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Glacial events in Carboniferous sequences from Paganzo and Río Blanco Basins (Northwest Argentina): Palynology and depositional setting

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ABSTRACT

The age and depositional setting of two glacial events recognized in the western basins of Argentina are discussed in this paper. The older one corresponds to diamictites identified in the upper member of the Cortaderas Formation (Visean, Río Blanco Basin). The glacial sequence consists of shales, dropstone-bearing shales massive matrix-rich diamictites, massive clast-rich diamictites, and stratified diamictites, all of them interpreted as deposited in distal glaciomarine settings. Palynological remains recovered from shales interstratified with diamictites were referred to the late Visean *Reticulatisporites magnidictyus-Verrucosisporites quasigobbettii* Biozone. Younger glacial deposits were studied at the base of the Guandacol Formation (Paganzo Basin) where are made up by clast-poor massive diamictites, clast-rich massive diamictites, stratified diamictites, thinly-bedded dropstone-bearing diamictites, rhythmites, dropstone-bearing shales, and barren of dropstone shales. The whole sequence is interpreted as deposited in low-relief proximal glaciomarine environments (morainal banks). The abundant palynological assemblages found in the glacial interval were included in the subzone A of the *Raistrickia densa-Convolutispora muriornata* Biozone which is considered Serpukhovian-early Bashkirian in age.

Palynological remains found in the Cortaderas Formation suggest that the beginning of the Glacial 2 event in Gondwana (according to Isbell's chronological proposal for glacial and interglacial stages) should be considered late Visean while the end, according to the assemblages recovered from the Guandacol Formation, was not younger than early Bashkirian. Moreover, sedimentological and stratigraphic data suggest the existence of a short interglacial period between the Cortaderas and Guandacol glacial events.

KEYWORDS **Carboniferous. Argentina. Glaciation. Palynology.**

INTRODUCTION

There is no doubt that the Late Paleozoic glaciation was one of the most relevant paleoclimatic events recognized along the Gondwana supercontinent (López Gamundí et al., 1992; López Gamundí, 1997; Isbell et al., 2003a; Fielding et al., 2008). Glacial accumulations have been reported in several and distant basins located in both Gondwanic (see López Gamundí et al., 1992; Crowell, 1999; Scotese et al., 1999; Isbell et al., 2003b; Fielding et al., 2008) and perigondwanic regions (Besems and Shuurman, 1987; Hyde et al., 1999; Milani and Zalán, 1999; Caputo 2006; Caputo et al., 2006). Glacial deposits occur not only as tillites but also as resedimented diamictites bearing faceted and striated clasts which appear closely related to shales with dropstones and varve-like sequences. Probably, one of the most interesting and controversial aspects of this glacial megaevent is the fact that glacial sequences appear at different stratigraphic levels in different basins and in some cases they are recurrent within the same basin. In fact, glacial sequences of Gondwana show alternation of waxing and waning glacial conditions (Veevers and Powell, 1987; Crowley and Baum, 1991).

The diachronism of glacial deposits has been supposed to result from the wandering of Gondwana through the pole during the Late Paleozoic, but the recurrence of glacial deposits in the same basins is not easily explained by this way. In fact, the recurrence of glacial sediments at different stratigraphic levels within the same basin has been reported from Argentina (González, 1990; Limarino et al., 2006), Brazil (Vesely and Assine, 2007), South Africa (Visser, 1997) and Australia (Fielding et al., 2008) among other areas.

In this paper, we document two glacial Carboniferous sequences located in different stratigraphic levels. The older one crops out at the top of the Visean Cortaderas Formation in the Río Blanco Basin (Fig. 1) while the younger one occurs 50Km to the east (Paganzo Basin, Fig. 1), at the base of the Guandacol Formation (Serpukhovian).

The chronostratigraphic divisions used in this paper are those recommended in Grandstein et al. (2004).

GEOLOGICAL SETTING

Late Paleozoic sediments were widely deposited in the southwestern margin of Gondwana from the Early Carboniferous to the Late Permian (Andreis et al., 1987; Archangelsky et al., 1996; Limarino and Spalletti, 2006). The completeness of the stratigraphic record and the large extension of the Late Paleozoic basins make this region a key area for studying the characteristics and age of glacial deposits (López Gamundí, 1997; Marenssi, et al., 2005; Limarino et al., 2006; Caputo et al., 2008).

In order to analyze the glacial events stratigraphy, we have chosen two areas where glacial diamictites have been reported at different stratigraphic positions. The older encompasses glaciomarine deposits identified in the Río Blanco Basin which belong to the Upper Member of the Cortaderas Formation (Limarino et al., 1993). The younger, are moraine bank sequences identified in the lower part of the Guandacol Formation in the Paganzo Basin (Marenssi et al., 2002; 2005).

Cortaderas Formation was deposited in the mainly marine Río Blanco Basin (Fig. 1) during the Late Mississippian. The stratigraphy of this basin is shown in figure 2 and can be basically divided into two major megasequences. The lower one comprises Mississippian sediments included in the Angualasto Group (Limarino and Césari, 1993) formed by the Malimán and Cortaderas Formations (Fig. 2). The Angualasto Group up to 2300m thick (Scalabrini Ortiz, 1973) comprises siliciclastic marine and coastal sequences bounded at its base and top by major regional unconformities, the Chánica tectonic phase (Devonian) and the Río Blanco tectonic phase (Upper Mississippian) respectively (Fig. 2).

Although diamictites of probable glacial origin were quoted in the lower part of the Angualasto Group (Malimán Formation, see Pazos et al., 2005), conclusive evidence for the glacial origin has not been reported yet. On the contrary, Cortaderas Formation shows glacial deposits including probable ice-dump tills (Thomas and Connell, 1987), dropstone-bearing shales and different types of resedimented diamictites bearing faceted and striated clasts (Limarino et al., 1993; Limarino and Césari, 1993).

The upper megasequence of the Río Blanco Basin is mainly Pennsylvanian in age and corresponds to shal-

FIGURE 1 | **Location map showing the paleogeography of the Paganzo and Río Blanco Basins during the Late Paleozoic, note that both areas were separated by the Protoprecordillera. Stars show the location of studied sections.**

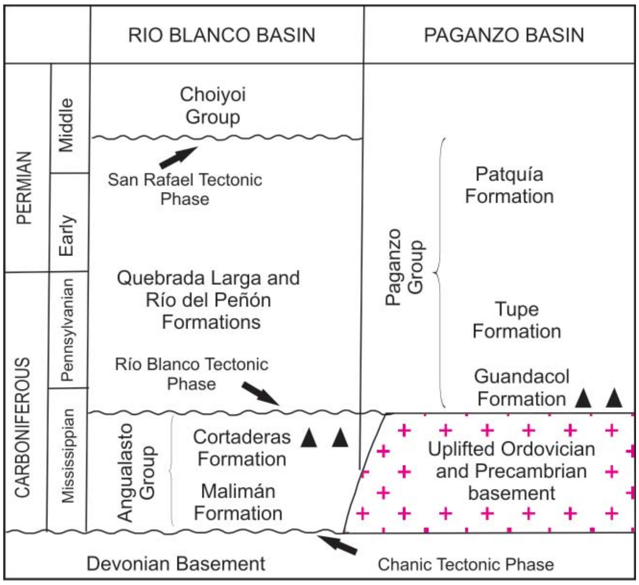

FIGURE 2 | **Stratigraphy of the Paganzo and Río Blanco Basins. Black triangles indicate the position of the glacial deposits.**

low marine and continental deposits included in the Quebrada Larga (or Río del Peñón Formation, Fig. 2). The existence of glacial sediments in the Río del Peñón Formation was largely ignored, but in the last years glaciomarine deposits have been described by Gulbranson et al. (2008).

The second sequence here studied, the Guandacol Formation, was deposited in the neighboring Paganzo Basin (Fig. 1) which includes a complete stratigraphic record from the Serpukhovian to the Middle Permian. Paganzo is a large (about 140,000Km^2), mainly continental basin, separated from Río Blanco Basin by a narrow highland area known as Protoprecordillera (Fig. 1). This upland region has been interpreted as a fold and thrust belt resulting from the Chilenia and South America collision during the Late Devonian – Early Carboniferous (Ramos et al., 1984; Limarino et al., 2002).

The stratigraphic record of Paganzo Basin can be divided into two major sequences (Fig. 2; Limarino et al., 2006). The lower one, Serpukhovian – Early Permian in age, includes well known glacial deposits at the bottom, followed by postglacial transgressive shales, and then fluvial sandstones and conglomerates bearing some coal beds. The upper sequence, deposited during the Early – Middle Permian (Fig. 2), comprises a red-bed succession dominated by fluvial deposits at the base which transitionally pass upwards to ephemeral lacustrine-fluvial sediments and finally to eolian deposits at the top. Differing from the lower sequence, glacial diamictites have been never described in the upper sequence.

