



New invertebrate peri-glacial faunal assemblages in the Agua de Lucho Formation, Río Blanco Basin, Argentina. The most complete marine fossil record of the early Mississippian in South America

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ABSTRACT

A new fossil record of early Mississippian marine faunas is described from the Agua de Lucho Formation in the Sierra de las Minitas (La Rioja province, Río Blanco Basin, western Argentina). Considered Tournaisian in age based on local palynological data and biostratigraphic correlations, this faunal record is notably diverse associated with glacially influenced deposits, in contrast with other early Mississippian assemblages from Argentina, traditionally described as developed in warm to temperate climates. The vertical distribution of bivalves and brachiopods, in particular, indicates significant faunal changes through the thick section studied, and their occurrences are compared with those described from the Zorritas Formation in northern Chile. The new records include some typical components of the regional *Michiganites scalabrinii*-*Azurduya chavelensis* assemblage Zone, but important vertical and lateral compositional variations of this biozone are discussed. It also highlights the importance of the species *Azurduya chavelensis* as a conspicuous component of the Early Mississippian deposits from South America, which would become a proper macrofaunal tool to intra and inter-basinal correlations.

1. Introduction

The Early Mississippian (Tournaisian), represents a key interval of the late Paleozoic Ice Age (LPIA) since it records both the initial stages of the LPIA and the recovery interval from the Late Devonian biodiversity crisis (McGhee 2018). In contrast to Late Mississippian to Permian high-latitude glacial faunas, which have been widely studied (Césari et al., 2007; Sterren and Cisterna, 2010; Waterhouse and Shi, 2013; Cisterna et al., 2014, 2017, 2019; Taboada, 2010; Taboada et al., 2019), the Tournaisian high latitude marine faunas are less well known. Virtually most of the Tournaisian faunas are restricted to tropical to subtropical regions (Qiao and Shen, 2014), and such a geographic bias limits our understanding of the biotic response to the start of LPIA, as well as the recovery of the Late Devonian crisis.

Early Mississippian marine faunas from high latitude in Gondwana have only been recorded from western Argentina (Río Blanco Basin, González, 1994; Sabattini et al., 2001, and references therein),

Patagonia (Valle Chico Formation, Tepuel-Genoa Basin, González et al., 1995; Taboada et al., 2018, 2019) and northern Chile (Sierra de Almeida, Isaacson et al., 1985; Dutro and Isaacson, 1990; Niemeyer et al., 1997; Isaacson and Dutro, 1999). In most of these regions record a low diversity marine fauna that would be dominated by the endemic brachiopod *Azurduya* Cisterna and Isaacson, and abundant bivalves (González, 1994; Cisterna, 1996, 2011; Sterren and Cisterna, 2010). The highly endemic nature of this low-diversity brachiopod fauna would define the Gondwanan Realm, one of the two biogeographic regions described for the Tournaisian (Qiao and Shen, 2014). The low faunal diversity registered in the early Mississippian assemblages, fundamentally in brachiopods, has been explained as a product of the highly stressed palaeoenvironmental local conditions in western Argentina (González, 1994; Cisterna, 1996, 2011; Sterren and Cisterna, 2010). However, the actual relationship between the marine fauna and the presence of glacial influence remained unknown due to the doubtful evidence to support

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ice-house conditions during the Late Devonian-earliest Carboniferous (Limarino et al., 2014).

We here describe the detailed stratigraphic distribution of a high-latitude Tournaisian fauna from the Agua de Lucho Formation in the Río Blanco Basin (Sierra de las Minitas, western Argentina). The fauna comes from two stratigraphic sequences with glacial influence (Ezpeleta et al., 2020), representing the oldest record of marine invertebrate fauna from ice-proximal regions during the LPIA. The contribution focuses on brachiopods and bivalves, the main components of the invertebrate assemblages, with paleoecological, paleobiogeographic, and biostratigraphic implications.

2. Stratigraphic setting

In southwestern Gondwana, the Mississippian sedimentary basins from the southern South America have been linked to a proto-Andean active tectonic margin and located at high paleolatitude (eg. Torsvik et al., 2012). Hence, these foreland basins show complex superimposed patterns of paleoclimatic and tectono-sedimentary processes in rich siliciclastic settings (Caputo et al., 2008; Montañez and Poulsen, 2013; Gulbranson et al., 2010, 2014; Limarino et al., 2014; Lakin et al., 2016).

The scarce Tournaisian fossiliferous marine records are only known in Chile and Argentina. The Chilean paleontological data correspond to

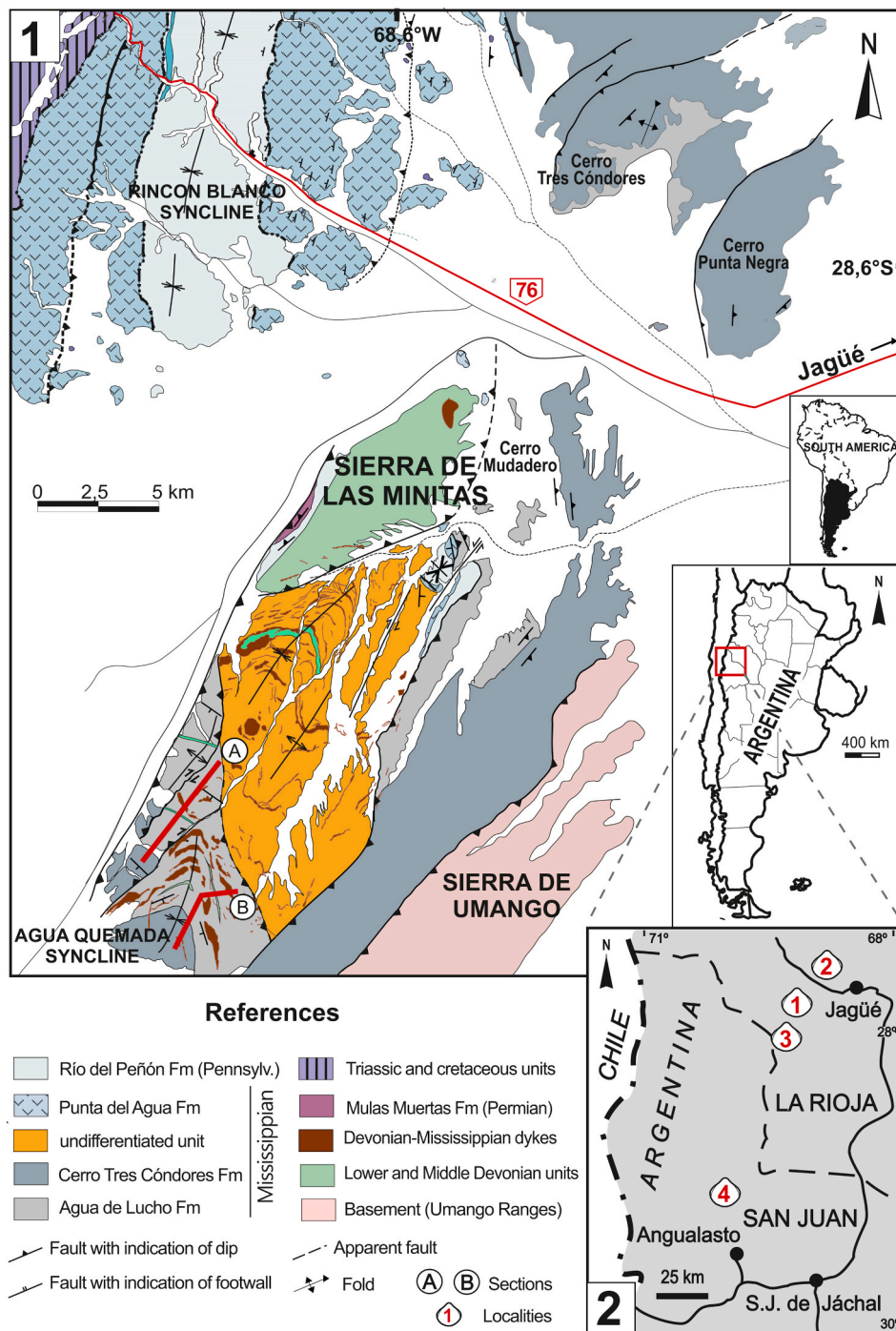


Fig. 1. Location map of the Sierra de las Minitas area, northern Río Blanco Basin, La Rioja Province, Argentina. 1. A and B are the studied sections (see Ezpeleta et al., 2020)(Modified from Coughlin, 2000). 2. Distribution of the early Mississippian marine faunas within the basin. 1, Sierra de las Minitas, 2, Cerro Agua de Lucho, 3, Quebrada de la Troya, 4, Malimán.

the Sierra de Almeida northern Chile, with ages constrained by palynomorphs and ammonoids (Isaacson et al., 1985; Dutro and Isaacson, 1990; House, 1996; Niemeyer et al., 1997; Isaacson and Dutro, 1999; Korn et al., 2003; Zong et al., 2015; Rubinstein et al., 2017).

In Argentina, in addition to some preliminary reports from central-western Patagonia (Taboada et al., 2019), the best fossiliferous Tournaisian records correspond to the Río Blanco Basin (Fig. 1.1), in central-western Argentina (Amos, 1958; Amos et al., 1973; Antelo, 1969, 1970; Riccardi and Sabattini, 1975; González, 1994; Sabattini et al., 2001, among others). This basin was also interpreted as a northernmost depocenter of a single larger Uspallata-Iglesia Basin, which virtually embraced the whole Argentine Precordillera, a morpho-structural present region defined along the Mendoza, San Juan and La Rioja provinces, from south to the north (González, 1985; Limarino and Spalletti, 2006; Carrizo and Azcuy, 2015).

The classical lower Mississippian units of the Río Blanco Basin include the Tournaisian-Viséan Malimán Formation (Scalabrini Ortiz, 1973b) and the mainly Viséan Cortaderas Formation (Scalabrini Ortiz, 1973a), in their type area near Malimán (Fig. 1.2), in the Sierra de la Punilla, San Juan province (Sabattini et al., 2001; Amenábar et al., 2007, 2009; Pérez Loinaze, 2007, 2008), grouped into the Angualasto Group (Limarino and Césari, 1993).

In the La Rioja province, to the north, Caminos et al. (1993) reported a marine fauna from the La Punilla Formation (Furque, 1956); and near there to the north, at Quebrada de la Troya (Fig. 1.2), another more diverse fauna had also been reported by Fauqué et al. (1989). These faunas were considered similar to those recorded in the Malimán Formation.

In the northernmost reaches of the basin (in the La Rioja province), equivalent units with fauna included the Tournaisian glaciomarine Agua de Lucho Formation (González and Bossi, 1987) and the Viséan mainly fandeltaic Cerro Tres Cóndores Formation (González and Bossi, 1987), in their type area of the Bolsón de Jagüé, including the Sierra de las Minitas region (Borrello, 1955; Scalabrini Ortiz and Arrondo, 1973; González and Bossi, 1986, 1987; Fauqué and Limarino, 1991; Caminos et al., 1993; Coughlin, 2000; Sabattini et al., 2001; Gutiérrez and Limarino, 2006; Carrizo and Azcuy, 2015; Prestianni et al., 2015; Ezpeleta et al., 2020). Carrizo and Azcuy (1998, 2015) proposed the inclusion of all these units in the Angualasto Group. A summary of the different local to regional lithostratigraphic units and correlations previously used was provided by Limarino et al. (2014), Carrizo and Azcuy (1998, 2015), and Ezpeleta et al. (2020). Virtually all previously known Tournaisian marine faunal records of the La Rioja province came from the Agua de Lucho Formation at its type section in the Cerro Agua de Lucho, to the north of the Sierra de las Minitas area. Hence, this unit was correlated with the Malimán Formation (Fig. 1.2). Ezpeleta et al. (2020), in a detailed stratigraphic analysis of the Agua de Lucho Formation at Sierra de las Minitas (Fig. 1.2), preliminarily reported an important paleontological content linked to glacial settings, particularly in the lower half of the unit. The present contribution is focused on the same two detailed stratigraphic sections (A and B) as described by Ezpeleta et al. (2020) in the Agua Quemada syncline to the southern part of the Sierra de las Minitas (Fig. 1.1). The previous paleontological reports by Cisterna and Isaacson (2003) come from the same outcrops.

