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Bimodal character of the Late Paleozoic glaciations in Argentina and bipolarity of climatic changes

Carlos R. González[a,*], Pamela Díaz Saravia[b]

[a] CONICET, Miguel Lillo 251, 4000 Tucumán, Argentina
[b] Fundación M. Lillo, Miguel Lillo 251, 4000 Tucumán, Argentina

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ABSTRACT

The Upper Paleozoic sedimentary rock sequences of Argentina show an outstanding record of climatic fluctuations during this interval and the complexity and rapidity of the climatic changes. There were two distinct events of cooling or glacial periods: the older in the “middle” Carboniferous (late Viséan–Bashkirian) and the younger in the Early Permian (Asselian–Tastubian), and these were separated by a long-lasting interval of warming during the Late Pennsylvanian. It is postulated that climatic fluctuations in the northern paleotemperate realm may have had the same causes as in Argentina, and that these periods of cooling and warming probably occurred at the same time in both hemispheres. In western Argentina and central Patagonia the occurrence of the Early Permian glacial phase and the absence of the younger phases like those present in eastern Argentina and South Africa, suggest that during the final deglaciation in Gondwana thawing gradually progressed to the east, then located closer to the paleopolar region.

1. Introduction

Upper Paleozoic glacial deposits in the Uspallata-Iglesia Basin of western Argentina and the Languiñeo-Genoa Basin of central Patagonia provide ample record of the climatic fluctuations that happened during the Late Paleozoic Ice Age. In the absence of isotopic data and sufficient radiometric dates, biostratigraphic method remains the only means to order glacial phases in time. The sediments were deposited in near-shore marine environments and the climatic fluctuations are closely linked with significant changes in marine faunas, so that a distinct faunal stage corresponds to each climatic episode. These faunal stages broadly correspond to the chronostratigraphic stages between Viséan to Sakmarian.

Available data suggest a bimodal character of the glaciations in Argentina, as is also recorded in Australia (Mory et al., 2008) where it is confirmed with isotopic dating (Roberts et al., 1995). This was also admitted by Dickins (1996), who accepted the existence of a long warm interval during the Late Pennsylvanian before the Early Permian glaciations, as shown in sequences of Argentina. These faunal-climatic stages can be correlated with floral-climatic events in the Angara continent (Cleal and Thomas, 2005), giving them more than regional significance. Although the paleo-Arctic region was oceanic, the bipolarity of glaciations seems to be supported by many lines of evidence from Gondwana and Angaraland, as discussed in this paper.

1.1. Climatic fluctuations in Argentina

Consecutive faunal assemblages reveal that Late Paleozoic glacial deposits in Argentina belong to two distinct episodes, respectively in the “middle” Carboniferous (late Viséan to Bashkirian) and in the Early Permian (Asselian to early Sakmarian) intervals. These glacial intervals are separated by a long-lasting interval without glaciation (González, 1981, 1990). However, the age and extent of these glacial deposits have been estimated differently by other authors (e.g. Caputo and Crowell, 1985; Veevers and Powell, 1987; López Gamundi et al., 1992; González Bonorino and Eyles, 1995), probably because of incomplete biostratigraphic knowledge and/or problems of correlation. In this regard, González and Díaz Saravia (2007) and González and Glasser (2008) made a revision of the current ideas, although some aspects need more research. Isotopic ages obtained by Roberts et al. (1995) initiated a more ample recognition of the bimodal character of the glaciations in Australia; these authors and Dickins (1996) briefly discussed previous thoughts and found close resemblances with the Argentinean occurrences. Data from different sources have been recently collated in a more ample context of Gondwana by Fielding et al. (2008b), who concluded that a series of short, discrete glacial events occurred in separate regions of Gondwana.

In the present paper, attention is focused on sequences of the western Andes of Argentina and central Patagonia, because these regions were affected by active subsidence and deposition during the Carboniferous–Permian and was the cause of discussions during recent years. The sequence of climatic fluctuations during the Late Paleozoic is compiled from the Uspallata-Iglesia Basin (see González, 1985) in the central western Andes, the Languiñeo-Genoa Basin in central Patagonia,

* Corresponding author.
E-mail address: crgonzalez@csnat.unt.edu.ar (C.R. González).

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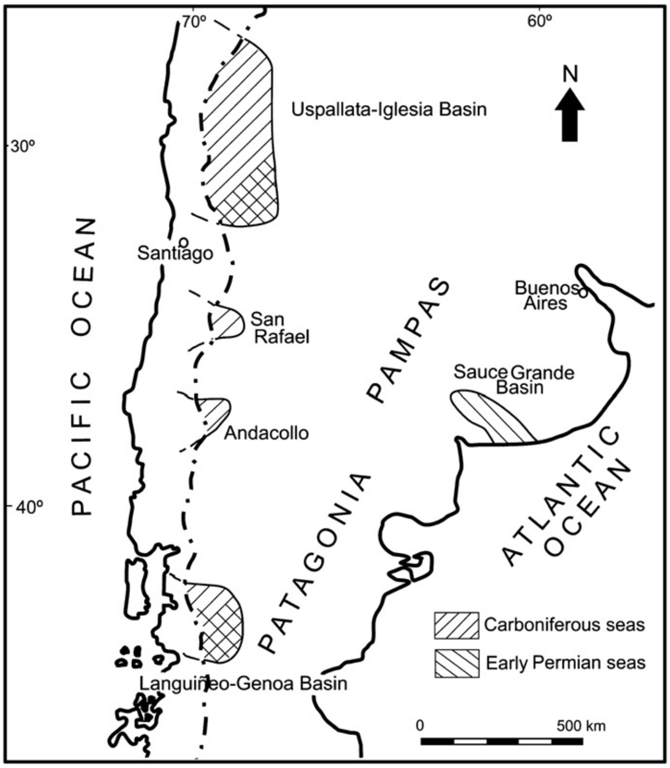

Fig. 1. Map showing the paleo-Pacific embayments in western Argentina during the Carboniferous and Early Permian, and the proto-Atlantic embayment in eastern Argentina during the Early Permian.