GLACIAL DEPOSITS IN THE CORTADERAS FORMATION

Cortaderas Formation crops out along the western flank of the Precordillera in the northwest of the San Juan province (Fig. 1). A geologic map of the Cortaderas Creek area is shown in figure 3. The Cortaderas Formation is composed of conglomerates, sandstones, and shales together with some levels of diamictites only exposed at the upper part of the unit (Fig. 4). Scalabrini Ortiz (1973) divided Cortaderas in three members, the Lower one (up to 212m thick) is almost entirely composed of coarse-grained breccias, conglomerates and sandstones, all of them interpreted as deposited in alluvial fans (Scalabrini Ortiz, 1973) or in fan delta environments (Limarino and Césari, 1993; Perez Loinaze, 2008a). The Middle Member reaches 980m in thickness, and comprises sandstones and shales deposited in both fluvial and shallow marine environments. Finally,

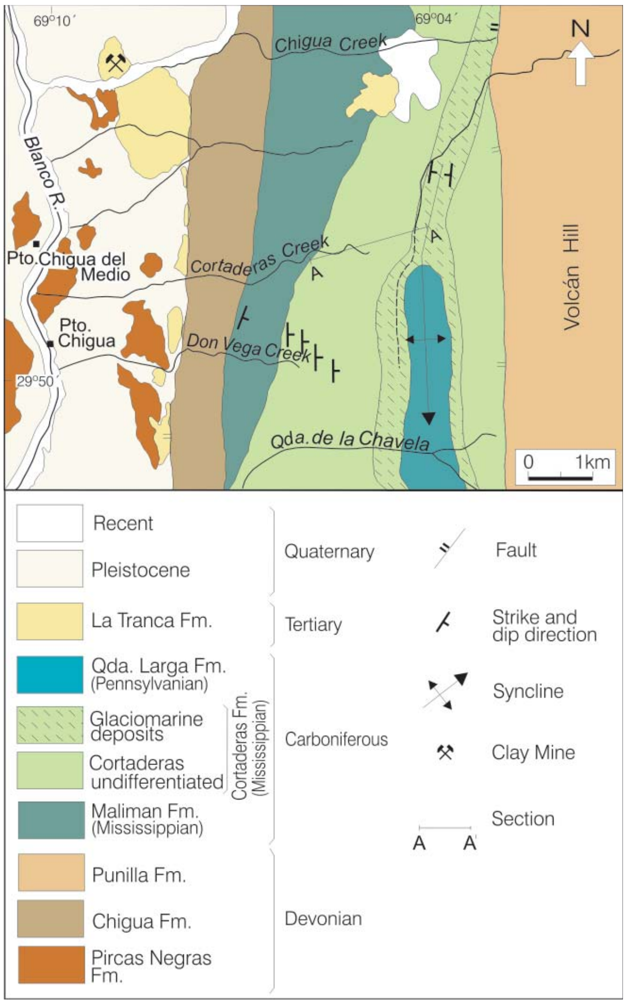

FIGURE 3 | **Geologic map of the Cortaderas creek.**

the Upper Member, reaching 138m in thickness, shows a different lithological composition because is mainly composed of a monotonous sequence of green shales with several diamictite intercalations (Fig. 4).

Sedimentology of the glacial deposits

Glacial deposits of the Cortaderas Formation were sedimented in a glaciomarine environment with fluctuating sea level position. The base of the glacigenic sequence is marked by a sharp flooding-surface covered by laminated shales, and in some cases, by discontinuous centimetric levels of disorganized reworked sandstones. The upper boundary corresponds to an erosive unconformity which separates the glacigenic interval from the Quebrada Larga Formation (Pennsylvanian, Figs. 4 and 5A).

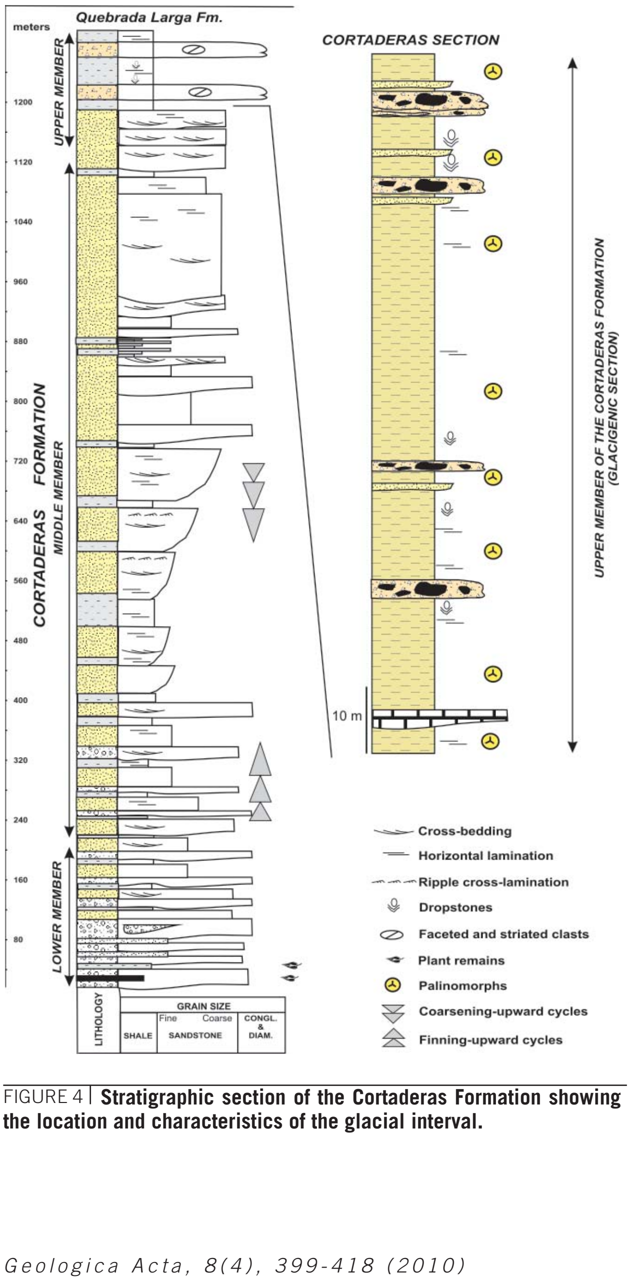

FIGURE 4 | **Stratigraphic section of the Cortaderas Formation showing the location and characteristics of the glacial interval.**

Lithofacies description

Five major types of lithofacies have been recognized in the studied sequences: 1) shales, 2) shales with dropstones, 3) massive matrix-rich diamictites, 4) massive clast-rich diamictites and 5) stratified diamictites.

Shales comprise more that 70% of the sequence (Fig. 5A) and they are composed of thinly laminated millimetric layers of clay and silt, or alternating laminae of fine- and coarse-grained silt.

Shales with dropstones are a diagnostic feature of the glacigenic interval (Fig. 5B). Frequently dropstones exhibit pentagonal forms, faceted and striated surfaces (Fig. 5C), ranging in maximum diameter from a few centimeters to 100cm They are mainly composed of low-grade metamorphic rocks belonging to the local Devonian basement (La Punilla and Chigua Formations) but fragments of granites, quartzites, gneisses, limestones and fine-grained sedimentary rocks have been also recognized.

Massive matrix-rich diamictites form tabular, lenticular or irregular beds up to 50cm. thick (Fig. 5D). The clasts, ranging in size from granules to boulders, exhibit subrounded forms and in some cases flat (pentagonal) shapes. They commonly float in a massive muddy matrix (clast/mud ratio lower than 0.3, Fig. 5E). Clast composition is dominated by sedimentary, low-grade metamorphic and quartzite rocks, fragments of granite, high-grade metamorphic rocks and limestones are much less common.

Massive clast-rich diamictites show similar features to the above described, but differing in the higher clast/mud ratio (from 0.4 to 0.7) and in the sporadic presence of grain to grain contact fabric. Additionally, clast-rich diamictites are better sorted and they show smaller size of clasts (up to 20cm in maximum diameter) and lenticular beds.

Despite the massive character of diamictites, some beds show irregular thin veneers of mud, suggesting vertical amalgamation of diamictic levels. A distinctive feature of this type of diamictites is the existence of out-sized clasts (up to 100cm in maximum diameter, Fig. 5C). This kind of clasts very probably corresponds to dropstones released from icebergs.

Under the label of stratified diamictites, we include a varied suite of diamictites showing poorly defined stratification, as for example clast orientation, graded beds or crude horizontal layers. Beds are lenticular in form and the clasts size range from granules to 35cm in maximum diameter being the matrix composed of sandy silt. Stratified diamictites show a better textural sorting and higher clast/mud ratio (frequently major than 0.5). Sedimentary deformation (small to large-scale folding) has been observed in some cases.

Interpretation

Although the described diamictites do not correspond to till accumulations, it is considered that the connection between glacial conditions and the studied deposits is evident taking in account the existence of shales with dropstones (Fig. 5B), clasts showing faceted and striated surfaces (Fig. 5C), out-sized clasts in diamictites interpreted as derived from melting of icebergs (Fig. 5F) and the abundance of resedimented diamictites also bearing faceted and striated clasts.

In this context two major facies associations are recognized: 1) diamictite dominated and 2) dropstone-bearing shales. Diamictite dominated association includes beds of massive matrix-rich diamictites, massive clast-rich diamictites, stratified diamictites and thin levels of shales with dropstones. The diamictites were not deposited directly from the glacier because they neither appear in association with striated pavements nor show subglacial deformational structures, foliated structure or maximum diameter of clasts oriented parallel to the flow ice directions, all these features characteristic of till deposits (Miall, 1983; Eyles et al., 1985; Maltman et al., 2000; Larsen et al., 2006). On the contrary, diamictites present in the Upper Member of Cortaderas Formation represent different types of coarse-grained debris flows deposits.