In this area, the unit shows a continuous exposure of approximately 1250 m, with a concealed base due to a tectonic contact with younger Carboniferous successions, and the top represented by a progressive and concordant passage to the conglomeratic successions of the Viséan Cerro Tres Cóndores Formation (Figs. 1 and 2). Several siliciclastic lithofacies were recognized by Ezpeleta et al. (2020), ranging from diamictites, and conglomerates (including faceted and striated clasts), sandstones and mudstones with dropstones, through to bioturbated and fossiliferous mudstones, recording glaciomarine and deltaic environments. Facies associations were arranged in depositional sequences that record relative sea-level variations associated to tectonism and glacial advance–retreat

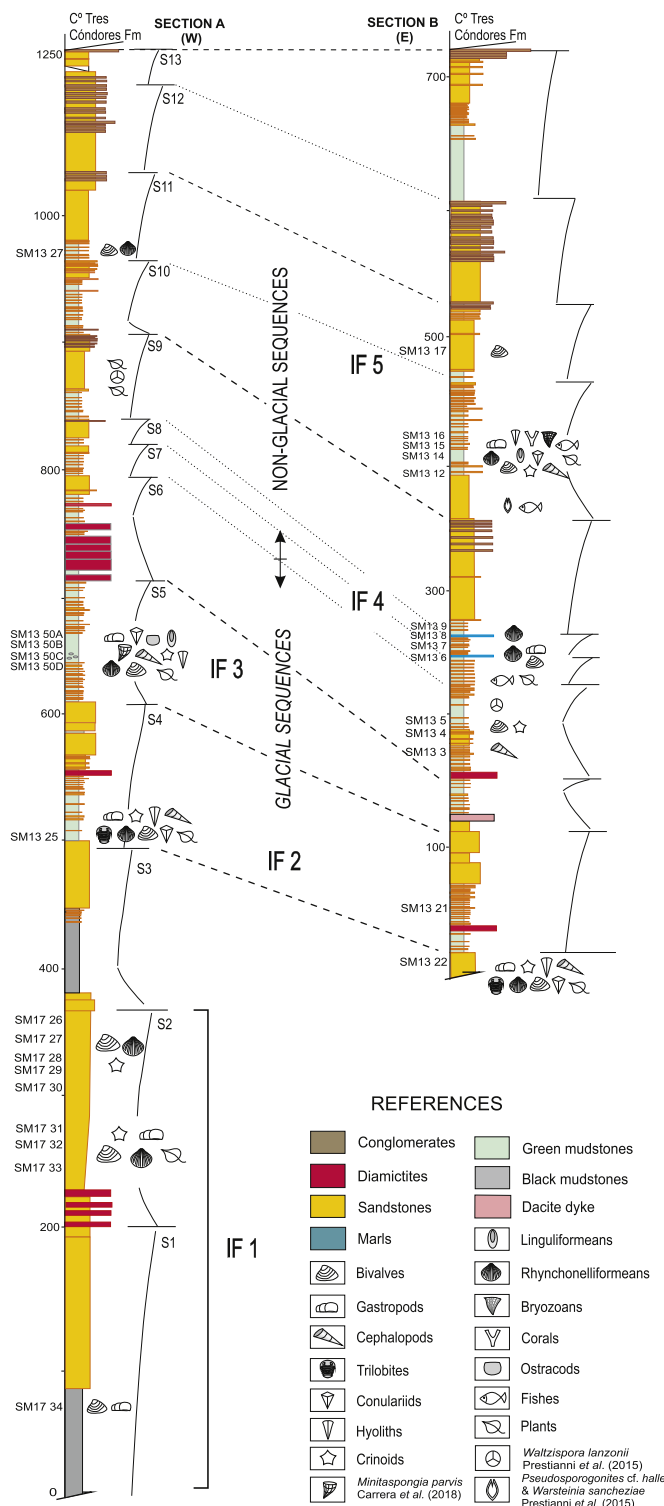


Fig. 2. Vertical distribution of the faunal associations identified in the stratigraphic sections of the Agua de Lucho Formation at Sierra de las Minitas. For detail of the stratigraphic sequences see Ezpeleta et al. (2020) (Modified from Ezpeleta et al., 2020).

cycles (Ezpeleta et al., 2020). These authors divided the thick succession of the Agua de Lucho Formation into thirteen sequences (comprising three main types of sequences), and interpreted them as deposited in extensional settings. They recognized varying degrees of glacial influence, from conspicuous evidence in the lower part of the column (sequences 1 to 6) to no glacial records at the top (sequences 7 to 13).

3. Age constraints and previous paleontological reports

The sedimentary successions of the Agua de Lucho Formation in the southern Sierra de las Minitas are considered Tournaisian in age due to the occurrence of the miospore *Waltzispora lanzonii* Daemon 1974, reported by Prestianni et al. (2015) from the lower half of Section B (Fig. 2). The index spore *Waltzispora lanzonii* indicates a middle to late Tournaisian age for at least that part of the section (see Playford and Melo, 2010; Lakin et al., 2016). Preliminary palynological reports suggesting Devonian ages in the very same stratigraphic position were interpreted as reworked material (see Prestianni et al., 2015).

The record of the brachiopod *Azurduya chavelensis* (Amos) above the level yielding *W. lanzonii* (Sterren et al., 2013) is consistent with a late Tournaisian age for the nearly whole section of the Agua de Lucho Formation (Ezpeleta et al., 2020). This brachiopod is a key element of the *Michiganites scalabrini-Azurduya chavelensis* Zone (Sabattini et al., 2001), defined in the Malimán Formation and recorded in other Mississippian basins of southwestern Gondwana (Cisterna, 2011; Cisterna and Isaacson, 2003; Isaacson and Dutro, 1999; Niemeyer et al., 1997; Sterren and Cisterna, 2010).

The fossil assemblages previously reported in the Agua de Lucho Formation, both in the studied area and in the type area (Cerro Agua de Lucho), are usually dominated by bivalves and brachiopods (González, 1994; Sterren and Cisterna, 2010; Sterren et al., 2013), with subordinate crinoids, non-ammonoid cephalopods, gastropods, hyoliths, conulariids, and corals. Scarce records of bryozoans, fishes, and trilobites (Vaccari et al., 2013) are restricted to a few specific intervals (Fig. 2). Also, the endemic hexactinellid sponge *Minitaspongia parvis* Carrera et al. (2018) was recognized in the levels SM50 A to C, in the middle part of section A (Fig. 2).

Carboniferous megaflora from this region have been exhaustively studied by Azcuy and Carrizo (1995) and Carrizo and Azcuy (1998, 2015). According to their biostratigraphic proposal, the Agua de Lucho formation would involve the *Gilboaphyton-Malimanium* Zone (Carrizo and Azcuy, 2015). Prestianni et al. (2015), in turn, reported *Warsteinia sancheziae* Prestianni et al. (2015), and *Pseudosporogonites* cf. *hallei* (Stockmans) from a level which corresponds to the upper half of Section B herein (Fig. 2). These records would represent the oldest seed occurrences from western Gondwana.

4. Material and methods

Several fossiliferous levels were identified in the outcrops of the Agua de Lucho Formation, at the Agua Quemada synclinal area in the southern portion of the Sierra de las Minitas (Fig. 1).

Paleontological sampling was undertaken bed by bed, in the two stratigraphic sections separated by 2.5 km, as described by Ezpeleta et al. (2020).

Section A (western) is approximately 1250-m-thick, and Section B (eastern) is about 730 m-thick (Figs. 1.1 and 2). The middle-upper part of section A was surveyed to the south from SM13 25 (located at GPS 28° 47'33.2" S/68° 45'24.6" W), and the lower part was surveyed to the north from SM17 26 (located at GPS 28° 47' 18.66" S/68° 44' 40.62" W). Section B was measured and described upwards and downwards from the main diamictite outcrops in the nucleus of the Agua Quemada syncline at GPS 28° 48' 31.7" S/68° 45' 00.7" W. A reliable correlation between both sections was based on sequential stratigraphic main boundaries along with paleontological vertical distributions (see Ezpeleta et al., 2020).

The stratigraphic range of each taxon was based on the occurrences of both sections, as shown in an integrated column (Fig. 3). Environmental interpretations of each fossiliferous level follow Ezpeleta et al. (2020).

Taxonomy and analysis of the stratigraphic distribution were focused on brachiopods and bivalves, the main components of the invertebrate fauna. Other taxa such as trilobites, gastropods, cephalopods,

conulariids, crinoids, hyoliths, bryozoans, ostracods, sponges, corals, and fishes have been just referred to the sections A and B.

Fossils have been prepared mechanically, using pneumatic vibrators and thin needles. In the case of external casts, latex molds were obtained using black colored latex. Photographs of specimens were taken using flash illumination after whitening with ammonium chloride. Images were captured using a Canon Power Shot S50 digital camera mounted on a Leica MZ75 binocular magnifier.

Material is housed in the paleontological repository of the Museo de Ciencias Antropológicas y Naturales, Universidad Nacional de la Rioja, La Rioja province, Argentina, with repository number prefixed PULR-I.

5. Stratigraphic distribution of the invertebrate fauna in the Agua de Lucho Formation in Sierra de las Minitas locality

Five fossiliferous intervals with abundant marine invertebrate fauna were identified in the studied sections (Fig. 2).

5.1. Fossiliferous interval 1

The oldest fossiliferous interval (FI 1) was only found in the western stratigraphic profile (Section A, 370 basal meters that involves the sequences 1 and 2 by Ezpeleta et al., 2020), where the sedimentary succession shows a greater thickness. The lower beds (SM17 34, Fig. 2) contain poorly preserved bivalves and gastropods, and appear 80 m over the base, at the top of black mudstones interval interpreted as mid-shelf to offshore environments (Sequence 1, Ezpeleta et al., 2020). Several levels were recorded in mudstones with sandstones interbedded (SM17 33 to 26, between the 230 and 370 m) interpreted as sedimentation in an outer shelf to offshore transition zone (lower to middle shoreface, Sequence 2, according to Ezpeleta et al., 2020).

This interval is strongly dominated by bivalves, with subordinated brachiopods (Figs. 3 and 4), gastropods, and crinoids. Nuculid bivalves are the most abundant, accompanied by modiomorphids and myalinids. Brachiopods are scarce and very fragmentary but dominated by rhynchonellids, with incomplete specimens (mostly internal molds) of indeterminate chonetids and spiriferids.

Taxa identified are *Malimania triangularis* González, *Phestia* sp., *Cypricardinia* sp., *Malimania malimanensis*? González, *Chonetida* indet., *Rhynchonellida* indet. (probably of the Family Leiorhynchidae) and *Spiriferida* indet. (Fig. 5).

5.2. Fossiliferous interval 2

The second fossiliferous interval (FI 2) occurs in medium-grained micaceous sandstones, nearly 500 m over the base of Section A (West) (SM13 25), and in the lower part of Section B (East) (SM13 22 and 21) (Fig. 2). In this latter occurrence, the fossiliferous succession reaches 70 m thick and is composed of medium to fine sandstones and mudstones, with dropstones in the middle part, interpreted as middle shoreface to inner shelf deposits with ice rafting influence (upper part of sequence 3 and 4, Ezpeleta et al., 2020).