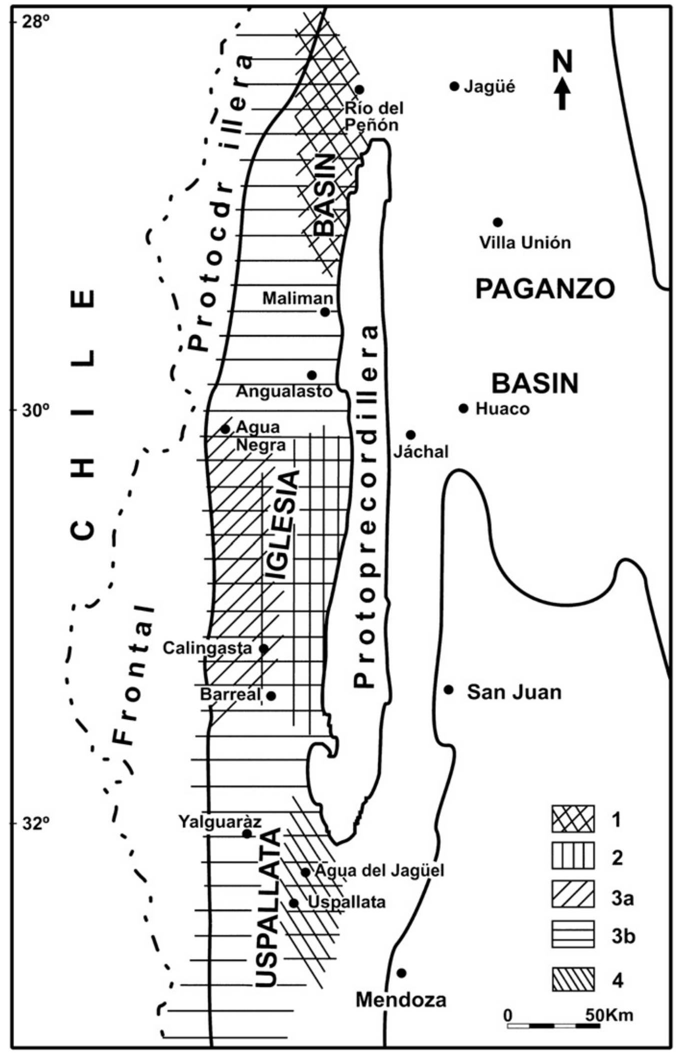

Fig. 2. Map of central western Argentina showing localities cited in text and areas flooded by the paleo-Pacific during the Early Mississippian to Early Permian. 1: Tournaisian transgression (Malimanian fauna). 2: Middle Carboniferous transgression (Barrealian fauna). 3a, 3b: Late Pennsylvanian interglacial, Aguanegran fauna, 3a: older transgression (*Balakhonia-Geniculifera* assemblage), 3b: younger ingression (*Kochiproductus-Heteralosia* assemblage). 4: Early Asselian transgression, Uspallatian fauna (=*Costatumulus amosi* fauna).

and the Sauce Grande Basin in eastern Argentina (Fig. 1). The two first mentioned basins were situated along the south-western margin of Gondwana, and show nearly similar development of deposits and faunas ranging from the Early Carboniferous to the earliest Permian (Amos and Sabattini, 1969; González, 1981). In the Uspallata-Iglesia Basin (Fig. 2) these sequences are known from dispersed outcrops, but the record of the climatic fluctuations here is more clearly exposed than other areas in Argentina, and they allow a ready comparison with the Angara region. In eastern Argentina Carboniferous rocks are lacking; subsidence of the Sauce Grande Basin started in the Early Permian, so in this region only the younger record of the Ice Age is preserved.

2. The Carboniferous glacial period

The existence of a latest Devonian–earliest Carboniferous glaciation in South America assumed by many authors, especially Veevers and Powell (1987), Díaz et al. (1993), Isaacson et al. (1999), and others, is not supported with multiple criteria (Dickins, 1985, 1993, 1996; González, 1990). As pointed out by Dickins (1996), this assumption "seems to be extended beyond the limits of the available evidence". An exception could be the Upper Devonian Cabeças Formation in the Parnaiba Basin and the Curiri Formation in the Amazonas Basin (Caputo et al., 2008). However, there seems to be a contradiction relating to the paleogeographic location of these basins and the occurrence of well-dated Upper Devonian to Early Carboniferous no-glacial sediments at higher paleolatitudes (Fig. 5), especially those of the Precordillera of western Argentina (Morel et al., 1993). Pazos et al. (2005) interpreted dropstones in the Tournaisian Malimán Formation as evidence of cooling, but this assertion is based on a single criterion, lacking other evidence and 'dropstones' may have other origins (Dreimanis, 1983). Moreover, the occurrence of diamictites in the Agua de Lucho Formation, northern equivalent of the Malimán Formation, was shown to be caused by debris flows (González, 1994).

Even though alpine glaciations cannot be ruled out during the Late Devonian or Early Missisipian (Díaz et al., 1993), the oldest Late Paleozoic rocks that has been confidently assigned to a glacial origin at relatively low altitudes are of "middle" Carboniferous age (late Viséan to Bashkirian). They are well preserved in the San Eduardo Formation exposed in an area near and east of Barreal (Figs. 2, 4), which have abundant and varied evidence of depositional and erosional features produced by glaciers (González and Glasser, 2008). This sequence is probably the clearest display of the climatic fluctuations that happened during the Carboniferous glaciations in Gondwana. Four successive glacial phases, represented by probably lodgement tills (terrestrial moraine) or tills deposited at the littoral zone (González and Glasser, 2008) can be recognized because they are separated by discrete advances of the sea (González 1990). The two lower phases, El Paso I and El Paso II (Fig. 6), are separated from each other and from the subsequent Hoyada Verde phase by marine beds bearing the *Rugosochonetes-Bulahdelia* assemblage (Taboada, 1989). Some authors (López Gamundi et al., 1992; Henry et al., 2008) neglect the existence of Early Carboniferous and Early Permian glacial events in basins of western Argentina and consider the El Paso I and II phases equivalent with the Hoyada Verde and Guandacol phases. However, the *Rugosochonetes-*

Bulahdelia assemblage belongs to an extended transgression in Gondwana that also flooded eastern Australia, where the *Rhipidomella fortimuscula* and *Marginirugus barringtonensis* faunas have elements in common. These faunas are assigned to the late Viséan (Taboada, 1989; Roberts et al., 1995). Instead, the two upper diamictites of the San Eduardo Formation: phases Hoyada Verde I and Las Salinas (or Hoyada Verde II), which are separated by an erosional surface marked by an extensive striated boulder pavement (González and Glasser, 2008), are limited at bottom and top by siltstones bearing fauna of the *Levipustula levis* Zone, which is ascribed to the Bashkirian-Serpukhovian interval (González, 1990, Roberts et al., 1995).

The *Rugosochonetes-Bulahdelia* and *Levipustula levis* faunas are consecutive steps in the evolution of a dynamic fauna, so called the "cold" fauna because of its association with glacial deposits, and are here grouped in the Barrealian faunal stage (González, 1993) (Fig. 4). The sections at El Paso and Hoyada Verde are considered the lower and upper members respectively of the same glacial sequence: the San Eduardo Formation (González, 1993). These deposits unconformably overlap pre-Carboniferous meta-sediments, as is clearly exposed at El Paso (Mésigos, 1953; González, 1990).