High amount of debris flow accumulations are common in both proximal and distal glaciomarine environments (Eyles et al., 1985; Eyles and Eyles, 1992) and their existence seem to be highly favored by periods of ice advance that produce large volume of glacial debris

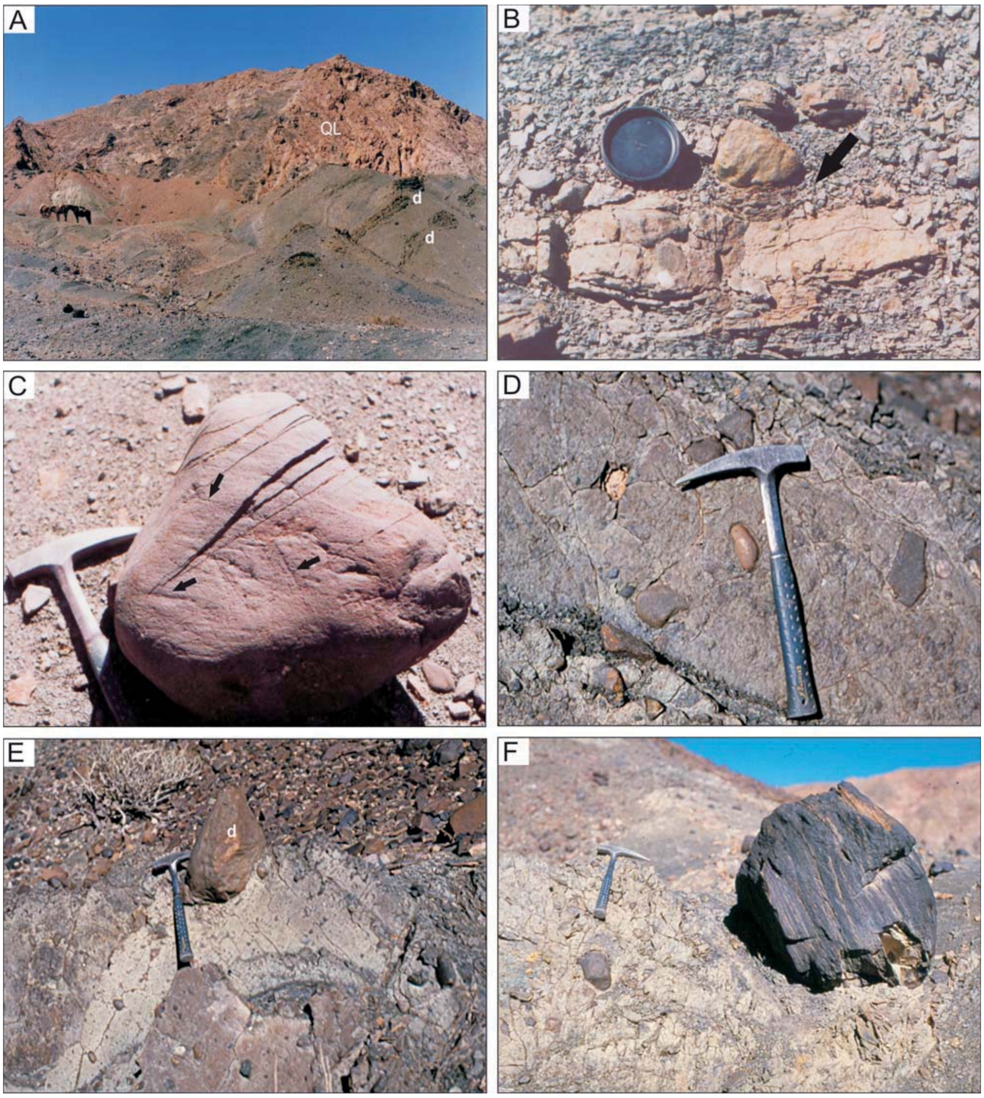

FIGURE 5 | **A) general view of the glacigenic sequence of the Cortaderas Formation covered by conglomerates and sandstones belonging to the Quebrada Larga Formation (QL). Note the predominance of shales showing several intercalations of diamictitic beds (d). B) small dropstone included in a shale bed, the arrow point out deformation in the lamination. C) dropstone showing pentagonal shape and glacial striations (arrows). D) aspect of the massive matrix-rich diamictite, observe that both sedimentary fragments (probably derived from Protoprecordillera) and granitic clasts (came from Sierras Pampeanas) occur in the same level. E) Massive matrix-rich diamictite including a large dropstone (d). F) Large boulder of low-grade metamorphic rock very probably derived from Protoprecordillera. This out-size clast is interpreted as derived from melting of icebergs.**

(Miall, 1983; King et al., 1998; Passchier et al., 2003; Nygård et al., 2007).

At least two interpretations can be given for the clast-rich massive diamictites. On the one hand, they may result from debris flows coming from the proximal glacial environment where rapid sedimentation, seismic shocks or grounding icebergs promote the collapse of unstable sediment piles (Eyles and Eyles, 1992). On the other hand, rain-out of coarse-grained clasts from grounded iceberg should not be ruled out (Thomas and Connel, 1987).

Stratified diamictites, showing channel geometry, represent gravity-flow deposits. This kind of diamictites is frequently deposited either in interchannel areas, where non-confined debris flows are common, or in shallow channels extending from the proximal to the distal glaciomarine environments.

Dropstone-bearing shales association is basically composed of shales, massive mudstones, shales with dropstones, and thin levels of massive matrix-rich diamictites.

Fine-grained rocks can be divided in three genetic types of deposits. Firstly, those related to the melting of icebergs which are conspicuous facies in distal glaciomarine environments. Shales with dropstones and thin levels of matrix-rich diamictites are good examples of this type of accumulations.

A second type, not directly related to iceberg or ice deposition, comprises massive mudstones showing a slight increase in silt grains. These rocks may have been sedimented by settling from turbid plumes that formed in proximal glaciomarine environments and extended away to deep sea areas. As discussed by Hesse et al. (2004) and Hesse and Khodabakhsh (2006), in glaciomarine environments large amounts of fine-grained sediments are transported to deep sea areas by low-velocity reduced-density currents developed in connection with fresh-water induced turbidites. According to Hesse and Khodabakhsh (2006) this surface diluted layer is progressively separated from the body of turbidity currents and lift up as a low-velocity flow bringing fine-grained sediments to distal glaciomarine environments.

Finally, shales very probably represent pelagic or hemipelagic sedimentation not necessarily related to glacial conditions.

The predominance of shales, fine-grained sediments bearing dropstones, blanket-like horizons of rain-out diamict facies and gravity flow deposits suggest that the Upper member of the Cortaderas Formation was deposited in distal or intermediate glaciomarine settings. This interpretation is also supported by the absence of glaciotectonic deformation, lodgment till accumulations, and well preserved foresets in resedimented facies.

Palynology of the Cortaderas Formation

The first palynological data from this unit were provided by Césari and Limarino (1992), suggesting an Early Carboniferous age, not older than Tournaisian (Limarino and Césari, 1993). The palynological associations recovered from the uppermost glaciomarine levels of the Cortaderas Formation were later analyzed in detail by Perez Loinaze (2007a; 2008 a, b) identifying 64 species in the 26 samples studied (Fig. 6). The recognized species show different stratigraphic ranges, one group is represented by species that persist within the Late Devonian-Early Carboniferous interval, such as *Auroraspora macra* Sullivan 1968, *Bascaudaspora collicula* (Playford) Higgs et al. 1988, *B. submarginata* (Playford) Higgs et al. 1988, *Colatisporites decorus* (Bharadwaj and Venkatachala) Williams in Neves et al. 1973 and *Spelaeotriletes pretiosus* (Playford) Utting 1987. A second group includes those species present all along the Mississippian time, for example *Crassispora trychera* Neves and Ioannides 1974 and *Grandispora spiculifera* Playford 1976. The third group is composed of spores with stratigraphic ranges constrained to the Visean, such as *Anapiculatisporites austrinus* Playford and Satterthwait 1986, *A. kekiktukensis* Ravn 1991, *A. semisentus* Playford 1971, *Apiculiretusispora microseta* Ravn 1991, *Archaeozonotriletes intrastricatus* Playford 1971, *Cristatisporites indolatus* Playford and Satterthwait 1988, *Grandispora debilis* Playford 1971, *Indotriradites tedantus* Playford and Satterthwait 1988 and *Verrucosisporites baccatus* Staplin 1960.

Some species with biostratigraphic significance as *Reticulatisporites magnidictyus* Playford and Helby 1968, *Rugospora australiensis* (Playford and Helby) Jones and Truswell 1992 and *Verrucosisporites quasigobbettii* Jones and Truswell 1992 are present in the studied assemblages. The first appearance of these spores was recorded by Playford and Helby (1968) in the Australian Italian Road Formation, late Visean in age. Their biostratigraphic importance was noted by some authors such as Dino and Playford (2002). In fact, the first record of *Reticulatisporites magnidictyus* has been used by Melo and Loboziak (2003) to characterize the base of the Mag Interval Biozone from northern Brazil. *Dibolisporites disfacies* Jones and Truswell 1992 with its oldest record in late Serpukhovian Australian sediments, is also recorded in the uppermost levels of Cortaderas Formation.

Finally, in the glacial interval of the Cortaderas Formation appears some characteristic spores of younger Carboniferous strata from Argentina and Brazil (Archangelsky