Bivalves that characterize this interval are more diverse than brachiopods (Figs. 3 and 4), and these are mainly integrated by malletids and anomalodesmatids: accompanied by pectinids and scarce modiomorphids. Of the brachiopods, a spiriferinid-dominated assemblage characterizes the interval, where productids and rhynchonellids are also identified. Other invertebrates found are trilobites, gastropods, conulariids, cephalopods, crinoids, and hyoliths.

Identified taxa are *Palaeoneilo* sp., *Malimania triangularis*, *Pholadomyidae* indet., *Streblochondria* sp., *Cypricardinia* sp., ?*Septosyringothyridinae* new genus, *Anopliidae* indet. A., *Leiorhynchidae* indet. (Fig. 5).

5.3. Fossiliferous interval 3

The third fossiliferous interval (FI 3) identified occurs between 620

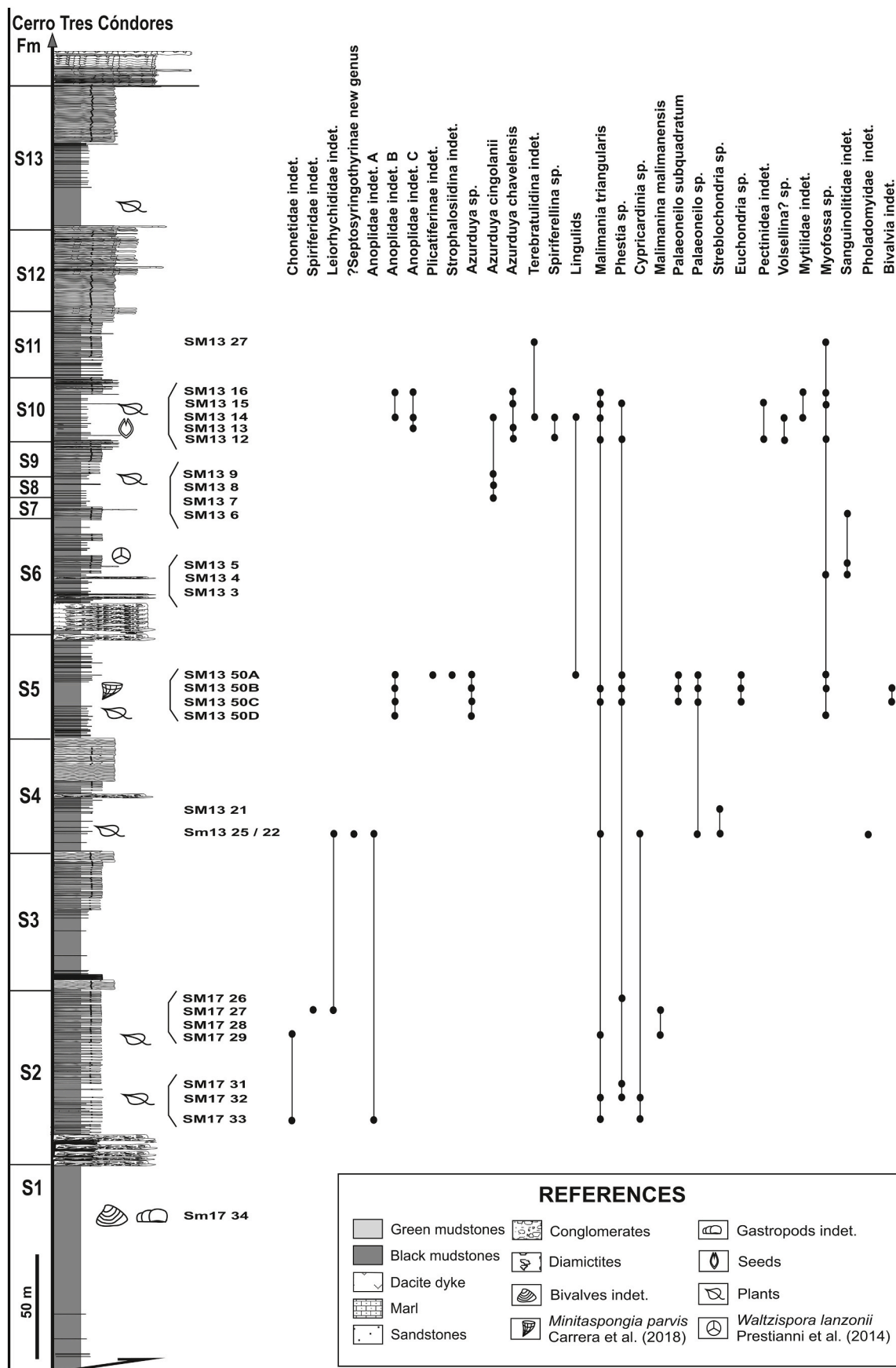


Fig. 3. Synthetic stratigraphic section of southern Sierra de las Minitas showing brachiopods and bivalves distribution (Modified [Ezpeleta et al., 2020](#)).

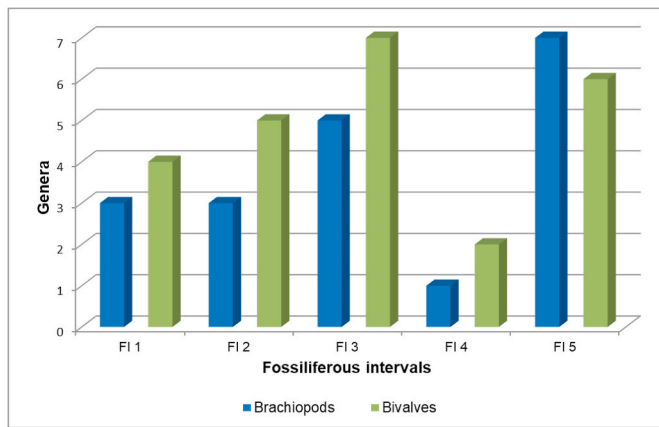


Fig. 4. Histograms showing the genera diversity of brachiopods and bivalves through the stratigraphic sections studied.

and 700 m in the western section (Section A). The fauna appears scattered through a predominantly pelitic interval with calcareous concretions and sandstone beds in the lower part, interpreted as a glacially influenced lower shoreface to inner shelf environments by Ezpeleta et al. (2020) (Sequence 5, Levels SM50 D, C, B, A) (Fig. 2). In this interval, the bivalves are more diverse than the brachiopods (Figs. 3 and 4).

A malletid-dominated assemblage characterizes this interval, with the species described by González (1994) in the Agua de Lucho and Malimán formations, accompanied by nuculids, pectinids and anomalodesmatids. In terms of brachiopods, a chonetid-dominated assemblage characterizes this part of the sections (FI 3), accompanied by productids, rhynchonellids, and scarce “inarticulates” (lingulids). Other components are sponges (*Minitaspongia parvis* Carrera et al., 2018), gastropods, conulariids, cephalopods, crinoids, hyoliths, and ostracods.

Taxa identified are *Palaeonello subquadratum*, *Malimania triangularis*, *Palaeonello* sp., *Phestia* sp., *Euchondria* sp., *Myofossa* sp., *Bivalvia* indet., Anopliidae indet. B, Plicatiferinae indet., Strophalosiidina indet., *Azurduya* sp. (Fig. 6).

5.4. Fossiliferous interval 4

The fossiliferous interval (FI 4) only occurs in the eastern section (Section B), between 170 and 280 m from the base; this succession is composed of interstratified grey mudstones, siltstone and tabular, massive sandstones with muddy intraclasts, interpreted as inner shelf and lower to upper shoreface (Sequences 6 to 8, Ezpeleta et al., 2020).

The fauna is dominated by bivalves accompanied by cephalopods, gastropods, crinoids, and fish in the basal part (levels SM13 3–5, Fig. 2). Brachiopod-dominated shell beds mainly composed of rhynchonellids characterize the upper part of the section (Levels SM13 6–9, Fig. 2).

Taxa identified are Sanguinolitidae indet., *Myofossa* sp. and *Azurduya? cingolanii* (Fig. 7).

5.5. Fossiliferous interval 5

The upper fossiliferous (FI 5) succession is identified between the 360 and 530 m in Section B (Levels SM13 12–16) and it can be correlated with some beds (i.e., SM13 27) of the Section A (West) (Fig. 2). This interval, interpreted as progradational systems with no glacial evidence (sequences 10 and 11, Ezpeleta et al., 2020) is mainly characterized by offshore to shoreface/deltaic facies, indicating a shallowing-and coarsening-upward. It is important to mention that in the base of Sequence 10 two seed genera, with the species *Pseudosporogonites* cf. *hallei* and *Warsteinia sancheziae* have been described by Prestianni et al. (2015).

Brachiopods are more diverse than bivalves (Figs. 3 and 4) and the rhynchonellid-dominated assemblage is more diversified than the lower

ones. The rhynchonellids are accompanied by scarce chonetids, spiriferinids, terebratulids, and “inarticulates” (lingulids). The nuculanid bivalves characterize this interval with anomalodesmatids, mytilids, and scarce and fragmentary pectinids. The associated fauna is composed of gastropods, conulariids, cephalopods, crinoids, hyoliths, bryozoans, corals, and fishes.

Taxa identified are *Azurduya? cingolanii*, *Azurduya chavelensis*, Anopliidae indet. C, *Spiriferellina? sp.*, Terebratulidina indet., *Phestia* sp., *Malimania triangularis*, *Volsellina? sp.*, Mytilidae indet., *Myofossa* sp. and Pectinidae indet. (Fig. 8).

6. Taxonomic comments of brachiopods and bivalves in new sections of the Agua de Lucho Formation

Some preliminary identified taxonomic aspects of the brachiopods and bivalves in sections of the Agua de Lucho Formation at Sierra de las Minitas are herein discussed, although most of the material is still under study by two of the authors (AFS and GAC) and has provisionally been left in open nomenclature.

The classification of Brachiopoda adopted herein follows for Productida, Brunton et al. (2000), for Rhynchonellida, Savage et al. (2002), for Spiriferinida, Carter and Johnson (2006) and Lee et al. (2006) for Terebratulida. While the classification of Bivalvia follows Newell (1942), Carter et al. (2011), and Morris et al. (1991) for Anomalodesmata.

