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A paleoclimatic review of southern South America during the late Paleozoic: A record from icehouse to extreme greenhouse conditions

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ABSTRACT

This paper provides a review of the Late Mississippian to Permian paleoclimatic history for southern South America based on lithologic indicators, biostratigraphic information, and chronostratigraphic data. The region is divided into three major types of basins: 1. Eastern intraplate basins (e.g., Paraná Basin), 2. Western retroarc basins (e.g., Paganzo Basin) and 3. Western arc-related basins (e.g., Río Blanco Basin). Four major types of paleoclimatic stages are recognized in these basins: 1. glacial (late Visean–early Bashkirian), 2. terminal glacial (Bashkirian–earliest Cisuralian) 3. postglacial (Cisuralian–early Guadalupian), and 4. semiarid–arid (late Guadalupian–Lopingian). The glacial stage began in the late Visean and continued until the latest Serpukhovian or early Bashkirian in almost all of the basins in southern South America. During the Bashkirian–earliest Cisuralian (terminal glacial stage), glacial deposits disappeared almost completely in the western retroarc basins (e.g., Paganzo Basin) but glaciation persisted in the eastern basins (e.g., Paraná and Sauce Grande Basins). A gradual climatic amelioration (postglacial stage) began to occur during the earliest Permian when glacial deposits completely disappeared across all of South America. During this interval, glacial diamictites were replaced by thick coal beds in the Paraná Basin while north–south climatic belts began to be delineated in the western basins, which were likely controlled by the distribution of mountain belts along the Panthalassan Margin of South America. Towards the late Permian, climatic belts became less evident and semiarid or arid conditions dominated in the southern South America basins. Eolian dunes, playa lake deposits, and mixed eolian–fluvial sequences occur in the Paraná Basin and in the western retroarc basins. Volcanism and volcaniclastic sedimentation dominated along the western margin of South America at that time. The stratigraphic record obtained in southern South America supports a long duration transition from icehouse to extreme greenhouse conditions.

1. Introduction

The complex paleoclimatic history of the late Paleozoic has captured the attention and imagination of geologists since the end of the XIX century when the existence of glacial deposits began to be reported from distant areas of Gondwana (Blanford et al., 1859; Sutherland, 1870; Keidel, 1916; Du Toit, 1921). The Gondwanic glaciation, which represents the longest duration glacial interval recorded during the Phanerozoic (Frakes et al., 1992), lead to the formation of glacial deposits in much of South America, South Africa, India, Antarctica and Australia and in several basins of the Perigondwanic region (López Gamundí et al., 1992; López Gamundí, 1997; Visser, 1997; Isbell et al., 2003a,b, 2008b; Rocha-Campos et al., 2008). The effect of the glacial conditions was not limited to Gondwana, and in fact, glacial and interglacial periods affected sedimentation patterns also in the equatorial region (Veevers and Powell, 1987; Heckel, 1994; Isbell et al., 2003a; Shi and Chen, 2005; Montañez et al., 2007; Rygel et al., 2008).

Although this glacial mega-event took center stage for a long time, the late Paleozoic paleoclimatic evolution was much more complex. As mentioned by Gastaldo et al. (1996) and Isbell et al. (2008a), the late Paleozoic was a unique period in the Earth history in which a long-term transition from icehouse to extreme greenhouse conditions has been preserved on a global-scale. Therefore, the glaciation

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represents only the icehouse end member of the transition, while warmer postglacial climates followed by increasing drier conditions, and ultimately arid climates (the extreme greenhouse end member) completed the series.

Evidence for the shift from glacial to arid climates, or at least strong seasonality, during the middle and late Permian comes from several different sources including: paleoenvironmental (López Gamundí et al., 1992; Limarino et al., 1997; López Gamundí, 1997; Retallack, 2005; Isbell et al., 2008a,b; Gulbranson et al., 2010), paleontological (Gastaldo et al., 1996; Rees et al., 2002; Retallack et al., 2006), and stratigraphic studies (Kidder and Worsley, 2004; Limarino and Spalletti, 2006; Retallack et al., 2006; Holz et al., 2008). Moreover, recent researches on the oxygen and carbon isotopic records during the late Paleozoic also suggest a progressive transition from icehouse to extreme greenhouse conditions from the middle Carboniferous to the late Permian (Hyde et al., 2006; Montañez et al., 2007; Grossman et al., 2008).

Extreme greenhouse conditions, reached towards the end of the Permian, coincided with a massive extinction that devastated not only terrestrial but also marine ecosystems (Erwin et al., 2002; Clapham et al., 2009; Metcalfe and Isozaki, 2009). The latest Permian extinction at ≈252 Ma was the largest biotic catastrophe of the Phanerozoic, resulting in the disappearance of ≈90% of skelenotized marine species and ≈70% of terrestrial vertebrate species, bringing life close to annihilation (Algeo et al., 2011; Chen and Benton, 2012; and references provided therein). The most accepted explanation to this end-Permian biotic crisis includes huge volumes of CO_2 during the eruption of basaltic lava of the Siberian traps, which led to rapid global warming and the short-term production of acid rain devastating land ecosystems. Terrestrial–marine teleconnections contributed to the marine biotic collapse where increased CO_2 concentration, anoxia, euxinia (anoxic and sulfidic conditions), and hypercapnia (CO_2 poisoning), among other potential triggers, were recorded (Algeo et al., 2011; Chen and Benton, 2012). Nevertheless, sanctuary or sanctuaries located in the Gondwanan polar or subpolar regions life to survive the end-Permian mass extinction and contribute to the recovery and restoration of marine Triassic ecosystems (Waterhouse and Shi, 2010).

The aim of this review is to examine and evaluate the icehouse–extreme greenhouse paleoclimatic evolution of the late Paleozoic basins in southern South America in the light of recent stratigraphic information. For these purposes the paleoenvironmental, paleontological, paleogeographical and geochronological information available at present is discussed and placed in a conceptual model of paleoclimatic evolution for the late Mississippian to the end of the Permian.

For this study, we have restricted our observations to South American basins included in the classical late Paleozoic Gondwanic realm located to the South of the Guaporé Craton (presently, south to 12° south latitude, Fig. 1). Patagonia has been excluded due to its imprecise paleogeographic location as it is considered to be an allochthonous terrane (Ramos, 1984, 2008) or a parautochthonous crustal block that collide with South America during the late Carboniferous–early Permian.

2. Paleogeography of the late Paleozoic basins

In terms of stratigraphy, tectonism, and magmatism, the late Paleozoic basins of southern South America can be grouped into two major types: the eastern intraplate basins and those located along the western active margin of Gondwana (Limarino and Spalletti, 2006; Fig. 1). These two types of basins were separated by a large upland area known as the Pampean Arch composed of crystalline late Precambrian and early Paleozoic rocks. The northern portion of the Pampean Arch is divided in two branches. The western branch, named the Puna Arch, separates the Navidad–Arizaro Basin from the Tarija Basin, while the eastern Michicola Arch merges northward with the Guaporé Craton forming the western flank of the Paraná Basin (Fig. 1).

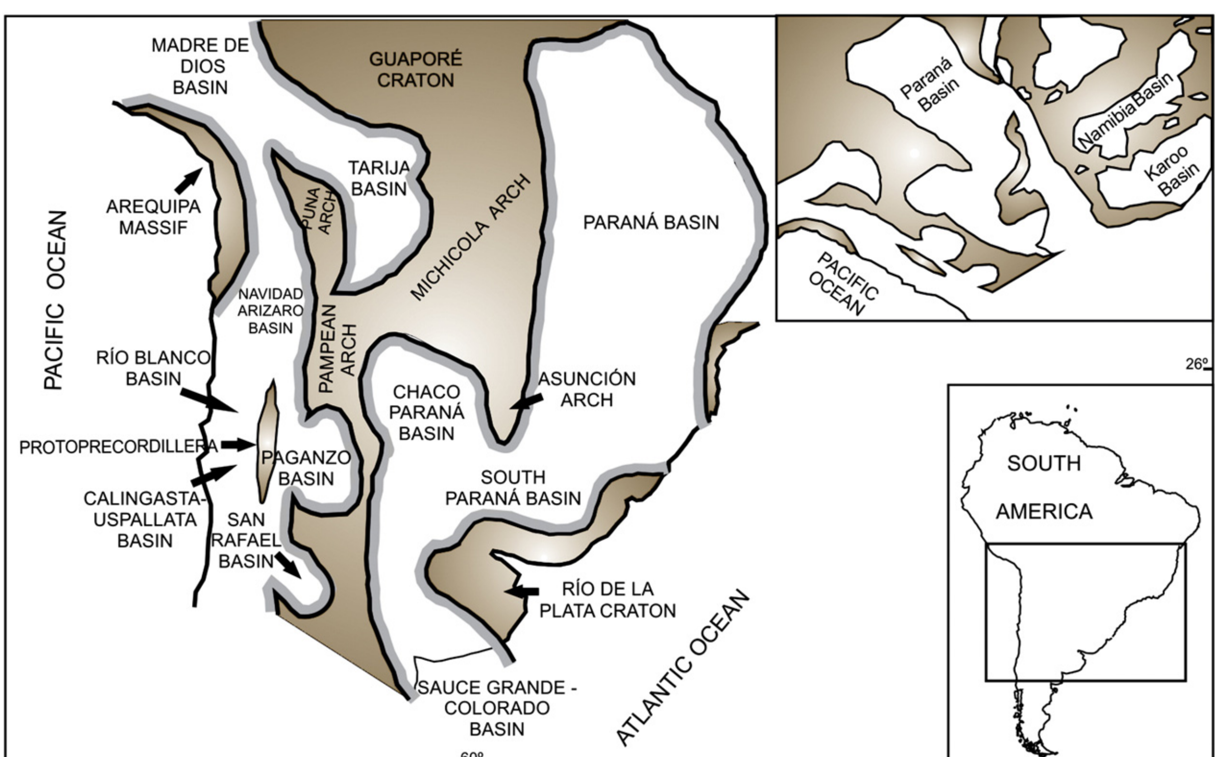

Fig. 1. Paleogeography of the study area. Shaded areas indicate positive regions.

To the west of the Pampean Arch, a discontinuous orogenic belt, known as the Protoprecordillera, was formed by the accretion of Chilenia to South America during the Late Devonian–early Carboniferous. The Protoprecordillera acted as a barrier that separated a large foreland area (Paganzo Basin) from a more tectonically and magmatically active region located in the present day Andean Cordillera (Río Blanco and Calingasta–Uspallata basins). During the latest Carboniferous, the Protoprecordillera began to collapse losing its paleogeographic expression during the latest Carboniferous–earliest Permian (Limarino et al., 2006; Net and Limarino, 2006; Isbell et al., 2012).

The intraplate basins in southern South America comprised of the Paraná, the Chaco–Paraná, and the Sauce Grande–Colorado basins, began to subside during the Early Pennsylvanian. The Paraná Basin is the largest late Paleozoic depositional center in South America encompassing 1,700,000 km^2 (Holz et al., 2000; Fig. 1). To the north, it is separated from the Parecis and the San Franciscana basins by Precambrian crystalline rocks of the Brasiliano and Guaporé Cratons, while the Río de La Plata Craton bounded the basin to the south (Fig. 1). The Chaco–Paraná Basin is located on the southwestern side of the Asunción Arch and essentially occurs as a subsurface basin. The Sauce Grande–Colorado Basin exposes a thick middle Carboniferous to middle Permian succession (up to 2800 m, Fig. 1) that is different from strata in the Paraná and Chaco–Paraná basins. Late Paleozoic strata in the Sauce Grande–Colorado Basin were highly deformed during the late Permian. Magmatic activity was almost absent within the basins in the intraplate region.

The basins located along the southwestern margin of Gondwana are much more complex than the basins in the intraplate region in terms of tectonic deformation, magmatism and variability of subsidence rates. Limarino and Spalletti (2006) divided these basins into two major subtypes; arc-related basins and retroarc basins (Fig. 1). The arc-related basins developed in northwestern and central Chile, western Argentina, Bolivia and Peru (Navidad–Arizaro, Río Blanco, Calingasta–Uspallata, San Rafael and Madre de Dios basins, Fig. 1). These depositional areas suffered high late Paleozoic deformation, extensive magmatism and local metamorphism of Carboniferous sediments (Sempere, 1996; Limarino and Spalletti, 2006).

Unlike the arc-related basins, the retroarc basins (including the Tarija, Paganzo and eastern San Rafael basins, Fig. 1) experienced little deformation during the late Paleozoic, less magmatic activity, and are characterized by a complete lack of metamorphism of the Carboniferous–Permian successions.

3. Stratigraphy of late Paleozoic basins: a synthesis

The Paraná intraplate basin began to subside during the Pennsylvanian when glacial diamictites and transgressive marine shales were being deposited throughout the basin (Bigarella et al., 1967). These rocks are included in the Itararé Subgroup in Brazil and in the San Gregorio Formation in Uruguay (Bigarella et al., 1967; de Santa Ana, 1993; Vesely and Assine, 2006; Rocha-Campos et al., 2008; Fig. 2). Diamictitic levels are also found in the lower half of the Ordóñez Formation (Chaco–Paraná Basin, Winn and Steinmetz, 1998) and in the Sauce Grande Formation (Sauce Grande–Colorado Basin, Andreis and Japas, 1996, Figs. 1 and 2) in Argentina.

Glacial conditions disappeared during the early Permian as diamictitic deposits were progressively replaced by fluvial–estuarine sediments including coal beds (Rio Bonito and Palermo Formations, Holz et al., 2002). In the Sauce Grande–Colorado Basin, the Piedra Azul and Bonete formations (Cisuralian age, Fig. 2) are dominated by shallow marine sandstones and mudstones bearing remains of *Glossopteris* flora and invertebrates of the *Eurydesma* fauna (Archangelsky et al., 1996).

The major part of the middle and early late Permian in the intraplate basins is recorded in the Passa Dois Group (Fig. 2) which includes several transgressive–regressive cycles deposited under a progressive change to semiarid conditions (Rohn, 1994). In Uruguay (south of the Paraná Basin), the middle–early Permian is represented by shallow marine and fluvial sediments belonging to the Yaguarí Formation, while in the Sauce Grande–Colorado Basin, the Tunas Formation (late Cisuralian–Guadalupian?, Fig. 2) shows a similar facies pattern.

Late Permian units (Lopingian–earliest Triassic) occur in the intraplate area in the Pirambóia and Sanga do Cabral formations (Brazilian Paraná Basin, Fig. 2), which correlate with the upper Member of the Yaguarí and Bella Vista formations in Uruguay.

Different from the intraplate basins, the retroarc basins show a complete Mississippian stratigraphic record. The Peruvian Madre de Dios Basin and the Titicaca Basin in Bolivia contained well-exposed early Carboniferous shales and sandstones in the Ambo Group (Grader et al., 2008; Fig. 2), which correlates southwards (Altiplano of Bolivia) with strata in the Cumaná, Kasa and Siripaca formations (Suárez Soruco, 1989; Grader et al., 2008).

Early Carboniferous rocks also occur in the northern portion of the Tarija Basin in the Itacua and Saipurú formations, which are composed of sandstones, shales, mudstones and some diamictites (Fig. 2). Similar deposits, also appear in northern and central Chile (Upper Member of the Zorritas, Arrayán and Chinches formations, among others) and in the Calingasta–Uspallata and Río Blanco basins from Argentina (Fig. 2). The Angualasto Group in the Río Blanco Basin contains one of the most complete Mississippian records (Limarino and Césari, 1993) that includes glacial diamictites at the top of the Visean Cortaderas Formation (Fig. 2); the Loma de Los Piojos Formation, in the Paganzo Basin, is laterally equivalent of the Cortaderas Formation (Fig. 2).