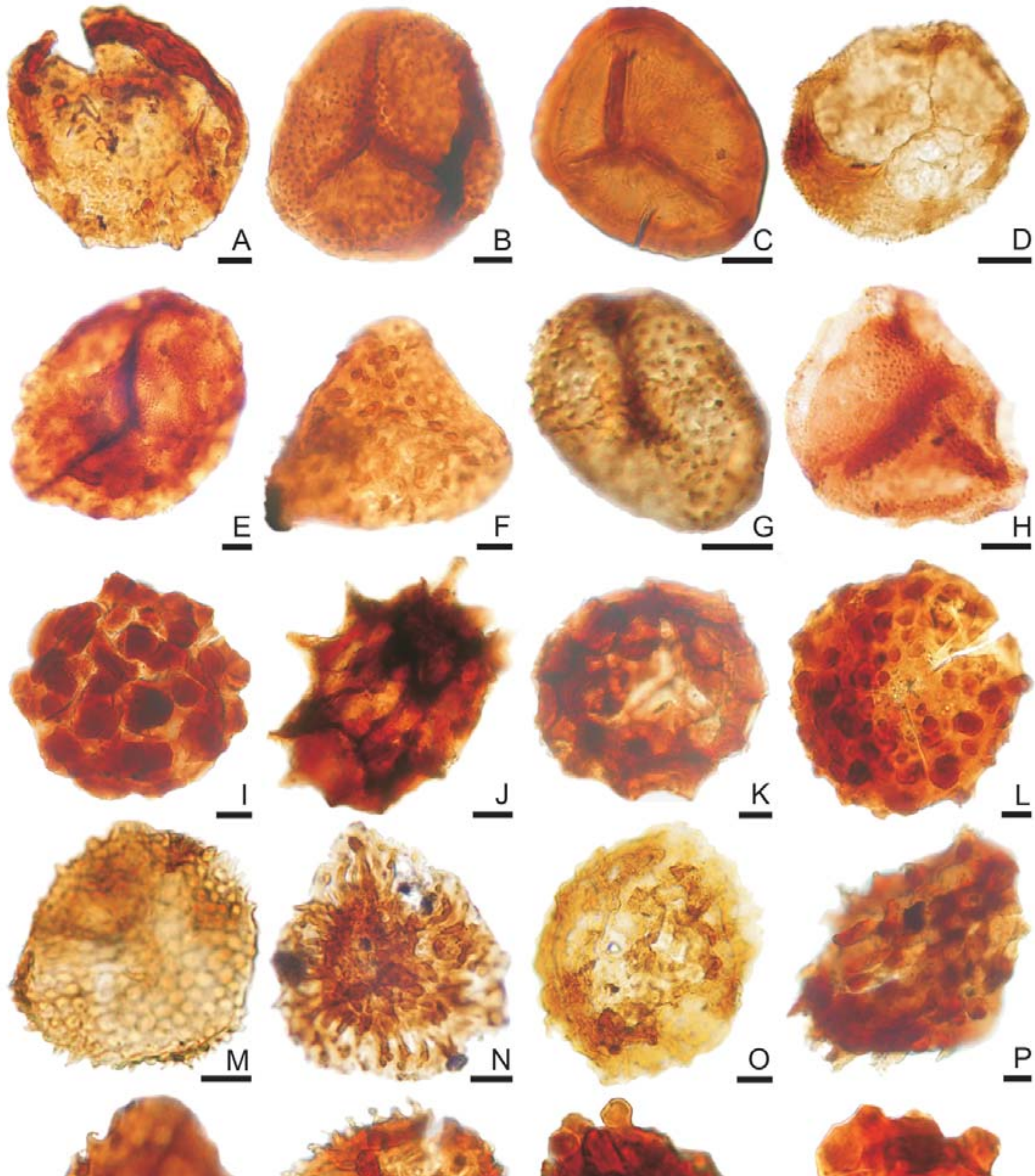

FIGURE 6 | **Palynological species from Cortaderas Formation. The specimens are curated in the palynological collection of the Museo Argentino de Ciencias Naturales Bernardino Rivadavia (BAPal). The slide number (prefixed BA Pal) and the 'England Finder' co-ordinates are given for each specimen. A) *Verrucosisporites baccatus* Staplin, BA Pal 5760-5: S29/4; B) *Anapiculatisporites kekiktukensis* Ravn, BA Pal 5742-1: E24/4; C) *Archaeozonotriletes intrastricatus* Playford, BA Pal 5749-2: L31/1; D) *Apiculiretusispora microseta* Ravn, BA Pal 5754: H25/3; E) *Anapiculatisporites semisentus* Playford, BA Pal 5762-6: V51/0; F) *Anapiculatisporites amplus* Playford and Powis, BA Pal 5762-4: Z47/4; G) *Anapiculatisporites austrinus* Playford and Satterthwait, BA Pal 5740-1: U54/4, H) *Grandispora debilis* Playford, BA Pal 5757-7: V34/3; I) *Verrucosisporites congestus* Playford, BA Pal 5756: Y47/2; J-K) *Reticulatisporites magnidictyus* Playford and Helby; J) BA Pal 5760-1:132.8/25.5; K) BA Pal 5754: Z50/1; L) *Verrucosisporites quasigobbettii* Jones and Truswell, BA Pal 5756: X48/0; M) *Dibolisporites disfacies* Jones and Truswell, BA Pal 5754-1: A53/1; N) *Indotriradites volkheimeri* (Azcuy) Perez Loinaze, Ba Pal 5760-8: W33/1; O) *Rugospora australiensis* Jones and Truswell, BA Pal 5778-2: E58/3; P) *Spinozonotriletes hirsutus* Azcuy, Ba Pal 5762-4: X52/2; Q) *Cristatisporites inordinatus* (Menéndez and Azcuy) Playford, BA Pal 5748-1: K31/0; R) *Apiculatisporis variornatus* di Pasquo, Azcuy and Souza, BA Pal 5762-4: V38/3; S) *Raistrickia rotunda* Azcuy, BA Pal 5762-2: H43/2; T) *Raistrickia paganciana* Azcuy, BA Pal 5761-5: B52/1. Scale bar: 20 µm.**

et al., 1996; Souza et al., 2003) such as *Apiculatisporis variornatus* di Pasquo et al. 2003, *Cristatisporites inordinatus* (Menéndez and Azcuy) Playford 1978, *Indotriradites volkheimeri* (Azcuy) Perez Loinaze 2008, *Raistrickia paganziana* Azcuy 1975, *Raistrickia rotunda* Azcuy 1975, *Retusotriletes anfractus* Menéndez and Azcuy 1969 and *Spinozonotriletes hirsutus* Azcuy 1975. These species are absent in the basal and middle sections of the Cortaderas Formation (Perez Loinaze, 2007a). Therefore, the most relevant features of the assemblages recovered from the uppermost strata of the Cortaderas Formation are: the occurrence of diagnostic species which first records are late Visean in age, together with some species recognized in younger Carboniferous floras and the absence of pollen grains. Based on these available palynological data, a late Visean age was proposed for the palynological samples which were referred to the *Reticulatisporites magnidictyus-Verrucosisporites quasigobbettii* (MQ) Interval Biozone, defined for western Argentina (Perez Loinaze, 2007a) in partial replacement of the former *Cordylosporites-Verrucosisporites* Biozone (Césari and Gutiérrez, 2001).

GLACIAL DEPOSITS IN THE GUANDACOL FORMATION

Guandacol Formation is one of the best known glacigenic sequences outcroping in Paganzo Basin. In this unit different types of till deposits, striated pavements, dropstone-bearing shales, large- and small-scale glacial deformation and resedimented diamictites have been described (López Gamundí, 1997; López Gamundí and Martínez, 2000; Pazos, 2002; Limarino et al., 2002; Marenssi et al., 2002; 2005).

A geologic map and a schematic section of the Guandacol Formation are shown in figures 7 and 8. The lower part of the section, corresponding to the glacial interval, is composed of different types of diamictites, dropstone-bearing shales, shales without dropstones and mudstones; reaching from only a few meters up to 90m thick (Fig. 8). These rocks are succeeded by transgressive shales and mudstones (Fig. 8) belonging to the "Namurian" postglacial transgression described by Limarino et al. (2002). The upper part of the Guandacol Formation comprises interbedded sandstones and mudstones, sandstones and scarce conglomerates, the whole of this sequence is arranged in coarsening- and thickening-upward sequences formed by the progradation of deltas or shallowing coastal systems (Fig. 8).

The best outcrops of glacial deposits occur at Huaco anticline area over the national road 40 and in Los Pozuelos Creek, nearly 6km to the northwest of the Huaco city (Figs. 1 and 7). In the former locality different types of resedimented diamictites and rain-out deposits have been described (López Gamundí and Martínez, 2000; Limarino et al, 2002), while in the later Marenssi et al. (2005) described a grounding-line system formed by morainal bank deposits.

Sedimentology of the glacial deposits

Low-relief proximal glaciomarine deposits, dominated by morainal bank accumulations, are well exposed at Los Pozuelos Creek (Marenssi et al., 2005, Fig. 7). Glacigenic deposits rest unconformably on Ordovician limestones belonging to the San Juan Formation (Fig. 9A), and pass upward to marine shales corresponding to a postglacial marine transgression

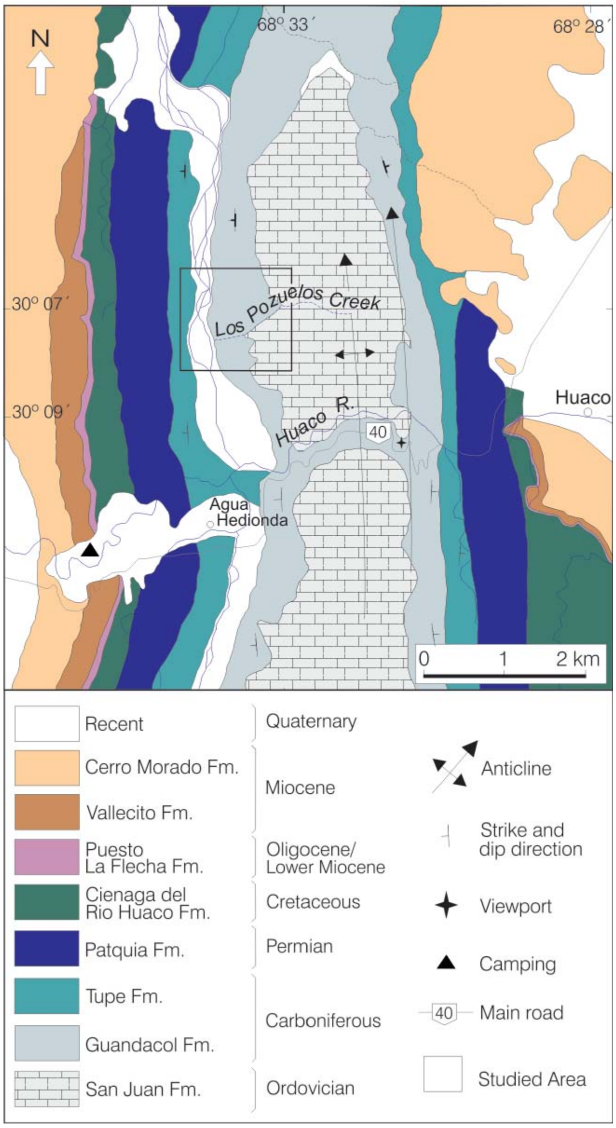

FIGURE 7 | **Geologic map of the Huaco area showing the location of the Los Pozuelos Creek.**

well exposed in several Late Paleozoic basins of the Andean region (Limarino el at., 2002).

Lithofacies description

Glaciomarine deposits outcroping in Los Pozuelos Creek are composed of six major lithofacies: 1) clast-poor massive diamictites, 2) clast-rich massive diamictites, 3) stratified diamictites, 4) thinly-bedded diamictites with dropstones, 5) rhythmites, 6) shales with dropstones and 7) shales without dropstones.