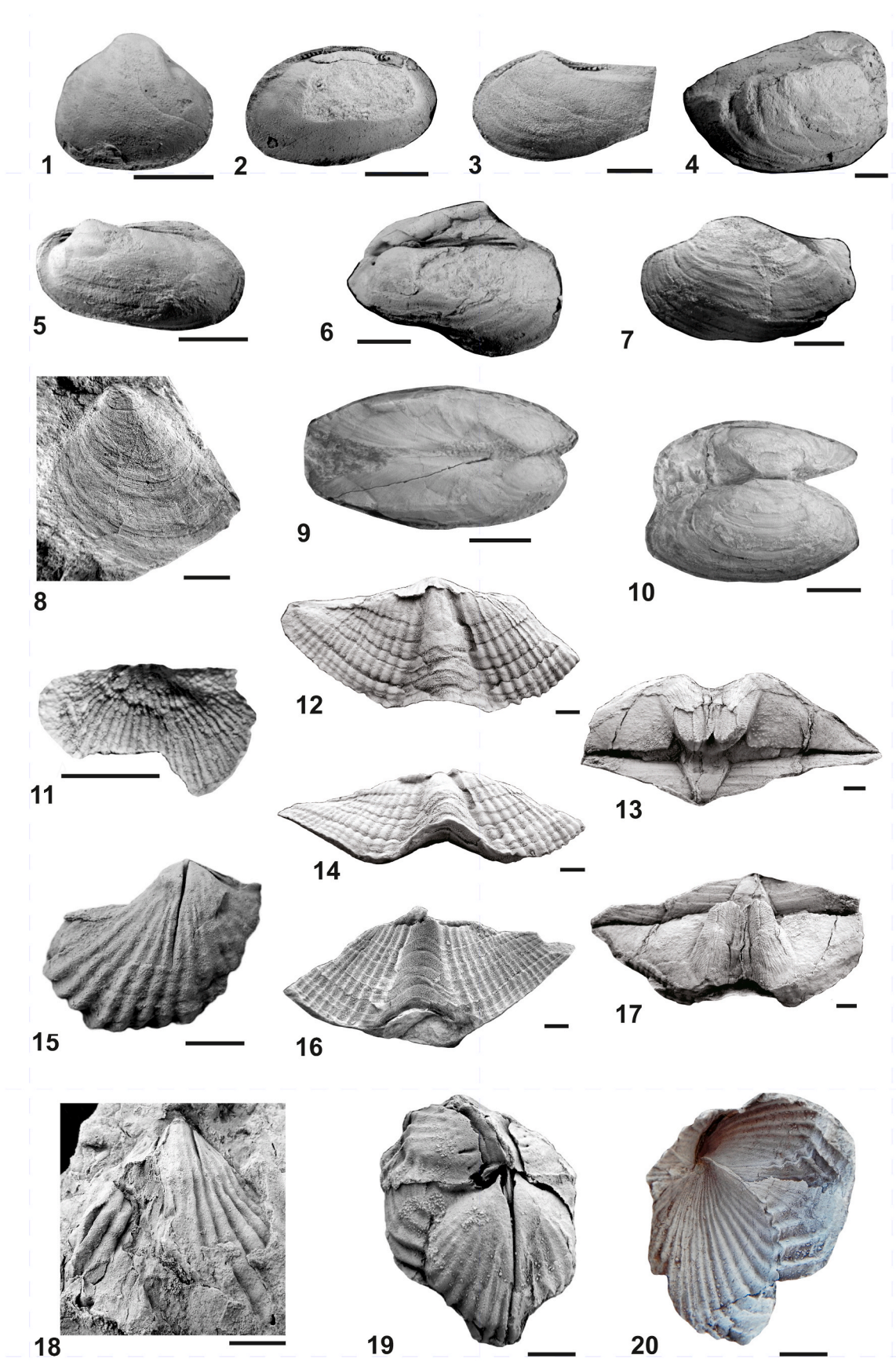
6.1. Brachiopods

Linguliform and rhynchonelliform brachiopods were recognized along the stratigraphic sections studied. Among rhynchonelliform, productids (chonetidines and productidines), rhynchonellids, spiriferinids, and terebratulids, were mainly identified.

6.1.1. Chonetidines

Specimens very fragmentary from levels SM17 33 and SM13 25, that show some diagnostic characters of the Family Anopliidae Muir-Wood (i.e. shell small, concavo-convex with capillate surface, ventral interior with short myophragm, dorsal interior with cardinal process pit, without median septum, but with a pair of accessory septa), have provisionally been assigned the Anopliidae indet. A (Fig. 5.11). Also, very small chonetids (the specimens are less than 5 mm long or between 5 and 10 mm), from levels SM50 A-D, SM13 14 and 16, which appear in different ontogenetic stages with a proportion of articulated valves relatively high, have been herein referred to Anopliidae indet. B (Figs. 6.10-14). Weakly concavo-convex shell with costellate radial ornamentation and orthomorph oblique symmetrically arranged spines, ventral valve with a short myophragm and dorsal valve with a minute alveolus, without median septum but with an inconspicuous pair of accessory septa, are some of the diagnostic characters identified in these specimens. Internal features of Anopliidae indet. B can be compared with the early Mississippian genera *Chilenochonetes* (= *Yagonia?* by Taboada and Shi, 2009) from northern Chile (Isaacson and Dutro, 1999) and *Saharonetes* Havlicek from Libya. However, Anopliidae indet. B differs considerably in size (it is particularly much smaller) and has finer ornamentation in relation to *Chilenochonetes*. Also, species from Sierra de las Minitas cannot be externally compared with *Yagonia* because it has a smooth external shell (see below).

A few chonetid specimens from the levels SM13 13, 14 and 16, have also been assigned to Anopliidae indet. C (Fig. 8.19). Although scarce and fragmentary, available material allowed the identification of some diagnostic features such a weakly concavo-convex profile, surface probably pseudocapillate by shell decorations, ventral interior with median septum, and dorsal interior without pit and with an inconspicuous pair of accessory septa. These features could, tentatively, be compared with those of the genus *Yagonia* Roberts, a large anopliid externally smooth characteristic of the *Michiganites scalabrinii-Azurduya*



(caption on next page)

Fig. 5. Bivalves and brachiopods of the Fossiliferous intervals 1 and 2 (FI 1, FI 2). 1–2, *Malimania triangularis* González, 1, interior of right valve with scarce of anterior adductor muscle, PULR-I 9, 2, internal mold of incomplete right valve showing the dentition (dorso-lateral view), PULR-I 10; 3, *Phestia* sp., incomplete internal mold of left valve, PULR-I 11; 4, *Malimanina malimanensis*? González, incomplete and articulated specimen, PULR-I 12; 5,6, *Cypricardinia* sp., 5, internal mold of left valve showing cardinal and lateral teeth, PULR-I 13, 6, internal mold of articulate specimen, PULR-I 14; 7,10, *Palaeoneilo* sp., 7, composite mold of incomplete left valve PULR-I 15; 10, composite mold of articulated specimen, PULR-I 16; 8, *Streblochondria* sp., composite mold of incomplete left valve, PULR-I 17; 9, Pholadomyidae indet., dorsal view of articulated specimen, PULR-I 18; 11, Anopliidae indet. A, external mold of ventral valve, PULR-I 137; 12–14, 16–17, ?Septosyringothyridinae new genus, 12, 14, 16, internal mold of articulate specimen, dorsal-anterior views and dorsal counter mold, PULR-I 139; 13,17, internal mold of a mature specimen, posterior and ventral view, PULR-I 136; 15, 18–20, Leiorhynchidae indet. 15, internal mold of dorsal valve, PULR-I 34; 18, incomplete internal mold of ventral valve, PULR-I 157; 19–20, internal mold of articulate specimen, dorsal view and its counter mold, PULR-I 138. Scale bars = 5 mm).

chavelensis Zone in its type section. However, Anopliidae indet. C is much smaller, the smooth external ornamentation is not clear, and accessory septa of the dorsal valve are inconspicuous in comparison with those of *Yagonia*. Material assigned to this genus was first described as *Chonetes* sp. cf. *Chonetes chesterensis* Weller by Amos (1958), and later assigned to *Rugoschonetes* cf. *chesterensis* (Weller) (Amos et al., 1973; Sabattini et al., 2001). Taboada and Shi (2009), studied Tournaisian chonetid brachiopods from the Malimán Formation and proposed the new specie *Yagonia furquei*, suggesting that specimens described by Amos (1958, 1979) from the same stratigraphic levels can be included in this species. These authors remark similarity with *Chilenoschonetes annae* Isaacson and Dutro described from the Zorritas Formation in the Sierra de Almeida, northern Chile (Isaacson and Dutro, 1999). However, the Chilean species has been provisionally assigned to *Yagonia* because the smooth external condition of this genus, which is interpreted as an artifact of preservation (Taboada and Shi, 2009), has not been observed in *Yagonia? annae*.

6.1.2. Productidines

Represent the first report for the early Mississippian successions in Argentina. Specimens with medium-sized ventral valves gently convex with rugae and fine spines irregularly scattered, thicker in clusters on ears, described from level SM50 A, have been tentatively assigned to Plicatiferinae indet. Also, a group of minute spiny specimens (less than 5 mm long), identified at the same level and still under study, could belong to Strophalosiidina indet.

6.1.3. Rhynchonellids

Several species of Family Leiorhynchidae Stainbrook are identified in different levels along the sections. Specimens from the levels SM13 12, 13, 15, and 16 assigned to *Azurduya chavelensis* (Amos) (Figs. 8.7–13), are close to those described from the Malimán Formation by Cisterna and Isaacson (2003). However, the material from Sierra de las Minitas includes markedly more robust forms, even than those previously identified in the Agua de Lucho Formation at Cerro Agua de Lucho locality (Cisterna, 1996). *Azurduya chavelensis* appears to be a dominant species in the early Mississippian marine assemblages from western Argentina and a valuable element for intra-basinal correlation since it has been described from the Agua de Lucho Formation in the Bolsón de Jagüé-Sierra de las Minitas area (La Rioja province), to the north of the Río Blanco Basin (Cisterna and Isaacson, 2003).

Specimens herein assigned to *Azurduya? cingolani* Cisterna and Isaacson (Figs. 7.4–10; 8.14–15), identified in the levels SM13 7, 8, 9, and SM13 14, show particular good preservation mainly as internal molds. These are characterized by their dorsibiconvex shells with sub-rounded outline ornamented by few, low costae, 4 on sulcus and fold and about 5–6 on lateral flanks. Ventral interiors with a distinctive muscle field outline subcircular deeply impressed, thick divergent dental plates and a conspicuous short median septum that appears to be developed in mature specimens (Figs. 7.5 and 7.7). Dorsal interiors with septalium supported by a conspicuous and long median septum, and muscle field also deeply impressed. This material was provisionally assigned by Sterren et al. (2013) to the species *Azurduya cingolani*, which had been initially described from possibly coeval horizons (Cisterna and Isaacson, 2003). However, concerning the genus *Azurduya*, the material herein studied can be differentiated by the presence of

a ventral median septum, dental plate much stronger and divergent, and subcircular muscle field deeply impressed. Some of these features have also been described in several specimens from the Zorritas Formation, northern Chile (to compare, Figs. 2.12–14, Isaacson and Dutro, 1999), assigned to *Paurorhyncha chavelensis* (Amos). Rhynchonellids from Sierra de las Minitas area, herein retain as *Azurduya? cingolani* Cisterna and Isaacson, could belong to a new genus but further studies are needed. A few incomplete smaller specimens from the levels SM13 8–9 show ventral interiors different from those described above, namely, the median septum and subcircular muscle field impressed are absent. However, for the time, considering that these variations could be related to the ontogenetic stage, the specimens are also included in *Azurduya? cingolani*.

Some specimens from the levels SM50 A, B, D, and concretions of SM50 C have been assigned to *Azurduya* sp. (Figs. 6.15–20). Smaller and delicate shells with less number of costae differentiated it from the genus *Azurduya*. However, specimens from the concretion levels, in particular (Figs. 6.17–20), show shells slightly more robust and strongly dorsibiconvex comparable with those of the genus *Azurduya* described from Malimán Formation (Cisterna and Isaacson, 2003). Due to the more delicate forms (Figs. 6.15–16) of the levels SM50 D, B, A, are mainly found as internal molds, the comparison with those from the concretions can be difficult, hence, all material is preliminary considered *Azurduya* sp.

Finally, fragmentary specimens with conspicuous ventral plates, muscle field deeply impressed, dorsal interior with septalium distinctive supported by a prominent and long median septum that suggest their inclusion in the Family Leiorhynchidae Stainbrook (Figs. 5.15, 18–20), have been identified in the levels SM17 27, SM13 25. These specimens seem to belong to a group of large Tournaisian rhynchonellids such as *Paurorhyncha*, *Rosirhynchus*, and *Azurduya* and also comparable with those described as *Paurorhyncha chavelensis* in the Zorritas Formation, northern Chile (Isaacson and Dutro, 1999).