During the Pennsylvanian, glacial diamictites were deposited in the Tarija (Machareti and Mandiyutí Groups), Paganzo (Agua Colorada, Guandacol and Malanzán formations), Calingasta–Uspallata (Hoyada Verde Formation) and San Rafael (El Imperial Formation) basins. These diamictites are abruptly overlain by transgressive postglacial shales that form a key stratigraphic marker horizon for regional correlations known as the “Namurian postglacial transgression” (Limarino and Spalletti, 2006). These transgressive facies were succeeded by deltaic and fluvial sequences bearing fossils of the *Nothorhacopteris–Botrychiopsis–Ginkgophyllum* (NBG) flora contained within coal beds of the Tupe Formation (Pennsylvanian, Gulbranson et al., 2010). Recent high-precision U–Pb ages obtained by Gulbranson et al. (2010) have identified a late Bashkirian age for the formation of extensive coal beds in the Paganzo and Río Blanco basins.

The latest Carboniferous and early Permian in the Paganzo Basin is characterized by widespread red-bed successions (Patquía Formation) including fluvial sandstones and conglomerates in the Lower Member, and ephemeral river, playa lake, and eolian deposits in the Upper Member (Limarino and Spalletti, 1986; Spalletti et al., 2010). These rocks are succeeded by fluvial conglomerates and sandstones belonging to the Talampaya Formation deposited during the latest Permian and probably the earliest Triassic. To the west, Pennsylvanian–early Permian rocks appear in transitional and shallow marine siliciclastic facies (Tres Saltos, Esquina Gris and Las Pircas formations) in the Río Blanco and Calingasta–Uspallata basins.

In the Andean Cordillera, the existence of Mississippian rocks has not yet been reported. However, it is likely that part of the turbiditic succession described in the Andes were early Carboniferous in age. During the Pennsylvanian, sedimentation in the Andean region was dominantly marine and is represented by the Cerro Agua Negra Formation (Fig. 2). This unit, up to 1500 m thick, is made up of mudstones, shales, sandstones and scarce diamictites that were deposited in transitional, nearshore and offshore environments. Calcic vertisols showing prismatic structure, frequently found in “salt-affected” paleosols of coastal areas, were recently recognized in the unit.

At the beginning of the Permian, siliciclastic sedimentation was progressively replaced by carbonate deposition in shallow marine and coastal lagoonal environments (Huentelauquén and San Ignacio formations, Fig. 2).

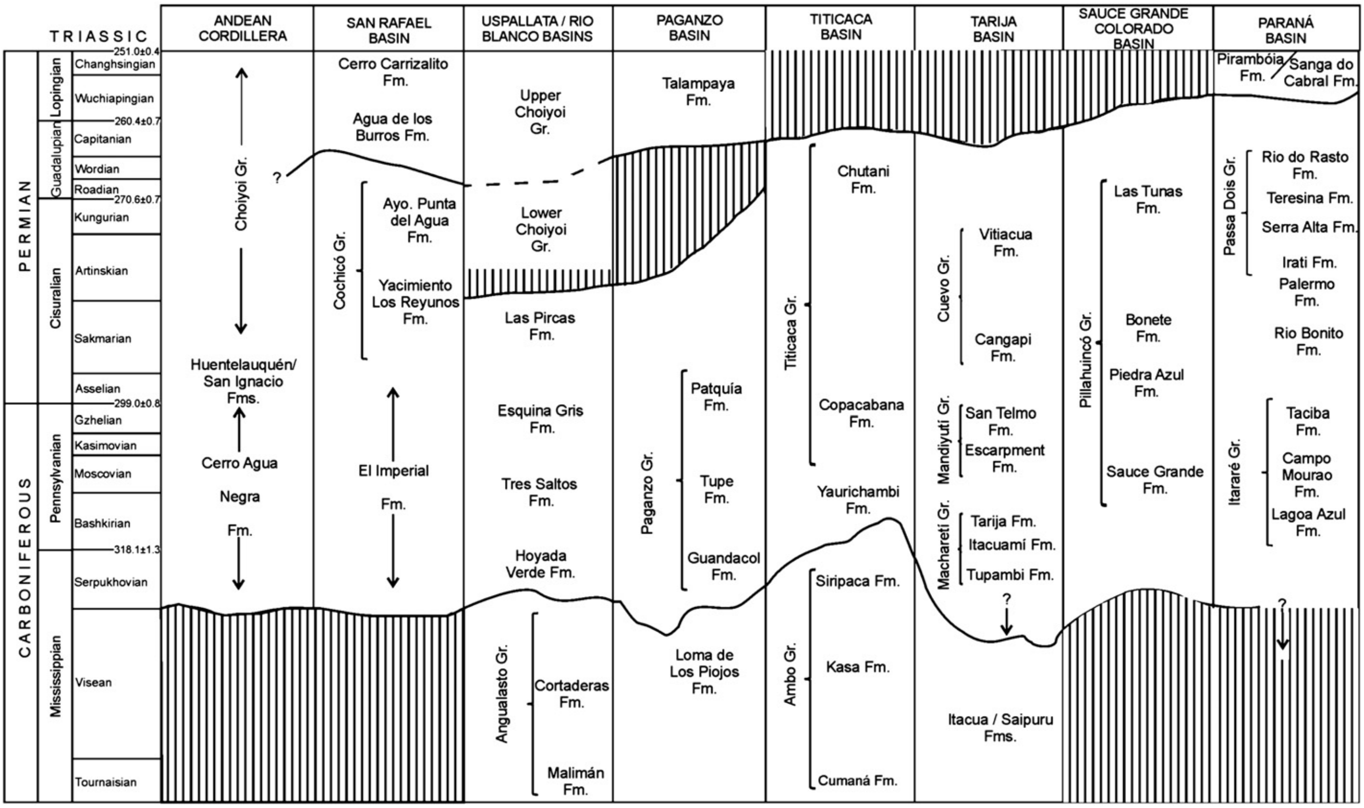

Fig. 2. Stratigraphy of the major late Paleozoic basins in southern South America.

Pennsylvanian rocks in the northern arc-related basins occur in the Tarma Group (southern Peru), in the Yaurichambi Formation (Altiplano of Bolivia) and in the lower Copacabana Formation, all of which consist of shallow marine and fluvial sandstones, mudstones, marls, and limestones (Fig. 2). Similar successions occur in northern Chile in the Cerro Oscuro, Arizaro and Cerro de Cuevitas formations.

From the middle Cisuralian, volcanic activity was dominant in the present day Cordillera de Los Andes of Chile and Argentina whereby volcanic and volcaniclastic rocks covered the major part of the arc-related basins. Siliciclastic and carbonate sedimentation was almost entirely replaced by very thick successions (up to 5000 m) of lava flows, volcanic breccias, ignimbrites, and tuffs belonging to the Choiyoi and Cochicó Groups. This volcanism also occurred in Bolivia (Chutani Formation) and Peru (lower Mitú Group).

4. Late Paleozoic paleoclimates deduced from the stratigraphic record

The late Paleozoic stratigraphic record contained in the South American basins is a tremendous source of stratigraphic, paleontologic and radiometric information that can be used to better determine and understand the paleoclimatic evolution during the Carboniferous and Permian. Two primary concerns for addressing this issue are: 1. the studied time interval, and 2. the paleogeographic region that will be considered. In this paper, we focus on the late Visean–Lopingian interval, which corresponds to the time span considered by Gastaldo et al. (1996) for the transition from icehouse to greenhouse conditions.

Although glacial events were also identified in the latest Devonian–earliest Tournaissian (Díaz-Martínez et al., 1993; Grader et al., 2008; Isaacson et al., 2008), the record of the Tournaissian and early Visean is not sufficient to develop a minimally convincing scheme about the climatic history during that interval. Moreover, the age of some glacigenic units considered to be Mississippian in Bolivia were recently re-identified as Late Devonian (Isaacson et al., 2008; Wicander et al., 2011).

With the current state of knowledge, we have identified four major paleoclimatic stages that can be deduced from the stratigraphic record: 1) Glacial (late Visean–early Bashkirian), 2) terminal glacial (Bashkirian–earliest Cisuralian), 3) Postglacial (Cisuralian–early Guadalupian), and 4) semiarid–arid (late Guadalupian–Lopingian, Fig. 3). We use the term stage for a time interval characterized by climatic conditions that, although changeable according to the paleogeographic position of the basins, can be tracked at a continental-scale. The stratigraphy of each of these intervals will be discussed paying particular attention to lithologic indicators, facies associations, the fossil records, and available radiometric ages.

5. The glacial stage (late Visean–early Bashkirian)

Gondwanic glaciation was initially considered to have occurred over a long and uninterrupted interval of time encompassing a major part of the Carboniferous and early Permian (Frakes et al., 1992). However, later studies in South American basins by López Gamundí et al. (1992), López Gamundí and Breitkreuz (1997), Díaz-Martínez et al. (1993), Iannuzzi and Pfefferkorn (2002), Isbell et al. (2003a,b), Caputo et al. (2008), Pérez Loinaze et al. (2010) and Gulbranson et al. (2010), among several others, showed that the glacial episode only spanned more shorter specific time intervals during the Carboniferous. Gulbranson et al. (2010) provide new U–Pb ages demonstrating that glacial episodes were of short duration and they established, for the first time, a precise timing of glacial deposition in the western basins of South America.

Isbell et al. (2003a,b) recognized, during the Gondwanic glaciation, three different glacial periods separated by inter- or non-glacial times. The oldest glacial event, latest Devonian–earliest Carboniferous, was recognized in South American basins of Bolivia and Brazil (Caputo, 1985; Díaz-Martínez et al., 1993; Isaacson et al., 1999; Grader et al.,

Paleoclimatic stage	Stratigraphy West: Andean basins	Western retroarc basins	Eastern intraplate basins East	Age
Semiarid-arid	Eolian, playa lake and ephemeral fluvial red-beds (Talampaya and La Veteada Fms.).	Eolian, playa lake and ephemeral fluvial red-beds (Talampaya and La Veteada Fms.).	Eolian sandstones (Pirambóia and Sanga do Cabral Fms.), fine-grained playa lake and ephemeral fluvial succesions (Morro Pelado Mb., upper Buena Vista Fm.).	middle Guadalupian-Lopingian
Postglacial	Shallow marine and fluvio-deltaic sedimentation. First thick succession of limestones and restricted volcanism in some localities (Huentelauquen, San Ignacio, Arizaro and Copacabana Fms.).	Fluvial sedimentation replaced by eolian successions including dune, interdune and extradune deposits. Playa lake and ephemeral fluvial deposits predominate in some localities (upper Paganzo Group).	Conglomerates, sandstones, mudstones and coal beds deposited in fluvial and paralic environments (Rio Bonito, Irati and Tres Islas Fms.). Locally dolomite-bituminous shales rhythmites (Passa Dois Group).	Cisuralian-early Guadalupian
Terminal glacial	Postglacial marine transgressions and thin coal beds in shallow marine and estuarine settings (upper Río del Peñon, upper Agua de Jagüel, Tres Saltos and Cerro Agua Negra Fms.).	Postglacial marine transgressions followed by fluvial sedimentation. Coal measures deposited in alluvial plains and estuarine environments (lower Paganzo Group).	Till deposits, reworked diamictites, striated pavements, and shales with dropstones. Several regressive-transgressive cycles (Itararé Group).	Bashkirian-earliest Cisuralian
Glacial	Proximal glaciomarine diamictites and shales with dropstones (upper Cortaderas, lower Hoyada Verde, lower Agua de Jagüel and lower Río del Peñón Fms.).	Two glacial intervals, the lower represented by proximal glaciomarine diamictites (Loma de Los Piojos Fm.), the upper by terrestrial diamictites filling paleovalleys and fjords (lowermost Paganzo Group).	Lodgement till deposits, striated pavements, reworked diamictites, and shales with dropstones in transgressive facies (Jandiatuba, Faro and Poti Fms.).	late Visean-early Bashkirian

Fig. 3. Stratigraphy and age of the paleoclimatic stages defined in this paper.

2008; Isaacson et al., 2008). In Bolivia, glacimarine sequences were described by Díaz-Martínez and Isaacson (1994) in the Fammenian Cumaná Formation while in the Brazilian Solimoes, Parnaiba and Amazonas basins, glacial deposits of Tournassian age were reported by Caputo (1985) and Caputo et al. (2008).

The latest Devonian–earliest Carboniferous glaciation is not included within the icehouse–extreme greenhouse megacycle since, in places, the Devonian glacigenic record is separated from Mississippian diamictites that mark the onset of widespread Gondwana glaciation by a thousand meters of strata. Moreover, at least at present, there is not enough evidence for supporting global-scale ice-house conditions during the Late Devonian–earliest Carboniferous.

The beginning of the icehouse interval is here referred to the late Visean when vast areas of Gondwana experienced glacial climates (Fig. 4). The late Visean–early Bashkirian was considered the "Ice-Age" by González (1997) and corresponds to the second glacial event proposed by Isbell et al. (2003a) in Gondwana. However, glaciation on other crustal blocks may have waxed and waned diachronously and out of phase across Gondwana during the late Paleozoic (Fielding et al., 2008b; Isbell et al., 2012).

5.1. Stratigraphy

Records of Visean glacial diamictites occur in the Solimoes (Jandiatuba Formation), Amazonas (Faro Formation) and Parnaíba (Poti Formation) basins in Brazil, as well as in the Río Blanco (Cortaderas Formation) and Paganzo (Loma de Los Piojos Formation) basins in Argentina (Caputo, 1985; Limarino and Césari, 1993; Caputo et al., 2008; Pérez Loinaze et al., 2010). Though neither fossil remains nor radiometric ages allow confirming that the Paraná Basin was glaciated during the Serpukhovian (or late Visean?), stratigraphic models suggest this possibility (Rocha-Campos et al., 2008).

Diamictites of probable glacial origin were also reported from the top of the Ambo Group (southeastern Peru) and the Kasa Formation in the Altiplano of Bolivia, but the precise age and origin of these deposits need to be confirmed (Díaz-Martínez and Isaacson, 1994; Isaacson et al., 2008).

The stratigraphic record of the icehouse stage includes striated pavements (e.g., Bigarella et al., 1967; Rocha-Campos et al., 1969, 1994; López Gamundí and Martínez, 2000, Fig. 5a), striated-boulder pavements (e.g., González, 1981; Trosdtorf et al., 2005a, Fig. 5b, c), iceberg keel marks and iceberg dump structures (e.g., Vesely and Assine, 2002; Henry et al., 2010), massive diamictites interpreted as tillites (e.g., Amos and López Gamundí, 1991; Marenssi et al., 2005), abundant striated and faceted clasts (e.g., Limarino and Gutiérrez, 1990), varve-like (rhythmites) successions (e.g., dos Santos et al., 1996; Buatois et al., 2006; Netto et al., 2009), dropstones in lacustrine and marine transgressive facies (e.g., Limarino and Césari, 1988; Caputo et al., 2008, Fig. 5d), morainal bank deposits (e.g., Marenssi et al., 2005; Figs. 5e and 4f) and glaciotectonic deformation (e.g., Rocha-Campos et al., 2000; Holz et al., 2008).

Three major scenarios are recognized during the icehouse stage in southern South America (Fig. 3). The first one includes the oldest glacial deposits identified in the Paraná basin (possibly Serpukhovian–Bashkirian) where thin levels of lodgment till deposits have been sporadically identified (Trosdtorf et al., 2005b; Rocha-Campos et al., 2008). A second scenario corresponds to glacial-related terrestrial diamictites (up to 80 m thick) that appear mainly confined to paleovalleys and in fjord-like environments. These types of deposits occur in the retroarc Paganzo and San Rafael basins, (Limarino and Gutiérrez, 1990; López Gamundí and Martínez, 2000; Kneller et al., 2004; Marenssi et al., 2005; Henry et al., 2008, Fig. 3). Kneller et al. (2004) and Dykstra et al. (2006) described coarse-grained fjord sequences in the Precordillera (La Laja Formation, Paganzo Basin), which correspond to the Serpukhovian deglaciation in the Paganzo Basin. On the other hand, morainal bank accumulations, linked to flooded glacial paleovalleys, were studied by Marenssi et al. (2005) who described bank-front, bank-core and bank-back facies at the base of the Guandacol Formation. The bank front deposits comprise coarse-grained resedimented diamictites grading laterally into prograding clinoforms composed of interbedded, matrix-supported, thinly-bedded diamictites and mudstones. The bank-core accumulations are composed of stacked coarse-grained diamictites showing five major erosional surfaces suggesting advances and retreats of a glacial front (Fig. 5e). Finally, bank-back successions are consist of striated lodgment till deposits and resedimented coarse-grained diamictites exhibiting synsedimentary deformation.