Diamictites (clast-poor, clast-rich and stratified ones) form more than 95% of the glacigenic sequence. They are composed of angular and subangular large clasts (up to 150cm in maximum diameter) almost totally composed of limestones belonging to the underlying San Juan Formation (Ordovician, Fig. 9B) or dark shales very probably derived from the nearly outcropping Los Azules Formation (Ordovician). Exotic clasts of granites or high-grade metamorphic rocks are unusual.

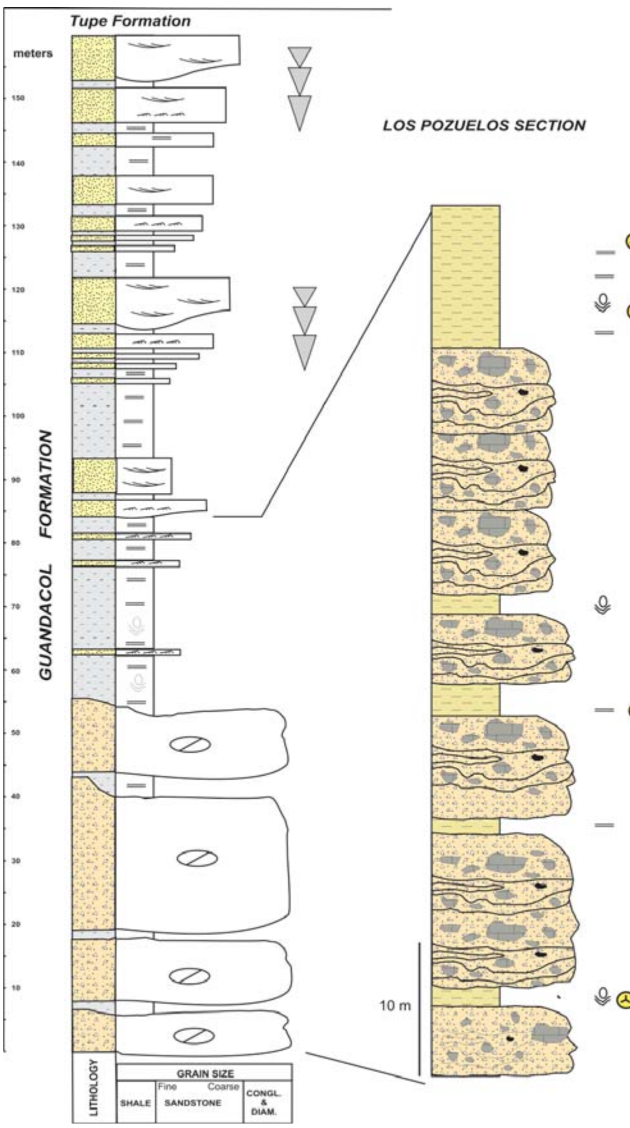

FIGURE 8 | **Stratigraphic section of the Guandacol Formation showing the location and characteristics of the glacial interval. For references see figure 4.**

Clast-poor diamictites form irregular massive beds (up to 2m thick), with low matrix/clasts ratios (less than 0.3) and clasts, floating in a muddy matrix, ranging in maximum diameter from 20cm to 110cm (Fig. 9C). This kind of diamictite is generally present along the contact between Guandacol and San Juan Formations, where a small boulder-striated pavement and injected diamicton into the Ordovician limestones have been identified (Marenssi et al., 2005, Figs. 9C and D).

Clast-rich diamictites are less common; they are composed of massive coarse-grained diamictites showing clast/matrix ratio between 0.8 and 0.9, better textural sorting than clast-poor diamictites, and discrete proportion of exotic granitic and high-grade metamorphic rocks.

Stratified diamictites comprise a varied group of poorly sorted rocks including gradded, faintly horizontal bedded and thinly stratified diamictites (Fig. 9E). These rocks were very probably deposited by density flows, originated by the collapse of oversteepened depositional slopes, commonly formed close to the ice front.

Thinly-bedded diamictites with dropstones form massive tabular beds, up to 8cm-thick, of dark gray to black pebbly sandstones. Two characteristic features are the existence of out-sized clasts (up to 70cm in maximum diameter) and the presence of low-angle clinoforms (up to 3.5m-thick, Marenssi et al., 2005). We interpreted the whole of the thinly-bedded diamictites as sedimented in subaqueous fan systems; the progradation of these depositional bodies appears clearly exposed in the clinoforms above mentioned.

Rhythmites consist of delicately laminated millimetric couples of claystones and silstones (rarely very fine-grained sandstones) that occasionally show out-sized clast (up to 5cm). They have been interpreted by Marenssi et al. (2005) as glacilacustrine deposits though recently, Perez Loinaze (2007b) described the presence of few species of marine microplankton in these rocks.

Shales with dropstones are very common at the top of the sequence. Clasts composition is different from that observed in the basal diamictites where limestone clasts are largely dominant. On the contrary, shales with dropstones show high amounts of exotic clasts of granites, gneisses and different types of metamorphic rocks.

Finally, shales without dropstones form the uppermost part of the glacigenic sequence marking the end of glacial conditions and the transition to progradational deltaic sequences.

Interpretation

Los Pozuelos Creek results a good example of low-relief proximal glaciomarine environment. This interpretation is supported by the existence of massive diamictites interpreted as till deposits (clast-poor and clast-rich massive diamictites), the presence of small faceted or striated pavements (Fig. 9C and F), rhytmites, faceted and striated clasts, and dominance of coarse-grained diamictites (Powell, 1981; Eyles and Eyles, 1992; Cai et al., 1997; Powell and Alley, 1997).

Based on architectural geometry of the deposits and facies associations, a model of morainal bank deposits (Powell, 1981; Cai et al., 1997) was proposed by Marenssi et al. (2005) who recognized bank-front, bank-core and bank-back subenvironments. This model is followed in this paper, where bank front deposits are mainly made up by resedimented diamictites (mainly stratified diamictites) that pass basinward to thinly-bedded diamictites and dropstone-bearing shales.

Bank core deposits are dominated by coarse-grained sediments, including clast-poor, clast-rich and some beds of stratified diamictites, as well as rhytmites. The clast-poor striated and injected massive diamictites, in-

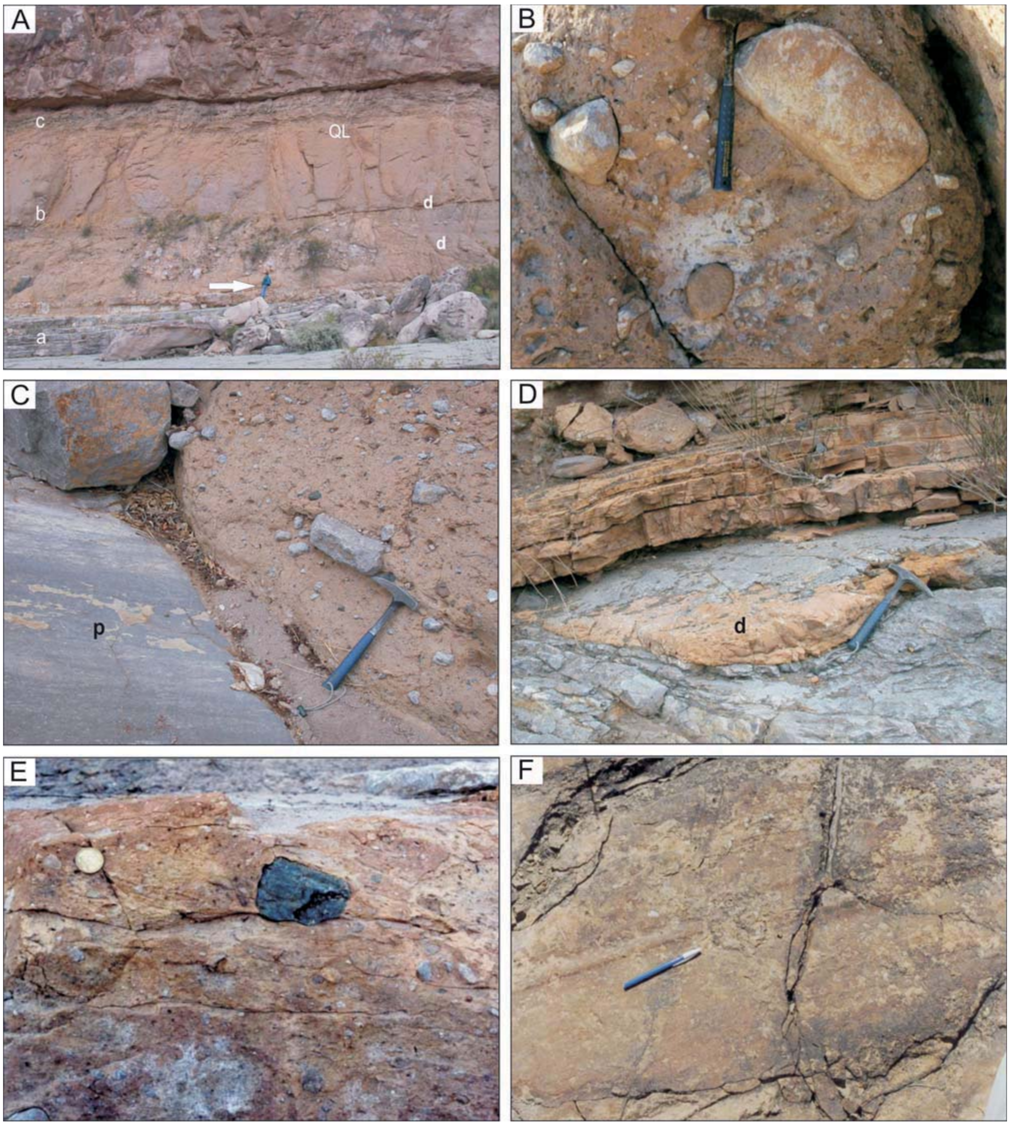

FIGURE 9 | **A) aspect of the glacial deposits of the Guandacol Formation (a: Ordovician basement, b: stacking of glacial deposits and c: thin interval of postglacial shales (see the person shown by arrow for scale). B) massive matrix-supported diamictite showing clasts up to 40 cm. in maximum-diameter. C) aspect of the massive-matrix supported diamictite composed entirely of angular fragments of limestones derived from the Ordovician basement. Note the polished aspect (p) of the underlying Ordovician limestones (San Juan Formation). D) injected diamicton (d) into the Ordovician limestones. E stacked beds of the stratified diamictites. F) striated pavement carved on the Ordovician limestones of the San Juan Formation.**

terpreted as lodgment till deposits, are also included in this group.

