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The southernmost record of the *Aseptella-Tuberculatella/Rhipidomella-Micraphelia* Fauna (late Serpukhovian-Bashkirian) in the Calingasta-Uspallata basin, Argentina

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ABSTRACT. The Agua del Jagüel Formation crops out in the southernmost part of the Calingasta-Uspallata basin, in central western Argentina. The lower part of the unit is characterized by a glacigenic sequence with diamictites and mudstones with dropstones. In the latter, elements of the *Aseptella-Tuberculatella*/*Rhipidomella-Micraphelia* Fauna (*AT/RM* Fauna), such as the brachiopods *Rhipidomella discreta* Cisterna, *Micraphelia indianae* Simanauskas and Cisterna and *Orbiculoidea?* sp., the gastropods *Murchisonia*? sp., and *Glabrocingulum* (*Stenozone*)? sp., the bivalve Nuculanidae indet., rugose corals, and indeterminate fragments of nautiloids and hyolithids, have been identified. The importance of this fauna mainly resides in its paleoenvironmental and biostratigraphic implications. *AT/RM* Fauna is characteristic of restricted environments with relatively low concentrations of oxygen and nutrients in the seafloor, which is consistent with the glaciomarine sequences in fjord-type coasts suggested for the Agua del Jagüel Formation. The relatively low diversity of the fauna in this unit compared to that defined in the El Paso Formation, located further north in the basin, might suggest more restricted sectors for benthic colonization, related to the paleovalle's isolation from oceanic waters. The postglacial mudstones with marine invertebrate faunas of late Serpukhovian-Bashkirian age would have been deposited in relatively restricted (palaeofjord) part of the Uspallata-Calingasta basin as well as in open shelf environments. The marine flooding over drastically different coast configurations and the availability of nutrient and oxygen in the water column would have propitiated the development of faunas with important differences in the taxonomic composition and the paleoecological structure (*AT/RM* and *Levipustula* Faunas) occurring at the same time interval. Radiometric data in Agua del Jagüel Formation and paleontological records in the glacial-postglacial sedimentary succession in the basin (marine invertebrate faunas, palynomorphs and plants) are the most important tools to adjust the timing of the postglacial transgression. This information herein presented complements the scheme proposed for the Carboniferous sequences throughout the central western of Gondwana but is not sufficient to assign a more precise age of the fauna studied within the late Serpukhovian-Bashkirian interval.

Keywords: AT/RM Fauna, Late Serpukhovian-Bashkirian, Calingasta-Uspallata basin, Agua del Jagüel Formation, Mendoza, Argentina.

RESUMEN. El registro más austral de la Fauna *Aseptella-Tuberculatella / Rhipidomella-Micraphelia* (Serpukhoviano tardío-Bashkiriano) en la cuenca Calingasta-Uspallata, Argentina. La Formación Agua del Jagüel aflora en el sector más austral de la cuenca de Calingasta-Uspallata, centro-oeste de Argentina. La parte inferior de esta unidad se caracteriza por una secuencia glacigénica compuesta por diamictitas y pelitas con clastos dispersos. En esta última se reconocen elementos de la fauna *Aseptella-Tuberculatella*/*Rhipidomella-Micraphelia* (Fauna *AT/RM*), tales como los braquiópodos *Rhipidomella discreta* Cisterna, *Micraphelia indianae* Simanauskas y Cisterna, *Orbiculoidea?* sp., los gastrópodos *Murchisonia*? sp. y *Glabrocingulum* (*Stenozone*)? sp., el bivalvo Nuculanidae indet., corales rugosos, y fragmentos indeterminados de hyolithes y nautiloideos. El hallazgo de esta fauna resulta importante desde el punto de vista paleoambiental y bioestratigráfico. La Fauna *AT/RM* es característica de ambientes restringidos, con relativamente bajas concentraciones de oxígeno y nutrientes en el fondo marino, lo cual es consistente con secuencias glacimarinas en costas tipo fiordos sugeridas para la Formación Agua del Jagüel. La baja diversidad relativa de la fauna en esta unidad comparada con la definida en la Formación El Paso, ubicado más al norte en la misma cuenca, podría sugerir sectores relativamente más restringidos para la colonización bentónica, relacionados con el aislamiento del paleovalle de las aguas oceánicas. Las pelitas postglaciales con invertebrados marinos del Serpukhoviano tardío-Bashkiriano se habrían depositado en sectores relativamente restringidos (paleofiordos) de la cuenca de Calingasta-Uspallata, como así también en ambientes de plataforma. La transgresión marina sobre las distintas configuraciones costeras y la disponibilidad de nutrientes y oxígeno en la columna de agua habrían propiciado el desarrollo de faunas con diferente composición taxonómica y estructura paleoecológica (Faunas *AT/RM* y *Levipustula*), en el mismo intervalo temporal. Los datos radimétricos en la Formación Agua del Jagüel y la información paleontológica en la sucesión glacial-postglacial dentro de la cuenca (invertebrados marinos, palinomorfos y plantas) constituyen las herramientas más importantes para ajustar la edad de la transgresión. Esta información complementa el esquema propuesto para las secuencias carboníferas en todo el centro oeste de Gondwana, pero no es suficiente para precisar las edades dentro del intervalo Serpukhoviano tardío-Bashkiriano.

Palabras clave: Fauna AT/RM, Serpukhoviano tardío-Bashkiriano, Cuenca Calingasta-Uspallata, Formación Agua del Jagüel, Mendoza, Argentina.

1. Introduction

Of the three episodes identified in the Late Paleozoic Ice Age (LPIA), the Glacial episode II is restricted to the westernmost part of Gondwana in Southern South America (López-Gamundí, 1997, 2010). This episode has been well documented in the central western Argentina (Fig. 1A), where the glacial-postglacial transition is recognized in several localities. In the Calingasta-Uspallata basin, the postglacial deposits, temporally constrained to the initial deglatiation (late Serpukhovian-Bashkirian interval) (Fig. 1B), are characterized by two well diversified marine faunas: the *Levipustula* Fauna, widely known by previous studies (Cisterna and Sterren, 2010 and references therein), and the *Aseptella-Tuberculatella*/*Rhipidomella-Micraphelia* Fauna (Cisterna and Sterren, 2016; Cisterna *et al.*, 2017). These faunas have been described from the Calingasta-Barreal area in the San Juan province (Césari *et al*., 2007 and references therein; Cisterna and Sterren, 2010; Taboada, 2010), and recently both have been considered coeval by Cisterna and Sterren (2016) and Cisterna *et al*. (2017). However, although *Aseptella-Tuberculatella*/*Rhipidomella-Micraphelia* Fauna is restricted to a same interval of time (late Serpukhovian-Bashkirian), new data on biostratigraphic relationship between the El Paso Formation and the overlying Pituil Formation (in the northern part of the Uspallata-Calingasta basin, Fig. 1B) obtained in recent field preliminary studies, suggests that these faunas could be only partially coeval.