A third type of glacial-related diamictites, dominated by glacimarine deposits, is exposed in the Calingasta–Uspallata and Río Blanco basins (Figs. 1 and 4). The Hoyada Verde Formation is a good example of proximal glacimarine successions (López Gamundí, 1987, 1991) that includes thick massive diamictites, striated boulder pavements (grounded ice

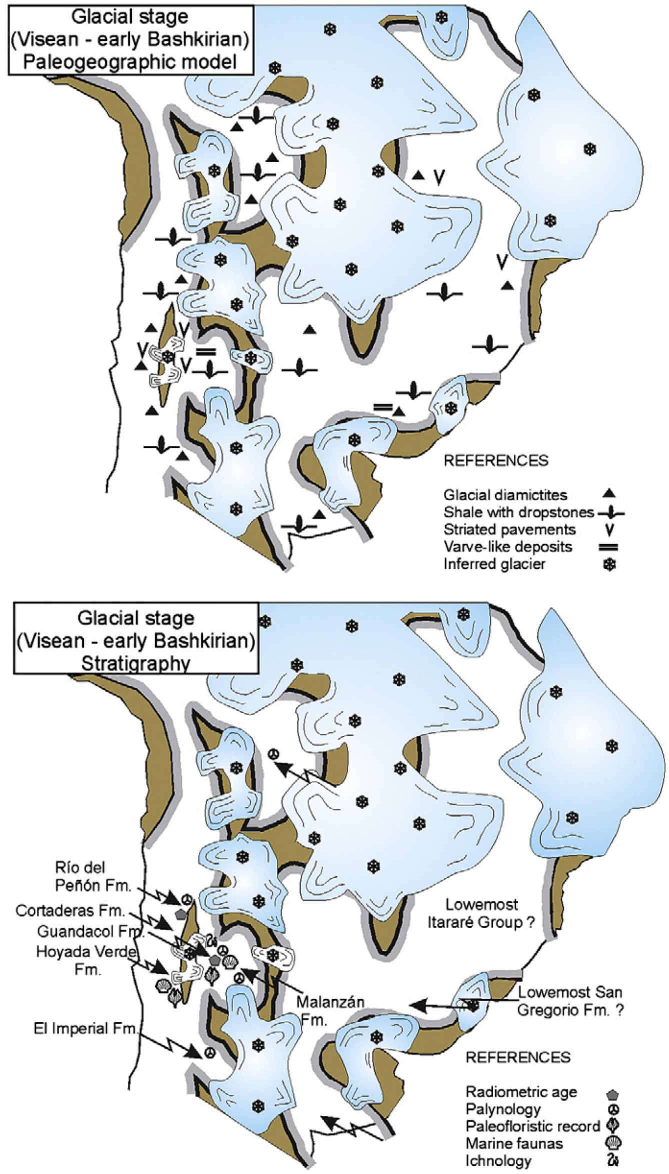

Fig. 4. Paleogeographic model, lithological indicators and stratigraphy of the glacial stage (Visean–early Bashkirian).

advance), thin-bedded resedimented diamictites (interpreted as subaqueous debris flows) and shales with dropstones. Similar deposits were recently described in the Agua de Jagüel Formation by Henry et al. (2010) who recognized four depositional stages: 1. morainal bank deposition by a wet-based tidewater glacier, 2. glacial retreat succession in a fjord setting, 3. continued glacial retreat with ice receding onto land and 4. postglacial transgression across the shoreface without iceberg deposition.

Late Visean glacimarine deposits appear at the top of the Cortaderas Formation (Pérez Loinaze et al., 2010) which is composed of shales with dropstones and several different types of resedimented diamictites (Fig. 2). The predominance of fine-grained sediments bearing dropstones, blanket-like horizons of rain-out diamictite facies and gravity flow deposits suggest an intermediate to distal glacimarine depositional setting.

5.2. Fossil assemblages

5.2.1. Flora

The stratigraphy of the glacial stage is poorly known. However, new data have provided insight into solving this problem. The glacial successions in the Paganzo and Río Blanco basins have been found to be composed of the deposits from two glacial events separated by an interglacial period (Fig. 6). The older glacial interval that occurs in the Upper Member of Cortaderas Formation have been found to contain palynological assemblages belonging to the *Reticulatisporites magnidictyus–Verrucosisporites quasigobbettii* Interval Biozone, which suggest a late Visean age (Pérez Loinaze et al., 2010; Césari et al., 2011). A remarkable feature of these Visean assemblages is the lack of pollen grains. These palynofloras are coeval with the assemblages from the Ambo Group in Peru (Azcuy and di Pasquo, 2005) and the Faro and Poti formations in the Amazon Basin in Brazil (Melo and Loboziak, 2003). Glacigenic deposits in the Itacua Formation from the Tarija Basin contain rich palynological assemblages referred by Di Pasquo (2007) to the early Visean. Moreover, Fasolo et al. (2006) described a late Visean–early Serpukhovian microflora from the Kasa Formation of Bolivia.

The glacimarine deposits of the Cortaderas Formation are sharply covered by yellowish and gray medium- to coarse-grained sandstones (up to 100 m. thick) probably deposited in deltaic or fluvial environments (interglacial interval, Fig. 6). In the Paganzo area these rocks yield plant remains (Balseiro et al., 2009) included in the *Frenguellia eximia–Nothorhacopteris kellaybelenensis–Cordaicarpus cesarii* Biozone, which are considered to be early Serpukhovian in age (Loma de Los Piojos Formation). According to Balseiro et al. (2009), this flora suggests the presence of the Paraca Floral Realm in Argentina, which indicates the occurrence of warm temperate conditions rather than glacial climates. Therefore, an interglacial period existed in the western basins near the Visean–Serpukhovian boundary. A similar situation was postulated by Grader et al. (2007) in the Siripaca Formation from the Titicaca Basin of Bolivia. The Paracas floral belt was defined by Iannuzzi and Pfefferkorn (2002), including macrofloras from Peru (Ambo Group), Bolivia (Kaka and Siripaca formations) and Brazil (Poti Formation), to be characterized by pteridosperm foliage and arborescent lycopsids of late Visean to earliest Serpukhovian age.

In the Paganzo Basin, Visean glacial deposits (Cortaderas Formation) and interglacial sandstones (Loma de Los Piojos Formation) were deeply eroded and incised into, thus forming the bottom and the walls of paleovalleys before the deposition of glacial diamictites of the Guandacol Formation (second glacial interval, Fig. 6). These diamictites are intercalated with shales and mudstones containing scarce plant remains of the Bashkirian NBG flora (Gutiérrez et al., 1994). Interglacial deposits also preserve permineralized logs (Brea and Césari, 1995; Césari et al., 2005; Pujana, 2005; Pujana and Césari, 2008) with growth ring characteristics that are consistent with a seasonally cool climate. Moreover, palynological assemblages recovered from shales show abundant pollen grains and spores belonging to the Subzone A of the *Raistrickia densa–Convolutispora muriornata* Biozone (Serpukhovian–early Bashkirian = early Namurian; Césari and Gutiérrez, 2001; Pérez Loinaze et al., 2010; Césari et al., 2011). Some palynofloras from Brazil included in the *Ahrensisporites cristatus* Interval Zone of the most basal Itararé Group, could be considered coeval to Subzone A of western Argentina (Césari et al., 2011). Like in Argentina, Brazilian macrofloras from this interval are distinguished by the species *Nothorhacopteris argentinica* and *Botrychiopsis weissiana*, and the absence of glossopterids remains (Holz et al., 2010).

5.2.2. Fauna

The Barrealian fauna (González, 1993) groups two faunal assemblages, the *Rugosochonetes–Bulahdelia* and *Levipustula* faunas, which are associated closely with the middle-Carboniferous glaciomarine deposits of western Argentina. The oldest (late Visean–earliest Serpukhovian) *Rugosochonetes–Bulahdelia* fauna (Taboada, 1989, 2010) is only known from the El Paso Formation, while the slightly younger (early-latest Serphukovian) *Levipustula levis* fauna was recognized in several units of the Calingasta–Uspallata Basin (Amos et al., 1963). The appearance

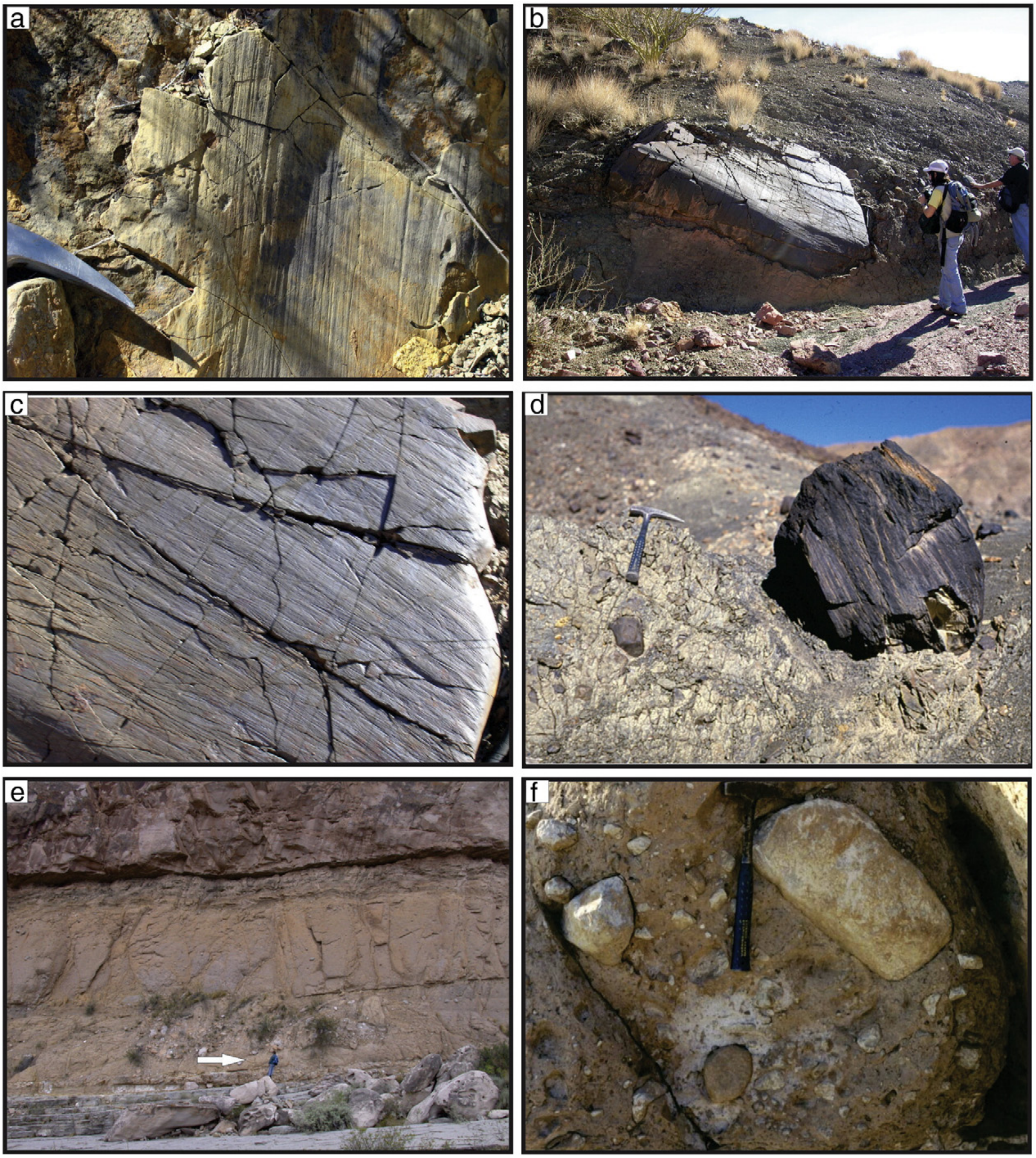

Fig. 5. a: Striated pavement carved on the Talacasto Formation (Devonian) and covered by glacial diamictites of the Guandacol Formation, b: Large striated and faceted clast forming part of a striated boulder pavement in the Hoyada Verde Formation, c: detail of b showing several features of glacial erosion, d: large clasts in glacimarine diamictites of the Cortaderas Formation, e: Several levels of diamictites forming morainal bank deposits at the base of the Guandacol Formation, f: massive diamictites in morainal bank deposits of the Guandacol Formation.

of the Barrealian fauna was linked to the onset of the middle-Carboniferous glacial episode, as a result of a global cooling and profound differentiation between marine biota of circum-polar and paleoequatorial regions since late Visean time. The Barrealian fauna lived in inland seas such as semi-restricted embayments or fjord-like settings (Zöllner, 1950) connected to the Panthalassic Ocean trough straits or sounds (González, 1989). The Barrealian fauna includes some endemic elements but also shares common genera and species with coeval faunas from the Tarija Basin (Bolivia), Antarctic Peninsula and eastern Australia, which collectively appear to typify early Late Carboniferous faunas, when glacial conditions prevailed in both western and eastern Gondwana.