Finally, bank-back succession comprises resedimented stratified diamictites that pinch-out into dropstone-bearing shales.

Palynology of the Guandacol Formation

Several contributions were made on the palynological content of this unit (Ottone and Azcuy, 1986; Césari and Vázquez Nístico, 1988; Ottone and Azcuy, 1989; Ottone 1991; Césari and Limarino, 2002). All these studies deal with assemblages from the middle and upper sections of the formation, which were referred to the Subzone A of the *Raistrickia densa – Convolutispora murirnata* Biozone, Serpukhovian-early Bashkirian (= early Namurian) in age (Césari and Gutiérrez, 2001).

Palynological assemblages recovered from moraine bank deposits were studied by Perez Loinaze (2007b) who analyzed 10 samples collected from shales bearing dropstones, mudstones and muddy matrix of clasts-poor diamictites outcroping in Los Pozuelos Creek. Seventy four spores and eighteen pollen species were identified (Fig. 10). Only a few acritarchs could be recognized. An important number of species of these palynofloras are usually found in Serpukhovian-Pennsylvanian assemblages of Argentina and Brazil, such as *Apiculatisporis variornatus* di Pasquo et al. 2003*, Apiculatasporites parviapiculatus* Azcuy 1975*, Apiculiretusispora alonsoii* Ottone 1989*, Convolutispora muriornata* Menéndez 1965*, Cyclogranisporites firmus* Jones and Truswell 1992, *C. microgranus* Bharadwaj 1957*, Dyctiotriletes cortaderensis* Césari and Limarino 1987*, Raistrickia densa* Ménendez 1965, *Reticulatisporites passaspectus* Ottone 1991 and *Spinozonotriletes hirsutu*s Azcuy 1975 (Archangelsky et al., 1996; Césari and Gutiérrez, 2001; Souza et al., 2003; di Pasquo et al., 2003; Souza, 2006). Whereas, *Brevitriletes cornutus* (Balme and Hennelly) Høeg and Bose 1960, *Convolutispora ordonezii* Archangelsky and Gamerro 1979 and *Granulatisporites autroamericanus* Archangelsky and Gamerro 1979 have wide stratigraphic range, from Serpukhovian to Lower Permian (Archangelsky et al., 1996; Souza et al., 1993, 1997; Stephenson, 2004; Souza, 2006).

Other group of species includes *Vallatisporites ciliaris* (Luber) Sullivan 1964 and *Raistrickia rotunda* Azcuy 1975 which have wider stratigraphical distribution, from late Visean to Permian (Archangelsky et al., 1996; García, 1995 and Beri et al., 2006). *Reticulatisporites magnidictyus*, elsewhere characteristic of late Visean-Early Serpukhovian sediments, is recognized in Argentina associated with glacigenic deposits, as was reported by Limarino and Gutiérrez (1990) and Perez Loinaze (2007b).

Regarding pollen species, these show a high diversity comprising 18 species, mostly bilateral or radial monosaccate pollen grains such as *Caheniasaccites densus* Lele and Karin *emend*. Gutiérrez 1993, *Cannanoropollis densus* (Lele) Bose and Maheshwari 1968, *C. janakii* Potonié and Sah 1960, *C. mehtae* (Lele) Bose and Maheshwari 1968, *Circumplicatipollis plicatus* Ottone and Azcuy 1988, *Costatascyclus crenatus* Felix and Burbridge emend. Urban 1971, *Crucisaccites monoletus* Maithy 1965, *Divarisaccus stringoplicatus* Ottone 1991, *Plicatipollenites gondwanensis* (Balme and Hennelly) Lele 1964, *P. malabarensis* (Potonié and Sah) Foster 1975, *P. trigonalis* Lele 1964, *Potonieisporites triangulatus* Tiwari 1965, *P. barrelis* Tiwari 1965, *P. densus* Maheshwari 1967, *P. lelei* Maheshwari 1967 and *P. magnus* Lele and Karim 1971. Only two species of bisaccate pollen are recognized in these assemblages: *Colpisaccites granulatus* Archangelsky and Gamerro 1979 and *Limitisporites rectus* Leschik 1956. All the identified species have long stratigraphic ranges within the Serpukhovian–Permian interval (Foster, 1975; 1979; Gutiérrez, 1993; Archangesky et al., 1996).

The presence of spores, along with the occurrence of pollen grains in the studied levels of the Guandacol Formation, allows us to constrain the age of the palynological assemblages as not older than Serpukhovian. Furthermore, the high diversity of monosaccate pollen grains and the extreme scarcity of taeniate pollen, suggest that the associations are probably late Serpukhovian.

Césari and Gutiérrez (2001) pointed out compositional differences between their CV Biozone (equivalent in part to MQ Biozone) and the succeeding Subzone A reflecting the appearance of a new flora under the influence of glacial conditions. One of the most significant changes was the incoming of monosaccate pollen in the fossiliferous record coinciding with the appearance of Cordaitales. The first records of monosaccate pollen grains occur worldwide during the Serpukhovian (Brugman et al., 1985; Clayton et al. 1990; Zhu, 1993; Clayton, 1995).

DISCUSSION

The Late Paleozoic Gondwanic glaciation is probably the most important glacial period during the Phanerozoic in the Earth (Frakes et al., 1992; Horton et al. 2007). A set of interesting questions about its origin, paleogeographic extension and duration are still unresolved (Hyde et al., 1999; Isbell et al., 2003b; Horton et al., 2007). The outcrops studied in this paper give interesting data to evaluate the timing of the Late Paleozoic glaciation in the western margin of Gondwana. A paleogeographic reconstruction of Gondwana during the latest Mississippian-earliest Pennsylvanian is showed in figure 11A. According to this re-