The aim of this contribution is to describe the faunal assemblage that characterizes the *Aseptella-Tuberculatella*/*Rhipidomella-Micraphelia* Fauna in the lower part of the Agua del Jagüel Formation (Amos and Rolleri, 1965), in the Uspallata area. The record of this postglacial fauna in the southernmost part of the Calingasta-Uspallata basin (Fig. 1B), provides new information related to the age, paleogeographic extent and depositional conditions of the Carboniferous marine transgression.

2. Geological setting

The Agua del Jagüel Formation (Amos and Rolleri, 1965) crops out south and north of the Agua del Jagüel Creek, located about 17 km northeast from Uspallata (S 32°30', W 69°14') in Mendoza

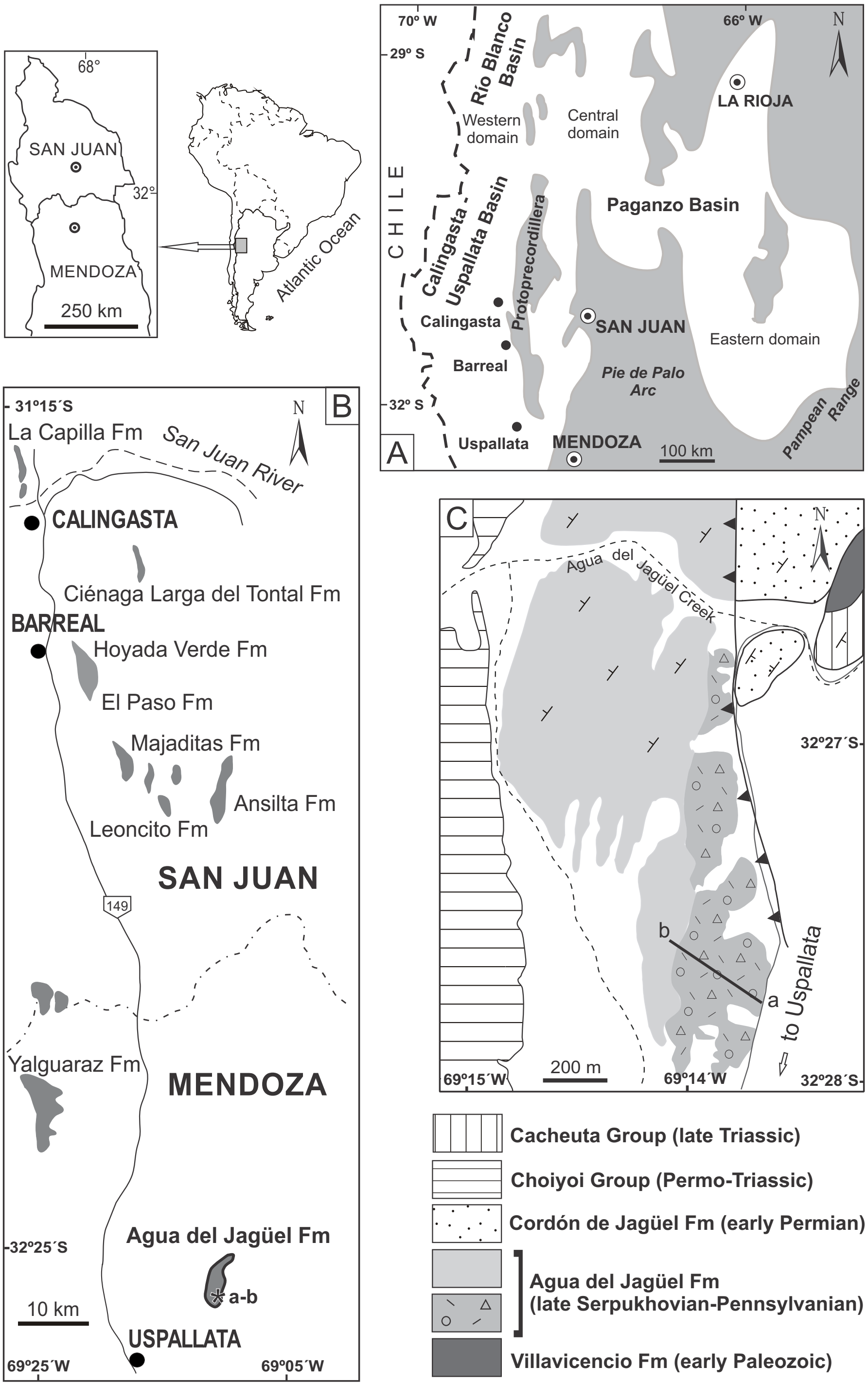

FIG. 1. **A.** Paleogeographic map of the late Carboniferous-early Permian basins, central-west of Argentina (after Salfity and Gorustovich, 1983; Limarino *et al*., 2002). **B.** Geographic distribution of the Carboniferous postglacial faunas in the Calingasta-Uspallata basin, showing the location of the studied section (a-b). **C.** Schematic geological map of Agua del Jagüel Formation outcrops (modified from Limarino *et al*., 2013), showing the studied section (a-b).

province (Fig. 1B). The Agua del Jagüel Formation (Amos and Rolleri, 1965) initially also comprised the sandstones, mudstones and conglomerates exposed along the western slope of the Cordón de Agua de Jagüel range. However, a recent lithostratigraphic scheme proposed by Limarino *et al*. (2013) assigns this succession to the Cordón de Jagüel Formation (Fig. 1C) and retains the name Agua del Jagüel Formation (Amos and Rolleri, 1965) for the sandstones, mudstones and diamictites deposits separated by a reverse fault. The sedimentary succession of the Agua del Jagüel Formation is in turn overlain by the Permo-Triassic Choiyoi Group (Stipanicic *et al.,* 1968), and rests by faulted contact on the early Permian deposits of the Cordón de Jagüel Formation (Limarino *et al*., 2013) (Fig. 1C). Sedimentologic and stratigraphic studies carried out in the Agua del Jagüel Formation allowed to identify a diamictite-bearing interval composed of predominantly muddy diamictites and mudstones with dropstones in the lower part of the unit (López-Gamundí, 1984; Henry *et al*., 2010) (Fig. 2, 3), and a sandstone-prone section with limestone lenses in the upper part (Amos and Rolleri, 1965; López-Gamundí and Amos, 1982; Taboada, 1987; Lech, 1990).