From Early Carboniferous to earliest Permian the Languiñeo-Genoa Basin was a paleo-Pacific embayment (Fig. 3), where a sequence of more than 5000 m of sediments, the Tepuel Group (Suero, 1948), was deposited. This consists, in order of decreasing age, of the Jaramillo, Pampa de Tepuel and Mojón de Hierro Formations (Figs. 4, 6). No unconformities are observed, but there is a stratigraphic gap between the Jaramillo and Pampa de Tepuel Formations. At the type locality of Tepuel Hills, the Pampa de Tepuel Formation is a nearly 3000 m thick succession, which in the lower half has four glacial phases intercalated with marine beds bearing fauna of the *Levipustula levis* Zone. The first three phases were deposited in near-shore marine environments. The fourth phase, consist of nearly 10 m thick stratified and massive diamictites with intraglacial pavements (Fig. 7B, C) and are overlain by dropstone-bearing siltstones and laminites (Fig. 7D). These diamictites were probably deposited at the littoral zone or very near the coast above sea level. This glacial section of the Pampa de Tepuel Formation closely resembles the San Eduardo Formation. A characteristic of the Pampa de Tepuel Formation is the frequent and rapid lateral facies changes. In the localities of Arroyo Pescado and El Molle, situated at the northern and south-eastern borders of the Languiñeo-Genoa Basin (Fig. 3), glacimarine deposits with dropstone-bearing siltstones and conglomerates and diamictites bearing glacially striated surfaces, reveal that glaciers were grounded at the littoral zone, and that ice tongues coming from the adjacent continental area penetrated deeply into this embayment. During the Carboniferous glacial period the ice perhaps covered an area as large as during the Early Permian; probably great part of central Patagonia was in these conditions (González Bonorino and Eyles, 1995). Henry et al. (2008) assume that in western Argentina glaciation was alpine. However, the presence of glaciers at sea level in the west of the proto-Precordillera and glacial deposits in the Paganzo Basin to the east of this range (González, 1990; López Gamundi et al., 1992) suggest that continental ice was extended to the east.

3. The *Levipustula* fauna and the origin of the endemic (Gondwana) fauna

During the Late Paleozoic, variations of sea-water temperature and/or sea level fluctuations have been interpreted to be the main cause that induced faunal changes and the origin and extinction of invertebrate taxa (Waterhouse and Bonham-Carter, 1975; Roberts, 1981 Clapham and James, 2008). This has been observed to have happened early in the Carboniferous glacial period, especially in central Patagonia.

The brachiopod species *Levipustula levis* was ubiquitous in the peri-glacial seas that extended through western Argentina, west Antarctica and eastern Australia (Amos and Sabattini, 1969; Campbell and McKellar, 1969; Kelly et al., 2001). Some authors (Simanauskas,

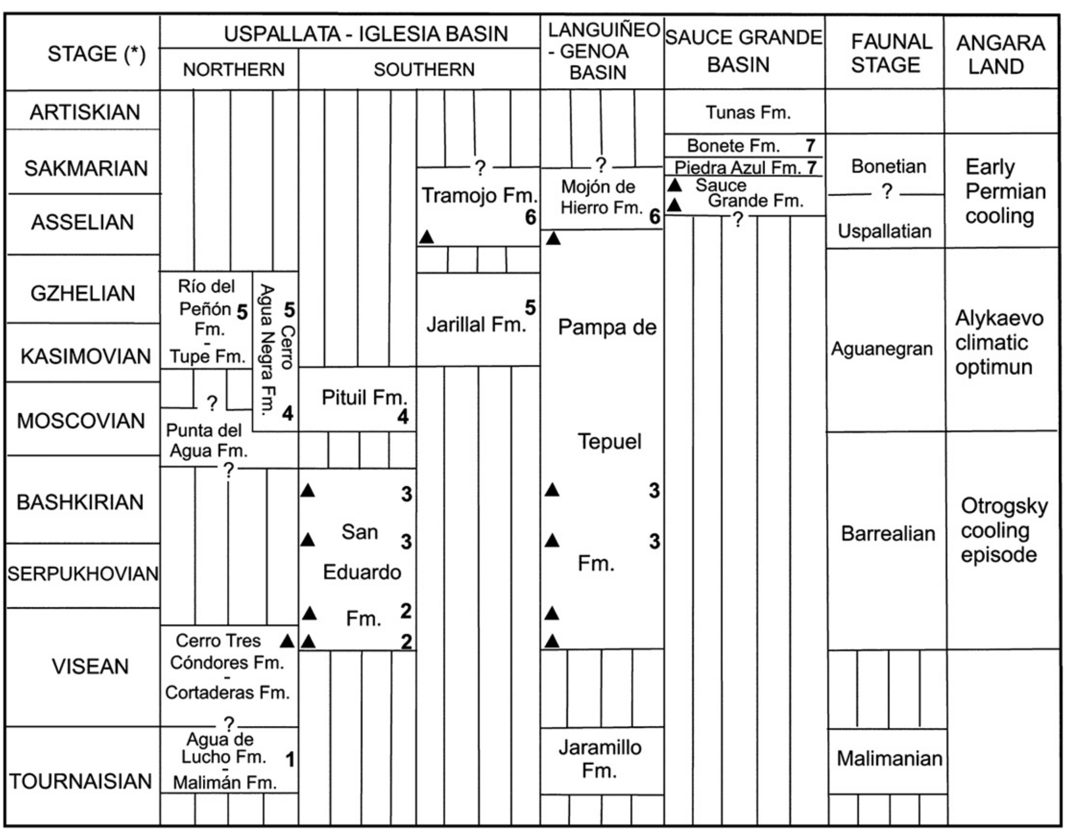

Fig. 3. Map of central Patagonia showing the Languiñeo-Genoa Basin and localities cited in text. After González (1984).