6.1.4. Spiriferinids

Big syringothyrids from the levels SM13 22, and 25, mainly composed of internal molds and found in different ontogenetic stages, were assigned to ?Septosyringothyridinae new genus (Figs. 5.12–14, 16–17). The specimens are characterized by a conspicuous delthyrial plate slightly below the plane of the interarea and a distinctive but incomplete wedge-shaped syrinx (that does not have the typical circular section of most syringothyrids), connected to the floor of the valve by an incipient ventral median septum. A few comparable specimens have been previously described from outcrops of the Agua de Lucho Formation in Cerro Agua de Lucho locality, to north Sierra de las Minitas (Fig. 1), as *Pseudosyringothyris? sp.* by Cisterna (1996). However, since *Pseudosyringothyris* Frederiks, included in the Subfamily Permasyrinxinae Waterhouse (Carter, 2006), is characterized by the absence of a syrinx, these early Carboniferous syringothyrids were retained as (?)Septosyringothyridinae new genus (Cisterna, 2011). It is especially noteworthy that the review of the new material here studied from Sierra de las Minitas, confirm its close similarity with that described in the Zorritas Formation, northern Chile (Isaacson and Dutro, 1999), as *Septosyringothyris covacevichi* (Figs. 3.1 and 3.6) and *Pseudosyrinx* sp. (Fig. 3.8). Nevertheless, considering the recent study of syringothyridoidea from the Carboniferous of North Africa provided by Mottequin and Cisterna

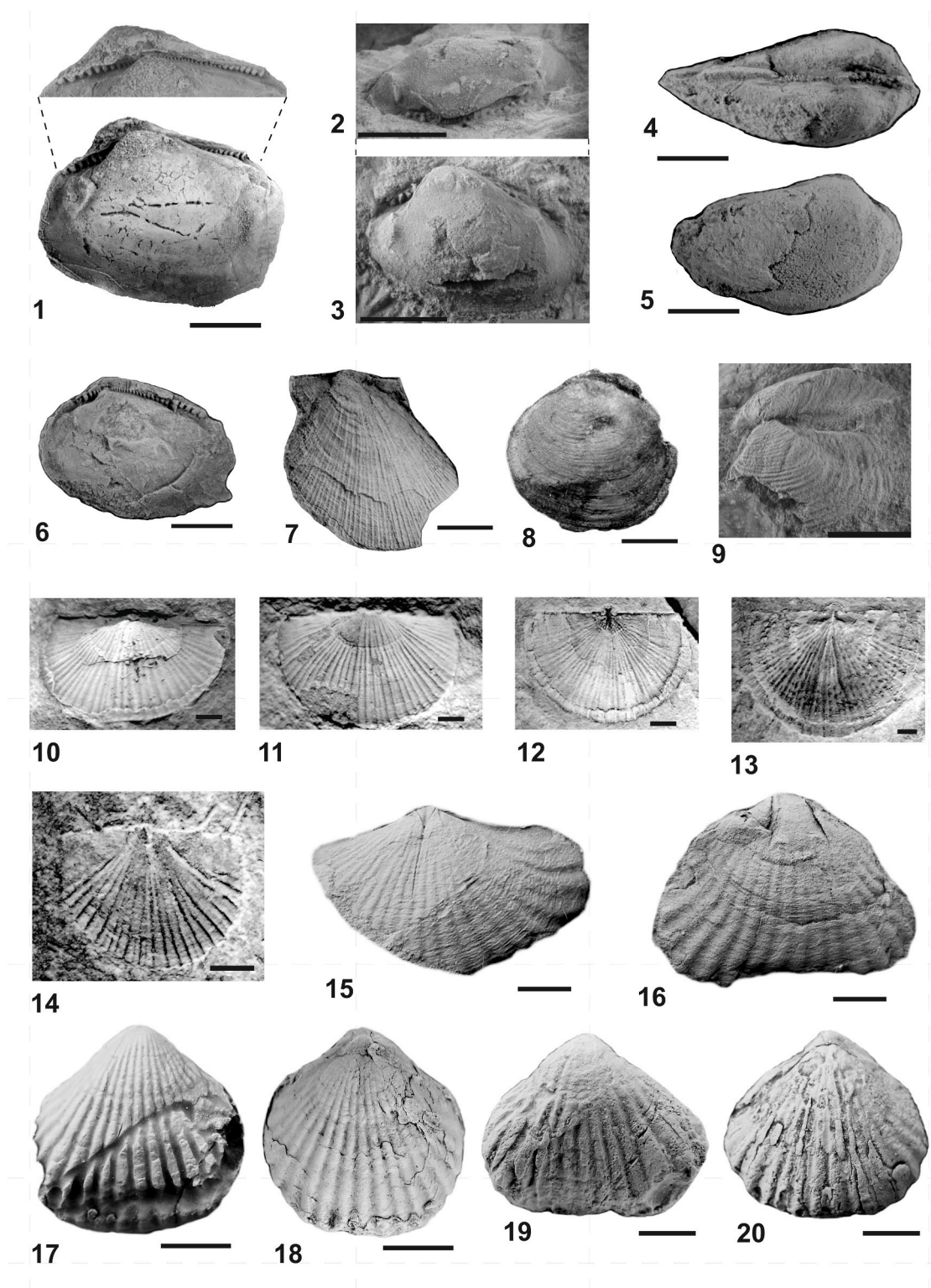


Fig. 6. Bivalves and brachiopods of the Fossiliferous interval 3 (FI 3). 1, 6, *Palaeoneilo subquadratum* González, 1, internal mold of left valve showing muscle scars (anterior and posterior adductors and subumbonal impressions), and detailed of the dentition, PULR-I 19; 6, internal mold of left valve laterally deformed, PULR-I 19; 2–3, *Malimania triangularis* González, left valve, dorsal and lateral views of internal mold showing dentition and muscle scars, PULR-I 20; 4–5, *Phestia* sp., dorsal and lateral views of composite mold of articulate specimen, PULR-I 21; 7, *Euchondria* sp., incomplete composite mold of left valve, PULR-I 22; 8, *Bivalvia* indet., lateral view of incomplete specimen, PULR-I 23; 9, *Myofossa* sp., incomplete composite mold of articulate specimen, PULR-I 24; 10–14, Anopliidae indet. B, 10–11, internal mold of ventral valve and its counter mold, PULR-I 140; 12, dorsal exterior, PULR-I 34; 13, dorsal interior PULR-I 141; 14, crushed internal mold of ventral valve showing a coarser ornamentation pattern by deformation, PULR-I 35; 15–20, *Azurduya* sp., 15, internal mold of dorsal valve, PULR-I 36; 16, internal mold of ventral valve, PULR-I 37; 17–18, articulate specimen, ventral and dorsal views, PULR-I 38; 19–20, articulate specimen, ventral and dorsal views, PULR-I 39. Scale bars = 5 mm, except in 10–14 where scale bars = 0.5 mm.

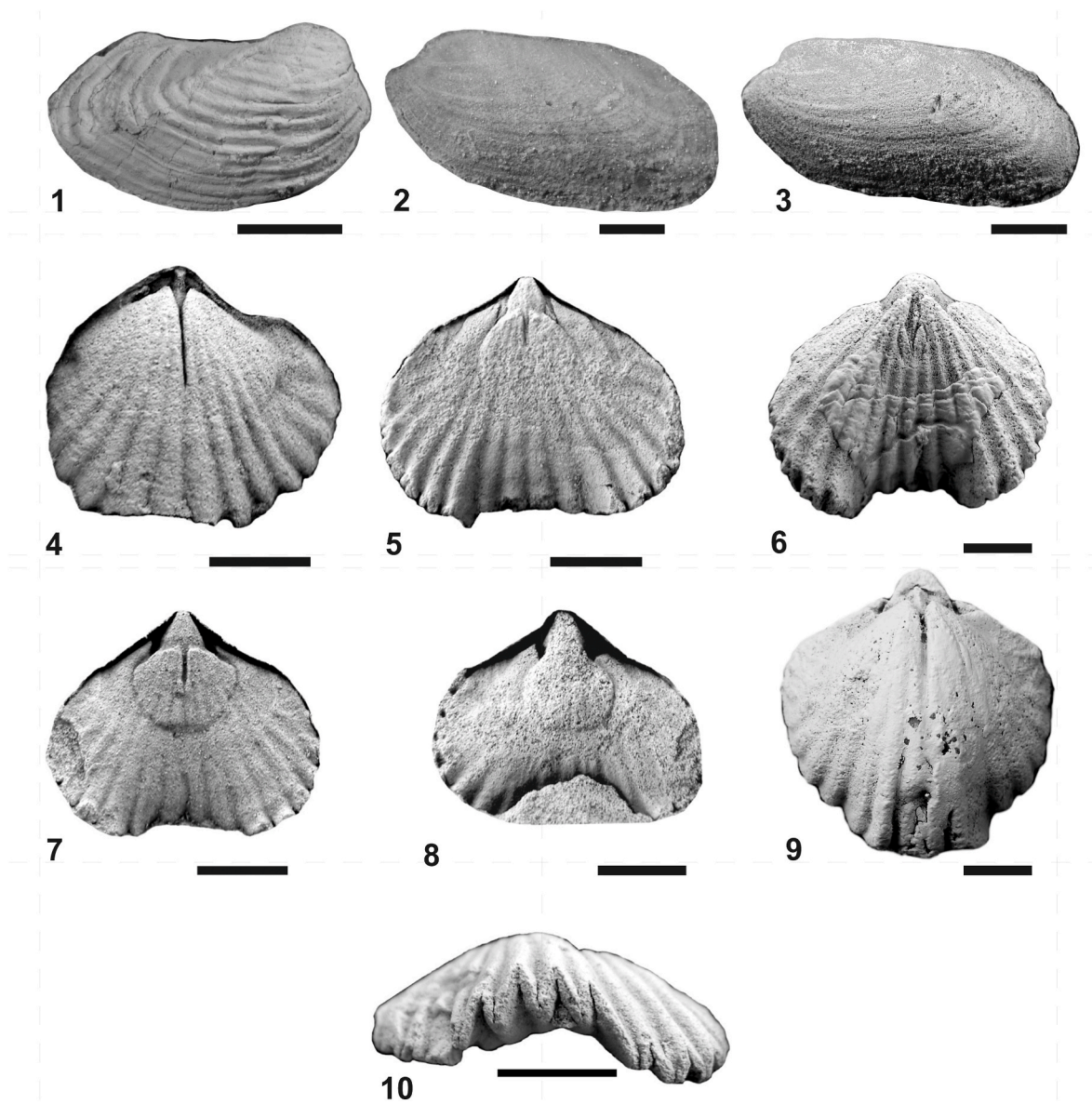


Fig. 7. Bivalves and brachiopods of the Fossiliferous interval 4 (FI 4). 1, *Myofossa* sp., lateral view of composite mold of right valve, PULR-I 25; 2–3, Sanguinolitidae indet., 2, latex mold of left valve, PULR-I 26; 3, composite mold of left valve, PULR-I 27; 4–10, *Azurduya? cingolani* Cisterna and Isaacson, 4, internal mold of dorsal valve, PULR-I 144; 5, internal mold of ventral valve, PULR-I 145; 6–9, articulate specimen, ventral and dorsal views, PULR-I 40; 7, internal mold of ventral valve, PULR-I 147; 8, internal mold of ventral valve, PULR-I 148; 10, articulate specimen, anterior view, PULR-I 146. Scale bars = 5 mm.

(2019), who discussed diagnostic characters of Septosyringothyridinae in particular, the specific assignment of South American taxa needs further investigations.

An incomplete internal mold of a ventral valve and an external mold of a dorsal valve from the levels SM13 12 and 14 have been tentatively assigned to *Spiriferellina?* sp. (Figs. 8.16–17). Specimens are small, moderately transverse with a narrow and smooth sulcus and fold, lateral slopes with four high, coarse, subangular plicae separated by deep interspaces; microornamentation with growth laminae irregularly spaced; ventral interior with short, subparallel dental adminicula and median septum high and long. Although fragmentary, *Spiriferellina?* sp. appears to be close with *Spiriferellina octoplicata* identified in the *Levipustula* Fauna (late Serpukhovian–Bashkirian) of the Hoyada Verde Formation (Cisterna and Sterren, 2010).