5.3. Chronostratigraphy

A radiometric age obtained from andesitic lava flows underlying the diamictitic succession in the eastern Río Blanco Basin provides a $^{206}Pb/^{238}U$ age of 335.99 ± 0.06 Ma (Gulbranson et al., 2010) suggesting that the onset of the glacial stage was not older than middle Visean. This is congruent with the palynology of the glacial interval of

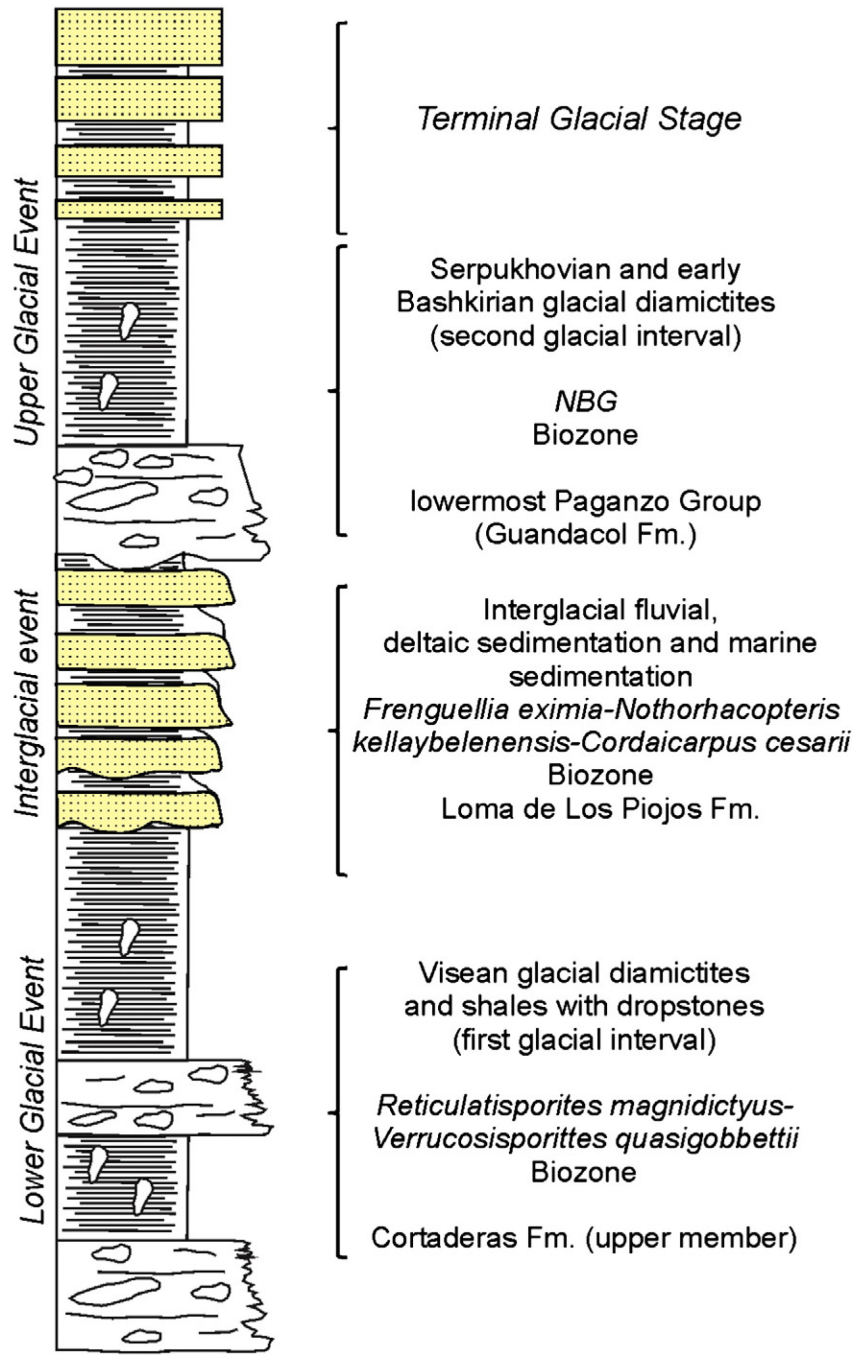

Fig. 6. Schematic representation of the glacial stage in the Paganzo and Río Blanco Basins. Note that an interglacial interval separates two glacial episodes (the lower Visean strata and the upper Serpukhovian or early Bashkirian strata).

the Cortaderas Formation discussed above (first glacial interval). Moreover, this is in agreement with the age of glacial diamictites identified in the Solimoes, Amazon and Parnaiba Basins of Brazil, which Caputo et al. (2008) considered to be middle–late Visean in age.

6. The terminal glacial stage (Bashkirian–earliest Cisuralian)

While glacial conditions seem to have persisted in the eastern basins of South America (Paraná Basin), glacial deposits disappeared during the early Bashkirian throughout the western retroarc and arc-related basins (Fig. 7).

6.1. Stratigraphy

A major portion of the glacial rocks in the Paraná Basin are considered to be Late Mississippian, but some authors extend the glaciation up to the early Permian, which is under debate (Souza and Marques-Toigo, 2005; Guerra-Sommer et al., 2008a,b; Rocha-Campos et al., 2008; Fig. 2). Glacial deposits encompassing much of the Paraná Basin are included in the Itararé Group, which is up to 1500 m thick and contains several glacial and interglacial deposits (Vesely and Assine, 2006; Rocha-Campos et al., 2008). Along the northwestern margin of the Paraná Basin, thick sand-rich glacial deposits are included in the Aquidauana

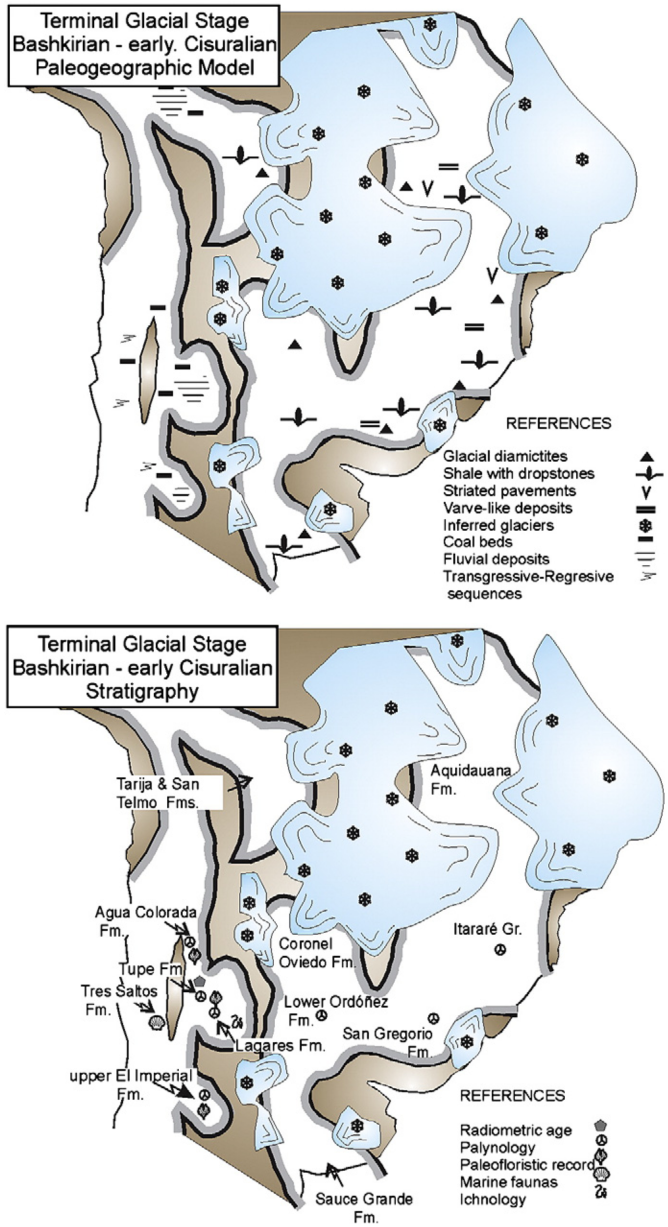

Fig. 7. Paleogeographic model, lithological indicators and stratigraphy of the terminal glacial stage (Bashkirian–earliest Cisuralian).

Formation that is as much as 500 m in thickness. These strata are correlative to strata of the Itararé Group (Figs. 2 and 7).

The lower part of the Itararé Group (Lagoa Azul Formation) is composed of mainly sandy sequences at the base and glacial diamictites at the top separated by subaqueous (marine?) shales and mudstones (Tarabaí Member, Vesely, 2007). Fine grained rocks of the middle part of the Lagoa Azul Formation were correlated with "Westphalian" mudstones of the Campo do Tenente Formation, which crop out in the southeastern part of Paraná State (França et al., 1996; Vesely, 2007). Campo do Tenente shales have yielded palynological assemblages of "Westphalian" age indicating that sedimentation of the Lagoa Azul Formation would have begun during the Early Pennsylvanian (or Late Mississippian, Souza et al., 2003; Souza and Marques-Toigo, 2005; Rocha-Campos et al., 2008). On the other hand, the top of the Itararé Group (Taciba Formation) contains the youngest glacial horizons in the basin. These strata are overlain by postglacial marine transgressive deposits bearing some remains of "*Eurydesma* fauna" (Rocha-Campos and Rösler, 1978). The age of the Taciba Formation is controversial, but according to radiometric ages would not be younger than the earliest Asselian (Guerra-Sommer et al., 2008a,b).

A distinctive feature of the glacial deposits of the Itararé Group is the existence or rhythmites at different stratigraphic levels (Rocha-Campos et al., 1981; dos Santos et al., 1996; Rocha-Campos, 2002; Netto et al., 2009). Dos Santos et al. (1996) distinguished "regular rhythmites", similar to Pleistocene varves, from "irregular rhythmites" resulting from turbidites and cyclopels. In some cases, regular rhythmites bear dropstones, like those of the Itú quarry, and the likelihood that they are varves has been highlighted in several papers (Rocha-Campos et al., 1981, 2008; Netto et al., 2009).

Pennsylvanian (and earliest Permian?) glacial deposits have been reported from the portion of the Paraná Basin that extends into Paraguay (Figs. 1 and 7). There, the Coronel Oviedo and Aquidabán formations (Pennsylvanian) are correlated with the Itararé Group. Both of these units include diamictites that contain faceted and striated clasts, shales with dropstones, and rhythmites (Fúlfaro, 1996). In Uruguay, the San Gregorio and Cerro Pelado formations are composed of diamictites and rhythmites of glacial origin interstratified with transgressive shales and fine-grained sandstones (Falconer, 1937; de Santa Ana et al., 2006, Fig. 6). According to de Santa Ana et al. (2006), the glacial sequence can be divided into two major facies associations: a terrestrial association dominated by glacial, glacifluvial and glacilacustrine deposits, and a glacimarine association composed of shales, fine-grained sandstones, and thin intercalations of fine-grained diamictites. The age of the glacial event, as identified from palynological studies, is latest Carboniferous–early Permian (de Santa Ana et al., 2006; Beri et al., 2010). However, unfossiliferous diamictites at the bottom of the San Gregorio Formation may represent the Bashkirian–Moscovian glacial episode (Limarino and Spalletti, 2006).

The late Paleozoic succession in the subsurface of the Chaco–Paraná Basin contains diamictites that are interstratified with shales, organic-rich mudstones, and fine- to medium-grained sandstones in the lower half of the Ordoñez Formation. Winn and Steinmetz (1998) interpreted these diamictitic beds as subglacial tills and subaerial ice-related mudflows. Southernmost, in eastern Argentina, glacial diamictites and shales with dropstones crop out in the Sierras Australes forming the Sauce Grande Formation (Figs. 2 and 7). There, glacial diamictites are covered by transgressive postglacial shales without dropstones belonging to the Piedra Azul Formation, which is supposed latest Carboniferous–earliest Permian in age (Andreis and Japas, 1996; Limarino and Spalletti, 2006).

Pennsylvanian glacial diamictites also appear in the Tarija and San Telmo formations (Tarija Basin, Figs. 2 and 7) where several levels of mainly resedimented diamictites, bearing striated and faceted clasts, occur intercalated with shales bearing dropstones.

Lithological evidence, as well as paleontological information, indicates that the Bashkirian–earliest Cisuralian climate was very different in the western basins of South America following disappearance of the glacial deposits there (Fig. 7). During the Bashkirian–earliest Cisuralian interval, the retroarc Paganzo and San Rafael basins were dominated by fluvial sedimentation alternating with marine transgressions. It is possible that the timing of the marine transgressions in the western basins was related to interglacial events in the Itararé Group (Vesely and Assine, 2006).

The most significant lithological expression for the end of glacial conditions in the retroarc area was the formation of organic-rich mudstones and coal measures, not only in alluvial plains, but also in estuarine and deltaic settings (Limarino et al., 2006, Fig. 9a). The coal beds are relatively thin (<80 cm), but coal shows a large areal distribution and contains abundant remains of the NBG flora (Fig. 8a–e).

Paleosols found in alluvial plain deposits mainly correspond to histosols characterized by high percentages of organic matter (O master horizons) associated with gleyed mineral horizons (Gulbranson et al., 2010). This type of soil indicates that the influx of organic matter exceeded the decomposition rate, which suggests very humid conditions (Gulbranson et al., 2010, Fig. 9b). Additionally, alluvial plain facies in the Paganzo Basin show thick (up to 2 m) kaolinite-rich mudstone beds that formed by the complete weathering of plagioclase and K-feldspar, which also indicates very humid conditions. In some places, the transformation of feldspar to kaolinite was so intense that some of these levels are presently used in the ceramic industry (Fig. 9b). However, during the late Moscovian and Kasimovian, the climate evolved towards drier conditions as suggested by the presence of vertisols and paleosols containing soil-formed calcite, which indicate the onset of an arid interval in the Paganzo Basin (Gulbranson et al., 2010).

Like the Paganzo and San Rafael basins, arc-related basins in Peru, Bolivia and Chile do not contain Bashkirian–earliest Cisuralian glacial diamictites. During this interval, the stratigraphic record is dominated by fluvial sandstones and conglomerates that are intercalated with shallow marine deposits (Donato and Vergani, 1985; Suárez Soruco, 1989; Sempere, 1996; Limarino and Spalletti, 2006; Grader et al., 2008). In the Atacama region of Chile, late Carboniferous rocks bear ostracodes and plant remains that suggest warm-humid and seasonal climatic conditions (Breitkreuz et al., 1992).

6.2. Fossil assemblages

6.2.1. Flora

The Pennsylvanian flora from southern South America is characterized by *Nothorhacopteris* together with *Botrychiopsis*, pteridosperms

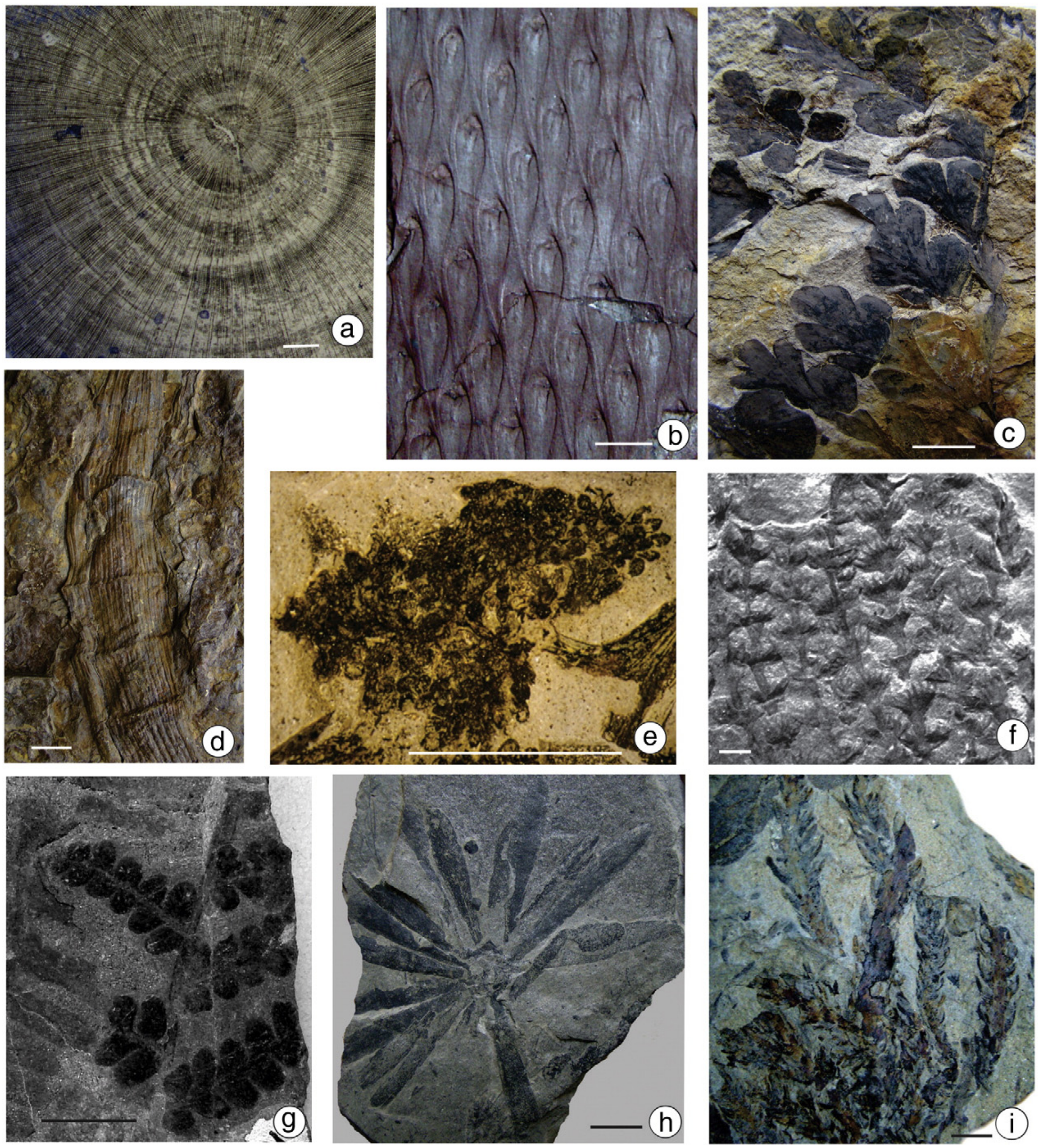

Fig. 8. a. Transverse section of cordaitalean root, San Ignacio Formation, PBSJ 465, b. *Bumbudendron nitidum* Archangelsky et al., Lagares Formation, c. *Fedekurtzia argentina* (Kurtz) Archangelsky, Volcán Formation, BAPb 12232, d. Equisetalean stem, Volcán Formation, BAPb 12238, e. *Rinconadia archangelskyi* Vega, Volcán Formation, BAPb 12235, f. *Stephanophyllites sanpaulensis* Millan and Dolianiti, Bajo de Véliz Formation, CORD PB 2643, g. *Asterotheca piatnitzkyi* Frenguelli BAFCPb 10617, h. *Cordaites* sp., Bajo de Véliz Formation, BAPb 16, i. *Ferugliocladus riojanum* Archangelsky and Cúneo, Arroyo Totoral Formation. Scale = 1cm.

