens*; *Levisograptus austrodentatus americanus*, *Paraglossograptus tentaculatus*, *Pseudotrigonograptus ensiformis*, *Tetragraptus*? sp., *Glossograptus* sp., *Pseudophyllograptus*? sp., and sinograptid gen et sp. indet.

Voldman *et al.* (2015; 2018) and Ortega *et al.* (2016), introduced four conodont and one graptolite biozones, found in limestones and quartz-arenite (ghost formation) blocks at the La Rinconada section. The authors recorded the conodont *Prionodus elegans* (early Floian), *Oepikodus evae* (middle to late Floian), *Lenodus variabilis*, and *Yangtzeplacognathus crassus* (early to middle Darriwilian) zones. The graptolite fauna is composed of *Holmograptus spinosus*, *Bergstroemograptus crawfordi*, *Cryptograptus schaeferi*, *Pseudophyllograptus* sp., *Glossograptus* sp., *Archiclimacograptus* spp., *Xiphograptus*? sp., and sinograptids indet., from the *Holmograptus spinosus* Zone (middle Darriwilian) (black-green star, Fig. 1a).

Recently, Lopez *et al.* (2023b) mentioned a graptolite assemblage assigned to the *Holmograptus spinosus* Zone, present in several allochthonous blocks of black shales in the Rinconada Formation matrix, La Rinconada section. This graptolite fauna is illustrated and partially described herein.

Finally, Peralta and Medina (1985) mentioned an allochthonous block fauna from the Pedernal Range, composed of the graptolites *Dicranograptus* sp. and *Climacograptus* sp., in levels of the lower lutitic Member. It is important to note that, in the Eastern Precordillera, the genus *Dicranograptus* has only been recorded in the La Pola Formation (Brussa, 2000). Therefore, the study of Peralta and Medina (1985) might indicate the presence of the latest formation as an olistolith in the Rinconada Formation.

Biostratigraphy of the Gualcamayo Formation

Several studies dealt with the stratigraphy and paleontology of the Gualcamayo Formation, especially dedicated to graptolites, conodonts, and trilobites, important for the biostratigraphy and evolution of the Ordovician basin of Precordillera. The first meaningful study about graptolites was made by Turner (1959), who described a late Arenigian to early Llanvirnian (Dapingian to early Darriwilian) fauna. Ortega *et al.* (1993; 1995) proposed, in the Guandacol area and Perico Range, the first biostratigraphic framework with four biozones of graptolites: the middle Dapingian *Isograptus maximus* Zone; the middle to late Dapingian *Oncograptus upsilon* Zone; the early to middle Darriwillian *Paraglossograptus tentaculatus* Zone; and the late Darriwillian *Hustedograptus teretiusculus* Zone; and four Darriwillian conodont biozones: *Paroistodus originalis-Pteracontiodus cryptodens*, *Periodon macrodentatus zgierzensis-Protopanderodus robustus*, *Paroistodus horridus-Baltoniodus medius*, and *Pygodus anitae-Protopanderodus* cf. *P. varicostatus* zones. Eventually, Ortega and Albanesi (2000) and Máspero Castro *et al.* (2003) increased the biostratigraphic knowledge of the unit. The first authors recorded the early Darriwillian *Levisograptus austrodentatus* and the late Darriwillian *Pterograptus elegans* graptolite zones, with conodonts from the *Lenodus variabilis* Zone-*Paroistodus horridus* Subzone and the *Eoplacognathus suecicus* Zone-*Pygodus anitae* Subzone, in the outcrops of the Potrerillo Hill. On the other hand, in the Corriditas Creek, Máspero Castro *et al.* (2003) described graptolites from the Darriwillian *Levisograptus dentatus*, *Holmograptus lentus*, and *Pterograptus elegans* zones. Recently, Mango and Albanesi (2023) recorded the middle Dapingian *Baltoniodus navis* conodont Zone and correlated it with the *I. maximus* graptolite Zone.

In the Eastern Precordillera, Peralta (1995) recognized the Gualcamayo Formation in the Villicum Range, and recorded the *Paraglossograptus tentaculatus* graptolite Zone. Later, Kaufmann and Ortega (2016) registered the middle Darriwillian *Holmograptus spinosus* graptolite Zone for the first time in Precordillera. Lastly, Kaufmann (2019) made an important biostratigraphic and descriptive study of the Gualcamayo Formation, registering the

L. dentatus, *H. lentus*, *H. spinosus*, and *P. elegans* graptolite zones (Darriwilian).

In the north of the Mendoza Province, in the Las Higueras Range, Heredia *et al.* (2009) identified the base of the Gualcamayo Formation and a late Floian-early Dapingian age was estimated due to the presence of the *Oepikodus intermedius* conodont Zone in the underlying San Juan Formation top most strata. In the same area, Beresi *et al.* (2017) described conodont, graptolite, trilobite, and brachiopod faunas from the overlying Los Azules Formation, and recorded the early Darriwilian *Y. crassus* and the *L. dentatus* conodont and graptolite zones, indicating a possible hiatus between those levels and the underlying San Juan Formation. These studies represent the southernmost record of these formations.

Finally, Serra *et al.* (2017; 2020) recognized the early Darriwillian *L. dentatus* graptolite Zone, together with a varied conodont fauna from the upper *Y. crassus* Zone at the La Chilca Hill section, the only recognized outcrop of the Gualcamayo Formation at the middle area of the Central Precordillera.

MATERIALS AND METHODS

Seven black shales successions, corresponding to allochthonous olistoliths, were observed in the La Rinconada Formation at the La Rinconada section and separated into two groups. The first group corresponds to the top most of large limestone olistoliths related to the San Juan Formation (Fig. 4a-b, d); and the second group was observed as isolated, m-scale allochthonous blocks, surrounded by matrix strata (Fig. 5a-d). The analysis included lithology (grain size), base and top contacts, lateral dimensions and thickness of the allochthonous blocks, and position of the bases of the layers. The location of the olistoliths was mapped (Fig. 1), together with the blocks studied by Peralta (1986), Voldman *et al.* (2015; 2018) and Ortega *et al.* (2016).

The studied graptolite fauna comes from the described black shale olistoliths (mentioned previously by Lopez *et al.*, 2023b) within the Rinconada Formation (Figs. 6-7). The specimens are moderately to well-preserved, and are associated with conodont elements on the bedding plane surfaces (Fig. 8a-d). Furthermore, the marlstone strata include trilobites, gastropods, and brachiopods (Figs. 4c, 4e, 8e-h). The graptolite assemblage possesses eight genera, together with four conodont genera and three trilobite genera. All fossils were photographed with a magnifier Leica S9D and a digital camera Nikon D3400.

The studied specimens are housed in the Instituto de Geología Dr. Emiliano Aparicio, Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de San Juan, under the repository code INGEO-PI-1965-1987.