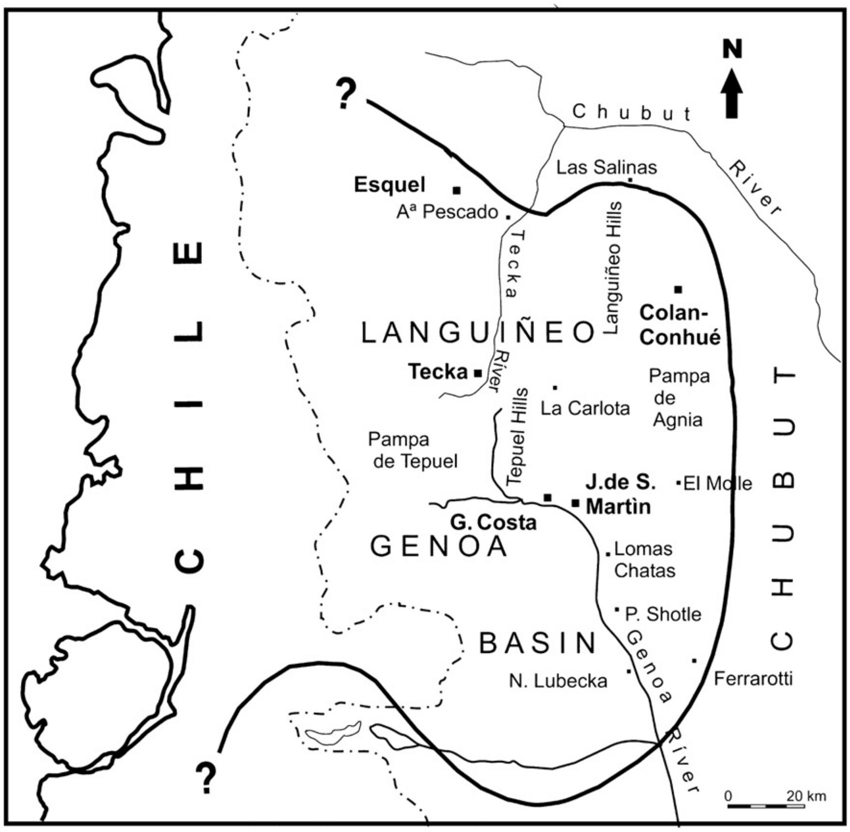

Fig. 4. Correlation chart of selected Carboniferous and Early Permian formations of Argentina, showing occurrence of glacial deposits and faunal stages (after González, 1990, 2003) and paleoclimatic events in the Angara continent (after Ganelin and Durante, 2002; Cleal and Thomas, 2005). *: Not to scale. ▲: glacial deposits, 1: *Protocanites-Azurduya* Zone (Malimanian faunal stage), 2: *Rugosochonetes-Bulahdelia* Zone, 3: *Levipustula levis* Zone (2 + 3 = Barrealian faunal stage), 4: *Balakhonia-Geniculifera* Zone, 5: *Kochiproductus-Heteralosia* fauna (4 + 5 = Aguanegran faunal stage, "intermediate fauna"), 6: *Costatumulus amosi* Zone (Uspallatian faunal stage), and 7: *Eurydesma* fauna (Bonetian faunal stage). Chronostratigraphic units after Mening et al. (2006). The informal term "middle" Carboniferous, as used in the text, makes reference to the time involving the late Viséan, Serpukhovian and Bashkirian stages, where the Serpukhovian is placed in the Upper Mississippian Subsystem and the Bashkirian in the Lower Pennsylvanian Subsystem of the bipartite subdivision of the Carboniferous.

1996; and others) claim that *Levipustula* does not occur in central Patagonia and that material previously assigned to this genus should be reassigned to *Lanipustula* Klets. However, this implies a biogeographic contradiction because central Patagonia is at an intermediate position and was the only way of connection between western Argentina and eastern Australia, which were located at the fringes of the peri-Gondwana seas (Fig. 5) and where the presence of *L. levis* is not questioned. This reassignment was also disapproved by Roberts et al. (1995) and Dr. J. B. Waterhouse (personal communication).

Dickins (1996) assumed that the differences in diversity between the *Levipustula* fauna and the Early Permian *Eurydesma* fauna, should be related to sea-water temperature, and suggested that the *Levipustula* fauna may not be indicative of cold-water in the same sense as the *Eurydesma* fauna. This opinion may be biased by the fact that in Australia *Levipustula levis* is not as distinctly associated with glacial rocks as it is in Argentina, where this brachiopod occurs within sediments of unquestionable glacial origin (González and Glasser, 2008). The ample distribution of this fauna around the southern margin of Gondwana (Amos and Sabattini, 1969; Campbell and McKellar, 1969; Kelly et al., 2001) means that free larval migration along the margins of Gondwana was possible, suggesting links with open sea. Also, the *Eurydesma* fauna may be regarded as moderately diverse, e.g. the Callytharra fauna of Western Australia (Skwarko, 1993); however, in restricted environments as the Sauce Grande–Karroo Basin of eastern Argentina–South Africa, this fauna shows very low diversity (Harrington, 1955; Dickins, 1961, Pagani, 1998). We regard that temperature alone should not be considered the only factor affecting diversity; paleogeographic constraints were probably

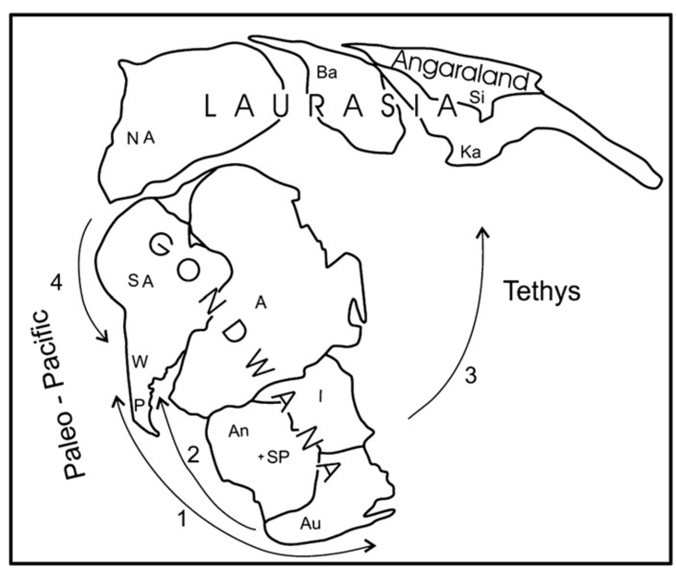

Fig. 5. Late Paleozoic paleogeographic map (modified from Blakey, 2008), with location of W: Calingasta-Uspallata Basin (western Argentina); P: Languiñeo-Genoa Basin (central Patagonia) and Angaraland; SP: South Pole. NA: North America; Ba: Baltica; Ka: Kazakhstan; Si: Liberia; SA: South America; A: Africa; An: Antarctica; Au: Australia; I: India. Arrows show proposed marine faunal migration routes of 1: *Rugosochonetes-Bulahdelia* fauna (late Viséan), *Levipustula levis* fauna (Serpukhovian-Bashkirian) and early endemic (Gondwana) fauna; 2: *Eurydesma* fauna of the Sauce Grande–Kalahari–Karoo Basins; 3: south to north route of some post-Sakmarian endemic taxa of Gondwana through eastern paleo-Tethys; 4: North to South route of some Late Pennsylvanian "warm" faunas from the Tethys to South America via the paleo-Pacific ocean.

important in the diversification of the *Levipustula* and *Eurydesma* faunas, as was observed in other faunas (González, 2002). The *Levipustula* fauna could be regarded diversified because it includes some cosmopolitan elements, but most important during this time is the first appearance of numerous new genera. We agree with Clapham and James (2008) that temperature was the cause of faunal changes and the origin and extinction of taxa, because there was like an "explosion" of life at the beginning of the Late Paleozoic Ice Age, especially seen in deposits of central Patagonia: many new bivalve lineages of the endemic (Gondwana) fauna, also found in the Early Permian *Eurydesma* fauna emerged, a circumstance that in Australia happened rarely (Runnegar, 1972). One of those is *Pyramus primigenius* González, which first appears at the lower *Levipustula* Zone (González, 1972), although Pagani and Sabattini (2002) and Biakov (2008) erroneously assign this species to the basal Permian. Some new bivalve genera of this epoch were short-lived (González and Waterhouse, in press), but others extended its range into the Permian (González, 2002). Central Patagonia was probably place of origin of the endemic fauna of Gondwana.