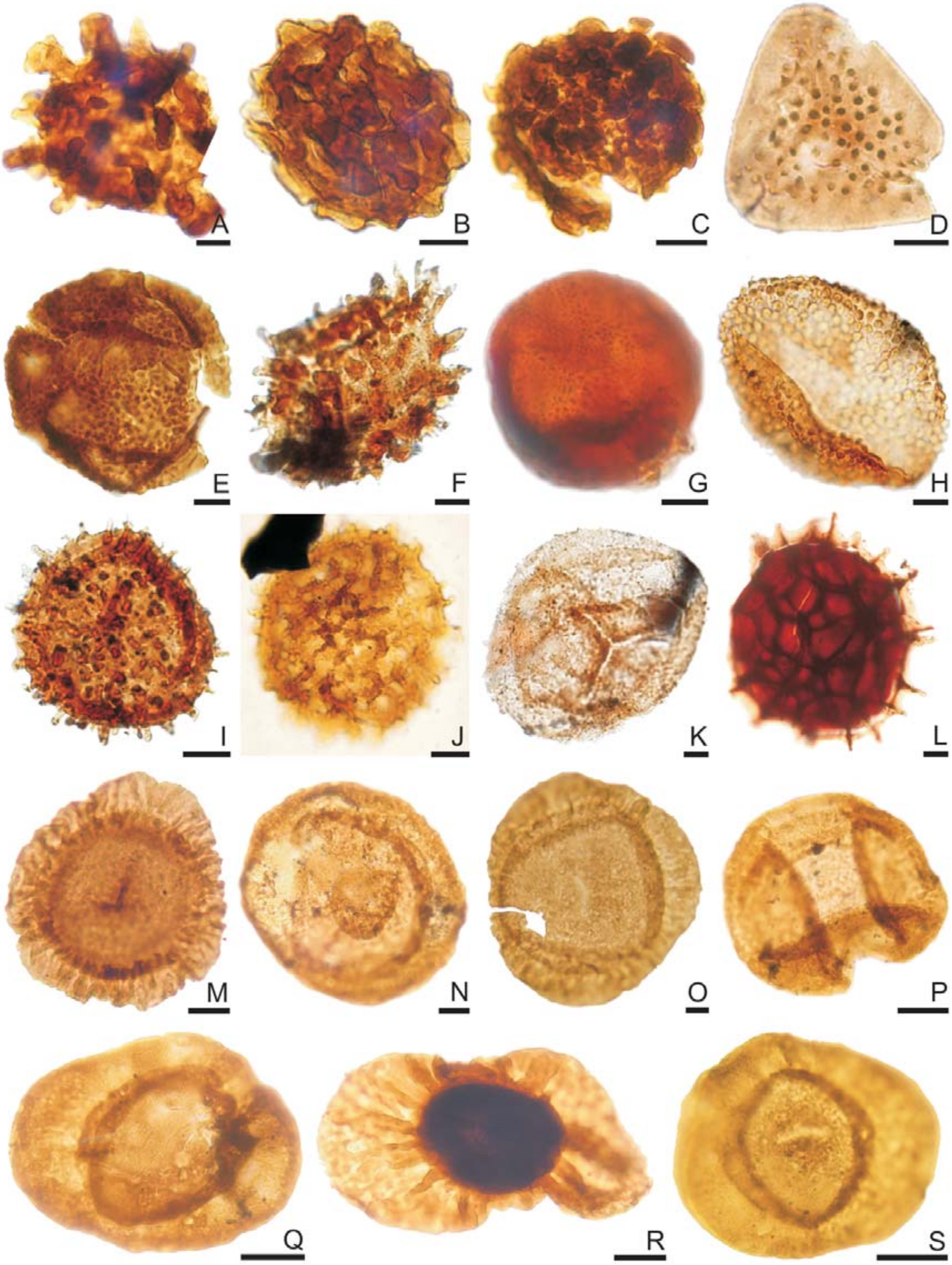

FIGURE 10 | **Palynological species from Guandacol Formation. The specimens are curated in the palynological collection of the Museo Argentino de Ciencias Naturales Bernardino Rivadavia (BAPal). The slide number (prefixed BA Pal) and the 'England Finder' co-ordinates are given for each specimen. A) *Raistrickia densa* Ménendez, BA Pal 5703-2: N22/3; B) *Convolutispora muriornata* Menéndez, BA Pal 5796-2: O26/1; C) *Raistrickia rotunda* Azcuy, BA Pal 5798-1: F34/3; D) *Anapiculatisporites concinus* Playford, BA Pal 5798/2: H25/3; E) *Verrucosisporites andersonii* (Anderson) Backhouse, BA Pal 5785/3: K46/1; F) *Spinozonotriletes hirsutus* Azcuy, BA Pal 5805-1: X33/4; G) *Cyclogranisporites firmus* Jones and Truswell, BA Pal 5810-3: N30/0; H) *Dibolisporites disfacies* Jones and Truswell, BA Pal 5803-1: Q31/3; I) *Apiculatisporis variornatus* di Pasquo et al., BA Pal 5704-1: K39/2; J) *Reticulatisporites asperidictyus* Playford and Helby, BA Pal 5799-1: D53/4; K) *Verrucosisporites menendezii Archangelsky and Gamerro, BA Pal 5799-1: M47/2; L) Reticulatisporites magnidictyus* Playford and Helby, BA Pal 5809-2: P29/1; M) *Cannanoropollis janakii* Potonié and Sah, BA Pal 5799-1: F25/1; N) *Circumplicatipollis plicatus* Ottone and Azcuy, Ba Pal 5797-3: V31/3; O) *Plicatipollenites trigonalis* Lele, BA Pal 5799-2: Z25/1; P) *Crucisaccites monoletus* Maithy, Ba Pal 5803-2: Y52/2; Q) *Potonieisporites magnus* Lele and Karim, BA Pal 5798-1: S3/3; R) *Caheniasaccites densus* Lele and Karin emend. Gutiérrez, BA Pal 5804-1: Z40/1; S) *Potonieisporites barrelis* Tiwari, BA Pal 5797-2: E38/1. Scale bar: 20 µm.**

construction the southwestern margin of Gondwana, including Paganzo and Río Blanco basin, was placed at high latitudes as well as the Paraná Basin in the eastern of South America. Australia seems to have been at lower latitudes (Fig. 11A) though glacial deposits of Late Mississippian-Early Pennsylvanian age were described from both, eastern and western basins (Eyles et al., 2002, 2006; Fielding et al., 2008). Visean-Sepukhovian glaciomarine rocks, at similar latitudinal position, were described by Garzanti and Sciunnach (1997) in South Tibet region (Fig. 11A). The absence of glacial record of stated Late Mississippian-Early Pennsylvanian age in South African and Antarctic basins, probably reflect the fact that this portion of Gondwana was exposed to the most severe glacial conditions. According to Streel and Theron (1999), the Dwyka glaciation began in South Africa shortly after (Sepurkhovian?) deposition of the uppermost Witteberg sediments referred to the Middle Tournaisian.

Initially, Gondwanic glaciation was considered a large and not interrupted period of time, encompassing the whole of the Mississippian and part of the Early Permian. Recent studies, founded in stratigraphic evidence, show that glacial conditions were not developed as a unique episode (Isbell et al., 2003a,b; Fielding et al., 2008). On the contrary, different glacial periods can be recognized in Gondwana during the Late Paleozoic. According to Isbell (2003a) three major glacial periods are recognized along Gondwana (Fig. 12). The oldest, Late Devonian-Tournaisian in age, would correspond to that described by Díaz Martínez and Isaacson (1994) in the Titicaca region, north of Bolivia, as well as the reported by Caputo (1985), Caputo and Crowell (1985) and Loboziak et al. (1995a, b) for Brazilian basins.

Following Isbell's proposal, the second glacial event took place during the Late Mississippian-Early Pennsylvanian. This episode shows a wide representation along the western margin of Gondwana and, indeed, is the better recognized in the Argentinean Andean basins. Glacial deposits of this interval have been described in the Calingasta-Uspallata (Mésigos, 1953; González, 1981; González, 1990; López Gamundí, 1997; López Gamundí and Martínez, 2000), Paganzo (Limarino and Gutiérrez, 1990; López Gamundí and Martínez, 2000; Césari and Limarino, 2002; Marenssi et al., 2005), Río Blanco (Gulbranson et. al., 2008), San Rafael (Espejo et. al., 1996) and Tepuel-Genoa (Suero, 1953; Andreis et al., 1987; González Bonorino, 1992) basins.

The younger glaciation was considered Early Permian in age by Isbell et al. (2003a, b), on the basis of glacial diamictites dated in Brazil and South Africa (Fig. 12). However, recently Fielding et al., (2008) described Middle to Late Permian glacial diamictites in the eastern basins of Australia (Fig. 12).

The glacial deposits described in this paper must be included in the second glacial interval proposed by Isbell et al. (2003a, b), and the existence of two palynofloras allow us to constrain the chronology of this glacial interval (Fig. 12). Likewise, the palynological assemblage found at the Upper Member of Cortaderas Formation would indicate the beginning of the "glacial interval 2" (Isbell et al., 2003a, b) which, taking into account the absence of pollen grains, would be not younger than late Visean. It is possible to correlate

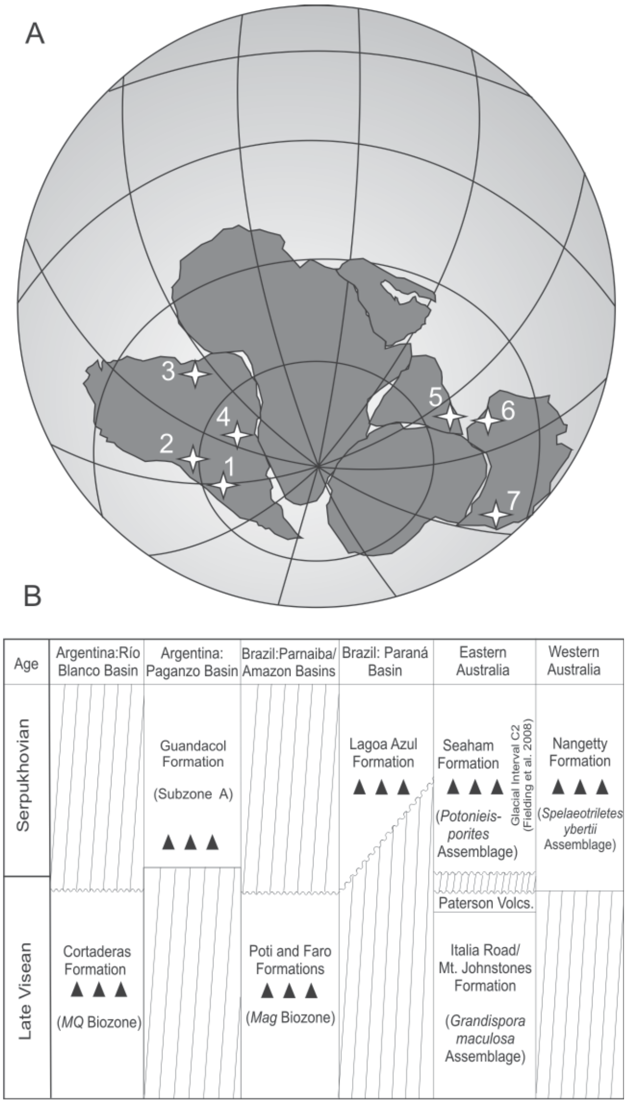

FIGURE 11 | **A) Location of glacial deposits in Río Blanco and Paganzo Basins, Argentina (1), Kaka Formation, Bolivia (2), Paraná Basin, Brazil (3), Amazon and Parnaíba Basins, Brazil (4), Rakyang Formation, South Tibet (5), Canning and North Perth Basins, Western Australia (6), New England Fold Belt, Eastern Australia (7). Carboniferous Gondwanaland is shown according to Blakey (2008). B) Distribution of Visean-Serpukhovian glacial deposits along Gondwana (from Rocha Campos et al., 2008; Fielding et al., 2008; Eyles et al., 2006)** these assemblages (Fig. 11B) with the ones identified in the Brazilian Poti Formation (Amazonas Basin) and Faro Formation (Parnaíba Basin) which were referred to the late Visean Mag Biozone (Melo and Loboziak, 2003). Both of the formations were interpreted as glacial in origin by Caputo (2006) and Caputo et al. (2006, 2008). As well, deposits of the Solimões, Jaindiatuba sub-basins have been interpreted as probably originated by iceberg-rafting (Caputo et al., 2008) and were assigned to the Mag Biozone by Melo and Loboziak (2003).

The Bolivian Kaka Formation records glaciomarine deposits (Suárez-Soruco, 2000) bearing palynofloras aged as late Visean and correlated with Mag Biozone (Melo, 2005). Fasolo et al. (2006) described assemblages from the uppermost part of the Kaka Formation partially correlated with the Mag Biozone but containing scarce monosaccate pollen.