6.1.5. Terebratulids

Finally, scarce and fragmentary brachiopod terebratulids from levels SM13 14, 27 have been provisionally left in *Terebratulidina* indet

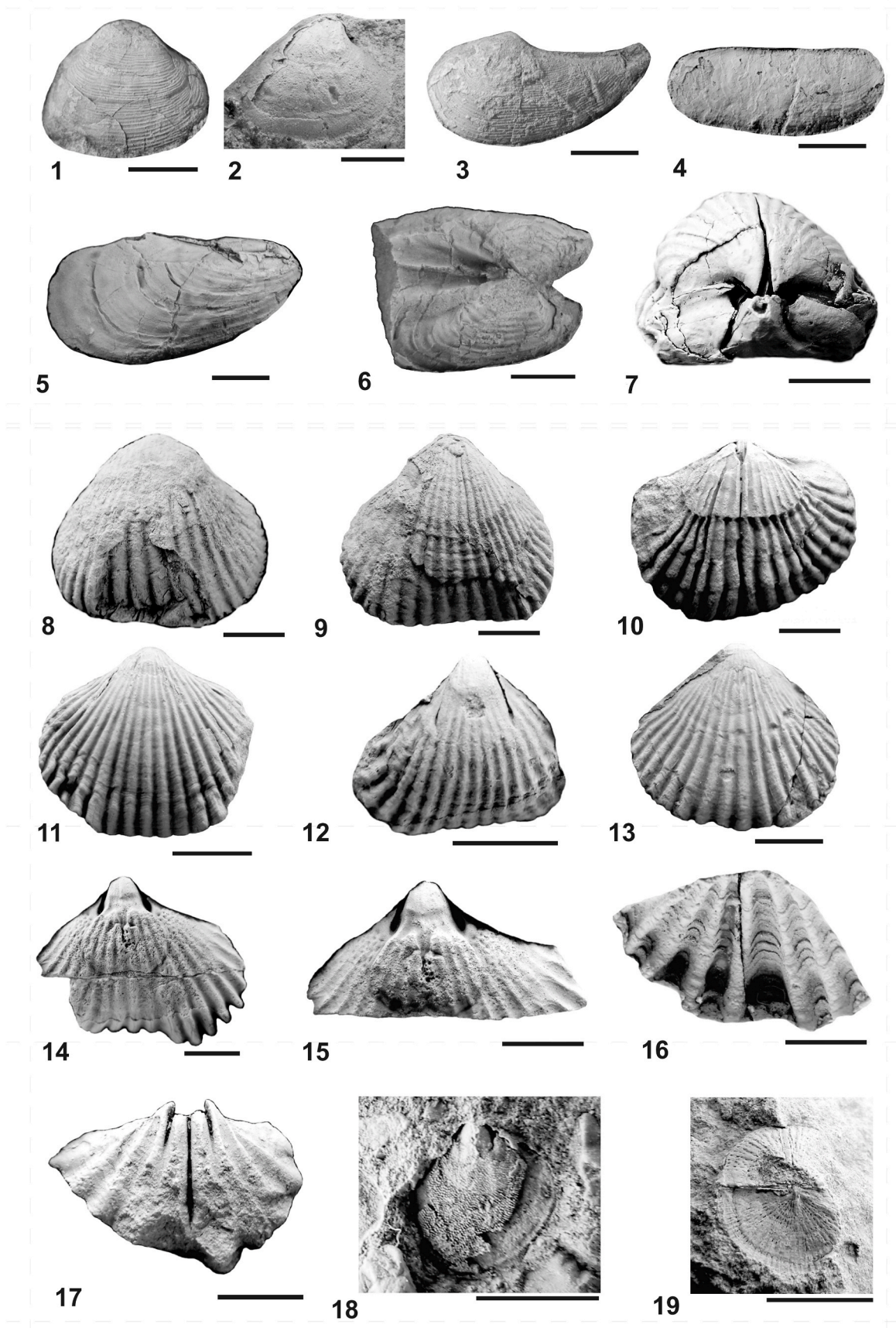
(Fig. 8.18), although they appear to be close to the dielasmatoid *Beecheria* Hall and Clarke or some related genus. Terebratulids such as *Beecheria* sp. have been reported from the upper part of the fossiliferous interval of the Malimán Formation (Scalabrini Ortíz, 1972). This material was not described or figured, hence the comparison with our material is not possible.

6.2. Bivalves

Nuculanids, mytilids, myalinids, pectinids, modiomorphids, and anomalodesmatids were recognized in the studied sections.

6.2.1. Nuculanids

Palaeoneilo Hall and Whitfield, *Malimania* González and *Phestia* Chernyshev are the most characteristic genera in the Agua de Lucho Formation (Figs. 5 and 6). The genus *Palaeoneilo*, a cosmopolitan malletid with large temporal distribution, is represented by two species: *Palaeoneilo subquadratum* González and *Palaeoneilo* n. sp.



(caption on next page)

Fig. 8. Bivalves and brachiopods of the Fossiliferous interval 5 (FI 5). 1–2, *Malimania triangularis*, 1, lateral view of right valve PULR-I 28; 2, lateral view of a partially decorticated right valve, PULR-I 29; 3, *Phestia* sp., composite mold of left valve, PULR-I 30; 4, *Volsellina?* sp., lateral view of right valve, PULR-I 31; 5, Mytilidae indet., lateral view of right valve laterally deformed, PULR-I 32; 6, *Myofossa* sp., dorsal view of incomplete articulate specimen, PULR-I 33; 7–13, *Azurduya chavelensis* (Amos), 7, internal mold of articulate specimen, posterior view, PULR-I 149; 8–9, articulate specimen, dorsal and ventral views, PULR-I 7; 10, internal mold of dorsal valve, PULR-I 8; 11, ventral valve, PULR-I 152; 12, internal mold of ventral valve, PULR-I 150; 13, ventral valve, PULR-I 151; 14–15, *Azurduya? cingolanii* Cisterna and Isaacson, internal mold of ventral valve and a detail of the muscle field and dental plates, PULR-I 153; 16–17, *Spiriferellina?* sp., external and internal mold of an incomplete ventral valve, PULR-I 154; 18, Terebratulidina indet., internal mold of ventral valve, PULR-I 156; 19, Anopliidae indet. C, internal mold of articulate specimen, PULR-I 155. Scale bars = 5 mm, except in 1, 6 where scale bars = 2.5 mm.

Palaeoneilo subquadratum González (levels SM50 C, B, A) is characterized by equivalved shells, subquadrate to subtrapezoidal shape with posteroventral sinus present and external ornament of thin commarginal lines. The taxodontid dentition and the elongated accessory muscle scars below the umbo are preserved in some internal molds (Figs. 6.1 and 6.6). This species was originally described by González (1994) in the Agua de Lucho Formation at Cerro Agua de Lucho locality. Based on the shape of the shells some specimens from lower to middle levels of the sections (SM13 25 and SM50 C, B, A) are tentatively assigned to *Palaeoneilo* n. sp. The new material, close to *P. subquadratum* González in the internal features and dentitions, mainly differs in the shape of the shells and a more marked postumbonal slope. The valves have a more trapezoidal outline, the anterior and ventral margin rounded, ventral margin forming an acute angle with the posterior margin, and anterior and posterior dorsal margin concave (Figs. 5.7 and 5.10).

Malimania triangularis was defined by González (1994, Fig. 4.E, F) in the Malimán and Agua de Lucho formations as a “malletiid with posterior tooth-row overlapping the anterior row below the beaks, trigonal shell and exterior densely covered with regularly spaced concentric ribs” (also identified in the studied sections, levels SM13 25; SM50 C, B). Also, some internal molds preserve the adductors muscle scars and several small subumbonal impressions (Figs. 5.1, 5.2, 6.2-3, 8.1-2). This genus was also recognized in the early Permian sediments of Patagonia by González (1994, 2006) with the species *Malimania patagoniensis*. However, those specimens were reassigned to *Nuculopsis* Girty (1911) based on different hinge structure (Pagani 2004a; Pagani and Ferrari, 2011). Further detailed studies of the internal features will shed light on the taxonomy of these genera.

Specimens that exhibit an elongate outline and posteriorly expanded shell, with orthogyrous beaks projecting above the dorsal margin, were assigned to *Phestia* sp. External surface is covered by thin commarginal growth lines, sometimes with radial ribs in the postumbonal area (Figs. 5.3, 6.4-5, 8.3). The material here analyzed (SM17 33, 32, 26; SM50 C, B, A; SM13 12, 15) can be differentiated from the *Phestia* sp. described by González (1994, Fig. 4.L) in the Malimán and Agua de Lucho Formations, by a widely rounded ventral margin, a posteriorly elongated shell, and the reticulated ornamentation patterns. Further studies are necessary to compare with the numerous species reported in Late Paleozoic sediments of Argentinean basins (González, 1969, 1972; Pagani, 2004b; Sterren 2003, 2005).

6.2.2. Mytilids

Scarce and badly preserved mytilids were only recorded in the upper part of the studied unit. Small and elongate valves with very low convexity, dorsal and ventral margins straight and parallel, and beaks near the anterior margin were assigned to *Volsellina?* sp. (SM13 12, 14) (Fig. 8.4) as previously described by González (1994, Fig. 5.J). A few specimens with modioliform elongate shells, (laterally deformed by compression), anterior beaks, straight hingeline, dorsal and ventral margins slightly diverging backward and closely spaced commarginal growth lines were tentatively identified as Mytilidae indet. (SM13 14, 16) (Fig. 8.5). The absence of well-preserved material does not allow a generic assignment.

6.2.3. Myalinids

Two fragmentary specimens (levels SM17 27, 29) preserved with the articulated valves were assigned to *Malimanina malimanensis?* described

by (González, 1994, Fig. 4.M, P) for the upper part of the Malimán Formation. The studied material exhibits some diagnostic features such as medium-size globose shells, inoceramid-like, suboval, prosocline, and the strong concentric folds) (Fig. 5.4). A possibly similar species was documented in the Zorritas Formation, northern Chile (*Posidoniella* sp. Isaacson and Dutro, 1999) later assigned to *Malimanina* by Waterhouse (2001).

6.2.4. Pectinids

Pectinids were recorded in several intervals throughout the studied unit. Specimens preserved as composite and internal molds were referred to *Streblochondria* sp. (SM13 22, 21, and 25 levels, Fig. 2) based on the general outline of the shell. Most of them are right valves which reach 4 cm in length, with well-developed auricles (the posterior one is shorter than the anterior) and ornamented by fine regular commarginal lines. The material shows upright to opisthocline shells with a short hinge line and irregular commarginal ridges, more conspicuous in the margin of the valves (Fig. 5.8). The absence of a complete left valve precludes the comparison with younger species known from Río Blanco and Calingasta-Uspallata basins (Sterren, 2000, 2002, 2003). *Streblochondria* sp. recorded in the Agua de Lucho Formation is the first mention of the genus for the Mississippian of Argentina. Pectinid shells with ridges and transverse furrows closely spaced in the cardinal areas are assigned to *Euchondria* sp. (SM50 C, B, A). Typical ornamentation of costae that increase by intercalation in the left valve and numerous, closely-spaced, commarginal filae of the genus are well preserved in the studied material (Fig. 6.7). These external features distinguish *Euchondria* sp. from the other two known species. *Euchondria sabattini* and *Euchondria* n. sp. from the Late Paleozoic of Patagonia and Calingasta-Uspallata Basin, which develop nodules or spines at the intersection of ribs and growth lines (González, 1972; Manceñido et al., 1976; González, 2002). Further studies are needed to clarify the specific assignment. The finding of *Euchondria* sp. in Sierra de las Minitas represents the first report of the genus for the early Mississippian successions in our country. Some fragmentary specimens with straight hinge line, smooth anterior and posterior auricles and radial costae over de body shell were provisionally assigned to Pectinidae indet (SM13 12, 15).