4. Late Pennsylvanian warming

The Late Pennsylvanian period is the lesser known in Gondwana because of widespread regression (Roberts et al., 1995; Dickins, 1996), although in the Argentinean portion of the Andean orogen and central Patagonia there was active deposition. Especially sequences in the Uspallata-Iglesia and Languiñeo-Genoa Basins are probably the most complete testimony of this time in Gondwana. However, because these deposits and their faunas cannot be matched with others, and no isotopic ages are available, they are cause of different interpretations. In the Uspallata-Iglesia Basin, the Cerro Agua Negra Formation (Polanski, 1970) consists of nearly 3000 m of sediments including two discrete marine members separated by no-marine deposits (Fig. 4). The lower marine member was deposited in an inland sea that was restricted to the central and southern part of the Basin (Fig. 2) from Iglesia (Cerro Agua Negra Formation) to Barreal (Pituil Formation) and bears the *Balakhonia-Geniculifera* faunal assemblage. The upper marine member was deposited during the most important transgression of the Late Pennsylvanian, which not only flooded the entire Basin from its northern border (Río del Peñón Formation) to Uspallata (Jarillal Formation), but also extended farther south along the Andean belt including embayments in western Mendoza and Andacollo at the north-western border of Patagonia (Fig. 1). This transgression is characterized by the *Kochiproductus-Heteralosia* fauna (González, 1993) (Fig. 2). Both, the *Balakhonia-Geniculifera* and *Kochiproductus-Heteralosia* assemblages, are regarded as "warm-water" faunas because they show paleotropical affinities and have no endemic taxa (González, 1993, 1997). These two faunal associations replace the superseded "intermediate fauna" (see below) and the lapse involved is assigned to the Aguanegran faunal stage (Fig. 4). Glacial sediments are lacking in these deposits and the no-marine section separating the lower and upper marine members contain beds bearing paleosoils, low quality coal seams and abundant vegetation of the *Nothorhacopteris* (NBG) flora (Archangelsky et al., 1987). The occurrence of non-marine bivalves having close affinities with their paleoequatorial relatives and the environmental conditions in that realm is also significant (Díaz Saravia and González, 2010). All these evidence suggest a moderately warm climate during the Late Pennsylvanian in western Argentina, and that there was some humidity and CO_2 was possibly higher during this interval (Cleal and Thomas, 2005; Frank et al., 2008). Although there are no isotopic data available yet from this region, these conditions to some extent resemble the environment that prevailed during the Late Pennsylvanian in the western Tethys, where non-marine bivalves were abundant in the Coal Measures.

The Aguanegran faunal stage and depositional sequence are separated from the preceding glacial deposits by an undetermined lapse of no-deposition related to the Saneduárdica diastrophic phase (Furque and Cuerda, 1984). The presence of some elements of this "warm" fauna at the northern border of Patagonia suggests that the Late Pennsylvanian warming probably affected a wider area of Gondwana (González, 1997).

In central Patagonia the Late Pennsylvanian warming is not so evident; deposits of this age indicative of climatic amelioration are missing. The middle section of the Pampa de Tepuel Formation that is placed stratigraphically between the lower glacial section bearing the *Levipustula* (Barrealian) fauna and the glacial member at the top of the Formation bearing the *Costatumulus* (Uspallatian) fauna is regarded coeval with the above mentioned Aguanegran "warm" interval or interglacial period. This section is nearly 1000 m thick, consisting mainly of fine grained sediments revealing slow depositional rate, and minor amount of sandstones and white sandstones all without evidence of glaciation (Fig. 6). Deposits like those in the southern Tethyan margin of Gondwana were ascribed by Wopfner (1999) to the Early Permian deglaciation. However, because of its position at higher paleolatitude during the Late Pennsylvanian (Fig. 5), climate probably remained colder in central Patagonia. In other regions of Gondwana, such as India (Waterhouse 1976), there are no clear-cut evidence of a Late Carboniferous glaciation; in South Africa the Early Permian *Eurydesma* fauna is interbedded within the Dwyka tillite (Dickins, 1961; McLachlan and Anderson, 1973; Anderson, 1977), although the lowermost beds may be in the Late Carboniferous (Isbell et al., 2008). Dickins (1985) rejected glaciation of this age in Brazil, but Rocha-Campos et al. (2008) placed glacial deposits of the Itararé Group mostly in the Carboniferous based on isotopic age determinations of Late Paleozoic strata that overlie the glacial deposits. These data do not contradict the hypothesis of global warming during the Late Pennsylvanian.

In eastern Australia glacial deposits previously assigned to the Late Carboniferous were demonstrated to be of "middle" Carboniferous or of Early Permian age as in Argentina (Claoué-Long et al., 1995; Dickins, 1996 and communication 1993). Roberts et al. (1995) showed the equivalence of the "middle" Carboniferous glacial rocks of Argentina and Australia, but explained that Late Carboniferous interglacial deposits like those of western Argentina cannot be recognized in eastern Australia because a major hiatus between the Carboniferous and Permian successions (see Fielding et al., 2008a). Pondering relative ages of faunal assemblages involved, Dickins (1996) suggested an extent of as much as 15 Ma to this interval without deposition. In Western Australia, however, a recent interpretation of data suggests that the base of glacial deposits may be of Latest Carboniferous age (Mory et al., 2008).

Wagner (1993) pointed out that during the Late Pennsylvanian there was a significant increase in floral diversity in the Angara province that he assigned to the occurrence of a warm interval. Cleal and Thomas (2005) showed that there was a marked increase in CO_2 level during the Early Kasimovian, assuming that this augment was enough to trigger an interglacial. This warm interval is known as the Alikaevo climatic optimum. This warming reveals the bimodal character of the glaciations and the rapid changes of the temperature. The acknowledgement of the Late Pennsylvanian interglacial thus supersedes the theory of a continuous glaciation stretching from the "middle" Carboniferous to the Early Permian, postulated by Veevers and Powell (1987) and others.

5. Remarks on the interglacial fauna

The Aguanegran fauna is of importance for the proper interpretation of the glacial and no-glacial sequences around the Carboniferous–Permian boundary in western Argentina.