RESULTS

Gualcamayo Formation olistoliths in the Rinconada Formation

The Rinconada Formation bears allochthonous olistoliths of different nature and variable lithologies. These rock bodies are present all over the stratigraphic column, without an apparent vertical or lateral arrangement. Three aspects can be taken into account to differentiate the olistoliths from the matrix. First, the contrasting lithology and colour: the greenish-yellowish claystones, sandstones and conglomerates from the matrix, versus the grey limestones, black shales or grey quartz-arenites from the olistoliths. Second, the paleontological content: Wenlockian-early Devonian fossils from the matrix of the Rinconada Formation, against the Ordovician-Llandoverian fossils from the olistoliths. And third, the rock body shape: lateral continuous beds from the matrix, and spindle-shapes for the olistoliths. Based on these criteria, grey limestones of the early to middle Ordovician San Juan Formation, black shales and marlstones of the middle Gualcamayo Formation, and dark brown conglomerates from the La Cantera or Don Braulio formations are here interpreted as olistoliths. According to their fossiliferous content, other olistoliths composed of greenish concretions and claystones possibly from La Pola Formation (Pedernal section; Peralta and Medina, 1985), and greenish siltstones possibly from the Don Braulio Formation (La Rinconada section; Cuerda, 1981) can be also found within the Rinconada Formation. Nevertheless, their true nature is still uncertain (Fig. 2).

Lithologic Description. The olistoliths studied here are isolated allochthonous blocks (surrounded by the matrix) composed of black shales or interbedded black shales and marlstones, or composed of black shales lying concordant on top of San Juan Formation carbonates (see Fig. 3). These allochthonous rock bodies possess vertical and lateral sharp contacts with the matrix, and are made up of finely laminated shales in beds up to 1 m thick, interspersed with thin levels of black marlstones 10-15 cm thick. These blocks have varied sizes, between 2-5 m thick and 10 m wide for isolated black shales and marlstones, to hundred m wide for limestones and black shales, wedged laterally in the matrix (Figs. 4-5). Most of the calcareous blocks with San Juan Formation affinity show transitional intercalations of nodular limestones and/or black shales and marlstones at their topmost levels, suggesting the recurrent presence of the lower levels of the Gualcamayo Formation in several olistoliths.

Internal olistoliths stratigraphy can show that middle Darriwilian graptolitic black shales interbedded with fossiliferous marlstones, are in some cases overlying middle Darriwilian limestones that can be related to the San Juan Formation, resembling the San Juan-Gualcamayo formations contact (Baldis and Beresi, 1981; Peralta, 1995). Furthermore, the intercalation of black shales and marlstones is lithologically similar to the lower meters of the lower member of the Gualcamayo Formation, described by Baldis and Beresi (1981) as the *transfacies.*

Fossil content. The graptolite fauna found in black shales from the olistoliths (previously mentioned by Lopez *et al.*, 2023b) is characterized by the index graptolite *Holmograptus spinosus* (Fig. 6a-c, 9), associated with *H. bovis* (Fig. 7a), *Cryptograptus schaeferi* (Figs. 6f, 7b, 7d III), *Paraglossograptus tentaculatus* (Fig. 6a), *Archiclimacograptus* spp. (Fig. 6d, 7d V), *Atopograptus* sp. (Fig. 7c-d IV), *Pseudophyllograptus* sp. (Fig. 6g, 7d I), *Tetragraptus* sp. (Fig. 6h), and *Xiphograptus* sp. (Fig. 6i). This assemblage allows recording the middle Darriwillian *Holmograptus spinosus* Zone. These, together with those reported by Kaufmann and Ortega (2016) and Ortega *et al.* (2016), are the only confirmed records of this biozone in Precordillera (and in South America).

Associated with the graptolite fauna, conodont elements of *Periodon macrodentatus* (Fig. 8d), *Paroistodus horridus* (Fig. 8a), *Histiodella* sp. (Fig. 8c), and *Protopanderodus* sp. (Fig. 8b) are observed on the bedding plane surfaces. On the other hand, the marlstones interbedded with the black shales, preserve the trilobites *Mendolaspis* sp., *Annamitella* sp., and *Carolinites*? sp. (Fig. 8e-h), and undetermined trilobites, gastropods, and brachiopods (Fig. 4e).

Comments on an important graptolite. The index graptolite *Holmograptus spinosus* (Ruedemann, 1904) (Figs. 6a-c, 9) represents a precise biostratigraphic marker. The specimens are present in black shales as a flattened carbon film or in full relief with moderate to poor preservation. The colonies are characterized by two declined to subhorizontal stipes (113º to 145º of divergence), with sinograptid thecal aperture and dorsal prothecal folds. The longest stipe is 7.09 mm in length; its width increases from 0.32 mm to 0.37 mm at th^1, to 0.86 mm distally. Thecae are long and slightly tilted with respect to the stipe axis. Both the dorsal folds and thecal apertures have spines, which vary from 0.05 mm to 0.32 mm long. Sicula is 0.62 mm to 0.84 mm long, and presents a virgella of 0.29 mm. 2TRD value is 1 mm proximally, and 1.45 mm distally. Thecal spacing counts 8/10 in 5 mm, and the overlap is 1/2 to 3/5. The Rinconada specimens coincide with the dimensions of *Holmograptus spinosus* (Ruedemann, 1904; Maletz, 2009; and Kaufmann, 2019).

Local, regional, and global correlation

The *Holmograptus spinosus* graptolite Zone was recorded in the Precordillera Geological Province in the Gualcamayo Formation at the Villicum section, and in quartz-arenite blocks within the Rinconada Formation (Kaufmann and Ortega, 2016; Ortega *et al.*, 2016). This biozone has not been recorded in another locality in South America.

Two possible correlations can be done with other Ordovician units from Precordillera. First, the Los Azules Formation cropping out in the Viejo de Huaco Hill contains colonies of the graptolites *Bergstroemograptus crawfordi* and *Archiclimacograptus pungens* in the upper levels of the *Holmograptus lentus* graptolite Zone (lower Member; Ortega et al., 2007). These two graptolites were later found in the *H. spinosus* graptolite Zone in the Gualcamayo Formation, thus this biozone could be present in the Los Azules Formation as well (Kaufmann and Ortega, 2016). Second, the Sierra de La Invernada Formation contains specimens of the graptolite *H. spinosus* in the upper *Paraglossograptus tentaculatus* graptolite Zone (Brussa, 1999). These

Figure 4. Field photographs of the Gualcamayo Formation olistoliths within the Rinconada Formation matrix. **a)** Panoramic view of the outcrops at the La Rinconada section. The prominent relief corresponds to limestone olistoliths (pointed by arrows), surrounded by matrix in lower relief and greenish-brownish colours. The beds top is located to the left. **b)** Graptolitic black shale block with *Holmograptus spinosus* (red-white asterisk) in contact with the sandstone strata possessing the *Skalograptus parultimus* graptolite Zone and early land plants (black-white asterisk). **c)** Trilobite specimens in marlstones from a Gualcamayo Formation olistolith. **d)** San Juan/Gualcamayo formations contact. Note the black shales at bottom left of the photograph. **e)** Brachiopod specimen from an allochthonous San Juan Formation block. Scale bar in **c** and **d** equals 1 cm.

specimens lack the characteristic dorsal spines; thus, it is probable they correspond to a different species (Kaufmann and Ortega, 2016). Moreover, the record of *Holmograptus spinosus* graptolite Zone would allow to a global biostratigraphic correlation with the Anse Au Crapaud Formation (Quebec, Canada; Maletz, 2009), and can be extended to other regions such as Scandinavia (Scania and Norway), other sections of North America (*e.g.*, New York, Newfoundland, Alaska), Australasia, and China, due to the presence of relatable graptolite faunas (Maletz, 2009).