Three depositional sequences have been identified by Henry *et al*. (2008) in the Agua del Jagüel Formation; a lowermost glaciogenic sequence composed by diamictites, conglomerates, sandstones, and mudstones (Sequence 1, late Serpukhovian-early Bashkirian), equivalent to the muddy and sandy diamictites (facies 1), interbedded shales, sandstones and thin bedded diamictites (facies 2), mudstones with dispersed outsized clasts (facies 3) and fine-to medium-grained and pebbly sandstones with cross stratification (facies 4) defined by López-Gamundí (1984). Sequences 2 and 3 of Henry *et al*. (2010) are characterized by fluvial and shallow marine sediments and would have an Asselian age (Henry *et al*., 2010 and references therein). Ages proposed by Henry *et al*. (2010) are consistent with the Moscovian radiometric age (307.2±5.2 Ma; Lech, 2002; Koukharsky *et al*., 2009) from a dacitic lava exposed close to the base of the Sequence 3.

The faunal assemblage identified in the upper part of the Agua del Jagüel Formation (Sequence 2 and 3,

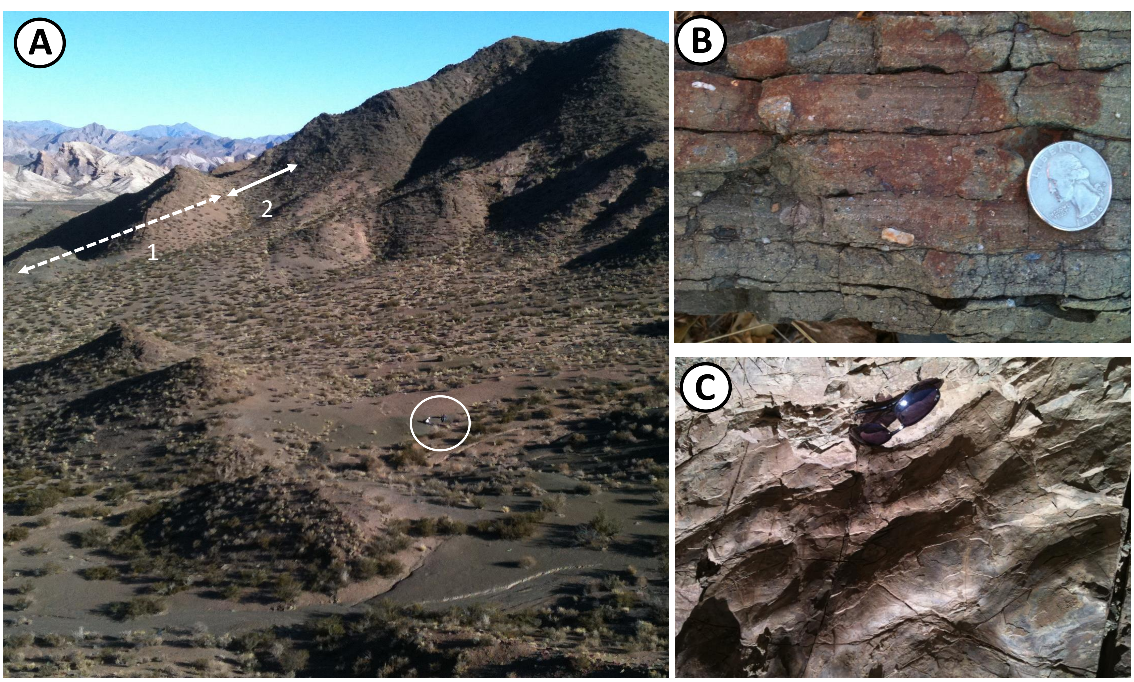

FIG. 2. **A**. Lower section of the Agua del Jagüel Formation, view to the south. 1 (dashed double arrow): basal diamictite-dominated section, 2 (solid double arrow): mudstone-dominated interval with *Aseptella-Tubercutella/Rhipidomella-Micraphelia* Fauna. Two persons as scale (circle). **B.** Thin-bedded muddy diamictites. **C.** Sinuous, symmetrical (wave) ripples in fine-grained sandstones.