The Late Pennsylvanian warming would have favored free faunal interchange between high latitudes of both hemispheres and transiently restored the North to South route of larval migration along the paleo-Pacific margin of South America (Fig. 5). Based on data previously published (González, 1997; Díaz Saravia and González, 2010), "warm" faunas from the paleotropical region, i.e. western Tethys, were able to

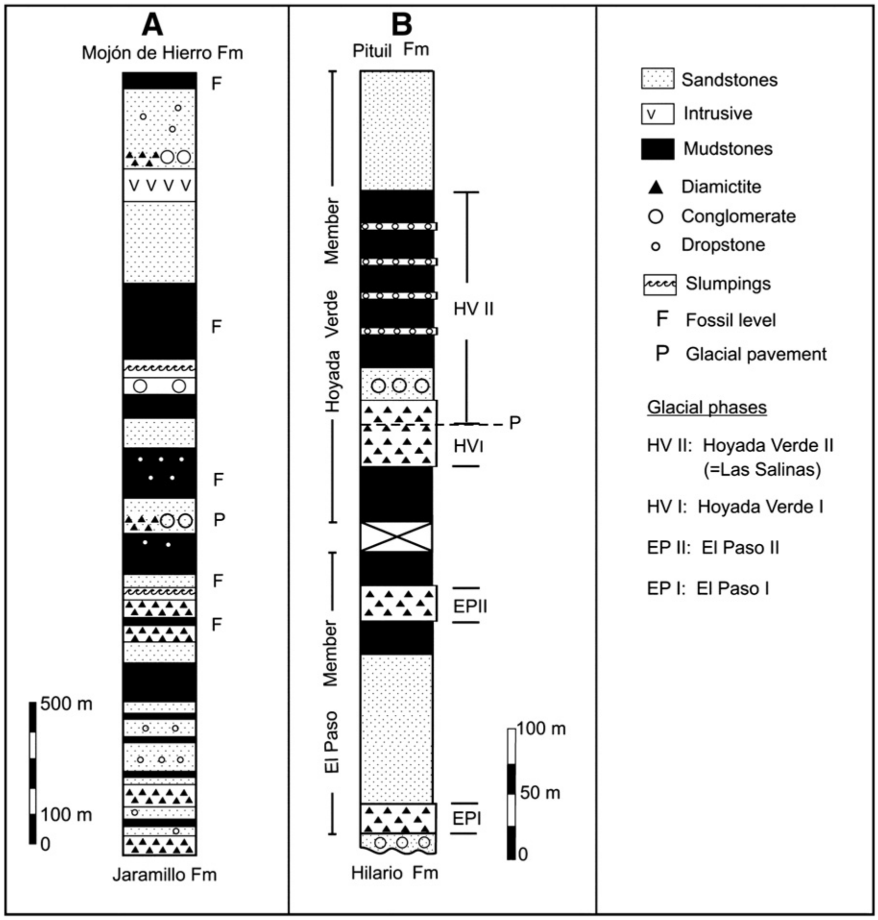

Fig. 6. Simplified columnar sections with glacial deposits in the Languiñeo-Genoa Basin, central Patagonia, and in the southern Uspallata-Iglesia Basin, western Argentina. A: the Pampa de Tepuel Formation (after Suero, 1948) and B: the San Eduardo Formation (after Mésigos, 1953).

penetrate into the inland seas of western Argentina, reaching as far south as the Andacollo region in the north Patagonian border (Fig. 1).

In this paper, faunas of this period are grouped in the Aguanegran faunal stage, which replace the superseded "intermediate fauna" of González (1985). Sabattini et al. (1990) proposed the "*Tivertonia-Streptorhynchus* Zone" to replace the "intermediate fauna", but these authors misinterpreted the original meaning of this term that includes two discrete assemblages, the other being the *Balakhonia-Geniculifera* fauna (Taboada, 1997). *Tivertonia* and *Streptorhynchus* are actually components of the *Kochiproductus-Heteralosia* fauna, the youngest assemblage within the Aguanegran faunal stage (Fig. 4). The main obstacle to more precisely date this fauna is that it cannot be closely compared to other faunas in Gondwana because of lack of records elsewhere, as mentioned above. For example, in Australia there is a hiatus at the Permo-Carboniferous boundary (Roberts et al., 1995; Kelly et al., 2001).

The Late Pennsylvanian age assigned to the Aguanegran faunal stage (González, 1993) is confirmed by the occurrence of *Nothorhacopteris* (NBG) flora (Archangelsky et al., 1987) and palynomorphs (Césari and Gutiérrez, 2000) in the Tupe Formation. However, this is not acknowledged by some authors (Archbold et al., 2004, and others), who instead assign an Asselian age to this fauna arguing that the brachiopods show morphologic characteristics that are ancestral to Sakmarian genera from other Gondwana regions, especially Australia. This reasoning is subjective because these brachiopod genera are not restricted to the Permian as they have also been thought to extend down to the Carboniferous (Dickins, 1963; Waterhouse, 1969). In fact, a similar range extension has also been observed for some bivalve genera associated with the brachiopod fauna (Runnegar, 1972; González, 2002). The Aguanegran fauna has clear Carboniferous affinities, even though the occurrence of precursors of Early Permian genera cannot be excluded, as shown by the mix of Carboniferous and Permian taxa also in the associated plant remains (Azcuy et al., 1987) and palynomorphs (Vergel, 2008).

In the sections of the Pampa de Tepuel Formation exposed at Tepuel Hills (Fig. 3) and its northern equivalent Las Salinas Formation at Languiñeo Hills (González, 1972), both regarded as having been deposited during the Late Pennsylvanian warming interval, with the exception of *Tivertonia*, no other elements of the Aguanegran "warm" fauna have hitherto been found. González (2002) suggested that during this interglacial period central Patagonia may have been located at a higher latitude and sea-water there remained much colder than in western Argentina, thus hampering the penetration of most elements of the "warm-water" Aguanegran fauna from the north into the region. This scenario is supported with the occurrence of abundant precursors of the endemic (Gondwana) fauna in the upper section (LS-9 member) of the Las Salinas Formation. This endemic "cold" fauna, which first appeared during the middle Carboniferous, probably endured the Late Pennsylvanian warming phase and survived in a sanctuary in central Patagonia.

Thus, a North to South faunal migration route might have existed in Argentina (western margin of Gondwana) during the Carboniferous–Early Permian interval, as shown in Fig. 4. On the other hand, in the eastern paleo-Tethys the migratory pathway for the same time period seems to have been from South to North (Fig. 5), as has been suggested in a number of previous studies (e.g., Shi and Grunt, 2000; González and Waterhouse, in press).