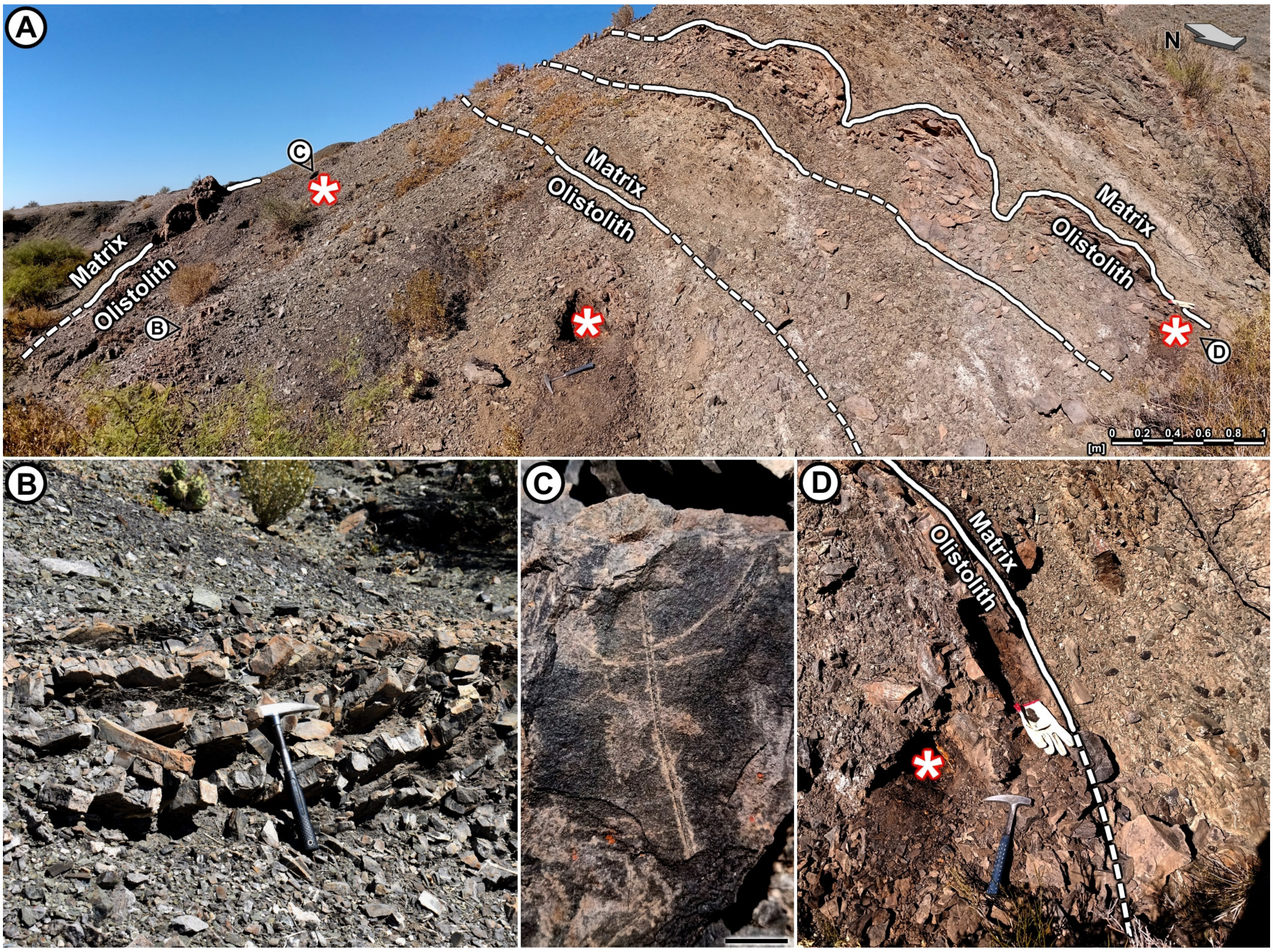

Figure 5. Detailed field views of the Gualcamayo Formation olistoliths within the Rinconada Formation matrix. **a)** Panoramic view of isolated blocks intercalated with greenish and yellowish sandstones and siltstones from the matrix. Olistolith lithologic composition is shown in **c**. The beds top is located to the left. **b)** Interbedded black shales and marlstones from a Gualcamayo Formation olistolith. **c)** Graptolitic black shale. More details in Fig. 7d. **d)** Matrix-olistolith contact. The asterisks represent graptolitic levels. Scale bar in **c** equals 5 mm.

DISCUSSION

Age of the Gualcamayo Formation olistoliths

Peralta (1986), Peralta and Uliarte (1986), Sarmiento *et al.* (1986), Lucena (1988) and Dorn (1993) described Ordovician graptolite and conodont faunas from black shales olistoliths at La Rinconada section. Although no stratigraphic links were proposed, the described lithology resembles to the Gualcamayo Formation olistoliths studied herein. These fossiliferous levels possessed colonies of *Levisograptus austrodentatus* sspp. and several other species, assigning an early to middle Darriwilian age to the black shales (*P. tentaculatus* graptolite Zone). This assemblage might correspond to older ages than the *H. spinosus* graptolite Zone due to the existence of *L. austrodentatus*. However, the presence of common graptolite (*i.e., Paraglossograptus, Pseudophyllograptus, Tetragraptus*) and conodont genera (*i.e., Histiodella, Periodon*) might indicate that both olistolith assemblages are contemporaneous. As no updated taxonomy has been made since then on that material, a taxonomic revision and new sampling could contribute to this issue.

Beginning of the Ordovician carbonate platform drowning in the central Precordillera basin

Throughout the Middle Ordovician, the carbonate platform deposition of Precordillera changed gradually to a mixed and then siliciclastic