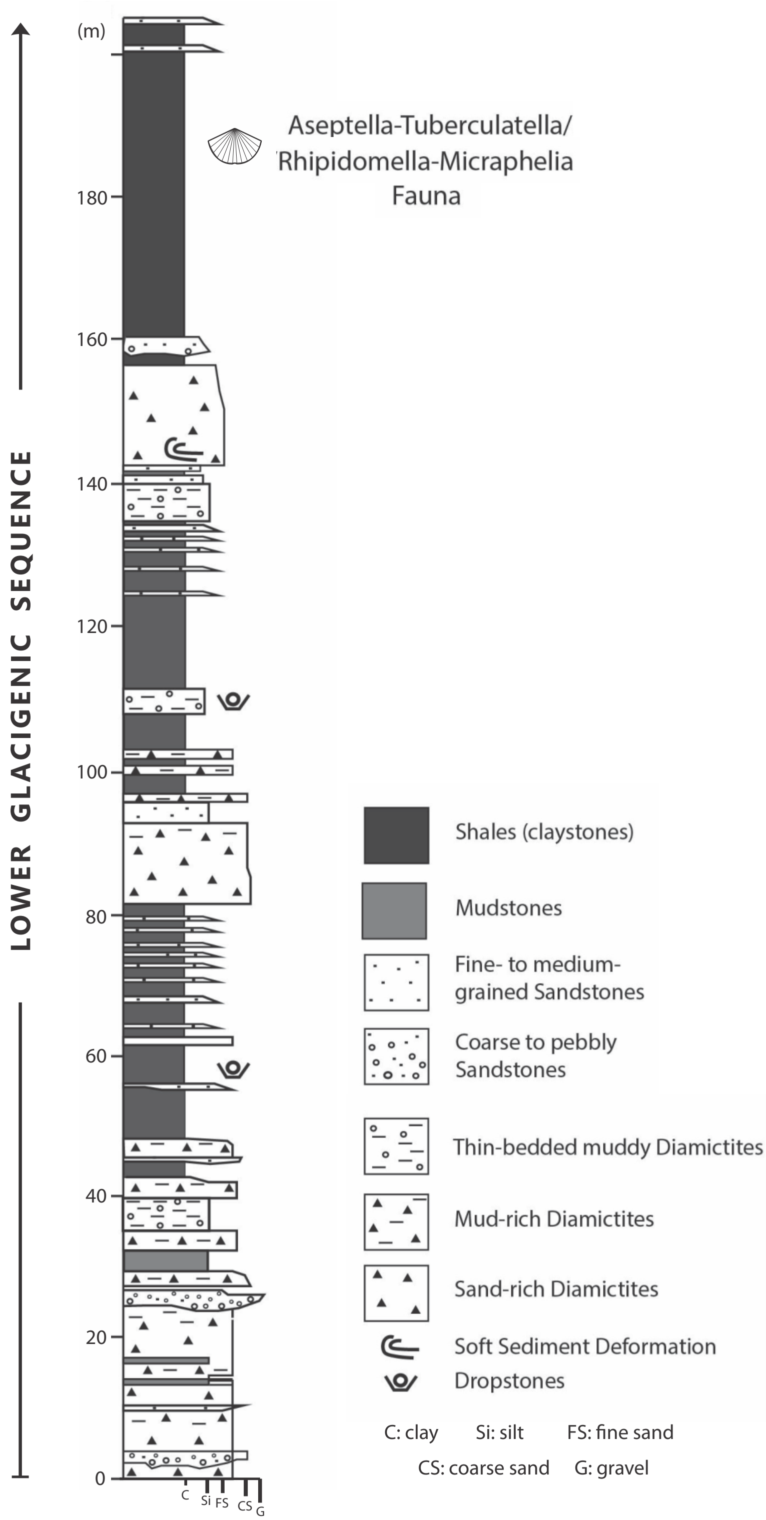

FIG. 3. Stratigraphic column of the lower section of the Agua del Jagüel Formation (1 and 2 in Fig. 2A) (modified from López-Gamundí, 1984), showing the fossiliferous interval of the studied fauna.

Henry *et al*., 2010) has been assigned to the Early Permian *Costatumulus amosi* Biozone (Taboada, 1998, 2006, 2010; Martínez *et al*., 2001; Cisterna, 2010; González and Díaz Saravia, 2010). However, more recent studies suggest that the fauna recognized in the upper part of the Agua del Jagüel Formation can be assigned to the Late Carboniferous *Tivertonia jachalensis-Streptorhynchus inaequiornatus* Biozone (Taboada, 2014).

The fossil record of the lower glacigenic sequence (Figs. 2 and 3) (Sequence 1, Henry *et al*., 2008), is very sparse. Serpukhovian-early Bashkirian spores have been identified in this part of the unit (Césari S.N. in Henry *et al*., 2010), and bivalves, gastropods and scaphopods were reported from shales interbedded with the diamictite levels (Amos and Rolleri, 1965; Taboada, 1987). Lech (2002) mentioned the presence of *Tivertonia* sp., *Sueroceras*? sp. and abundant trace fossils. The mudstone-dominated interval immediately above the basal diamictites is characterized by a faunal assemblage composed of brachiopods, gastropods, bivalves and corals of the earliest postglacial fauna. Diagnostic species of the *Aseptella-Tuberculatella/Rhipidomella-Micraphelia* Fauna have been recognized in this assemblage (Martínez *et al*., 2001; Simanauskas and Cisterna, 2001; Cisterna, 2010; Sterren *et al*., 2017) and their biostratigraphic and palaeoenvironmental implications are discussed in this paper.

3. *Aseptella-Tuberculatella/Rhipidomella-Micraphelia* Fauna

The invertebrate assemblages of the marine mudstones associated with the glaciomarine deposits present in the upper part of the El Paso Formation (Mésigos, 1953), south of Barreal Hill in the northern part of the Calingasta-Uspallata basin (Fig. 1A, B), have been recently defined as *Aseptella-Tuberculatella/Rhipidomella-Micraphelia* Fauna (Cisterna and Sterren 2015, 2016; Cisterna *et al*., 2017). The importance of this postglacial fauna is mainly resided in its biostratigraphic and paleoenvironmental implications.

The age of the faunal assemblages in the El Paso Formation has been widely discussed (Taboada, 1989, 1997, 2010; Cisterna and Simanauskas, 1999; Simanauskas and Cisterna, 2001; Cisterna, 2010; Cisterna *et al*., 2013, Cisterna and Sterren, 2016; Cisterna *et al*., 2017), and it could be defined as late Serpukhovian-Bashkirian (Vergel *et al*., 2008, 2015) based on the presence of palynomorphs of the Subzone A of the *Raistrickia densa-Convolutispora muriornata* (DM) Biozone (Césari *et al*., 2011). The presence of the *Aseptella-Tuberculatella/Rhipidomella-Micraphelia* Fauna (*AT/RM* Fauna) in several glacial-postglacial successions deposited along the Calingasta-Uspallata basin margin allows us to consider it as an important intrabasinal correlation tool. Typical elements of *AT/RM* Fauna appear in other two stratigraphic units: the herein studied Agua del Jagüel Formation and the Ciénaga Larga del Tontal Formation (Casa de Piedra Formation, Lech *et al*. 1998), exposed in the northern part of the basin (Fig. 1B) (Cisterna and Sterren, 2016; Cisterna *et al*., 2017).

A paleofjord setting has been suggested for this area by Zöllner (1950), and more recently proposed for the El Paso Formation (Cisterna *et al*., 2017). Marine incursions in relatively deep and narrow portions of the fjord would have favored the development of the *AT/RM* Fauna. The assemblages identified have been interpreted as indicators of environmental stress related to restricted oxygen and nutrient availability (Cisterna *et al*., 2017).

Brachiopods, bivalves and gastropods, accompanied by conulariids, nautiloids, corals and ostracods are the typical elements that characterize the *AT/RM* Fauna. Two fossil assemblages distinguish this fauna in the El Paso Formation: the *Aseptella-Tuberculatella* assemblage identified in the lower fossiliferous interval, and the *Rhipidomella-Micraphelia* assemblage, in the upper interval (Cisterna *et al*., 2013, 2017). The *Aseptella-Tuberculatella* assemblage is dominated by the brachiopods *Tuberculatella peregrina* Simanauskas and Cisterna, *Aseptella* aff. *A. patriciae* Simanauskas, Overtoniinae indet., Linoproductoidea indet., *Micraphelia indianae* Simanauskas and Cisterna, *Micraphelia*? sp., *Rhipidomella discreta* Cisterna, and the less abundant *Beecheria patagonica* Amos, *Orbiculoidea* sp., lingulids indet., and athyrids indet. Furthermore, the bivalves *Nuculanella camachoi* González, *Quadratonucula*? sp., *Nuculopsis*? sp., *Phestia* sp. and *Myofossa calingastensis* González, and the gastropods *Ananias* sp., *Glabrocingulum* (*Stenozone*) sp., and *Murchisonia*? sp., appear typically associated with the brachiopods in this assemblage. The *Rhipidomella-Micraphelia* assemblage is characterized by the brachiopods *Micraphelia indianae* and *Rhipidomella discreta* Cisterna, accompanied by *Orbiculoidea* sp. and *Beecheria patagonica* Amos, the bivalves *Aviculopecten barrealensis* Reed (in Du

Toit, 1927), *Myofossa calingastensis*, *Schizodus*? sp., and the gastropods *Glabrocingulum* (*Stenozone*) sp., and *Murchisonia*? sp.