6. The Early Permian glacial period

After the Late Pennsylvanian interglacial a lowering of the temperature installed a new glacial period. Different opinions exist regarding the age of the inception of this event: either at the end of the Carboniferous or at the beginning of the Permian, reflecting the ongoing debate over the position of the Carboniferous–Permian boundary for Gondwana. For example, Dickins (1977, 1985) pointed out that this glacial period is exclusive of the Permian and started at the earliest Asselian. However, several closely-related glacial phases of supposedly Late Carboniferous age have been reported in Western Australia (Dickins, 1996), the Paraná Basin of Brazil (Frakes and de Figueiredo, 1967; Gravenor and Rocha-Campos, 1983), and from the Karroo Basin of South Africa (Visser, 1983). In Brazil, the glacial deposits are regarded older (uppermost Carboniferous) at the north of the Paraná Basin than in the south (Petri and Souza, 1993). The lower Dwyka tillites of South Africa (Visser, 1983) and the Sauce Grande tillites of eastern Argentina (Andreis and Torres Ribeiro, 2003) have both been assigned to the latest Carboniferous (see also Rocha-Campos, 1970; Petri and Souza, 1993). However, a Carboniferous age is in discrepancy with the presence in these deposits of the *Eurydesma* fauna and the *Glossopteris* flora, which are assigned to the Sakmarian (Archbold and Dickins, 1989). In the Uspallata-Iglesia Basin of western Argentina (Keidel, 1939) and in the Languiñeo-Genoa Basin of central Patagonia (González, 1981; Cúneo, 1990) deposits of this glacial period are below the *Costatumulus amosi* fauna. In both basins these glacial sediments occur stratigraphically above Late Pennsylvanian interglacial deposits and consist of massive diamictites, pebbly mudstones and mixtites including striated pavements and Glendonite (pseudomorph after ikaite). The *C. amosi* fauna, representing the Uspallatian faunal stage (González, 1993), is assigned to the Asselian extending upwards perhaps to the Tastubian (González, 1981, 1993; Taboada, 2001). For this reason, these glacial deposits are regarded belonging to the oldest (first?) phase of the Early Permian glacial period: the Uspallata glaciation (Fig. 4).

In the southern Uspallata-Iglesia Basin, Late Paleozoic deposits that crop out to the east of Uspallata (Fig. 2) are known as the Jarillal and Tramojo Formations (Keidel, 1939). They are strongly faulted and folded and the contact is not visible, but can be distinguished from each other by their fossil flora and fauna that support their assignment to the Late Pennsylvanian and Early Permian respectively. Twenty kilometers to the NNE of Uspallata, these deposits are known as the Agua del Jagüel Formation. Henry et al (2008) assigned the glacial member of the Agua del Jagüel Formation to the Carboniferous. However, data previously published and recent research by the present authors at the type locality of Agua de Jagüel, allows a different interpretation. The lower member of the Formation is made of marine beds bearing Late Carboniferous invertebrates of the late Aguanegran faunal stage and continental beds with plant remains of the *Rhacopteris* (NBG) flora and paleosoils with *in situ* stems. To the east, these sediments unconformably overlap pre-Carboniferous rocks (Harrington, 1971) and to the west they are followed by the glacial member and siltstones and sandstones bearing the Early Permian *Costatumulus amosi* fauna (Rocha-Campos, 1970; González, 1982), and pollen remains (Césari et al., 2008) of the Uspallatian faunal stage. The contact between these two members is not seen but is probably tectonic (Cortés et al., 1997). Actually, this Formation is the northern continuation of the Jarillal Formation (the lower member) and the Tramojo Formation (the glacial member). Thus, the existence of strata partly equivalent to the Jarillal Formation intercalated in the Agua del Jagüel Formation cannot be ruled out (Lech, 2002). The proper interpretation of the sequences in this area is necessary in order to understand the complicated Late Paleozoic stratigraphy of the Precordillera and the glacial deposits (Fig. 4).

In central Patagonia, the upper member of the Pampa de Tepuel Formation (Suero, 1948) is a glacial phase that consists of diamictites, conglomerates, pebbly mudstones with dropstones up to 1 m diameter and glendonite. These sediments were probably deposited at the littoral zone because they are coeval with marine sediments bearing the Asselian *Costatumulus amosi* fauna. Striated pavements have been observed in two localities (Fig. 7A). This is probably the oldest phase of the Early Permian glacial period. The Pampa de Tepuel Formation is conformably overlain by the Mojón de Hierro Formation. This latter formation includes numerous horizons with the *Costatumulus* fauna, and is made up of nonglacial deposits showing a rapid change to warmer climate in this region (Cúneo, 1990).

In the Sauce Grande Basin of eastern Argentina (Fig. 1) the Sauce Grande Formation consist of nearly 1 km of glacial sediments where Andreis and Torres Ribeiro (2003) identified two different phases, herein named Sauce Grande I and II (Fig. 4). These glacial deposits are covered by marine beds bearing the *Eurydesma* fauna and the *Glossopteris* flora; together they constitute the Bonetian faunal stage (González, 1993). The Sauce Grande tillites are considered representing the last phases of the Early Permian glacial period in Argentina, being probably contemporaneous with those of South Africa, western and southern Australia, Tasmania and India, because all of them underlay the post-glacial transgression bearing the Bonetian fauna and flora. Conversely, in western Argentina and central Patagonia, the phase associated with the *Costatumulus amosi* fauna is older, being probably the oldest of this glacial period; but in these regions the younger Sauce Grande I and II glacial phases bearing the *Eurydesma* fauna are lacking. González (2006) suggested that the different ages of glacial deposits in western and eastern Argentina were probably consequences of two factors: tectonic dominated subsidence and climatic. Tectonic is suggested because subsidence started in the Early Permian in eastern Argentina (Harrington, 1955), whereas in western Argentina and central Patagonia tectonism continued more or less uninterruptedly since the Early Carboniferous (Suero, 1948; Rolleri and Baldis, 1969). The climatic factor also appears evident because of difference in the timing of the final deglaciation, in that in western Argentina it probably started in the middle or late Asselian, coinciding with the appearance of the *Costatumulus* fauna (early Uspallatian), whereas eastern Argentina during this time was moving closer to the polar area and, as a result, the deglaciation occurred later in the early or middle Sakmarian when the *Eurydesma* fauna (Bonetian faunal stage) developed.

Du Toit (1927) proposed the theory of "eccentric ice-capping", an idea that probably inspired the notion of "migration of glacial centers" differently depicted by King (1958), Frakes et al. (1971), and Caputo and Crowell (1985). This theory implies significant shifting of the South Pole, but this suggestion is not consistent with some paleogeographic reconstructions (Golonka and Ford, 2000; Blakey, 2008) (Fig. 5), nor with paleomagnetic results (Valencio, 1973; Archangelski, 1996).

7. Remarks on the Early Permian fauna

During the Early Permian two successive faunal stages can be recognized: the oldest, the Uspallatian, characterized by the *Costatumulus amosi* fauna, which may be regarded "cold" at its lower half because of its association with glacial deposits and endemic taxa, and "warm" at its upper half because of its association with widely distributed taxa and nonglacial sediments. The most complete record of this faunal stage occurs in central Patagonia. The youngest is the Bonetian fauna, involving the lapse of the *Eurydesma* fauna; it is only present in eastern Argentina and some other Early Permian marine deposits of Gondwana. The relationship between these two faunas remains a matter of speculation because they lived at two disconnected regions and do not have elements in common. Notwithstanding this, in terms of time the uppermost segment of the Uspallatian faunal stage possibly overlaps the lower segment of the Bonetian faunal stage in the course of the final deglaciation, perhaps during the Tastubian.