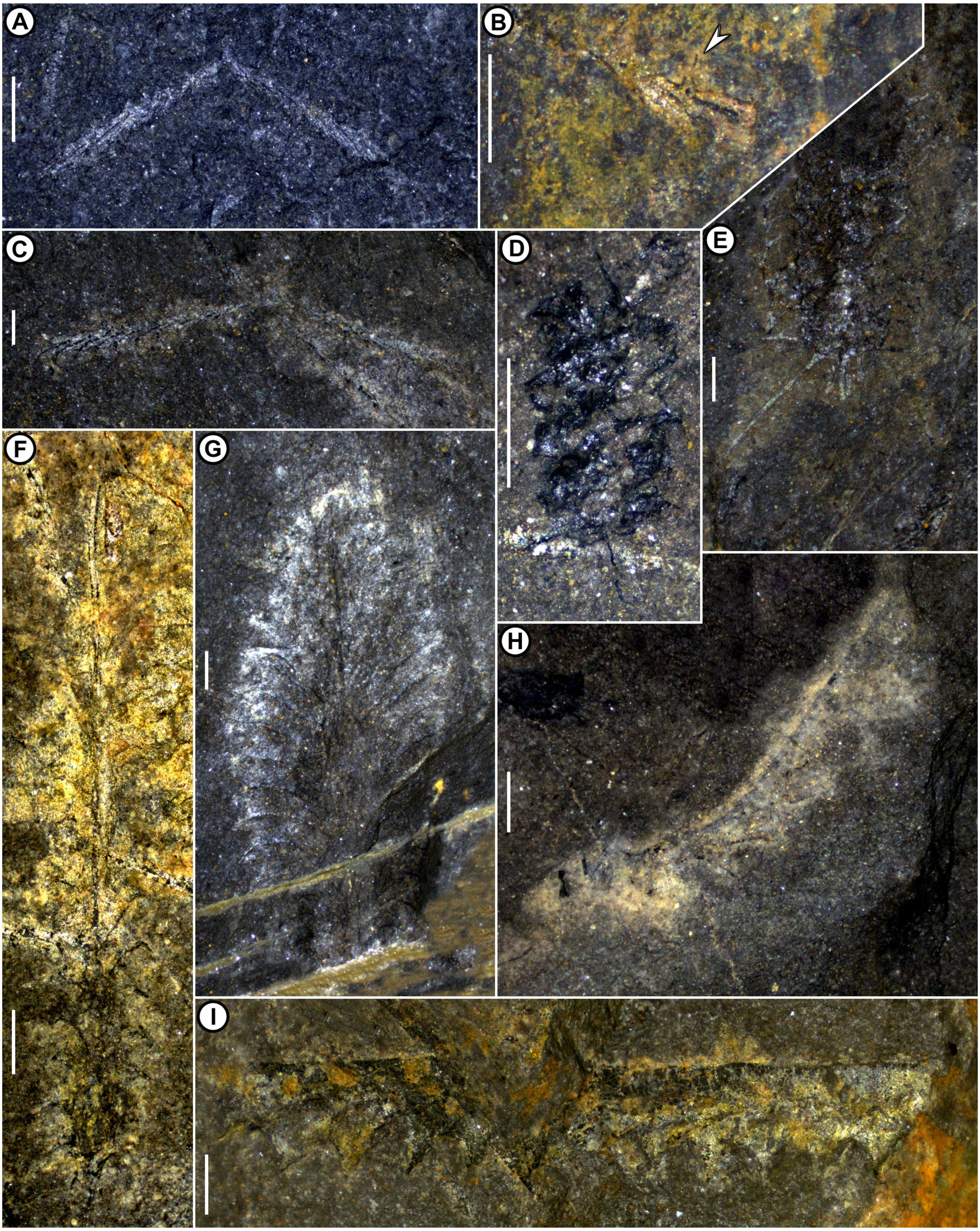

Figure 6. Graptolites from the *Holmograptus spinosus* Zone. **a-c)** *Holmograptus spinosus.* **b**. The arrow indicates the dorsal spines that characterized the species. INGEO-PI-1976, 1978, 1980. **d)** *Archiclimacograptus* sp. INGEO-PI-1981. **e)** *Paraglossograptus tentaculatus.* INGEO-PI-1975. **f)** *Cryptograptus schaeferi*. INGEO-PI-1982. **g)** *Pseudophyllograptus* sp. INGEO-PI-1974. **h)** *Tetragraptus* sp. INGEO-PI-1973. **i)** *Xiphograptus* sp. INGEO-PI-1983. All the scale bars equals 1 mm.

deposition. This regional process is associated to the accretion of the exotic Cuyania terrane to the western margin of Gondwana during the Guandacol Tectonic Phase (Furque and Cuerda, 1979; Ramos *et al.*, 1986; Astini, 1998; Astini *et al.*, 1995; Ramos, 2004). This facies change marks the boundary between the limestones of the San Juan Formation from the overlying interbedded shales and limestones (*transfacies*), and the black shales of the Gualcamayo Formation (Furque, 1963).

Based on the geologic and paleontologic observations on the olistoliths from the La Rinconada Formation presented herein, a regional correlation is proposed for the transition between the limestones of the San Juan Formation and the black shales of the Gualcamayo Formation (Fig. 10). This correlation includes five localities in Precordillera: 1) the Gualcamayo-Guandacol area, 2) the Villicum Range (Don Braulio and La Pola creeks), 3) La Rinconada (this study), 4) the Pedernal Range, and 5) north and south areas of the Las Higueras Range.

In the Gualcamayo-Guandacol area, northern San Juan, Central Precordillera (Fig. 1), the contact between the San Juan and Gualcamayo formations has been dated as middle Dapingian based on the presence of the *Isograptus maximus* graptolite Zone, associated with the *Baltoniodus navis* conodont Zone (Ortega *et al.*, 1993; 1995; Mango and Albanesi, 2023). The top of the Gualcamayo Formation is eroded and overlaid by other Ordovician or younger formations, spanning up to the *Pterograptus elegans* and *Hustedograptus teretiusculus* graptolite zones (Ortega et al., 1993; Ortega and Albanesi, 2000; Máspero Castro *et al.*, 2003).

In the Villicum Range, the beginning of the drowning of the carbonate deposits and the base of the Gualcamayo Formation was dated as early Darriwillian, based on the record of the *Levisograptus dentatus* graptolite Zone. The top of the Gualcamayo Formation possesses the *P. elegans* graptolite Zone and is paraconformably covered by the late Darriwillian La Cantera Formation (Peralta, 1993; Peralta 1995; Kaufmann, 2019).

Recent paleontologic observations from allochthonous limestone olistoliths related to the San Juan Formation and embedded in the matrix of the Rinconada Formation at La Rinconada section, allowed dating those levels as late Floian to early-middle Darriwillian (Voldman *et al.*, 2015; 2018). Even though the presence of Gualcamayo Formation blocks was already mentioned (Ramos *et al.*, 2000) and their fossil content was analyzed (see Peralta, 1986; Peralta and Uliarte, 1986; Sarmiento *et al.*, 1986; Lucena, 1988; Dorn, 1993), no link between the stratigraphic nature of the blocks and the fossiliferous content was made. The present study describes for the first time the base of the Gualcamayo Formation from allochthonous blocks within the Rinconada Formation and, based on the presence of the *Holmograptus spinosus* graptolite Zone, provides new biostratigraphic dates for those levels as middle Darriwillian. The latter represents the youngest age ever recorded for the beginning of the Gualcamayo Formation.

In the Pedernal Range, the stratigraphic contact between the San Juan and Gualcamayo formations is absent, although a contact with black shales (probably of the Los Azules Formation) possibly represent the carbonate platform drowning process in that area (Mestre and Heredia, 2014). Lehnert (1995) recorded the *Eoplacognathus suecicus* conodont Zone in the top most levels of the San Juan Formation, suggesting that the age of the drowning process might be, at least, middle Darriwillian or post-E. suecicus Zone, representing the youngest age for the contact between the San Juan and overlying formations. A graptolite analysis in the black shales at the Pedernal Range section might show even younger ages for the carbonate platform drowning process, although further studies are needed to test this hypothesis.