4. *Aseptella-Tuberculatella/Rhipidomella-Micraphelia* Fauna in Agua del Jagüel Formation

Diagnostic components of the *AT/RM* Fauna have been identified in the mudstone-dominated interval that overlies the diamictite beds (upper part of Sequence 1 according Henry *et al*., 2010) (Fig. 1C, a-b section), of the Agua del Jagüel Formation by (Martínez *et al*., 2001 and Cisterna *et al*., 2013, 2017). The fauna is scarce and very scattered within thick grey mudstone packages with dispersed clasts, and the small size appears to be characteristic of most specimens. Low degree of fragmentation has been observed in the shells. Also, bivalves exhibit a predominance of articulated valves. Brachiopods appear in different ontogenetic stages and the spines of *Micraphelia* are preserved.

The brachiopods *Rhipidomella discreta*, *Micraphelia indianae*, *Orbiculoidea?* sp., the bivalve Nuculanidae indet., gastropods, corals, and indeterminate fragments of nautiloids and hyolithids (Sterren *et al*., 2017) (Fig. 4), were identified in this interval.

Rhipidomella discreta (Fig. 4A-F) is a particularly small species of the genus *Rhipidomella* with subtriangular to subcircular outline, conspicuous concentric, fine and dense, growth lines (Cisterna *et al*., 2017). There are few described species as small as *Rhipidomella discreta,* among these are *Rhipidomella plana* Yang from the Carboniferous of China (Yang *et al*., 1977) and the Permian *Rhipidomella cordialis* Grant from Thailand (Grant, 1976). Type material of *Rhipidomella discreta* has been described from the Barreal Hill, through the entire fossiliferous interval of the El Paso Formation (Fig. 1B), and specimens that probably belong to this species have also been identified immediately above of the El Paso Formation, in the basal beds of the Pituil Formation (Taboada, 1997, Tres Saltos Member).

Rhipidomella discreta appears typically associated with *Micraphelia indianae* in the El Paso Formation, and this assemblage characterizes the upper part of the unit. However, these diagnostic species can also be identified in the lower part (Cisterna and Sterren, 2016; Cisterna *et al*., 2017). This assemblage is also recorded in the postglacial mudstones here studied. The Rugosochonetidae *Micraphelia indianae* (Fig. 4G-I) characterized by cyrtomorph intraversed cardinal spines has been compared with Permian species from west Texas (Simanauskas and Cisterna, 2001), such as *Micraphelia scitula*, *M. pumilis* and *M. subalata* (Cooper and Grant, 1975).

Specimens of *Rhipidomella discreta* and *Micraphelia indianae* from the Agua del Jagüel Formation can be particularly distinguished from those of the El Paso Formation because they are smaller and, in both species, consist of rather delicate forms.

Gastropods are also relatively abundant in the postglacial mudstones of Agua del Jagüel Formation. Two forms were identified: *Murchisonia*? sp., the most abundant, and *Glabrocingulum* (*Stenozone*)? sp. (Fig. 4M, N), similar to those present in the El Paso Formation.

Only five specimens of bivalves were registered in the studied unit, all of them belonging to Nuculanidae indet. (Fig. 4I-J), which shows strong similarity with *Nuculopsis*? sp. recognised in the lower interval in the El Paso Formation and in the lower part of the Ciénaga Larga del Tontal Formation (Fig. 1B, "diamictitic member" of Lech and Milana, 2006). The suborbicular shape of the shell and the ornamentation, that consists of sharp and homogeneous commarginal very fine ridges, are the main features in common. In all cases the specimens do not exceed one centimeter in length.

A specimen of solitary rugose coral of few millimeters (Fig. 4O) was also identified in Agua del Jagüel Formation. Similar specimens were found by the authors in the upper part of the El Paso Formation and in the basal interval of the Pituil Formation (Esquina Gris Member, Taboada, 1997) in outcrops of the Barreal Hill, and they are being studied. *Orbiculoidea?* sp. and nautiloids are also common elements in this fauna.

Although scarce and low diversified, the fauna of the Agua del Jagüel Formation contains some of the characteristic components of *AT/RM* Fauna, particularly of the *Rhipidomella-Micraphelia* assemblage that characterizes the upper fossiliferous interval of the El Paso Formation (*i.e*., the brachiopods; the gastropods and the corals). Other mollusks such as bivalves and nautiloids are common in the *Aseptella-Tuberculatella* assemblage, which is typical of the lower fossiliferous interval in the El Paso Formation.