(Fig. 8c, e), lycophytes (Fig. 8b), cordaitalean, and equisetaleans (Fig. 8d). Western Argentinean assemblages are included in the NBG Zone. The NGB Zone is succeeded by the Interval Zone (Archangelsky and Cúneo, 1991), which is distinguished by the occurrence of fern and conifer fossils. Coeval Brazilian paleofloristic associations, some of them interbedded with glacigenic deposits, are comparable with the Argentinean flora (Holz et al., 2010).

Souza and Marques-Toigo (2003) recognized two palynozone intervals that characterize the palynological succession of Pennsylvanian strata in the Paraná Basin, namely (in ascending order): the *A. cristatus* and the *Crucisaccites monoletus* Biozones. Palynological assemblages of the rhythmites of Itu were assigned to the *C. monoletus* Zone by Souza et al. (2010) suggesting a Late Pennsylvanian (Kasimovian/Gzhelian) age for these rhythmites.

Approximately coeval palynofloras from western Argentina are included in the Subzones B and C of the DM Biozone (Césari and Gutiérrez, 2001). Palynological assemblages with scarce specimens of the taeniate pollen *Protohaploxypinus* are referred to the Subzone B. These palynofloras characterize coal beds and organic-rich mudstones. The succeeding Subzone C lacks significant compositional

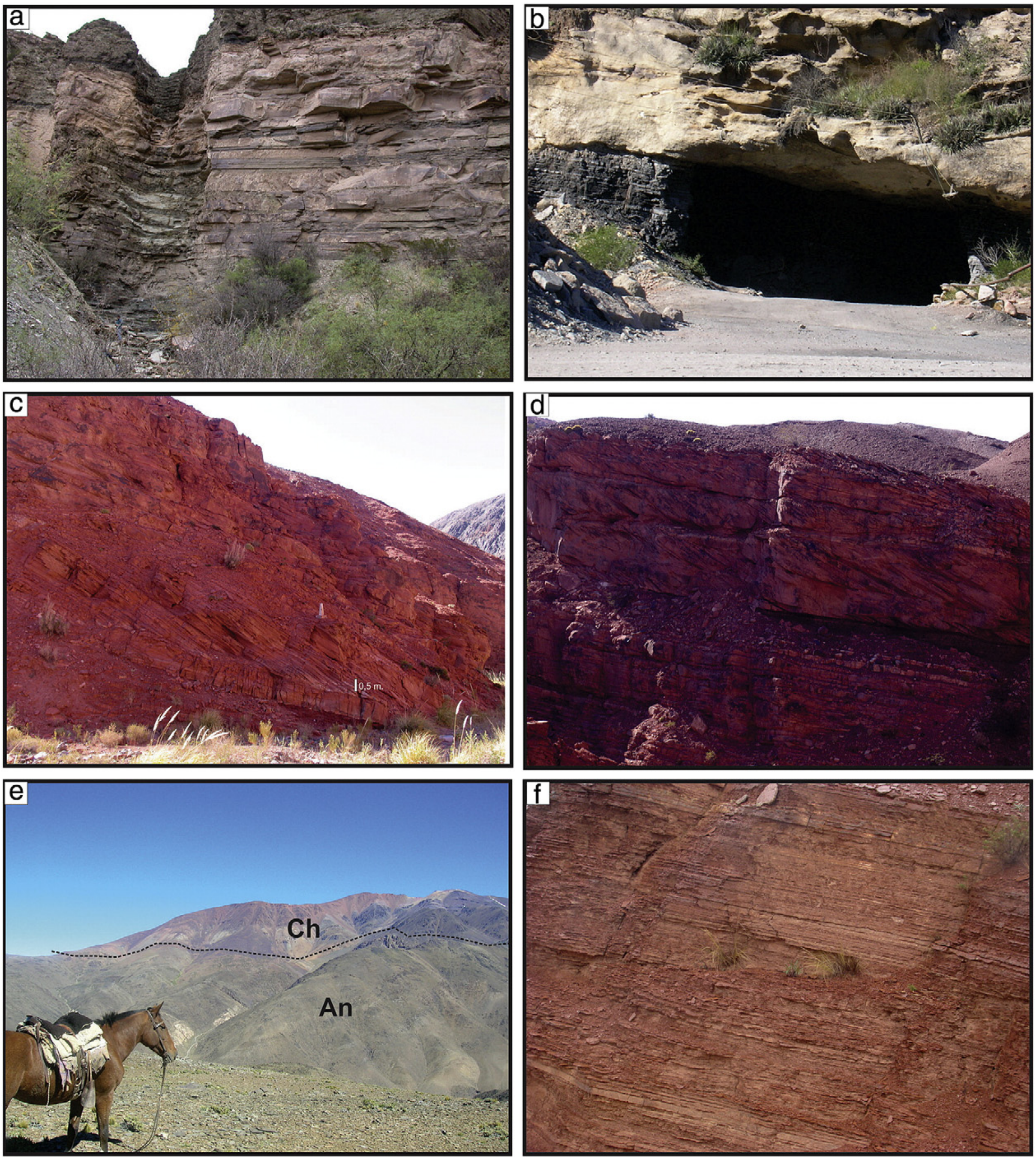

Fig. 9. a: Highly constructive deltaic successions (terminal glacial stage) formed during the fall of the postglacial transgression in the western basins of southern South America (Guandacol Formation), b: kaolinite-rich carbonaceous mudstones formed during the terminal glacial stage in the Paganzo Basin, kaolinite was mainly formed by weathering of feldspars under highly humid conditions, c: eolian sandstones forming large cross-stratified sets in the De La Cuesta Formation (postglacial stage), d: alternation of eolian dune deposits (stacked cross-bedded sets) and playa lake successions in the upper De La Cuesta Formation (postglacial stage), these rocks indicate the existence of semiarid or arid conditions in the retroarc area during the postglacial stage, e: volcanics of the Choiyoi Group (Ch) covering Pennsylvanian rocks of the Cerro Agua Negra Formation (AN, onset of the semiarid–arid stage), f: playa lake deposits in the latest Permian Talampaya Formation (semiarid–arid stage), an age of 253 Ma was obtained for a tuff level in this section.

changes, but it is distinguished by an increase in taeniate pollen and the occurrence of some marine or brackish palynomorphs (*Maculatasporites*, *Michrystridium*, *Veryhachium*, *Navifusa*, *Brazilea*, *Quadrisporites* and scolecodonts).

In northern Argentina, the occurrence of lycophytes, seeds and palynological assemblages of the *Dictyotriletes bireticulatus–Cristatisporites chacoparanensis* (BC) Palynozone from diamictites in the Tarija Formation suggests a late Bashkirian–Moscovian age for the fossiliferous strata (di Pasquo, 2004, 2009). A similar age was proposed by di Pasquo et al. (2001) for the San Telmo Formation.

6.2.2. Fauna

Marine postglacial deposits in western Argentina document a faunal turnover connected with the climatic amelioration. The oldest fauna linked with faunal recovery and regional warming is the *Marginovatia–Maemia* fauna (formerly *Balakhonia–Geniculifera* fauna of Taboada, 1997) recorded in a short marine interval in both the Río Blanco (lower section of the Cerro Agua Negra Formation) and the Calingasta–Uspallata basins (Taboada, 1997, 2010). Recent age estimations for the *Marginovatia–Maemia* fauna, based on its brachiopod age ranges, indicate it lived during late Bashkirian–earliest Moscovian time (Taboada, 2010). In western Argentina, the migration of brachiopods from paleoequatorial and boreal belts of the Northern Hemisphere, such as *Marginovatia* and *Maemia*, among others, provides evidence for the establishment of a paleobiogeographic faunal connection with the Northern Hemisphere through the Austropanthalassic–Rheic corridor and its epicontinental Appalachian seaway branch and beyond (Taboada and Shi, 2009; Taboada, 2010).

The succeeding invertebrate assemblage is the so called *Tivertonia–Streptorhynchus* fauna (formerly *Lissochonetes–Streptorhynchus* fauna), which was first recognized in the Río Blanco and San Rafael basins (Sabattini et al., 1990), and later in the Calingasta–Uspallata Basin (Lech, 2002; Taboada, 2006). The marine transgression containing the *Tivertonia–Streptorhynchus* fauna was able to bypass the highlands of the Protoprecordillera through inlets breaching the mountain belt, thus reaching eastern flanks forming the most extensive late Paleozoic marine incursion to have covered western Argentina. The *Tivertonia–Streptorhynchus* faunal assemblage represents a middle to high paleolatitude temperate and mixed fauna with both boreal and Gondwana taxa (Taboada, 2010).

In the southern Paraná Basin, in Uruguay, cephalopods and other fossil remains have been reported from shales contained in a marine intercalation between glacial deposits of the “Itararé Group”, which are currently ascribed to the San Gregorio Formation. A Late Pennsylvanian age (Kasimovian–Gzhelian) is suggested for the concretionary horizon bearing the cephalopods.

The low diversified marine invertebrate faunas intercalated throughout the glacial sequence in the Itararé Group have been interpreted as a mixture of cosmopolitan and Gondwana taxa with variable affinities to the Amotape fauna of Peru, the *Eurydesma* fauna of eastern Argentina, as well as with the early Permian faunas of eastern and western Australia (Simões et al., 1998; Pagani, 2000). The uppermost faunas of the Itararé Group are closely associated with diamictite beds, while the *Eurydesma* fauna from the Bonete Formation in eastern Argentina occurs in a postglacial interval, suggesting a slightly younger age for the Argentinean assemblage.

6.3. Chronostratigraphy

The age of glaciation in the Paraná Basin is uncertain, but it is possible that the beginning of the glaciation could be as old as Serpukhovian or late Visean (Rocha-Campos et al., 2008). The end of the glacial conditions in the Paraná Basin can only be estimated by using stratigraphic relations with the overlying nonglacial deposits included in the Rio Bonito Formation. Chronostratigraphic data obtained from tonsteins in the Candiota Coals (upper Rio Bonito Formation) indicate ages ranging from 267.1 ± 3.4 Ma (Artinskian, Matos et al., 2001) to 298.5 ± 2.6 Ma (early Asselian, Rocha-Campos et al., 2006).

Regarding the western basins, a $^{206}Pb/^{238}U$ zircon age of 319.57 ± 0.086 Ma was obtained in the postglacial dropstone-free shales in the Paganzo Basin indicating that glacial conditions ceased in this region in the late Serpukhovian (Gulbranson et al., 2010; Césari et al., 2011; Figs. 7 and 10). This is in agreement with the Serpukhovian–early Bashkirian age identified from invertebrate fossils included in the *Levipustula* Zone, which occur in shales that cover glacial deposits in Argentina (Taboada, 2010). Moreover four $^{206}Pb/^{238}U$ zircon ages (Fig. 10) obtained from the non-glacial uppermost part of the Guandacol Formation and the overlaying Tupe Formation vary from 318.79 ± 0.1 Ma (upper Guandacol Formation, Bashkirian) to 309.89 ± 0.082 (Tupe Formation Moscovian, Gulbranson et al., 2010; Césari et al., 2011). These ages clearly point out that the glaciation ceased during the Serpukhovian in the western basins.

7. The postglacial stage (Cisuralian–early Guadalupian)

The postglacial stage is characterized by the complete disappearance of striated pavements, diamictites interpreted to be of glacial origin, and the disappearance of other features that indicate glacial climates in South America (Fig. 11). Glacial diamictites were progressively replaced in the Paraná and Chaco Paraná basins by shallow marine, estuarine, deltaic (Fig. 10a), and fluvial (Fig. 10b) successions that dominated starting in the Sakmarian.

7.1. Stratigraphy

In the Brazilian Paraná Basin, postglacial deposits are included in the Rio Bonito Formation. However, postglacial time may have started in the uppermost part of the Taciba Formation (upper Itararé Group) where glossopterids first appear (Iannuzzi and Souza, 2005). The Rio Bonito Formation is made up of sandstones, mudstones, and coal beds deposited in paralic environments (Holz, 1998; Holz et al., 2000; Fig. 11).

Geochemical and compositional studies of mudstones and sandstones in the Paraná Basin suggest deep climatic changes near the Carboniferous–Permian boundary (Goldberg and Humayun, 2010). The CIA (chemical index of alteration) measured in 55 claystones and shales shows a sharp contrast when CIA values of the Itararé Group and Rio Bonito Formation are compared. Itararé strata exhibit extremely low values while Rio Bonito Formation strata show high CIA indices (Goldberg and Humayun, 2010). This change likely indicates the transition from very cool climates (glacial and terminal glacial stages) to warmer and very likely humid climates during the Cissuralian (postglacial stage). Similar climatic conditions can also be deduced from the lithological composition of the early Permian successions in Uruguay (Tres Islas Formation, de Santa Ana et al., 2006; Crisafulli et al., 2009) and Paraguay (Tacuary Formation, Fúlfaro, 1996). In these cases, diamictites and other features of glacial deposits were replaced by shallow marine and fluvial successions containing organic-rich mudstones.