Finally, Heredia *et al.* (2009) reported the presence of the Gualcamayo Formation above the limestones of the San Juan Formation in the southern area of the Las Higueras Range, Mendoza Province (Fig. 1). A conodont analysis allowed dating the top most carbonate beds of the San Juan Formation as late Floian (*Oepikodis evae* and *O. intermedius* conodont Zones), but no fossils were recovered in the overlying unit. Based on its stratigraphic position, these authors suggested a late Floian-early Dapingian age for the Gualcamayo Formation. Similar to the case of the Gualcamayo-Guandacol area, this would represent the oldest beginning of the drowning process in Precordillera. This age assignment would conflict with the hypothesis of a gradual drowning of the carbonate platform towards the southwest (Astini *et al.* 1995; Astini, 1998), suggesting that this process would have started synchronously in two different zones: the Gualcamayo-Guandacol area (North) and in Las

Higueras Range (South). Furthermore, this would complicate the accretionary model of the Cuyania terrane at the Gondwanic margin during the Middle Ordovician: *i.e.* the accretion of the Cuyania terrane would have started in the north-east area of Precordillera and produced the subsidence of the basin and the consequent carbonate drowning (the San Juan-Gualcamayo contact). As a consequence, the oldest deposits of the Gualcamayo Formation are found at the Gualcamayo-Guandacol area.

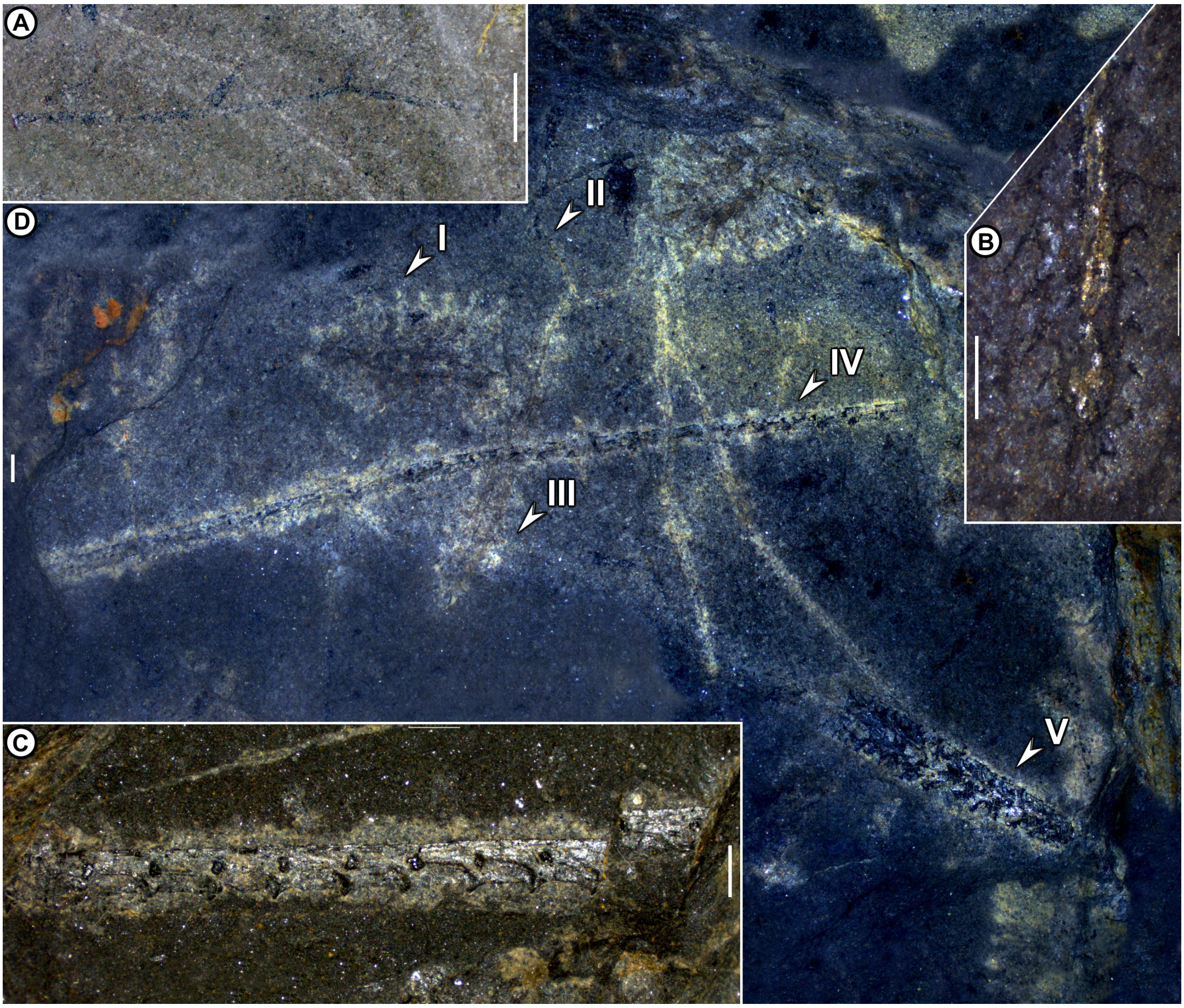

Figure 7. Graptolites from the *Holmograptus spinosus* Zone. **a)** *Holmograptus bovis.* INGEO-PI-1986. **b)** *Cryptograptus schaeferi*. INGEO-PI-1987. **c)** *Atopograptus* sp. INGEO-PI-1984. **d)** Sample showing the typical disposition and preservation of the graptolite assemblages: **I.** *Pseudophyllograptus* sp. **II.** *Holmograptus spinosus*. **III.** *Cryptograptus schaeferi*. **IV.** *Atopograptus* sp. **V.** *Archiclimacograptus* sp. INGEO-PI-1985. All scale bars equals 1 mm.

The presence of similar and age-equivalent deposits in the southernmost Precordillera (Las Higueras Range) would implicate a different and more complex collision model than the present proposal, added to the fact that no evidence have been found that support this variation. In contrast, Beresi *et al.* (2017) recorded the early Darriwilian *Y. crassus* and *L. dentatus* conodont and graptolite zones in the lower levels of the Los Azules Formation, located 7 km northward of those analyzed by Heredia *et al.* (2009). This shows more consistent ages with regard to the current collision model and with the drowning process of the carbonate platform in the southern sectors of the Ordovician basin. Stratigraphic and