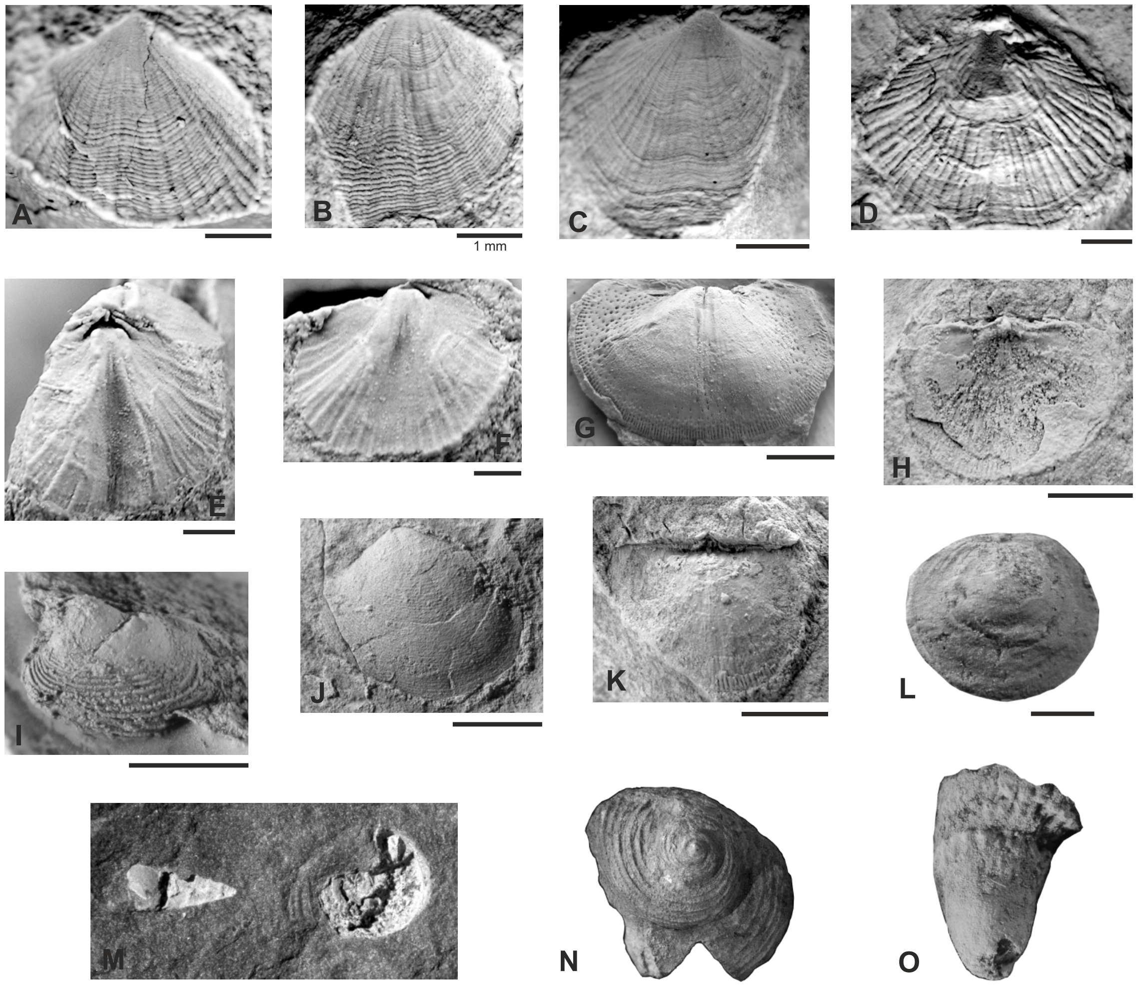

FIG. 4. *Aseptella-Tuberculatella* / *Rhipidomella-Micraphelia* Fauna. **A-F.** *Rhipidomella discreta* Cisterna *et al*., 2017. **A.** External mould of ventral valve CEGH-UNC 27280; **B.** External mould of ventral valve CEGH-UNC 27281; **C.** External mould of ventral valve CEGH-UNC 27282; **D.** External mould of dorsal valve CEGH-UNC 27283; **E.** Internal mould of articulate specimen, dorsal view CEGH-UNC 27284; **F.** Internal mould of dorsal valve CEGH-UNC 27285; **G-H, K.** *Micraphelia indianae* Simanauskas and Cisterna, 2001. **G.** Internal mould of ventral valve CEGH-UNC 27286; **H-K.** Countermould and external mould of dorsal valve CEGH-UNC 27287a, b; **I-J.** Nuculanidae indet. **I.** Internal mould of right valve CEGH-UNC 27289; **J.** Internal mould of left valve CEGH-UNC 27290; **L.** *Orbiculoidea?* sp. internal mould of dorsal valve CEGH-UNC 27293; **M.** Gastropods *Murchisonia*? sp. and *Glabrocingulum* (*Stenozone*)? sp. CEGH-UNC 27297; **N.** *Glabrocingulum* (*Stenozone*)? sp. CEGH-UNC 27296; **O.** Latex mould of rugose coral CEGH-UNC 27295. **Scale bars:** 1 mm (figs. A-F, I, L, O), and 3 mm (Figs. G, H, J, K, M-N). The material is deposited in the palaeontological collection "Centro de Investigaciones Paleobiológicas", Universidad Nacional de Córdoba-CONICET, housed in the CICTERRA (Centro de Investigaciones en Ciencias de la Tierra) under the institutional abbreviation CEGH-UNC.

The development of *AT/RM* Fauna in the Agua del Jagüel Formation provides additional evidence about the paleogeographic extent of the marine postglacial transgression in the Calingasta-Uspallata basin, and supports the late Serpukhovian-Bashkirian age for this part of the sequence.

5. Discussion

5.1. Palaeoenvironmental considerations

Sedimentary successions recording the glacial-postglacial transition are present in a variety of basin types, namely, those ranging from backarc foreland basins to rifts, and exhibit common characteristics across Gondwana (López-Gamundí, 2010).

The transition from glacially dominated settings through glacially influenced early postglacial environments to late postglacial, ice-free open marine conditions can be identified in central western Argentina. In this region the marine transgression is recorded in three major paleogeographic domains: in the western domain, it is mainly recognized by open marine facies, in the central domain, transitional, fjord-type environments prevail; and in the eastern domain, is characterized by flooded paleovalleys and glaciolacustrine settings or very shallow marine facies, according Limarino *et al*. (2002) (Fig. 1A).

The postglacial marine deposits with invertebrate fauna are common and abundant along the indented coastline of the western Protoprecordillera (Fig. 1B), where several paleovalleys, or paleofjords are recorded (López-Gamundí, 1997; López-Gamundí and Breitkreuz, 1997).

In some areas of the basin, the marine transgression flooded the valleys and the inner and deeper parts of the fjords (Zöllner, 1950; Henry *et al*., 2008, 2010; Cisterna *et al*., 2017), generating restricted environments characterized by *AT/RM* Fauna. In in other sectors, an open marine coast with more circulation of ocean waters favoured the development of the widely distributed *Levipustula* Fauna (Cisterna *et al*., 2017).

The basal glaciomarine succession recorded in the lower part of the Agua del Jagüel Formation ranges from proximal glaciomarine deposits to more distal glacially influenced sediments (Figs. 2 and 3). Massive to stratified diamictites, clast-poor diamictites and subordinate thinly bedded diamictites with ice-rafted debris (IRD), are interpreted as the combined product of rain out from icebergs and melt water plumes, cohesive debris flows and ice rafting (López-Gamundí, 1984, 1991; Henry *et al*., 2010). High sedimentation rates and/or steep slopes, common in glaciomarine fjord settings, provide exceptional conditions for subsequent resedimentation of glacial material as gravity flows (Powell and Domack, 2002), and the formation of subaqueous debris flows (glaciogenic debris flows, Gravenor *et al*., 1984). This process is coupled with rain out from ice rafting. The glaciomarine facies association grades upward into an interval dominated by IRD-free shales considered the marine flooding related to the deglaciation, completing the submarine-retreat facies association (López-Gamundí, 2010). In sequence stratigraphic terms, this mudstone-prone interval represents the maximum flooding surface (or interval) [MFS or MFI] which defines the top of the transgressive systems tract (López-Gamundí, 1997, 2010; Pazos, 2002; López-Gamundí and Martínez, 2003).