6.2.5. Modiomorphids

Numerous specimens that appears mainly articulated and dorso-ventrally deformed in the lower part of the unit (SM17 33 and 32) have been assigned to *Cypricardinia* sp. The recorded material is modioliform in shape and shows the surface covered with strong concentric ridges. The hinge plate shows two not horizontal anterior teeth and a posterior lateral tooth subparallel to the dorsal margin, in the left valve (Figs. 5.5-6). The right valve preserves a single anterior tooth and a posterior lateral one at the posterior cardinal margin. This material is very close to the only available specimen described as *Cypricardinia?* sp. by González (1994, Fig. 5.A, B), in the northern sector of the basin in the Agua de Lucho Formation. More detailed studies are necessary to compare this *Cypricardinia* sp. with other known species.

6.2.6. Anomalodesmatids

Myofossa sp, Sanguinolitidae indet. and Pholadomyidae indet. were identified in the studied sections. Several specimens were assigned to *Myofossa* sp. (SM50 D, B, A, SM13 4, 12, 15, 16), based on their general

Table 1
Composition and stratigraphic record of the early Mississippian marine faunas in western of South America. (1) González and Bossi (1987), (2) Fauqué et al. (1989), (3) González (1994), (4) Cisterna (1996), (5) Isaacson and Dutro (1999), Niemeyer et al. (1997), (6) Sabattini et al. (2001), (7) Cisterna and Isaacson (2003), (8) Taboada and Shi (2009), (9) Cisterna (2011), (10) Material reviewed for this paper.

TAXA	South ARGENTINA North				CHILE
	Malimán Fm.	La Punilla Fm.	Agua de Lucho Fm.		Zorritas Fm.
	Malimán	Quebrada de la Troya	Sierra de las Minitas	Cerro Agua de Lucho	Sierra de Almeida
	(3) (6) (7) (8)	(2) (7)	This paper	(1) (3) (4) (9) (11)	(5)(10)
BRACHIOPODS	Lingulida indet.			X	
	"Schuchertella"? sp.				X
	Yagonia furquei Taboada and Shi	X			
	Yagonia? annae Isaacson and Dutro				X
	Anopliidae indet. A			X	
	Anopliidae indet. B			X	
	Anopliidae indet. C			X	
	Chonetidina indet.			X	
	Plicatiferinae indet.			X	
	Strophalosiidina indet.			X	
	Azurduya chavelensis (Amos)	X	X		X
	Azurduya cingolanii Cisterna and Isaacson		X		
	Azurduya? cingolanii			X	
	Azurduya? sp.			X	
	Leiorhynchidae indet.			X	
	Spiriferida indet.			X	
	Septosyringothyris covacevichi Isaacson and Dutro				X
	Septosyringothyris? sp.				
	Pseudosyrinx sp.				X
	?Septosyringothyridinae new genus			X	X
Spiriferellina? sp.					
Terebratulida indet.					
BIVALVES	Palaeoneilo subquadratum González			X	
	Palaeoneilo sp.			X	
	Malimania triangularis González	X			X
	Phestia sp.	X			X
	Volsellina? sp.			X	X
	Mytilidae indet.			X	
	Malimanina malimanensis (González)	X			X
	Malimanina sp.				
	Leptodesma? sp.				X
	Streblochondria sp.			X	
	Euchondria sp.			X	
	Pectinidae indet.			X	
	Schizodus sp.	X			
	Cypricardinia sp.			X	
	Cypricardinia? sp.				X
	Edmondia? sp.				X
	Vacunella? sp.	X			
	Sanguinolites? punillanus González	X			
	Myofossa sp.				
	Sanguinolitidae indet.				
Pholadomyidae indet.					
Bivalvia indet.					
CEPHALOPODS	X				
GASTROPODS	X	X		X	X
CONULARIIDS	X			X	
HYOLITHS				X	

(continued on next page)

Table 1 (continued)

TAXA	South ARGENTINA North						CHILE	
	Malmán Fm. Malmán (3) (6) (7) (8)	La Punilla Fm. Quebrada de la Troya (2) (7)	Sierra de las Minitas This paper	Agua de Lucho Fm. Cerro Agua de Lucho (1) (3) (4) (9) (11)	Zorritas Fm. Sierra de Almeida (5)(10)			
TRILOBITES		X	X	X	X			X
GRINOIDS			X					
SPONGES			X					
OSTRACOIDS			X					
BRYOZOANS			X					
CORALS			X					
FISHES			X					

outline and commarginal ornamentation covering the entire shell surface although diffuse at the posterior flank (Figs. 6.9, 7.1, 8.6). The specimens appear articulated, and in several cases incomplete and dorso-ventrally deformed by compression, making it difficult the comparison with other species reported from central western Argentina. *Myofossa calingastensis* González and *Myofossa antiqua* González were previously documented in late Serpukhovian–Bashkirian sediments of the Calingasta-Uspallata Basin (González, 2002; Cisterna et al., 2017). These new occurrences of *Myofossa* sp. extend the stratigraphical and geographical distribution of the taxon in Argentina. Specimens with elongate, subtrapezoidal and slightly convex shell, anterior end short and rounded, posterior margin truncate, dorsal and ventral margins nearly parallel, were assigned to *Sanguinolites* indet. (SM13 4, 5, 6). The ornament consists of thin commarginal growth lines and very fine radial ribs on the dorso-posterior area, only preserved in a few specimens (Figs. 7.2-3). The outline and very low convexity are the main features that distinguish these specimens from *Sanguinolites? punillanus* González (1994, Fig. 5.E, G, H), described in the Malimán Formation. The generic assignment of the studied material needs further investigation.

A significant number of bivalves preserved as composite molds, commonly articulated with edentulous hinge have been included in the Family Pholadomyidae Newell. These specimens recorded in the level SM13 25 are characterized by an elongate shell, strongly inequilateral, with relatively small posterodorsal gape, and orthogyrous beaks moderately projected above the dorsal margin. External ornamentation consists of coarse and rounded commarginal ridges (Fig. 5.9). Unfortunately, the studied material is mainly preserved as external molds, so that it is not possible to specify the assignment.

6.2.7. *Bivalvia* indet

Some specimens with orbicular shape and concentric ornamentation were designated as *Bivalvia* indet. (SM50 B, C) (Fig. 2). The size of the valves ranges between 5 mm length and height (smallest specimen), and 30 mm length and height (greater specimen). Exterior densely covered with two orders of thin regularly spaced concentric ribs (Fig. 6.8). The poorly preserved material does not allow a more precise analysis.

7. Discussion

7.1. Paleologic and paleobiogeographic implications

The marine invertebrate fauna from the Agua de Lucho Formation in the Sierra de las Minitas constitutes the most diverse fossil record for the early Mississippian in South America (Table 1), which is also particularly relevant because it appears associated with a glacial event recently identified in the region by Ezpeleta et al. (2020). These authors recognized several glaciomarine cycles responding to the local advance and retreat of glaciers in the lower half of the Agua de Lucho Formation, while the uppermost part lacks evidence of ice activity indicating the demise of glacial conditions (Ezpeleta et al., 2020). In this stratigraphic context, the relative increase of the diversity in the fauna here analyzed, particularly clear in the brachiopods, towards the top of the unit could be related to the glacial dynamics (Figs. 3 and 4). Also, this fauna exhibits important compositional variations through the thick section of the Agua de Lucho Formation at Sierra de las Minitas. Thus, while spiriferinid brachiopods only occur in the lower part, rhynchonellids and chonetids are present in all the fossiliferous intervals, as nuculid and anomalodesmatid bivalves. Infaunal bivalves (i.e. *Malimania*, *Phestia*, *Palaeoneilo*) are abundant throughout the unit and, conversely, epifaunal and suspension-feeding bivalves are subordinate although also present in the mudstone intervals related to the maximum flooding surface.

It is important to note that the lower part of the section studied (i.e. the fossiliferous intervals 1 and 2), are closely similar, in terms of lithology and faunal content, to the type section the Agua de Lucho

Formation located to the north (Fig. 1). Syringothirid brachiopods (? Septosyringothyridinae new genus), the bivalves *Malimania triangularis*, *Cypricardinia* sp., *Palaeoneilo* sp., and trilobites are common in both sections.

On the other hand, *Malimania triangularis* and *Palaeoneilo subquadratum*, characteristic bivalves of the *Michiganites scalabrinii-Azurduya chavelensis* Zone, display a regular vertical distribution pattern throughout the studied unit in Sierra de las Minitas. The occurrence of *Malimania malimanensis*? in the lower fossiliferous interval (FI 1), would be particularly important since these species have also been described in the lower part of the fossiliferous interval of the Malimán Formation (Sterren, 2002, 2008). Instead, diagnostic brachiopods of the *Michiganites scalabrinii-Azurduya chavelensis* Zone type section, such as the key species *Azurduya chavelensis*, occurs to the upper fossiliferous interval identified in sections studied.

Study of the composition and distribution of the invertebrate faunas along the Agua de Lucho Formation at Sierra de las Minitas also confirms the strong faunal affinities with the Zorritas Formation faunas in Chile suggested by the different authors (González, 1994; Isaacson and Dutro, 1999; Cisterna, 1996, 2011; Cisterna and Isaacson, 2003; Sabattini et al., 2001; Sterren and Cisterna, 2010; Taboada and Shi, 2009; Taboada, 2010) and the probable connection of this region with the different areas of the Río Blanco Basin.

The faunal succession from the middle member of the Zorritas Formation analyzed in several stratigraphic sections (Niemeyer et al., 1997, sections A to D, Fig. 4), exhibits a particular distribution pattern that could be compared with that identified in the sections here studied. The faunal assemblage recognized in the middle-upper part of this member clearly shows a distribution pattern in which the fauna is more diversified in the lower part, and dominated by rhynchonellid brachiopods to the top. (*Rossirhynchus?* *chavelensis*, Niemeyer et al., 1997, now *Azurduya chavelensis* (Amos), Cisterna and Isaacson, 2003). Among the taxa identified in the lower part, some brachiopods (i.e. *Septosyringothyris* n. sp., Niemeyer et al., 1997, now *Septosyringothyris covacevichi*, Isaacson and Dutro, 1999), *Trichochonetes* n. sp., Niemeyer et al. (1997), *Chilenoconetes*, Isaacson and Dutro (1999), *Yagonia?*, Taboada and Shi (2009), trilobites (*Phillipsia*) and bivalves (*Posidoniella*, now *Malimania* Waterhouse), are common with those of the lower fossiliferous intervals described in the Agua de Lucho Formation at Sierra de las Minitas.

The second interval of the Agua de Lucho Formation in the studied sections (FI 2), is mainly distinguished by the large ?Septosyringothyridinae new genus, also consistent with the “big shell brachiopod assemblages” from northern Chile described by Isaacson and Dutro (1999), which are composed of large shells of *Septosyringothyris covacevichi*, *Pseudosyrinx* and *Azurduya chavelensis* that are associated to lenticular sand bodies in delta platform distributary-channel deposits.

Faunal assemblages from the middle part of the sections here studied (i.e. FI 3) can be differentiated from other fossil associations known in the early Mississippian Gondwanan sequences by their particular composition. Chonetid brachiopods are dominant with Anopliidae indet. B and the occurrences of productids represent the first mention in the Early Mississippian of Argentina. In addition, the associated fauna is particularly diverse with sponges, such as *Minitaspongia parvis* Carrera et al. (2018), ostracods, linguliform brachiopods, and gastropods, that are added to the classic invertebrates (conulariids, cephalopods, crinoids, hyoliths) that characterize the *Michiganites scalabrinii-Azurduya chavelensis* Zone.