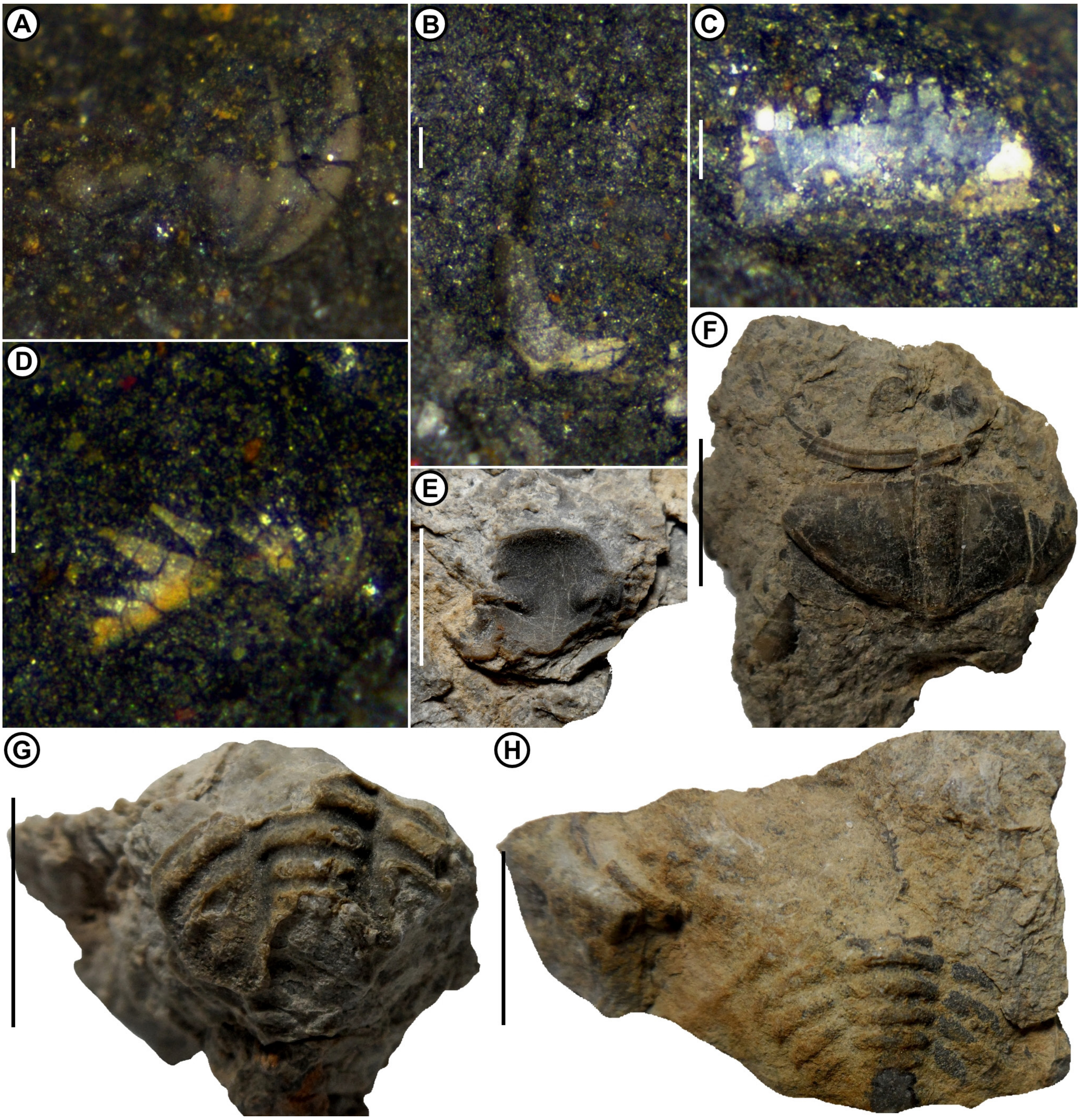

Figure 8. Conodonts and trilobites from allochthonous black shales and marlstones samples. **a)** *Paroistodus horridus*. INGEO-PI-1971. **b)** *Protopanderodus* sp. INGEO-PI-1969. **c)** *Histiodella* sp. INGEO-PI-1970. **d)** *Periodon macrodentatus*. INGEO-PI-1969. **e, g-h)** *Annamitella* sp. INGEO-PI-1966-1968. **f)** *Mendolaspis* sp. INGEO-PI-1965. Scale bars equals: 0.1 mm (a-d); 1 cm (e-h).

biostratigraphic studies in intermediate outcrops (south of the Pedernal and north of the Las Higueras ranges) and a graptolite-conodont biostratigraphic study in the south area of the Las Higueras Range black shales, would add clues for the morphology and development of the Ordovician basin of the Eastern Precordillera during the Guandacol Tectonic Phase.

The correlation presented in Figure 10 shows older ages for the Gualcamayo Formation base (and equivalent units) in the north and south areas of the Precordillera basin, whereas the younger ages are

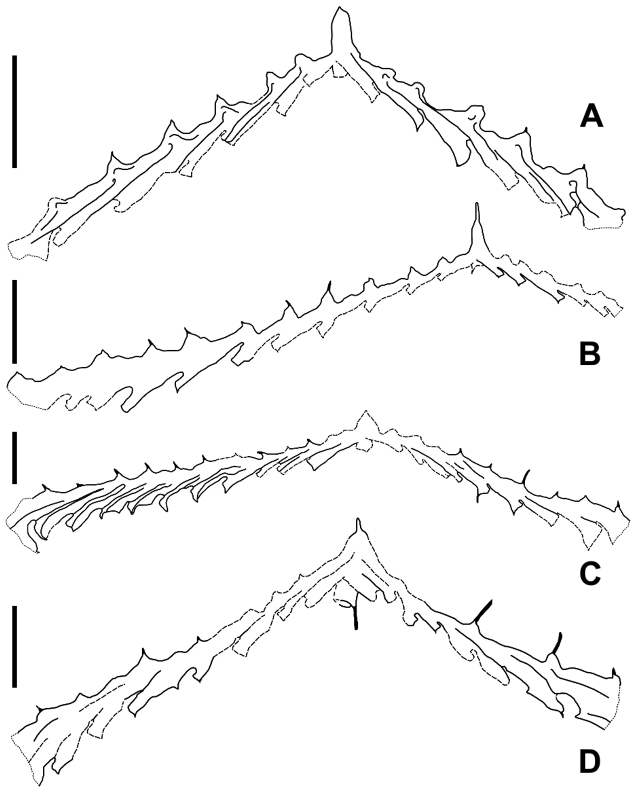

Figure 9. Transparent drawings of some colonies of *Holmograptus spinosus* with proximal ends. INGEO-PI-1976, 1978-1980. Scale bars equals 1 mm.

located at the La Rinconada section (this study) and possibly at the Pedernal Range section (central areas of the basin), highlighting the upward convexity of the basin shape. The existence of post-San Juan Formation Ordovician units in the central area of the Precordillera disagrees with the north-south regional section of Astini (1992), which showed no Ordovician siliciclastic deposits in the Tambolar and surrounding areas, with the local exception of the Katian Sassito Formation in the Los Caracoles dam area (Astini and Cañas, 1995; Keller and Lehnert, 1998; Ernst and Carrera, 2008). This discrepancy can be explained by a Central Precordillera location of the section of Astini (1992), whereas the Figure 10 shows mostly Eastern Precordillera deposits. On the other hand, the west-east section of the cited study showed a deepening to the east of the Pachaco area (La Chilca and Villicum sections), allowing the deposition and preservation of siliciclastic deposits. The presence of the black shale olistoliths of the Gualcamayo Formation within the Rinconada Formation matrix represents strong evidence to support both the west-east basin model proposed by Astini (1992), which can be extended to the southern La Rinconada section; and the Alto del Tambolar influence during the deposition of the Ordovician units in the Central and Eastern Precordillera. The collision-driven subsidence produced the carbonate drowning process to occur first in the Gualcamayo-Guandacol area (middle Dapingian) and later in almost all the Precordillera sections (Lower Darriwilian). The upward convex basin shape delayed the carbonate drowning phase at the Rinconada and Pedernal sections (middle Darriwilian).