The late Cisuralian Irati Formation (base of the Passa Dois Group) represents the regressive phase of a large postglacial transgression that flooded the Paraná Basin during much of the early Permian. The Irati Formation is characterized by claystones and siltstones (Taquaral Member), and abundant organic-rich shales and mudstones intercalated with lenticular beds of limestones (Assistência Member, Fig. 11). A $^{206}Pb/^{238}U$ age of 278.4 ± 2.2 was obtained from ash levels intercalated in the sequence (Santos et al., 2006, Fig. 10). The importance of the Irati Formation lies in the fact that it forms a thin stratigraphic interval (a few tens of meters thick) but with a large regional distribution (about 4 million km^2 in Paraná Basin and

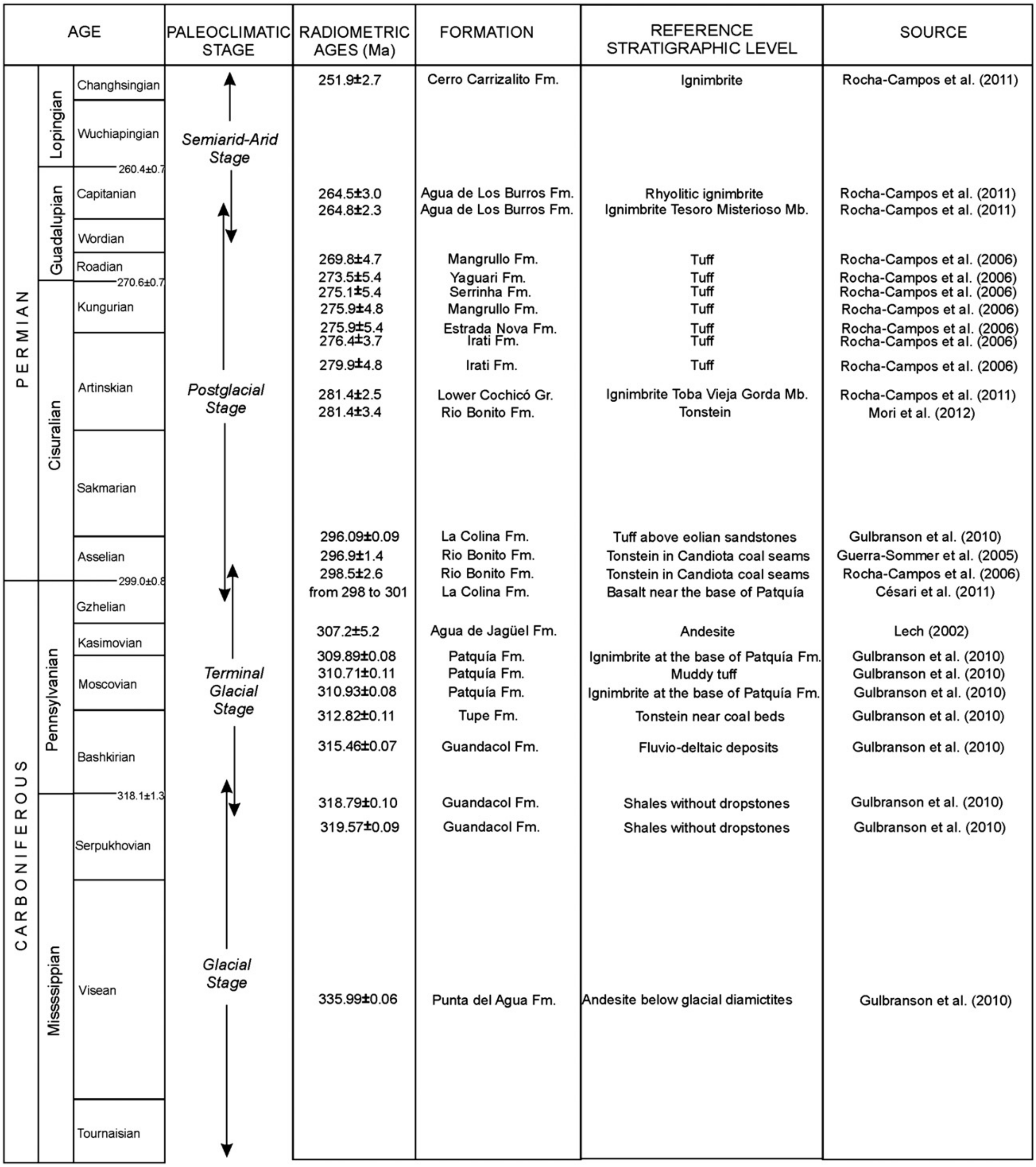

Fig. 10. Synthesis of the available radiometric ages for the late Paleozoic sequences in southern South America.

Africa) that can be used as a key stratigraphc horizon for climatic correlations.

Neither lithological features nor paleontological information suggest the occurrence of severe climates during the late Cisuralian in the Paraná Basin. On the contrary, warm and probably seasonal climates prevailed during this time. In this way, Holz et al. (2010) suggested that a cyclic alternation of dry and humid climates coupled with minor sea level changes promoted the formation of dolomite–bituminous shales, and rhythmites. Similar climatic conditions were deduced from the anatomic characteristics of pycnoxylic woods of gymnosperms from the Tres Islas Formation (Lower Permian of Uruguay). According to Crisafulli et al. (2009) study of the growth rings suggests wet climates during this time in the Paraná Basin.

Towards the Guadalupian, a transitional change to a seasonal and probably drier climate is suggested for strata in the Corumbataí Formation and the middle part of the Passa Dois Group (Rohn et al., 2005; Tavares and Rohn, 2009). This is consistent with a transition from humid to semiarid climates in the western basins during the late Cisuralian–early Guadalupian (López Gamundí et al., 1992; Limarino and Spalletti, 2006; Spalletti et al., 2010).

In the retroarc region, the postglacial stage is characterized by the total absence of glacial deposits and the dominance of fluvial and shallow marine sedimentation.

A remarkable feature of the Paganzo, San Rafael, and Tarija basins is the large distribution of eolian sandstones of early Permian age, which indicate a second semiarid–arid phase in the western basins (Sakmarian?,

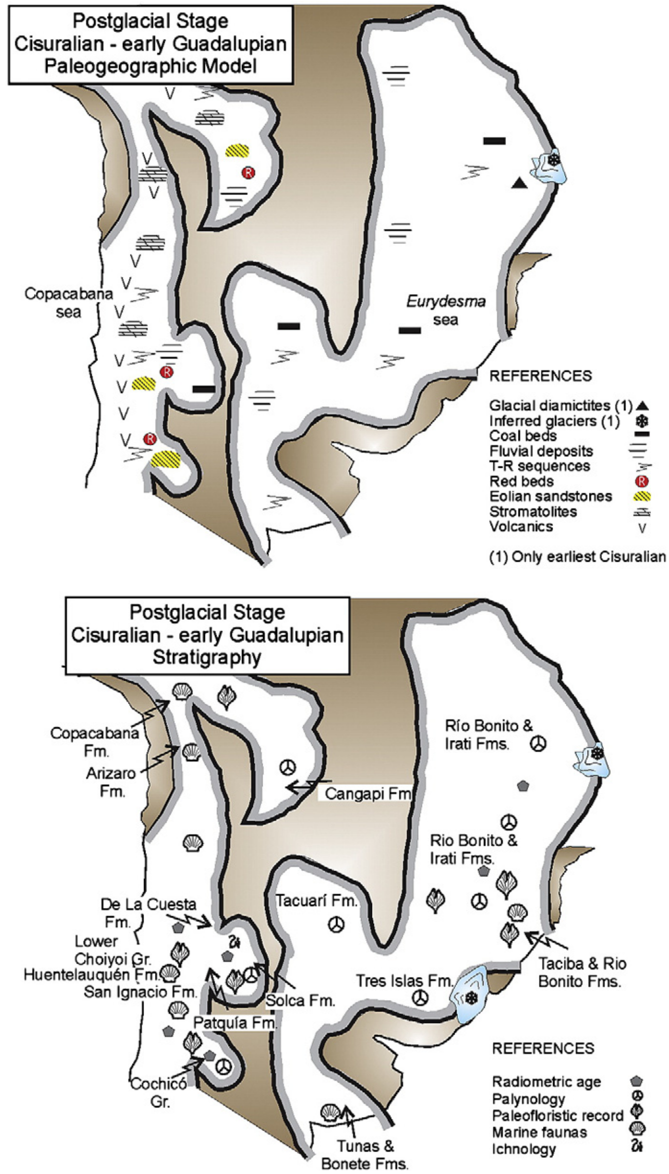

Fig. 11. Paleogeographic model, lithological indicators and stratigraphy of the postglacial glacial stage (Cisuralian–early Guadalupian).

Limarino, 1984; Limarino and Spalletti, 1986; Gulbranson et al., 2010, Fig. 11). Early Permian eolian deposits were reported from the La Colina, Patquía, and De La Cuesta formations in the Paganzo Basin (Limarino, 1984; Limarino and Spalletti, 1986; Spalletti et al., 2010; Fig. 9c and d). Recently, Gulbranson et al. (2010) reported an Asselian age for an ash level intercalated within eolian sandstones in the Paganzo Basin, which indicate that arid conditions began in the earliest Permian, but that arid conditions probably became of regional significance by the Sakmarian. In this area, Spalletti et al. (2010) recognized eolian (erg) successions alternating with non-eolian (terminal alluvial fan–mudflat) successions. These are bounded by regionally extensive *sand-drift surfaces* and *extinction erg surfaces* at the top of the eolian successions. In the neighboring San Rafael Basin, well exposed eolian sandstones occur in the Toba Vieja Gorda Member of the Cochicó Group (Fig. 11) where thick eolian dune deposits were described by Spalletti and Mazzoni (1972). Moreover, a substantial part of the Cangapi Formation (Tarija Basin) is made up of eolian sandstones including dune and interdune deposits (Starck, 1995, Fig. 11). Tomezzoli (1996) reported arid climatic conditions during the deposition of the Cangapi Formation due to the presence of eolian sandstones, abundant carbonate concretions, and levels of chert.

During the Asselian, the interarc basins were dominated by shallow marine and fluviodeltaic sedimentation as represented by the Huentelauquén (Andes of Chile), Quebrada del Mal Paso (coastal region of Chile), San Ignacio (Andes of Argentina), Arizaro (Puna Argentina) and middle-upper Copacabana (southern Peru and western Bolivia) formations (Fig. 11). All these units exhibit a similar stratigraphic pattern with a lower part dominated by siliciclastic rocks that pass up into limestones, which are interpreted to have been deposited under temperate to cold water conditions (Charrier et al., 2007). The upper member of the Huentelauquén Formation (La Cantera Member) is mainly composed of limestones (calcarenites and marls), and is considered to be early Permian based on foraminifera biostratigraphy (Díaz-Martínez et al., 2000; Charrier et al., 2007).

The upper part of the San Ignacio Formation consist of mudstones (bearing silicified trunks), volcanics (andesites), marls, and limestones (stromatolites and thrombolites, Busquets et al., 2007). Paleoecological studies of stromatolites and trunk remains (some of them in life position) suggest temperate seasonal climates during the deposition of the San Ignacio Formation in the latest Pennsylvanian–Cisuralian.

The middle-upper Copacabana Formation and the Arizaro Formation (latest Carboniferous–early Permian) are composed of fossiliferous limestones, sandstones, mudstones, and marls deposited in lagoonal and shallow marine environments. The shale to carbonate-shoaling cycles, characteristic of the Copacabana Formation, were driven by recurrent sea level changes under warm climates (Grader et al., 2008).

The major part of the interarc basins was dominated by volcanism and volcaniclastic sedimentation starting in the middle Artinskinan (lower part of the Choiyoi Group, Fig. 11). The onset of the volcanism seems to be recorded in the Yacimiento Los Reyunos Formation where Rocha-Campos et al. (2011) reported a SHRIMP U–Pb zircon age of 281.4 ± 2.3 Ma. Volcanism prevailed throughout the whole of the present day Andean region forming thick successions of mesosilicic flows, ignimbrites, and tuffs. The appearance of this new positive area displaced the Permian shoreline to the west isolating the Calingasta–Uspallata and Río Blanco basins from the Permian sea.

7.2. Fossil assemblages

7.2.1. Flora

The Permian coal beds, which contain the most important coal reserves in Brazil, contain abundant plant remains of the Gondwana “*Glossopteris* flora” characterized by arborescent and shrubby lycophytes (i.e. *Brasilodendron pedroanum*), ferns (*Pecopteris* and *Asterotheca*), sphenophytes (i.e. *Annularia* spp. and *Sphenophyllum brasiliensis*), pteridophylls (*Botrychiopsis*), glossopterids, cordaitaleans, and conifers (for a review see Iannuzzi, 2010). The earliest Permian flora was designated as the *Phyllotheca–Gangamopteris* flora by Iannuzzi and Souza (2005). This flora is more diverse than that found in the organic-rich mudstones and coals deposited during the terminal ice-house stage (mainly in the retroarc basins) and it indicates progressive climatic amelioration. According to Guerra-Sommer and Cazzulo-Klepziga (2000), the dominance of *Rubidgea* and *Gangamopteris* leaves, associated with glossopterids with pinnate venation, indicate a gradual climatic warming. Besides, the later dominance of pinnate glossopterids, arborescent lycophytes, and the scarce representation of *Gangamopteris* and *Rubidgea* (palmate forms) in the *Glossopteris–Brasilodendron* flora (Iannuzzi and Souza, 2005) suggest the occurrence of moist seasonal climates in the Paraná Basin during the late Cisuralian (Guerra-Sommer and Cazzulo-Klepziga, 2000).

The paleoflora of the Bajo de Véliz Formation is the best example in the Paganzo Basin of a fossil assemblage characterized by the first occurrence of glossopterids (*Gangamopteris*, *Glossopteris* and *Euryphyllum*), together with cordaitales (Fig. 8h) and the incoming of new sphenopsids (Fig. 8f), conifers (Fig. 8i) and lycophytes (see Césari and Hünicken, 1991, 1992; Césari et al., 1995; Archangelsky et al., 1996). The Bajo de Véliz Formation also includes a rich association of continental invertebrates (see Archangelsky et al., 1996). The paleoflora and the coeval assemblages of the Tasa Cuna, El Imperial, La Colina and Arroyo Totoral formations were assigned to the *Gangamopteris* Biozone (Archangelsky et al., 1996).

Palynological assemblages associated with the *Gangamopteris* Biozone are included in the *Pakhapites fusus–Vittatina subsaccata* Biozone (FS) defined by Césari and Gutiérrez (2001). This zone is equivalent to the Brazilian *Vittatina costabilis* Zone (Césari, 2007). These palynofloras, which are well represented in the coal beds of the Rio Bonito Formation, are characterized by diverse taeniate pollen and spores reflecting a parental biome composed of gymnosperms, ferns, sphenophytes and lycophytes.

An overall change in the floral composition occurs in the Palermo Formation (Paraná Basin) where the change is marked by the basal part of *Lueckisporites virkkiae* interval Zone (LvZ) (Souza and Marques-Toigo, 2005) and the transition from the *Glossopteris–Brasilodendron* flora to the *Polysolenoxylon–Glossopteris* floras. This change probably reflects a strong transgressive signature within the Palermo Formation (Iannuzzi and Souza, 2005), which probably generated significant changes in the flora.

The Irati Formation contains abundant remains of permineralized logs and a macroflora referred to as the *Polysolenoxylon–Glossopteris* flora and palynomorphs included in the *L. virkkiae* (Lv) Biozone, which are characterized by the predominance of taeniate pollen. Radiometric data constrain the lower part of the Lv Zone to the middle Artinskian (Santos et al., 2006; Mori et al., 2012). The last records of the biozone are identified in the lowermost Rio do Rasto Formation, which is regarded as Wordian/Capitanian in age (Holz et al., 2010).

The coeval Argentinean *Lueckisporites–Weylandites* Biozone is considered representative of increasing aridity, which is marked by an impoverishment in the spore richness, and the abundance of taeniate pollen (Césari and Gutiérrez, 2001; Césari et al., 2007). Palynological assemblages referred to the LW Biozone were described from Cisuralian mudstones outcropping in the Frontal Cordillera (San Juan Province) by Ottone and Rossello (1996). A rich association of silicified trunks, roots (Fig. 8a), and stumps occurs in the same area belonging to the San Ignacio Formation, which preserves evidence of several adaptations of the trees to a periodically stressed environment that was affected by waterlogging and volcanism. Discontinuous and indistinct growth rings in the wood suggest cessation in growth due to stress, and the presence of adventitious roots can be interpreted as an adaptation to flooding. Moreover, the abundance of fecal pellets inside tunnels in the wood indicates aerial exposition. Epicormic branching of the trees enhanced its ability to rapidly overcome environmental stress. A nurse log strategy for the trees supported the recovery of the vegetation under adverse conditions (Césari et al., 2010). Aerenchyma in the young rootlets (growing inside the decaying wood) allowed growth in anoxic, waterlogged soils.

Palynofloras contained in shallow lacustrine and playa lake deposits of the De La Cuesta Formation (or La Veteada Formation) at Sierra de Narváez represent the uppermost limits of the LW Biozone in Argentina (Aceñolaza and Vergel, 1987; Gutiérrez et al., 2011).