The lower sequence of the Agua del Jagüel Formation has been interpreted as deposited under anoxic conditions (Henry *et al*., 2010). This is supported by geochemical studies on mudstones and marls, which display V/Cr ratios above 2, indicative of anoxia (Henry *et al*., 2010), and are consistent with a rather confined palaeogeographic setting, such as a palaeofjord environment with the glaciers still present at the beginning of the transgression (Henry *et al*., 2008, 2010). A complex range of abiotic factors are directly related to the dynamics of glacial retreat. Variations in the salinity due to high fresh-water discharge in deglacial process, high sedimentation rates, variable degree of substrate consolidation, oxygen-depletion and high turbidity could have been some of the parameters that conditioned the development of the fauna in these environments (Syvitski *et al*., 1987; Buatois and Mángano, 2011). Additionally, the presence of morainal banks could isolate different sectors of the paleovalley and obstruct the circulation of water within the fjord (Cai *et al*., 1997; Willems *et al*., 2009).

Although scarce, the occurrence of the marine fauna in the postglacial interval of the Agua del Jagüel Formation suggests a relatively favorable environment for the development of invertebrate assemblages with at least minimum oxygen conditions and availability of nutrients. Also, the presence of a very impoverished record of the *AT/RM* Fauna in this unit in comparison with that of the El Paso Formation, could indicate a more stressful environment for benthic colonization, probably related to a restricted oceanic waters circulation in this part of the basin. Typical components of *AT/RM* Fauna identified in the postglacial marine interval of the Ciénaga Larga del Tontal Formation, in the Casa de Piedra Creek (Fig. 1B), suggest a similar restricted environment related with a paleofjord setting (Cisterna *et al*., 2017).

In the Calingasta-Uspallata basin the invertebrate marine faunas of the postglacial mudstones could have lived in fjords or open marine conditions, showing distinct characteristics. Therefore, the marine flooding over different coast configurations and the availability of sediment would have conditioned the development of invertebrate assemblages with significant differences in their taxonomic composition and paleoecological structure. These differences are well exemplified in the case of *AT/RM* Fauna and *Levipustula* Fauna, extensively discussed in recent studies (Cisterna and Sterren, 2016; Cisterna *et al*., 2017).

5.2. Stratigraphic and biostratigraphic considerations

The Late Carboniferous glacial-postglacial sequences present in the basins of central western Argentina (Fig. 1A), can be constrained with radiometric and paleontological data (principally palynomorphs, and brachiopods) to the late Serpukhovian-Bashkirian (Taboada, 1997; Pazos, 2002; Limarino *et al*., 2002; Césari *et al*., 2011). However, the biostratigraphic resolution is not sufficient to locate it temporally within this range of time.

In the Calingasta-Uspallata basin, western domain, the glacial-postglacial succession provides paleontological data (Subzone A of *Raistrickia densa-Convolutispora muriornata* Biozone; *Aseptella-Tuberculatella*/*Rhipidomella-Micraphelia* Fauna and *Levipustula* Fauna) that contributes to correlate the different lithostratigraphic units (Fig. 5).

In the Agua del Jagüel Formation, the first invertebrate assemblage occurs immediately above the basal diamictite levels (Sequence 1 according Henry *et al*., 2010), constraining the maximum age of the *AT/RM* Fauna to Serpukhovian, while its upper limit is marked by a radiometric age (307.2±5.2 Ma, Lech, 2002; Koukharsky *et al*., 2009). The *AT/RM* Fauna defined in the El Paso Formation, located further north in the basin, is associated to palynological elements

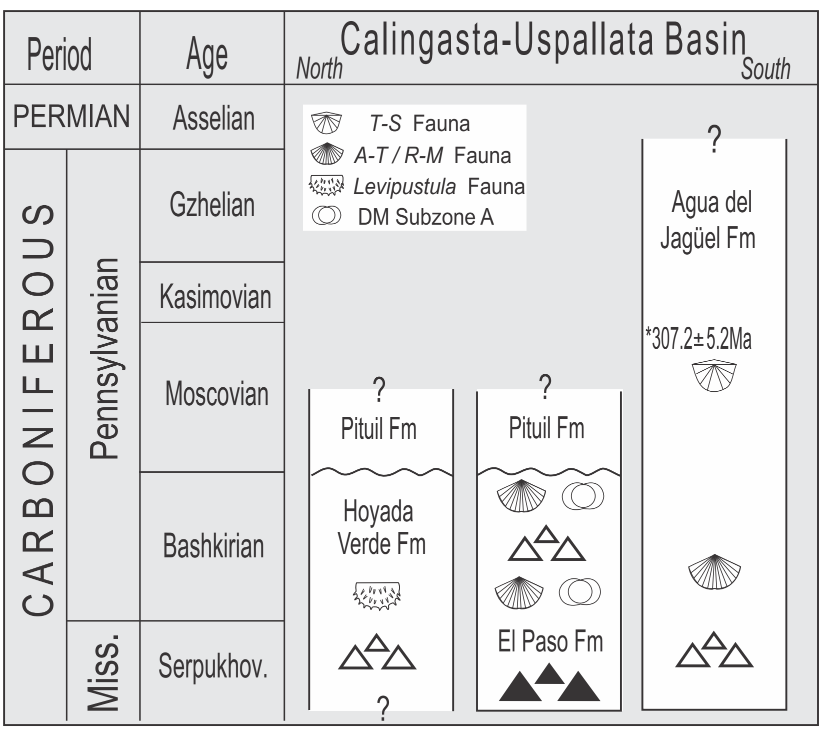

FIG. 5. Paleontological and radiometric data in the Carboniferous marine sediments in Calingasta-Uspallata basin. *A-T/R-M* Fauna: *Aseptella-Tuberculatella*/*Rhipidomella-Micraphelia* Fauna. *K-Ar in biotite age of 307.2±5.2 Ma. Radiometric data from Lech, 2002). Stratigraphic and paleontological data from López-Gamundí and Martínez (2003), Henry *et al.* (2010), Taboada (2014), Cisterna and Sterren (2010, 2016), Vergel *et al*. (2016), Cisterna *et al*. (2017). Black triangles: basal glacially-influenced proximal deposits levels and white triangles: glacial marine deposits and associated gravity flow deposits. Units without scale. Periods and ages according to the Global Time Scale (Cohen *et al*., 2018).

of the Subzone A of *Raistrickia densa-Convolutispora muriornata* Biozone, late Serpukhovian-Bashkirian (Vergel *et al*., 2008, 2015; Cisterna *et al*., 2017). A comparable paleontological content was recorded in the Ciénaga Larga del Tontal Formation (Fig. 1B). The palynological association identified in the upper part of this unit was referred to DM Biozone-Subzone A by Barredo and Ottone (2003), suggesting an early late Carboniferous age or Serpukhovian-Bashkirian (Césari *et al*., 2011). Also, some typical brachiopods of the *AT/RM* Fauna have been identified in the glaciomarine interval of the lower part of the unit, *i.e*., *Aseptella*? sp. and *Productella* sp. (Lech *et al*., 1998; Lech and Milana, 2006), then reassigned to *Aseptella* sp. aff. *A. patriciae* and *Tuberculatella peregrina* respectively (Simanauskas and Cisterna, 2001; Cisterna *et al*., 2017). The paleontological information detailed herein agrees with a late Serpukhovian-Bashkirian age.