Rhynchonellid brachiopods accompanied by the bivalve *Malimania*, corals, bryozoans, and fishes characterize the youngest faunal assemblages of the Agua de Lucho Formation in the sections studied (FI 5). Terebratulid brachiopods (probably close to *Beecheria* sp.) and *Spiriferellina?* sp. have also been recognized in the youngest faunal assemblages from the upper fossiliferous interval. The terebratulid *Beecheria* sp. was previously documented in the upper part of the fossiliferous mudstones of the Malimán Formation (Scalabrini Ortíz, 1972). *Spiriferellina?* sp. here described appear to be close with *Spiriferellina octoplicata*

associated with younger successions (late Serpukhovian-Bashkirian), in the Calingasta-Uspalla Basin (Cisterna and Sterren, 2010), related with the second glacial episode (Episode II, López-Gamundí, 1997) of the Late Paleozoic Ice Age (LPIA) identified the western Gondwana margin (López-Gamundí, 1997). The marine faunas associated to this event have an excellent in the Argentine Precordillera (Calingasta-Uspallata Basin) and Patagonia (Tepuel Genoa Basin) (Simanaukas and Sabattini, 1997; Pagani and Sabattini, 2002; Césari et al., 2007; Cisterna and Sterren, 2010; Cisterna and Sterren, 2016; Cisterna et al., 2017). However, no marine faunas have yet been described in the earliest glacial episode (Episode I of López-Gamundí, 1997), recorded in the Cumaná Formation (late Devonian-Early Carboniferous, Díaz Martínez et al., 1993), which seems to be linked to glacially-influenced marine deposits of latest Devonian age from the Amazonas and Solimões basins (López-Gamundí, 1997). The faunal associations of the Agua de Lucho Formation in the Sierra de las Minitas locality would have developed concomitantly with the successive processes of advance and retreat of the ice in the context of the earliest glacial episode of LPIA in South America, which has been recently described in this area (Ezpeleta et al., 2020). A very different scenario is observed in the Calingasta-Uspallata Basin, where the invertebrate marine faunas appear in the late Serpukhovian-Bashkirian glacial-postglacial succession, registered in different localities laterally disconnected and without vertical relationship.

The typical moderate-to-low diversity of early Mississippian assemblages from northern Chile above mentioned has been explained as influenced by high environmental stress conditions in a semi-restricted marine embayment in (González, 1994; Cisterna, 1996, 2011; Isaacson and Dutro, 1999; Sabattini et al., 2001; Cisterna and Isaacson, 2003; Taboada and Shi, 2009; Taboada, 2010; Sterren and Cisterna, 2010).

The early Mississippian fauna (i.e. Malimanian fauna, González, 1993) was also described as a warm to temperate (pre-glacial conditions) fauna developed previously to the pronounced cooling associated with the LPIA (González 1993; Taboada and Shi, 2009; Taboada, 2010). On the contrary, Sterren and Cisterna (2010) related the low diversity of the Early Carboniferous assemblages with the retraction (areal reduction) of the marine basin associated to tectonic and the glacial conditions suggested by some authors in this region (Pazos et al., 2005; Ezpeleta and Astini, 2008). New studies carried out in the Sierra de las Minitas confirm that the development of the early Mississippian fauna would be closely related to glacial conditions (Ezpeleta et al., 2020).

7.2. Biostratigraphic implications

The first early Mississippian marine fauna from southwestern Gondwana was recognized in the Malimán Formation (Sierra de la Punilla, San Juan province). It is virtually restricted to a green mudstone interval located in the lower-middle part of the Malimán Formation (Scalabrini Ortíz, 1972, 1973). In the type area, this assemblage is composed of the ammonoid *Michiganites scalabrinii* (Antelo, 1969), together with the brachiopods *Azurduya chavelensis* (Amos) and *Yagonia furquei* Taboada and Shi, and bivalves such as *Malimania triangularis* González, *Posidoniella malimanensis* González, *Sanguinolites punillanus* González, *Phestia* sp, *Schizodus* sp. and *Vacunella?* sp., accompanied of nautiloids (*Pseudorthoceras* sp.), gastropods (*Mourlonia punillana* Sabattini, Azcuy and Carrizo and *Bellerophon* (*Bellerophon*) sp.), conulariids (*Paraconularia anteloi* Sabattini, Azcuy and Carrizo), hyolith (*Hyolithes malimanensis* Sabattini, Azcuy and Carrizo) and indeterminable crinoid remains (González, 1994; Sabattini et al., 2001).

This fauna was included in the *Michiganites scalabrinii-Azurduya chavelensis* Zone, first considered the *Protocanites* Zone (González, 1981), then the Malimanian Fauna (González, 1993), and finally the *Protocanites scalabrinii-Paurorhyncha chavelensis* Zone by Sabattini et al. (2001), i.e. *Michiganites scalabrinii-Azurduya chavelensis* Zone, after the taxonomic update (Azcuy et al., 1990; Cisterna and Isaacson, 2003). Sabattini et al. (2001) formally erected the *Michiganites*

scalabrinii-*Azurduya chavelensis* Zone with the type locality at the Quebrada Cortaderas, on the west flank of the Sierra de la Punilla, San Juan Province, and as the stratotype the lower section of the Malimán Formation. The age of this biozone, according to the faunal composition and the presence of the genus *Michiganites* Ruzhencev, was considered to be Tournaisian-Viséan (Sabattini et al., 2001). Also, the paleofloristic content, corresponding to the *Archaeosigillaria-Malimanium* and *Frenquellia-Paulophyton* phytozones (Césari and Limarino, 1992, 1995; Carizo and Azcuy, 1998, 2015) and the associated palynological data correlated to the *Endoculeospora larga* Assemblage defined in Australia, and also with the CM and Pu Zones of Euramerica (Amenábar et al., 2009), indicate an undefined Tournaisian-Viséan age. However, Korn (1997, p. 35) based on the opinions of House (1996) regarding a lineage of prolecatinids involving *Eocanites-Becanites* and *Michiganites*, ranging from the earliest Tournaisian to the Viséan, noted that the type species of *Becanites* is closely related to early *Michiganites* species like *M. scalabrinii*, thus suggesting a most probable Tournaisian age. In a personal communication, Korn suggested us a probable late Tournaisian age for *M. scalabrinii* based on the basal characters of the suture.

Some faunal components of *Michiganites scalabrinii*-*Azurduya chavelensis* assemblage biozone are also recognized in two localities north to the outcrops of the Malimán Formation, i.e. in the type locality of the Agua de Lucho Formation (Cerro Agua de Lucho, La Rioja Province) (González and Bossi, 1986, 1987; González, 1994) and in the La Punilla Formation (Sierra de La Punilla, La Rioja province) (Fauqué et al., 1989; Caminos et al., 1993).

Typical components of the *Michiganites scalabrinii*-*Azurduya chavelensis* Zone have been here recognized in the Agua de Lucho Formation at the Sierra de las Minitas. The precise stratigraphic ranges of brachiopods, bivalves, and associated fauna identified in thick section studied (about 1250 m), palynologically constrained to the late Tournaisian based on *Waltzisporea lanzonii* (Prestiani et al., 2015), indicates that the *Michiganites scalabrinii*-*Azurduya chavelensis* faunal assemblage in its type area could be just a part of a much more rich Tournaisian fauna, exhibiting a wider stratigraphic distribution, with noticeable compositional variation. This new information, challenges the usefulness of the assemblage biozone, as originally it was defined. In this sense, the biostratigraphic marker *Michiganites scalabrinii* is just restricted to a couple of specimens coming from the Quebrada Chigua in the type area of the biozone (Antelo, 1969, 1970), which impedes its usefulness, for stratigraphic correlation. On the other hand, some components described in the original definition of the assemblage biozone (i.e. “crinoids”) consist of open nomenclature reports of high-rank taxa, which are virtually present in the whole Phanerozoic. In turn, other components were reported in open nomenclature at genus level, including bivalves with a very long stratigraphic ranges, while some other taxa, are restricted to the type area of the biozone and referred to classic long range Paleozoic and potentially wastebasket-genera, such as *Paraconularia anteloi* or *Hyalithes malimanensis*.

In such a regional biostratigraphic scenario, the rhynchonellid brachiopod *Azurduya chavelensis* is extremely significant, as suggested by Cisterna and Isaacson (2003) and Sterren, (2008), since it represents the only one taxon invariably present in the paleontological records from all the early Mississippian localities from Southwestern Gondwana (Table 1). Accounting for age accurements from these localities, where ammonoid and palynological biostratigraphic markers are available, *Azurduya chavelensis* could be interpreted as a middle to late Tournaisian taxon. The presence of the typically middle Tournaisian ammonoid species *Becanites serageominus* (House) (House, 1996; Korn et al., 2003; Zong et al., 2015), together with *Azurduya chavelensis* at the Zorritas Formation (Chile), constrains the oldest known record of this brachiopod to the middle Tournaisian. In turn, the youngest age could be constrained to the late Tournaisian by the occurrence of *M. scalabrinii* at the Malimán Formation, which could be probably correlative to the uppermost assemblages (FI 5) here studied in the Agua de Lucho Formation at Sierra de las Minitas. *Azurduya chavelensis* is a conspicuous

facies-independent easy to identify species, which has been recorded in several sedimentary environments either with or without glacial evidence, accounting for a useful biostratigraphic marker.

This genus characterizes the successions of the Agua de Lucho and Malimán Formations, and was also cited for several intermediate localities in Sierra de la Punilla (Fauqué et al., 1989; Caminos et al., 1993; Cisterna and Isaacson, 2003; Pazos et al., 2005), and Chile (Isaacson and Dutro, 1999; Cisterna and Isaacson, 2003). Therefore, *Azurduya chavelensis* becomes a suitable macrofaunal tool for intra- and inter-basinal correlations for the Early Mississippian deposits of southwestern Gondwana.

8. Conclusions

1. The new records of marine invertebrate in the Agua de Lucho Formation at Sierra de las Minitas, La Rioja province, increase the diversity known for the early Mississippian marine faunas from the high paleolatitude of Gondwana.
2. The fauna represents the most diverse fossil record for the early Mississippian in South America, appears associated with a glacial event recently identified in the region (Ezpeleta et al., 2020), which suggests a review of the paleoclimatic implications of the early Mississippian faunal assemblages from Argentina, usually described as a warm to temperate faunas.
3. Typical components of the *Michiganites scalabrinii*-*Azurduya chavelensis* Zone (Sabattini et al., 2001) are recognized in the fauna studied, although the new records suggest important compositional variations of this biozone within the different localities in the Río Blanco Basin.
4. The stratigraphic ranges of the brachiopods and bivalves of the *Michiganites scalabrinii*-*Azurduya chavelensis* Zone in the studied sections are palynologically constrained as late Tournaisian in age.
5. The study of brachiopods and bivalves, in particular, exhibits important compositional variations through the thick section of the Agua de Lucho Formation at Sierra de las Minitas, and confirms the strong affinity with other units of the western Gondwana. Thus, the faunal assemblages of the basal part can be compared with those of the type section of the Agua de Lucho Formation. Also, their general stratigraphic distribution in Sierra de las Minitas section confirms the strong affinity with those from Zorritas Formation in northern Chile.
6. The new records, particularly the occurrence of *Azurduya chavelensis* as a conspicuous component of the fauna in the studied sections of the Agua de Lucho Formation at Sierra de las Minitas and in other contemporaneous successions of Argentina and Chile, suggest revisiting the usefulness of the *Michiganites scalabrinii*-*Azurduya chavelensis* assemblage biozone, as it was originally defined. The rhynchonellid brachiopod *Azurduya chavelensis* becomes a proper macrofaunal tool to intra- and inter-basinal correlations for the Early Mississippian deposits of Southwestern Gondwanan margin.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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