Also, it is possible to establish a correlation with the Australian *Grandispora maculosa* Assemblage (Fig. 11B), dated as late Visean–Early Serpukhovian in age (Roberts

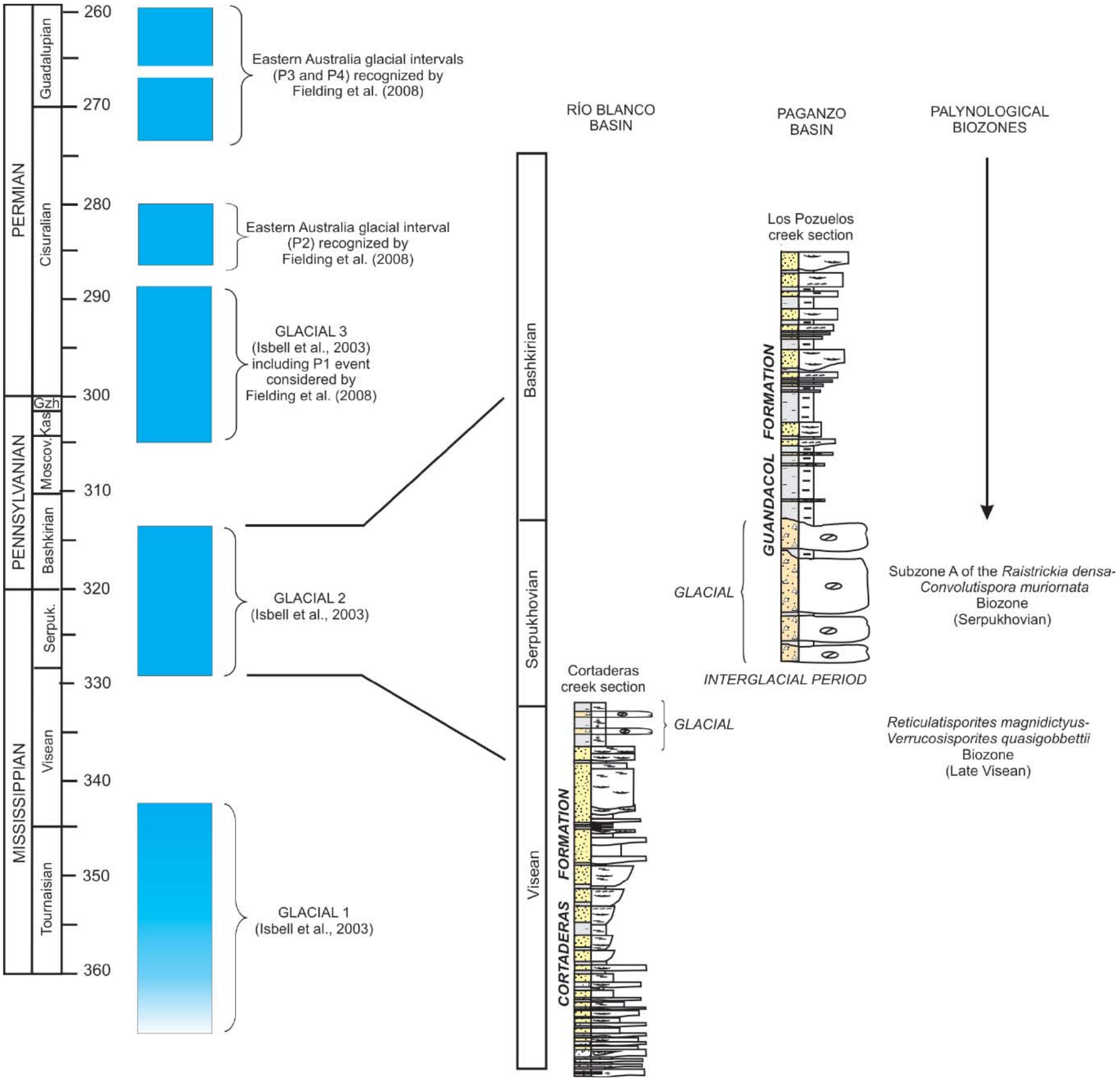

FIGURE 12 | **Chronology of the Gondwanic glaciation using the glacial intervals proposed by Isbell et al. (2003a) and Fielding et al. (2008). The glacial deposits described in this paper fit with the Glacial 2 event and are separated by a brief interglacial period. For references see figure 4.**

et al., 1995; Dino and Playford, 2002). The Australian biozone is characterized by palynological assemblages described by Playford and Helby (1968) from the Italian Road Formation (an equivalent of the Mount Johnstones Formation), which share biostratigraphic key species with the palynofloras from the Cortaderas Formation, such as: *Reticulatisporites magnidictyus*, *Rugospora australiensis* and *Verrucosisporites quasigobbettii*. The Italian Road Formation is overlied by the Paterson Volcanics considered the marker for the onset of the glaciation by Roberts et al. (1995). Claoué-Long et al. (1995) obtained zircon ages of 328 + 1.4 Ma from this volcanic horizon that underlies the glacigenic Seaham Formation bearing the *Potonieisporites* Assemblage characterized by the presence of abundant monosaccate pollen (Helby, 1970; Foster, 1993). As it was noted by Helby (1970) the glacial event in eastern Australia (Fig. 11B) is accompanied by a rapid replacement of the components of the *G. maculosa* Assemblage. The oldest glacial deposits in western Australia (Fig. 11B), consist of fossiliferous glaciomarine diamictites (Eyles et al., 2002; 2006), preserved in the Canning and North Perth basins (Nangetty Formation) where subsidence and sediment preservation seems to have begun in the Serpukhovian.

In the same way, the palynological associations described at the lower section of the Guandacol Formation contain pollen grains as *Potonieisporites*, *Plicatipollenites* and spores characteristics of the subzone A of the *Raistrickia densa–Convolutispora muriornata* Biozone. The presence of abundant pollen suggests that this glacial event is not older than Serpukhovian. These deposits would correspond to the end of the Glacial 2 interval (Isbell et al., 2003a, b) in this part of Gondwana and probably correlate with the lowermost glacial levels identified in the Brazilian Itararé Group (Rocha Campos et al., 2008). These glacigenic rocks, included in the Lagoa Azul Formation (França and Potter, 1991; França and Vesely, 2007), have yielded palynological assemblages which share with those found in the glacigenic interval of the Guandacol Formation, the presence of monosaccate pollen (Fig. 11B). Besides, radiometric ages reported by Rocha Campos et al. (2006; 2008) suggest a Carboniferous age for the glaciation in the Paraná Basin. Palynological assemblages from the lower part of the Itararé Group were referred to the *Ahrensisporites cristatus* biozone (Souza, 2006) characterized by the presence of up to 5% of taeniate pollen, not recognized in the Guandacol glacial levels. Unfortunately, detailed studies about the first appearance of taeniate pollen in the basal Itararé Group are not available yet. Therefore, a precise correlation between both palynofloras is not possible.

The underlying question is, was this glacial interval continuous or, on the contrary, punctuated by interglacial periods? Despite the scarce stratigraphic evidence, the record of the glacial interval in Cortaderas and Guandacol Formations can be used for unraveling the glacial history. Figure 12 shows a stratigraphic model which relates Los Pozuelos Creek and Cortaderas Creek sections. Along the western flank of the La Punilla range, the glacial deposits belonging to the Cortaderas Formation are covered by fluvial coarse-grained sandstones and conglomerates included in the Quebrada Larga Formation (fig. 2). The vertical change from glaciomarine shales and diamictites (late Visean) to fluvial sandstones and conglomerates might suggest a climatic amelioration, at least during a short time interval.

Indirect evidence for cooling and glacial conditions in latest Visean and Serpukhovian time was obtained by Mii et al. (1999) who recorded in δ^{13}C and δ^{12}O excursions on brachiopod shell calcite from North America. Bruckschen et al. (1999) also documented two peaks in δ^{13}C and δ^{12}O in the Tournaisian and possibly Visean, suggesting short-lived glacial episodes but noted lack of described glacial deposits. Smith and Read (2000) realized carbonate stratigraphic studies and suggested that the onset of the glaciation was late Visean in age.

CONCLUSIONS

Most of the available paleoclimatic models identify a unique glacial period during the "Middle" Carboniferous in the southern Andean basins (López Gamundí et al., 1992; Limarino et al., 1997). However, according to the palynological information and stratigraphic evidence presented in this paper, two glacial events are recognized. The oldest occurs at the Upper Member of the Cortaderas Formation and consists of different types of resedimented diamictites, shales with dropstones and fine-grained rocks deposited in distal glaciomarine environment. These rocks have yielded abundant palynological assemblages dominated by spores of the *Reticulatisporites magnidictyus-Verrucosisporites quasigobbettii* Biozone, late Visean in age. This palynoflora would be coeval with the "Paracas flora", defined by Iannuzzi and Pfefferkorn (2002) as a Gondwanic frost-free floral belt developed between 30º and 60º South, before the beginning of the Carboniferous glaciation. However, the evidence of a glacial event at high latitudes during the late Visean recorded in the Cortaderas Formation, suggests that the Paracas flora would not be useful to interpret warm global conditions, as was previously suggested (Iannuzzi and Pfefferkorn, 2002).

A younger glacial interval occurs at the lower part of the Guandacol Formation; in this case glacial deposits consist of tillites, resedimented diamictites, shales with dropstones and fine-grained rocks, all of them interpreted as sedimented in a proximal glaciomarine setting. According to the presence of abundant monosaccate pollen and the scarce record of taeniate pollen a Serpukhovian age was proposed for the assemblages recovered from these rocks.

Glacial deposits of the Upper member of the Cortaderas and the lower part of Guandacol Formation are both included in the Glacial 2 period according to Isbell's model. It is highly probable that the glacial interval found in Cortaderas Formation point out the beginning of the Glacial 2 period in the western margin of Gondwana. Based on the palynological information here presented, the start of the Glacial 2 period should be considered late Visean and then slightly older than supposed in previous studies.

The uppermost levels of the glacial deposits outcroping in the lower part of Guandacol Formation probably represent the end of the Glacial 2 period which would have finished close to the Mississippian-Pennsylvanian boundary in the region considered in this paper.

Sedimentological, stratigraphic and palynological information suggests the existence of a short interglacial period between the Cortaderas and the Guandacol glacigenic deposits.

The stratigraphic evidence presented in this paper clearly shows that the recurrence of glacial sequences can not be only explained by the drifting of Gondwana around the pole. Other factors, such as major global climatic changes or subtle paleogeographic modifications (promoting high altitude glaciation), should be considered.

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