Analysis of the Rinconada Formation Basin

A north-south comparison along the Villicum, La Rinconada, and Pedernal sections of the Rinconada Formation in Eastern Precordillera shows marked stratigraphic differences (Fig. 11a). The first one is the nature of the sedimentary succession underlying the Rinconada Formation. At the Villicum section, it is composed of the Gualcamayo, La Cantera, La Pola, and Don Braulio formations (Peralta, 1984; 1993; Astini, 2001; and later studies), with a thickness of 268 m. At the La Rinconada section, the Rinconada Formation overlies the San Juan Formation, with no evidence of autochthonous siliciclastic Ordovician deposits (Peralta, 1986; Voldman *et al.*, 2015; 2017; 2018; this study). Southwards at the Pedernal section, the Rinconada Formation rests on top of two, 14

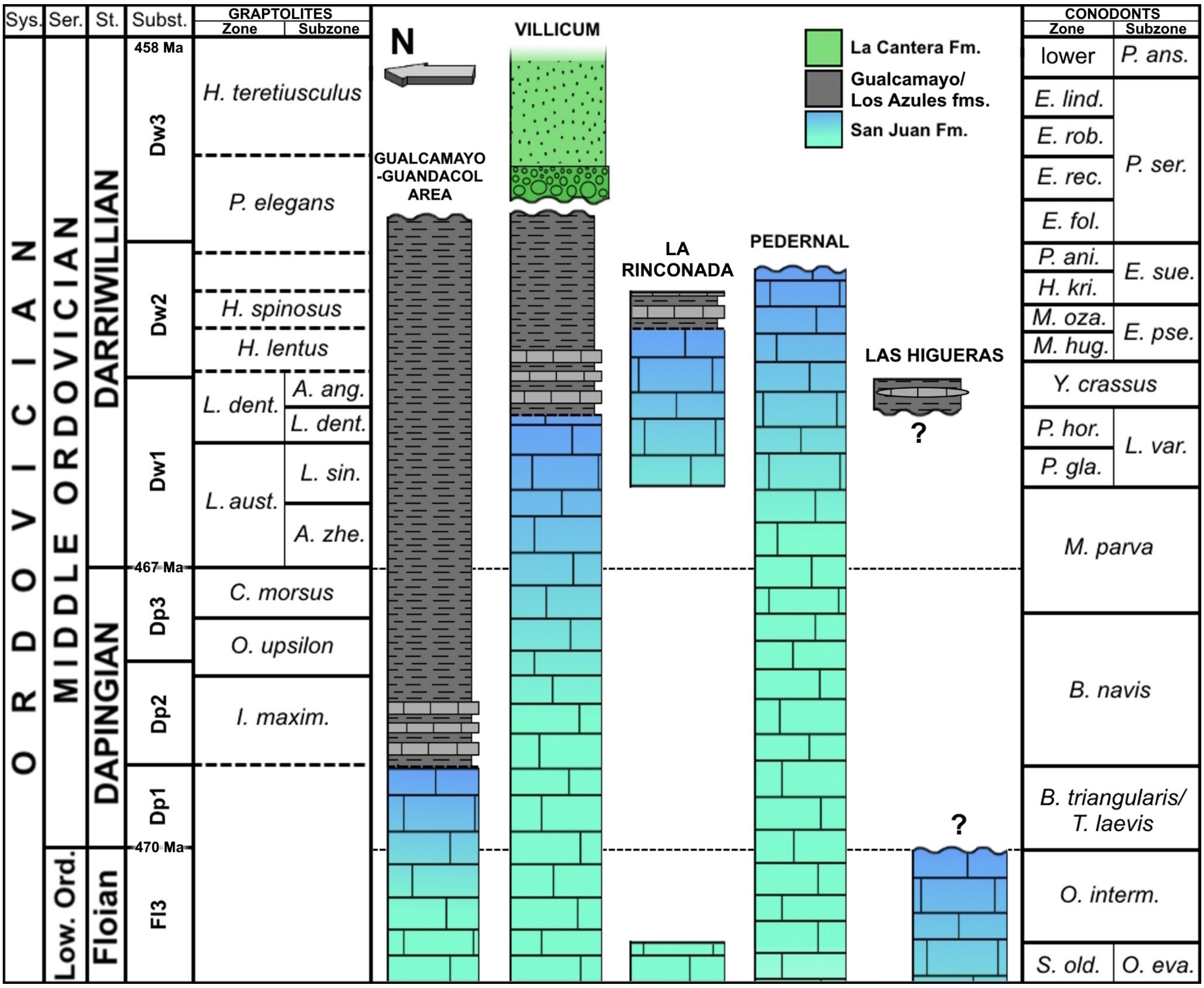

Figure 10. Chronostratigraphic correlation of the San Juan-Gualcamayo formations contact and the drowning phase (*transfacies*) strata. Biostratigraphic chart of graptolites and conodonts taken from Albanesi and Ortega (2016). Stratigraphic data from Ortega *et al.* (1993), Heredia *et al.* (2009), Mestre and Heredia (2014), Beresi *et al.* (2017), Kaufmann (2019), and this study.

m-thick siliciclastic deposits of the Los Azules and Don Braulio formations (Mestre and Heredia, 2014; Fig. 11b).

A second remarkable difference among these localities is the Rinconada Formation thickness, which varies from *ca.* 800 m in the Villicum section (Peralta, 1984), to 600 m or less in the La Rinconada section (Peralta, 1986; Lopez *et al.*, 2023a), and *ca.* 640 m in the Pedernal Range (Peralta and Medina, 1985). Thickness variations were already identified in the Ordovician, Silurian, and Devonian deposits of Central and Eastern Precordillera and related to the Alto del Tambolar activity (and Arco Talacasto-Tambolar; Astini, 1992; 1994; 1996; Astini and Maretto, 1996; Sánchez *et al.*, 1996; and later studies). Astini (1992) identified the influence of this structure conditioning the accumulation of the San Juan Formation, the siliciclastic Ordovician units, as well as the Tucunuco (marine late Ordovician-early Devonian) and Gualilán groups (marine Devonian). Following this idea, the absence of autochthonous Gualcamayo Formation and younger units in the La Rinconada section, might be explained by erosional processes favoured by the Alto del Tambolar tectonic activity, synchronous with the deposition of the Rinconada Formation. This structural high, together with the main basin faults, reconfigured the east side of the basin, possibly enabled the erosion of the Ordovician units (*e.g.*, Gualcamayo Formation/ghost formation, La Cantera, La Pola, and Don Braulio formations), and included them as olistoliths in the matrix (Fig. 2). Moreover, the existence of autochthonous Ordovician deposits at the Villicum and Pedernal sections supports the upward flexure of the basin, and indicates a strong influence of the Alto del Tambolar during the deposition of the Rinconada Formation (Fig. 11b). The Alto del Tambolar might have controlled the thickness reduction in the middle of the Eastern Precordillera (La Rinconada area), located eastward to the Tambolar area. This thickness trend could be a response to this elevated structure, which might have produced the thinning of the deposits. This feature has been observed in many other Paleozoic formations in the Precordillera (*e.g.*, San Juan, La Chilca, Los Espejos/Tambolar formations, among others; Astini, 1996; Astini and Maretto, 1996; Sánchez *et al.*, 1996). Unfortunately, the synsedimentary-tectonic complexity of the Rinconada Formation prevents reliable thickness measurements, and the mentioned values may not be accurate. Future studies with more precise stratigraphic columns might shed light on this proposal.