7.2.2. Fauna

The *Costatumulus* fauna and biozone were proposed by Taboada (1998) to replace the former *Cancrinella* Zone of Amos and Rolleri (1965). The marine incursion bearing the *Costatumulus* fauna was geographically restricted to an embayment located at the southern border of the Calingasta–Uspallata Basin. The *Costatumulus amosi* fauna, when compared with the Moscovian *Tivertonia–Streptorhynchus* assemblage, exhibits lower brachiopod diversity suggesting stressed environmental conditions perhaps linked with colder seawater temperatures. This fauna was estimated to be late Sakmarian–early Artinskian (Taboada, 2010).

In central Chile, the upper section of the Huentelauquén Formation contains a mixed siliciclastic calcareous shallow marine facies (platform ramp), which have yielded a brachiopod fauna along with other invertebrate groups including: bivalves (González, 1980), bryozoans, crinoids, sponges, and scarce foraminifera, which would have lived under cool to cold water temperatures (Rivano and Sepulveda, 1983).

The belt typified by the Copacabana sea extends from southern Peru southward reaching its southernmost extension in central Chile (López Gamundí and Breitkreuz, 1997) or possibly extending as far south as the Madre de Dios archipelago (Tarlton limestone) in southern Chile (49°–52°S) where fussulinids were reported (González, 1989). The Copacabana sea appeared to have involved mostly cool to cold early Permian faunal assemblages (Díaz-Martínez et al., 2000), but also warmer faunas, which yield abundant conodonts as was documented in the Copacabana Formation of Bolivia and Peru (Grader et al., 2008).

The Taió assemblage includes the only known marine association in the postglacial succession of the Paraná Basin, which occurs in the middle part of the Rio Bonito Formation (Paraguaçu Member, Rocha-Campos and Simoes, 1993). It is thought that this assemblage is Artinskian and may be linked with the *Eurydesma* fauna of eastern Argentina (Simões et al., 1998; Pagani, 2000). Nevertheless, the faunal relationship between the Taió assemblage and the *Eurydesma* fauna was questioned by some authors (e.g. González and Díaz Saravia, 2010). In eastern Argentina, the conspicuous Gondwanic bivalve *Eurydesma* and its associated fauna appears in the postglacial Bonete Formation in the Sauce Grande–Colorado Basin. The *Eurydesma* fauna was a biotic event indicative of a cold-water, shallow marine paleoenvironment, which was also present in overseas sequences of Australia, New Zealand, India, South Africa and eastward to the Cimmerian region (Dickins, 1961, 1978).

The main late Cisuralian–Lopingian faunas, which lived under a climatic amelioration trend and variable semi-arid conditions are known from the Paraná Basin in Brazil, Uruguay, and Paraguay. Previous marine incursions (e.g. *Eurydesma* transgression) flooded an almost linear rift valley depression from southern Africa through the Brazilian interior (Stollhofen et al., 2000) forming the precursor or incipient stages of the so-called *Mesosaurus* Inland Sea. The widespread basinal Irati Formation records a large and shallow epicontinental sea inhabited mostly by mesosaurid reptiles, including the conspicuous *Mesosaurus brasiliensis*, crustaceans, and fishes (Ricardi-Branco et al., 2008; and references provided therein). This unit is traditionally correlated to the Whitehill Formation from the Karoo Basin, in southern Africa, based on lithology and the fossil record. It is also correlated to the Mangrullo Formation in Uruguay, where mesosaurids were recognized (Piñeiro et al., 2011).

After the maximum flooding stage (Palermo and Irati formations), sea level fell slowly, and the Paraná Basin became a late Cisuralian–early Guadalupian restricted lake/sea. Formation of this lake/sea was accompanied by the appearance of an endemic, diverse, bivalve-dominated fauna, represented primarily by burrowing species of Heterodonta (Astartidae) and Anomalodestama (Megadesmidae), along with subsidiary fossil remains documented throughout the Serra Alta and Teresina/Corumbataí formations (Simões et al., 2010). The main association of this interval is known as the *Pinzonella* fauna, and is represented, from base to top, by the bivalve species of the *Anhembia froesi*, *Pinzonella illusa* and *Pinzonella neotropica* biozones (Rohn, 1994; Simões et al., 2010). The *Pinzonella* fauna was also reported from the Tacuary Formation in Paraguay.

In the Paraná Basin, most of the Serrinha Member of the Rio do Rasto Formation corresponds to the bivalve *Leinzia similis* Zone. The species *L. similis* was also found in the Gai-As Formation in Namibia, of which the top of the formation is dated as 265 ± 2.2 Ma, an age close to the Wordian–Capitanian boundary (Stollhofen et al., 2000; Holz et al., 2010).

7.3. Chronostratigraphy

The postglacial Brazilian Rio Bonito Formation was considered Middle Permian (Guadalupian) according to a U–Pb zircon age of

267.1 ± 3.4 Ma coming from tonstein levels from the Candiota Coals (Matos et al., 2001, Fig. 10). In the last years, however, this age has been reconsidered based on new dating of 290.6 ± 1.5 Ma, 296.9 ± 1.65 and 296 ± 4.2 Ma assessed by Guerra-Sommer et al. (2008a,b) and 298.5 ± 2.6 Ma for the same levels by Rocha-Campos et al. (2006). More recently, Mori et al. (2012) reported an age of 281.4 ± 3.4 Ma for the uppermost strata of the Rio Bonito Formation (Fig. 10 for more details).

The age of the arid episode in the retroarc basins can be constrained on the basis of paleontological correlation and radiometric dating. On the one hand, eolian rocks cover red bed successions bearing remains of the *Glossopteris* flora (Limarino and Césari, 1985) and an U–Pb age of 296.09 ± 0.08 Ma was obtained in the lowermost levels of the eolian unit (Gulbranson et al., 2010, Fig. 10). On the other hand, eolian deposits in the San Rafael Basin are covered by ignimbrites belonging to the Toba Vieja Gorda Member of the Cochicó Group aged in 281.4 ± 2.5 Ma (Rocha-Campos et al., 2011). This information suggests that arid conditions prevailed in the western retroarc basins during the Sakmarian–Artinskian.

The Irati Formation and equivalent units of the Paraná Basin, the Whitehill Formation and the Huab Formation in NW-Namibia, and the Black Rock Member of the Malvinas Islands, are considered to represent a transcontinental isochronous (middle Artinskian age) unit (Oelofsen, 1987).

8. The semiarid–arid stage (late Guadalupian–Lopingian)

Late Guadalupian–Lopingian sedimentation was dominated by arid or semiarid climates throughout the major part of southern South America as suggested by lithological indicators such as a widespread record of eolian deposits (including erg sequences), evaporites, large playa lake successions, interbedded eolian and fluvial deposits, and a concomitant absence of coal beds (Figs. 3 and 12).

8.1. Stratigraphy

The stratigraphic record of the Paraná Basin shows progressive continentalization and aridization from the late Guadalupian to the Permian–Triassic boundary (Fig. 12). The upper part of the Rio do Rasto Formation (Morro Pelado Member, early Lopingian) is largely composed of sandstone and some mudstone intercalations deposited in fluvial, ephemeral lacustrine and eolian environments (Rohn et al., 2005; Lavina 1991 in Holz et al., 2010).

Towards the late Lopingian–earliest Triassic, two thick eolian deposits have been described in the Paraná Basin: the Pirambóia (north-northwest of the basin) and the Sanga do Cabral (south-southeast, Fig. 12) formations. The Pirambóia Formation comprises fine- to coarse-grained red sandstones showing stacked large-scale cross-bedded sets (up to 7 m) alternating with horizontal and low-angle, cross-bedded strata (Lavina et al., 1993; Delorenzo Nardi Dias and Scherer, 2008). Delorenzo Nardi Dias and Scherer (2008) recognized three major facies associations in the Pirambóia: eolian sand sheet, eolian dune and interdune facies associations. The Sanga do Cabral Formation is composed of reddish fine- to coarse-grained sandstones deposited in alluvial, fluvial, and eolian environments. Although some author correlates the Sanga do Cabral Formation with the previously considered Pirambóia Formation, its age is presently under debate as some authors refer to it as latest Permian while others refer to it as earliest Triassic (Delorenzo Nardi Dias and Scherer, 2008; Holz et al., 2010).

In the Uruguayan portion of the Paraná Basin, the Upper Member of the Yaguarí Formation is dominated by variegated sandstones and mudstones with intercalations of marls, gypsum, and levels of bentonite (altered fine-grained tuffs?, Goso et al., 2001; de Santa Ana et al., 2006, Fig. 12). All of these rocks were deposited in lagoonal and estuarine environments that were dominated by brackish and fresh waters with abundant conchostraceans and bivalves (Goso et al., 2001). The presence of marls, limestones, some levels of gypsum, caliche paleosoils in alluvial plains deposits, and mudstones bearing large calcareous concretions suggest desiccation periods that were probably related to semiarid climatic regimes (Goso et al., 2001).

The upper Buena Vista Formation forms a thick sequence (up to 670 m., de Santa Ana et al., 2006) of red sandstones with minor intercalations of mudstones and fine-grained conglomerates that were deposited in fluvial, eolian, and lacustrine environments (Goso et al., 2001, Fig. 12). According to de Santa Ana et al. (2006), the upper part of the Buena Vista Formation (Cerro Conventos Member) exhibits dune and extradune eolian deposits.

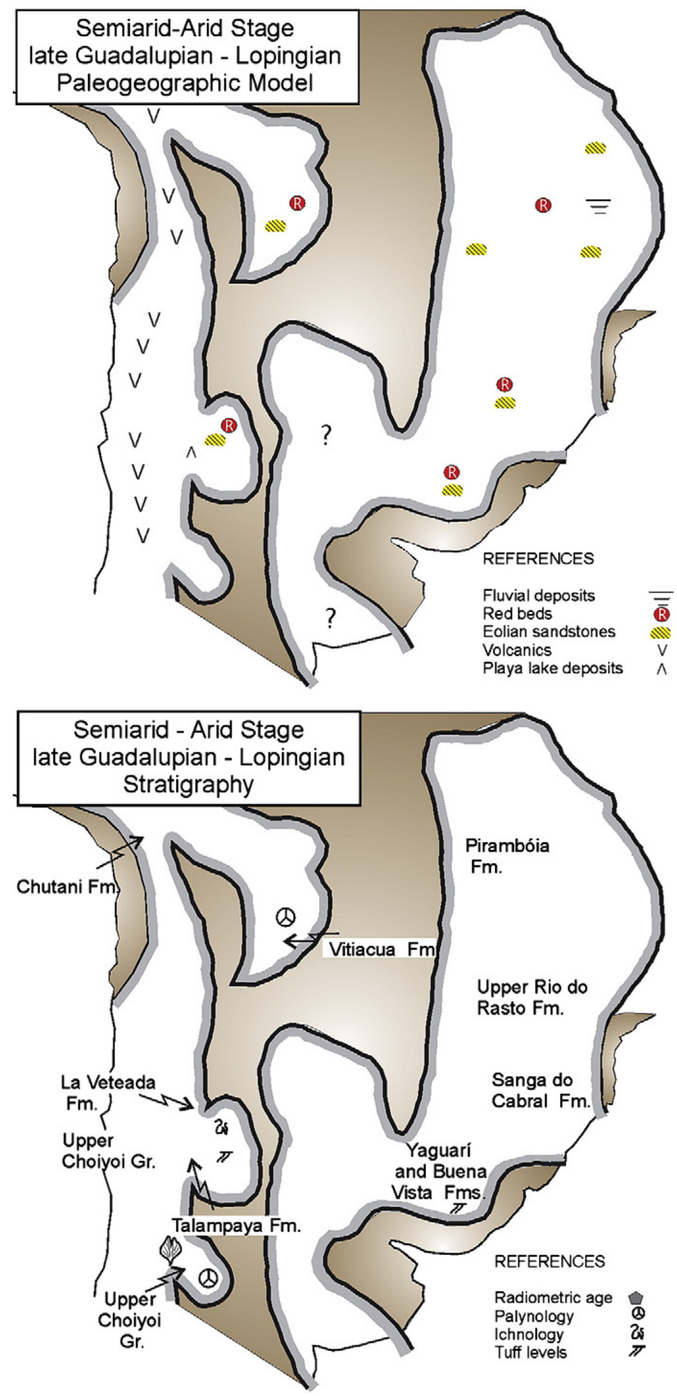

Fig. 12. Paleogeographic model, lithological indicators, and stratigraphy of the semiarid–arid stage (late Guadalupian–Lopingian).

The existence of late Permian rocks was unknown in the western basins of Argentina until recently when Zavattieri et al. (2008) described a late Permian palynological assemblage from the La Veteada Formation at Sierra de Famatina (Paganzo Basin).

The Talampaya Formation comprises three sections, the lower one is composed of conglomerates, breccias and coarse-grained sandstones deposited in alluvial fans and braided rivers (Fig. 12). The middle section is composed almost entirely of sandstones sedimented in braided ephemeral fluvial systems and in alternating eolian–fluvial environments. Finally, the upper section is made up of a muddy playa–lake succession that, in some localities, includes thin horizons of evaporites and eolian dune deposits (Fig. 9f). The vertical pattern of sedimentary facies found in the Talampaya Formation clearly suggests a progressive increase in aridity towards the Permian–Triassic boundary.

The La Veteada Formation at Sierra de Famatina consists of interbedded fine-grained sandstones and mudstones containing several thick levels of marls, gypsum, and chert (silcrete-type paleosols, Dávila et al., 2005, Fig. 12). The presence of silcrete-type paleosols, marls, levels of gypsum, and a predominance of mudstones suggest sedimentation in shallow lakes that was subjected to intense evaporation in arid–semiarid environments (Dávila et al., 2005).

Other units outcropping in the retroarc Tarija Basin and in Peru, such as the Vitiacua, Chutani, and Ene formations, could offer important paleoclimatic information. However, their stratigraphic positions are unclear as some authors considered them to be late Permian, and others have correlated the Vitiacua and Chutani formations with the late Cisuralian Irati Formation of Brazil (Starck, 1995; Sempere et al., 2002).

Volcanism prevailed along the whole of the arc related basins where thousands of meters of volcanics, tuffs, ignimbrites, and breccias accumulated (upper section of Choiyoi Group in Argentina, Lower Pastos Blancos–Peine Group in Chile, Mitú Group in Peru and Tiquina Formation in Bolivia; Fig. 9e). During inter-eruptive periods, breccias, conglomerates, and sandstones were deposited, which provide some paleoclimatic information. In the north of Chile, the latest Permian–earliest Triassic El Peine and Cas formations are made up of mafic and silica-rich pyroclastic rocks, andesites, and ignimbrites together with intercalations of fluvial, eolian, and lacustrine red beds including stromatolites (Breitkreuz and Van Schmus, 1996). Based on the presence of rhythmic deposition in the alluvial plains, raindrop imprints, desiccation cracks, and thin soil horizons, Breitkreuz and Van Schmus (1996) proposed moderate climatic conditions.

8.2. Fossil assemblages

8.2.1. Flora

Fossil plants belonging to the morphogenera *Glossopteris*, *Pecopteris* and *Asterotheca* were collected from the upper part of the Chutani Formation (Iannuzzi et al., 2004; Vieira et al., 2004). The presence of *Pecopteris dolianitii* Rösler and Rohn, also reported from the late Permian beds of the Rio do Rasto and Estrada Nova formations in the Paraná Basin, suggests a late Permian age for the fossil plant-bearing beds in the Chutani Formation.

The La Veteada Formation at Sierra de Famatina (Argentina) contains an interesting palynological assemblage (Zavattieri et al., 2008) dominated by *Lundbladispora–Densoisporites* and *Protohaploxypinus–Lunatisporites*, which was referred to as late Permian based on the presence of *Guttulapollenites hannonicus* Goubin, *Densoisporites complicatus* Blame, *Osmundacidites* spp., *Minutosaccus–Protodiploxypinus*, *Vitreisporites* spp., *Klausipollenites staplinii* Jansonius, *Reduviasporonites chalastus* (Foster) Elsik and *Syndesmorion stellatum* (Fijalkowska) Foster and Afonin, among other species.