In view of the distribution of Permian brachiopods, Shi and Grunt (2000) proposed antitropicality to explain the biogeographic phenomenon whereby a taxon occurs at high latitudes in both

Fig. 7. A: Glacial striae in sandstone of the upper glacial member of the Pampa de Tepuel Formation, base of the *Costatumulus amosi* Zone. Eastern slope of the Tepuel Hills, Languiñeo-Genoa Basin, central Patagonia. B: Striated (intratill) pavement within diamictites of panel C, lower half of the Pampa de Tepuel Formation. *Levipustula levis* Zone. Western slope of the Tepuel Hills, Languiñeo-Genoa Basin, central Patagonia. C: Side view of upper diamictites in the lower half of the Pampa de Tepuel Formation. *Levipustula levis* Zone. Western slope of the Tepuel Hills, Languiñeo-Genoa Basin, central Patagonia (see panel B). D: Ice-rafted block of sandstone dropped in siltstones above diamictites of Fig. 6. Lower half of the Pampa de Tepuel Formation. *Levipustula levis* Zone. Western slope of the Tepuel Hills, Languiñeo-Genoa Basin, central Patagonia.

hemispheres (Boreal and Gondwana realms) and is lacking in the Paleoequatorial Realm. These authors show that the stratigraphic ranges of antitropical genera of Permian brachiopods overlap during a lapse that started at the late Sakmarian, i.e. during the post-glacial warming that eliminated the climatic barrier that might have previously interrupted the faunal interchange in the earliest Permian glacial period; the same as could also have happened during the Late Pennsylvanian warming. Along the western margin of Gondwana a North to South faunal migration route is here considered to represent a probable migratory mechanism (Fig. 5). On the contrary, in the eastern Paleotethys the faunal migration route appears to have been from South to North (Astafieva, 1987 and Astafieva and Astafieva Urbaytis, 1992, in Shi and Grunt, 2000; González and Waterhouse, in press).

8. Paleogeographic reflections

The "*Eurydesma* sea" flooded the Sauce Grande Basin and the Kalahari–Karroo basins of Namibia and South Africa. Shi and Archbold (1993) argued that this sea was connected with Australia and the Himalayas through South Africa. However, McLachlan and Anderson (1973) showed that the Karroo Basin was closed to the east, a condition that is also endorsed by the rapid decreasing of faunal diversity in that direction (González, 1985). We suggest that the Sauce Grande–Karroo was probably connected with Western Australia by means of a "proto-Atlantic" arm of sea extended between South Africa and the Malvinas (Falkland) Islands (Fig. 5). This "*Eurydesma* sea" was not linked with western Argentina and central Patagonia, as alleged by Frakes and Crowell (1968) and Rocha-Campos (1970), because of the existence of a geographic barrier, the Central Cratogen (Bracaccini, 1960) that closed the Sauce Grande Basin to the west.

In the Brazilian portion of the Paraná Basin, Frakes and de Figueiredo (1967) and Gravenor and Rocha-Campos (1983) reported Early Permian glacial sediments, which are associated with fossils that Rocha-Campos (1970) compared with those of the Bonete Formation of eastern Argentina. Even though these basins are very close, there are no clear-cut evidences of marine connection; these faunas may be contemporaneous but do not have species in common. The ubiquitous *Eurydesma* and other conspicuous elements of the Bonete Formation are not present in the Paraná Basin.

At the end of the Early Permian a generalized uplift in the Andean Orogen closed the communication of basins of western Argentina and central Patagonia with the paleo-Pacific. During the latest Cisuralian a transgression coming from Salar de Navidad of northern Chile (Niemeyer et al., 1997) flooded a small area at the north-western border of Argentina, depositing platform limestones bearing a "warm" fauna with fusulínids, myalinids and other elements. Fossiliferous deposits of this age crop out as patches along the Pacific margin of South America as far as southern Chile. The proximity between this "warm" facies and the "cold" (glacial) facies of the South American Gondwana area was a long-lasting puzzle because these faunas had been erroneously regarded coeval.

9. The bipolarity of glaciations

Glaciations were recurrent in the geologic history, showing that the Earth was from time to time affected by periods of cooling. Climate changes and especially major changes of temperature work at global scale. The Late Paleozoic Ice Age was a phenomenon of planetary causes that probably affected equally the austral and boreal regions. The paleo-arctic region was totally oceanic during the Late Paleozoic so that the presence of ice in this region is only conjectural. However, it is possible that during the Carboniferous and Early Permian glacial periods of Gondwana limited ice, or at least strong cooling, may have also been present in the paleo-Arctic region. In spite of the paucity of evidence, the effect of glaciation in the boreal region can be accredited through information collected from different sources.

Based on the analysis of the distribution of invertebrate faunas all over the world, Waterhouse (1987) concluded that there were two glacial intervals, the first during the Bashkirian and Moscovian and the second during the Asselian–Sakmarian, and that these were separated by a warm interval of Late Pennsylvanian age. Especially significant are variations in the paleotropical and northern temperate floras. Durante (2000), Ganelin and Durante (2002), and Cleal and Thomas (2005), pointed out that sudden changes in the flora of Angaraland at the end of the Viséan was a result of strong cooling that affected this region during the Serpukhovian–Bashkirian. This event is known as the Ostrogsky episode, which coincides with the "middle" Carboniferous glacial period of Gondwana (Fig. 4). In this regard, it is necessary to point out the existence of Carboniferous tillites reported in the Kolyma region, northeast Siberia and possibly in Jilin Province of China (in Waterhouse, 1976, 1987). These deposits would suggest the bipolar nature of the "middle" Carboniferous glaciations. The present authors agree with Ganelin and Durante (2002) in considering that this episode is a global correlation level. Following this glacial interval of apparently bipolar character, atmospheric CO_2 levels had significantly increased according to Cleal and Thomas (2005) during Late Pennsylvanian, coupled with an increase in floral diversity (Wagner, 1993). The global climate during this time has been considered warm and described as the Alikaevo climatic optimum in the Angaraland (Ganelin and Durante, 2002) (Fig. 4).

Glacial deposits of Early Permian age are widespread in Gondwana showing that ice sheets covered a vast continental area. The cooling favored the diversification of the endemic (Gondwana) fauna that appeared during the middle Carboniferous glacial period but had been restricted in distribution (mainly cold waters of high latitudes such as central Patagonia) during the Late Pennsylvanian warming phase. In Angaraland the vegetation showed a marked reduction in diversity, a circumstance that Durante (in Cleal and Thomas, 2005) assigned to the decrease of temperature, which is supported by the presence of Sakmarian tillites in the region of Verchoyan, in northeast Siberia (Waterhouse, 1976). This cooling that affected Angaraland happened during the Early Permian glacial period of Gondwana and may be related to the presence of ice in the Arctic region during this time. Based on recent research, Fielding et al. (2008b) also referred to the possible bipolar nature of Early Permian glaciations.

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