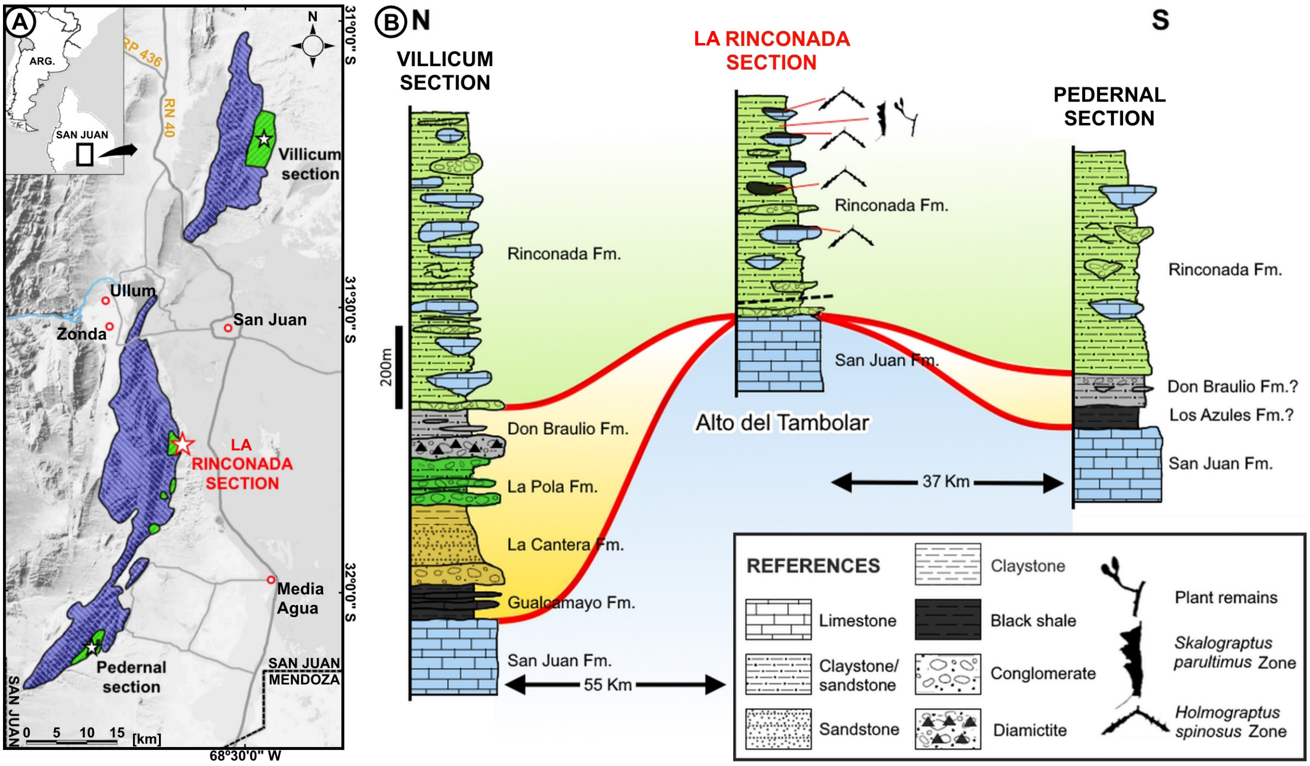

Figure 11. Schematic cross section of the Rinconada Formation basin across the Eastern Precordillera. **a)** Synthetic map of the Eastern Precordillera (marked in blue), showing the three main study sections of the Rinconada Formation. **b)** Stratigraphic correlation of the formational content described in each section (stratigraphy after Peralta and Medina, 1985; Peralta, 1986; 1993; Mestre and Heredia, 2014; Lopez *et al.*, 2023a; this study). Ordovician units not to scale.

CONCLUSIONS

This contribution describes the occurrence of allochthonous olistoliths of varied sizes composed of black shales and marlstones embedded within the Silurian-early Devonian Rinconada Formation matrix. The olistoliths, interpreted to come from the lower beds of the Gualcamayo Formation or from the transition between the limestones of the San Juan Formation and the lower beds of the Gualcamayo Formation, show an important fauna of graptolites in their bedding planes, as well as conodonts and trilobites.

The analyzed graptolite fauna includes the index fossil *Holmograptus spinosus*, associated with *H. bovis*, *Cryptograptus schaeferi*, *Paraglossograptus tentaculatus*, *Archiclimacograptus* spp., *Atopograptus* sp., *Pseudophyllograptus* sp., *Tetragraptus* sp., and *Xiphograptus* sp.. Also, specimens of the conodont *Histiodella* sp., *Paroistodus horridus*, *Periodon macrodentatus*, and *Protopanderodus* sp. are found. In the interbedded marlstones, the trilobites *Annamitella* sp., *Mendolaspis* sp., and *Carolinites*? sp. were registered. This discovery allows recording the middle Darriwilian *H. spinosus* Zone, representing the third record of this biozone in South America.

These results are of relevance because allow dating the drowning phase (*transfacies*) of the Ordovician carbonate platform at the La Rinconada section as middle Darriwilian, which represents the youngest age ever assigned to this event. This, together with the location of the study area within the Precordillera context, indicates a progressive southward drowning model of the Ordovician carbonate platform. In addition, the differences in the stratigraphic arrangement of the underlying units of the Rinconada Formation, together with contrasting thickness measurements, might indicate evidence of the Alto del Tambolar tectonic activity during the deposition of the Rinconada Formation, a process previously recognized for the deposition of the Tucunuco Group in the Central Precordillera.

Acknowledgements. The authors are grateful to Dr. Blanca Toro and an anonymous reviewer, as well as to the editors Dr. Raigembron and Dr. Cuitiño, for their important comments, which substantially improved the original manuscript. Thanks to Dr. Gladys Ortega and Dr. Guillermo L. Albanesi for their comments and advice on taxonomic determinations; to the Instituto y Museo de Ciencias Naturales (IMCN), and the Universidad Nacional de San Juan for their instrumental support; and to the Consejo Nacional de Investigaciones Científicas y Técnicas *CONICET* for funding this study. Finally, this is a contribution to IGCP 735 project *Rocks and the Rise of Ordovician Life*.

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