The succession of the Majaditas Formation (Amos and Rolleri, 1965), located further north in the basin (Fig. 1B), has provided palynological data from its middle part suggesting a correlation with the Subzone A of the DM Biozone (Vergel *et al*., 2016). Invertebrates were found in lenses of siltstones with dropstones associated with diamictites; they have been assigned to the *Levipustula levis* Zone (Amos and Rolleri, 1965) based on the brachiopods *Beecheria* sp., chonetids and spiriferids (González, 2002). A preliminary revision of two specimens of brachiopod spiriferids by one the authors (GAC; material provided by A.C. Taboada), would indicate the presence of *Costuloplica*? in the Majaditas Formation. The genus *Costuloplica* occurs in the *Levispustula levis* Zone but this material is still under study. Some bivalves and gastropods identified previously by Taboada (1997), González (2002), and Pinilla and Taboada (2018) were assigned to this Zone.

The presence of *Levipustula* Fauna has been considered the only data available to estimate the age in several postglacial marine successions of the Calingasta-Uspallata basin (Fig. 1B), such as Hoyada Verde, Leoncito, La Capilla and Yalguaraz formations (Taboada, 1997; González, 2002; Cisterna and Sterren, 2010, and references therein). This fauna characterizes the late Serpukhovian-early Bashkirian along with plant and palynological associations like the *Nothorhacopteris-Botrychiopsis-Ginkgophyllum* Biozone and Subzone A of the DM Biozone (Césari *et al*., 2011).

Therefore, as indicated by López-Gamundí (1997) and Henry *et al*. (2010), the same deglacial succession has been identified in the Hoyada Verde and Agua del Jagüel formations, it would be possible to recognize the same postglacial event in several units inside the basin, which is also characterized by a particular biota identified in other basins.

To the east of the Protoprecordillera (Fig. 1A), in the Central domain, marine invertebrates, platyspermic seeds and plant remains were registered in Guandacol Formation (Huaco area) (Martínez, 1993; Gutiérrez and Pazos, 1994; Pazos, 2002), and the transgression was there dated in 318.79±0.10 Ma (Gullbranson *et al*., 2010). The scarce fauna composed by fish scales, inarticulated brachiopods, gastropods and bivalves was associated with environmentally stressful conditions (Martínez, 1993). Sections such as Jejenes Formation, exposed at the Quebrada Grande and Quebrada de las Lajas localities (Kneller *et al*., 2004; Dykstra *et al*., 2006), Guandacol Formation in Talacasto and Loma de los Piojos (Aquino *et al*., 2014; Alonso-Muruaga *et al*., 2018), and Quebrada Larga Formation in the Cerro Veladero area (Limarino *et al*., 2014), from the adjacent Paganzo basin are characterized by similar successions of fine-grained sandstones, shales and mudstones, deposited during a postglacial marine transgression that flooded glacial valleys forming fjord environments (Limarino *et al*., 2002). The presence of A Subzone of the DM Biozone in Guandacol, Agua Colorada, Malanzán, Jejenes and Lagares Formations, has been calibrated to a late Serpukhovian-early Bashkirian U-Pb zircon radiometric age (319.57±0.09 Ma and 318.79±0.10 Ma; Césari *et al*., 2011). Also, tuffaceous levels containing platyspermic seeds, plant remains and palynomorphs of the A Subzone (DM Biozone) in the Jejenes Formation (Amos, 1954), Quebrada Grande paleofjord, were recently studied. The volcanic zircons analyzed by SHRIMP indicate a Bashkirian age (321±5.3 Ma; Valdez *et al*., 2017) for the material associated to this subzone.

The characteristics of the *AT/RM* and *Levipustula* faunas, analyzed in the context of the glacial event recorded in this part of Gondwana, allow to infer different coastal configurations with specific depositional conditions for each of them. In addition, radiometric and paleontological data (marine invertebrate faunas, palynomorphs and plants) studied in several localities of the Calingasta-Uspallata basin and the neighboring Paganzo basin constitute the most important tools to calibrate the timing of the postglacial transgression. However, all this information is not sufficient to discern ages within the late Serpukhovian-Bashkirian interval.

6. Conclusions

Aseptella-Tuberculatella/Rhipidomella-Micraphelia Fauna (*AT/RM* Fauna), was identified in postglacial marine mudstones (late Serpukhovian-Bashkirian) of the lower part of the Agua del Jagüel Formation, in the southernmost part of the Calingasta-Uspallata basin. This fauna is composed by *Rhipidomella discreta*, *Micraphelia indianae*, *Orbiculoidea?* sp., *Murchisonia*? sp., *Glabrocingulum* (*Stenozone*)? sp., Nuculanidae indet., rugose corals, and indeterminate fragments of nautiloids and hyolithids.

The *AT/RM* Fauna is characteristic of restricted environments with relatively low concentrations of oxygen and nutrients in the seafloor, which is consistent with the glaciomarine sequences in fjord-type coasts suggested for the Agua del Jagüel Formation. The relatively low diversity of fauna in this unit compared to that defined in the El Paso Formation (located further north in the basin and where this fauna was defined), might suggest more stressful environmental conditions for benthic colonization, related to the paleovalle's isolation from oceanic waters.

The postglacial mudstones with marine invertebrate faunas would have been deposited in relatively restricted (palaeofjord) part of the Uspallata-Calingasta basin as well as in open shelf environments, during the late Serpukhovian-Bashkirian. The marine flooding over different coast configurations and the availability nutrient and oxygen would have favoured the development of faunas with important differences in the taxonomic composition and the paleoecological structure (*AT/RM* and *Levipustula* Faunas) in the same time interval.

Radiometric data in Agua del Jagüel Formation and paleontological records in the glacial-postglacial sedimentary succession in the basin (marine invertebrate faunas, palynomorphs and plants) are the most important tools to adjust the timing of the postglacial transgression. This information herein presented complements the scheme proposed for the Carboniferous sequences throughout the central western of Gondwana but is not sufficient to assign a more precise age to the fauna studied within the late Serpukhovian-Bashkirian interval.

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