8.2.2. Fauna

A large portion of the Morro Pelado Member of the Rio do Rasto Formation encompasses the *Palaeomutela platinensis* Zone (Holz et al., 2010; Simões et al., 2010). In the Uruguayan portion of the Paraná Basin, the Yaguarí Formation has yielded conchostraceans (*Cyzisus falconeri*) and bivalves (*Pyramus cowperesoides*), which lived in lagoonal and estuarine environments (Gallego et al., 1993). The overlying Buena Vista Formation is characterized by a dominant-amphibian temnospondyl fauna with subordinate basal reptilian records, which collectively suggest an age close to the Permian–Triassic boundary, according to its evolutionary stage as compared with faunas in Brazil and South Africa (Piñeiro et al., 2011).

8.3. Chronostratigraphy and age

There is little chronostratigraphic information about the semiarid–arid stage in southern South America. Most of the data come from volcanics including the upper section of the Choiyoi Group near the Argentina–Chile boundary. There, Rocha-Campos et al. (2010) reported three SHRIMP U–Pb zircon ages for this interval. The oldest ages (264.8 ± 2.3 Ma and 265.5 ± 3.0 Ma) are from rhyolitic ignimbrites belonging to the Agua de Los Burros Formation, whereas, the youngest is from an ignimbrite of the Cerro Carrizalito Formation (251.9 ± 2.7 Ma).

All the mentioned ages suggest that the arid–semiarid stage begun no earlier than the late Guadalupian and continued into the late Lopingian.

9. Paleogeographic features and north–south climatic belts in South America

The drift of Gondwana across the South Pole during the late Paleozoic and the paleogeographic position of the studied region are shown in Figs. 13 and 14 respectively. The polar wander path is based on paleomagnetic data (Powell and Li, 1994; McElhinny et al., 2003; Geuna et al., 2010; just to name a few) and shows large uncertainties for some time segments (e.g. large confidence circles around the 370–330 Ma mean poles in Fig. 13). The uncertainties mainly result from incorrect age assignment for the acquisition of the magnetic remanence, from the use of incorrect reconstruction parameters for the plates forming Gondwana, or due to possible intra-Gondwana movements being overlooked (see for example McElhinny et al., 2003).

Leaving aside the uncertainty, the broad movement of the pole can be followed from northeastern South America in the Late Devonian, shifting to central Africa in the early Carboniferous, then migrating into Antarctica in the Pennsylvanian, to reach Australia in the early Permian (Fig. 13). Although this pole path roughly follows the general trend of glacier occurrence (i.e. older glaciation in South America, younger in Australia), it cannot explain by itself the pattern of glacial deposits in Gondwana. If the paleolatitudinal position of the different parts of Gondwana is taken as the unique criteria to explain the occurrence and expansion of glacial centers, it is not clear what the origin of the climatic shift from glacial to terminal glacial stages was in South America as the paleolatitudinal position in both climatic stages was essentially the same. Therefore, it is clear that the glaciation that affected the Gondwana supercontinent requires additional factors, than paleolatitude, to explain fluctuating cooling conditions that produced periods of expansion and contraction of the ice masses during the latest Mississippian and latest Pennsylvanian (Isbell et al., 2003a; Fielding et al., 2008b; among others).

Additionally, the effect of tectonism and paleogeography on initiating glacial nucleation, and their controls on the later stability of ice sheet in southern South America should be taken into consideration. Recently, Isbell et al. (2012) discussed how the balance between the ELA line position (equilibrium-line altitude) and the land surface could be influenced by tectonism promoting or avoiding the formation and nucleation of glaciers. In southern South America, the case of the Protoprecordillera is a good example for analyzing the ELA effect (Fig. 15).

The Protoprecordillera was uplifted during the Late Devonian–Early Mississippian and likely reached its maximum altitude during the Visean by which time the land surface resided well above the local ELA (Isbell et al., 2012, Fig. 15a). This situation, coupled with a favorable latitudinal position and a worldwide cooling, would have favored the conditions for glacier formation in the Protoprecordillera, thus promoting the onset of glaciation on the western margin of Gondwana during the late Visean (Pérez Loinaze et al., 2010; Isbell et al., 2012).

During the Early Pennsylvanian (probably Bashkirian), the Protoprecordillera became unstable and began to collapse (Fig. 15b) until the range lost its topographic significance at the beginning of the Permian (Net and Limarino, 2006; Limarino et al., 2006; Fig. 15c). When the land surface fell below the local ELA, glacial centers developed negative mass balances and began to vanish (Fig. 15b to c). This is in agreement with the complete disappearance of glacial deposits during the Bashkirian in western South America. Probably the situation was very different in the eastern basins (Paraná and Sauce Grande–Colorado basins) where the positive areas of the Sierras Pampeanas, Río de la Plata and Guaporé, as well as the highlands in western Africa, show no evidence of having collapsed during the Mississippian–early Permian. Based on the above mentioned differences in tectonic activity, tectonism could have controlled the position of the ELA and indirectly driven the differences in glaciation observed between eastern and western basins during the Mississippian and Pennsylvanian.

Chumakov and Zharkov (2002) proposed narrow semiarid belts between 40°–45° and 50°–55° during the Sakmarian–earliest Artinskian, a similar age to that of the eolian sandstones and playa lake deposits of the Patquía Formation in the Paganzo Basin (Limarino and Spalletti, 1986; Starck, 1995; Tomezzoli, 1996; Spalletti et al., 2010).

Local paleogeographic features played an important role in the formation of north–south paleoclimatic belts, which increased the complexity of the paleolatitudinal belts postulated by Chumakov and Zharkov (2002). A good example occurs when the early Cisuralian paleoclimatic conditions in southern South America are analyzed in detail (Fig. 16). In the western Paganzo Basin (retroarc area), lithological indicators suggest semiarid to arid climates that favored the formation of eolian sandstones, playa lake successions, and promoted changes in clay mineral associations in mudstones, which indicate the occurrence of semiarid environments (Limarino and Spalletti, 1986; Net et al., 2002; Figs. 9c, d and 16). Moreover, the transition from argillosols and vertisols to calcisols in the Late Pennsylvanian would indicate a progressive decrease in humidity in the western Paganzo Basin (Gulbranson et al., 2010).

Easternward, along the eastern flank of the Paganzo Basin, more humid conditions are suggested by the abundance of organic-rich mudstones that contain abundant plant remains of the *Gangamopteris* flora in the Arroyo Totoral and Solca formations (wet belt in Fig. 16). Both units were deposited in the easternmost part of the Paganzo Basin within paleovalleys developed into the Sierras Pampeanas. Moreover, Crisafulli and Herbst (2008) described anatomically preserved wood of conifers in the Solca Formation, which would indicate warm and humid climates. A similar situation is also present in the Bajo de Véliz and Tasa Cuna formations where warm and wet climatic

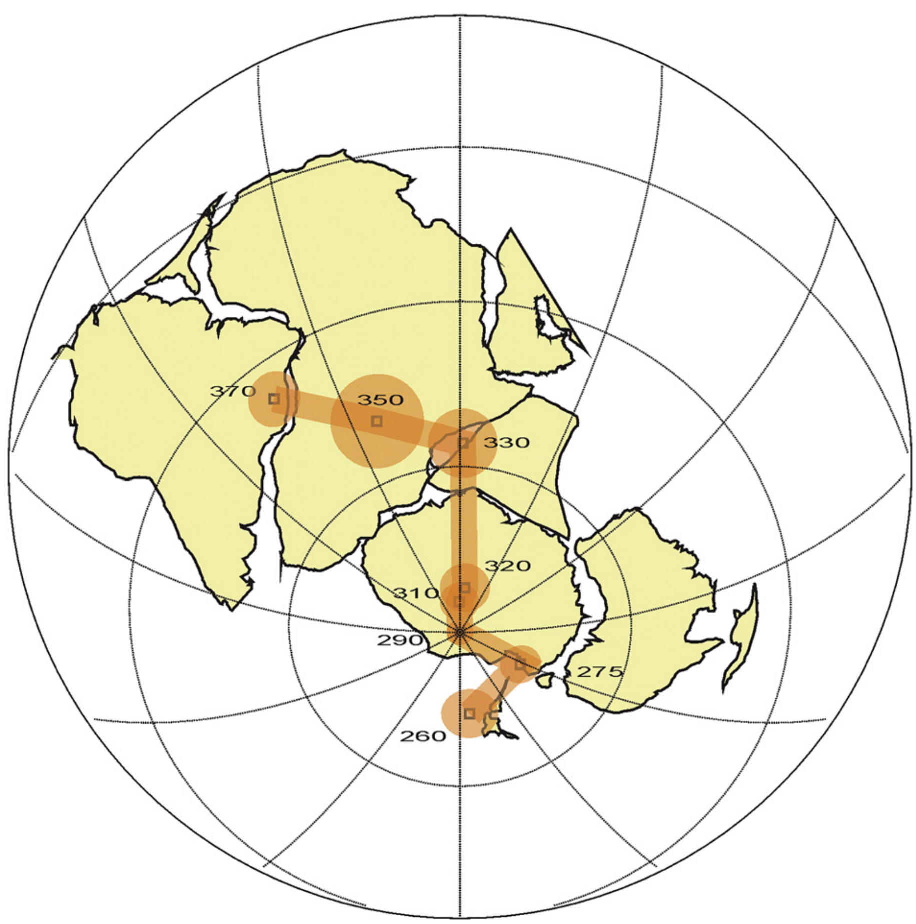

Fig. 13. Polar wander path for the Carboniferous and Permian relative to Gondwana, based on the Gondwana paleomagnetic poles selected by Geuna et al. (2010). Schmidt projection, south hemisphere.

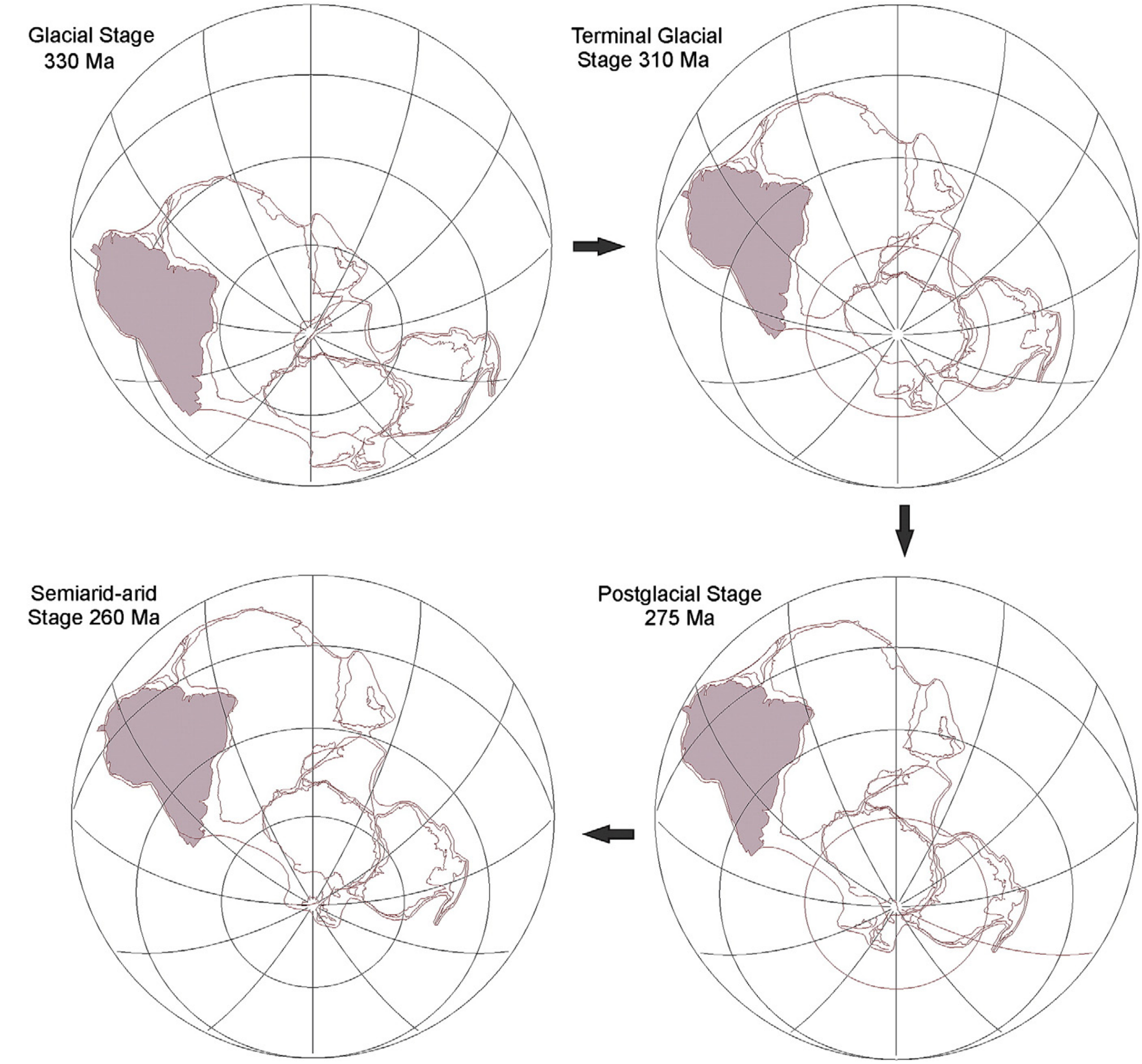

Fig. 14. Gondwana paleolatitudinal reconstruction for the stages considered in this work, based on the paleomagnetic poles in Fig. 13. Schmidt projection, south hemisphere.

conditions are suggested by the occurrence of abundant remains of the *Gangamopteris* flora. Further east, in the Paraná Basin, climatic conditions were humid enough to allow for the formation of thick coal beds and organic-rich mudstones of the Rio Bonito Formation (humid belt in Fig. 16).

The origin of the Cisuralian north–south climatic belt was likely related to the formation of a long volcanic barrier (Choiyoi Group and equivalents) along the western margin of South America. This volcanic chain, of several thousand kilometers length, separated the retroarc basins from the Permian sea thus transforming almost the entire retroarc region into an inland area starting in the middle Cisuralian (Fig. 16). Thus, many of these basins were enclosed between two mountain ranges, the volcanic Permo-Triassic chain to the west and the Sierras Pampeanas to the east (Fig. 16). It is interesting to speculate about the effect that those positive areas may have had on the formation of climatic belts. It should not be ruled out that humid winds coming from the west (Protopacific Ocean, Fig. 16) would have been forced to rise over the volcanic chain leaving the majority of their moisture in the coastal region due to the orographic effect. Similarly humid winds coming from the east (Protoatlantic Ocean) could have left most of their moisture within the Paraná Basin or, even exceeding the Sierras Pampeanas, would have turned the remaining moisture along its western flank. These situations, although hypothetical, may explain the existence of north–south climatic belts in southern South America during the postglacial stage: 1. the western semidesertic areas (western Paganzo Basin), 2. the central wet belt (eastern Paganzo Basin) and 3. the humid belt in the Paraná Basin (Fig. 16).

10. Paleoclimatic evolution of southern South America: discussion

The paleoclimatic evolution of southern South America consistently shows a transition from icehouse conditions in the Late Mississippian–Early Pennsylvanian to extreme greenhouse conditions in the late Permian (Fig. 17). Similar paleoclimatic patterns have been found on a global scale using different techniques and methods (Gastaldo et al., 1996; López Gamundí et al., 1992; Guerra-Sommer and Cazzulo-Klepziga,

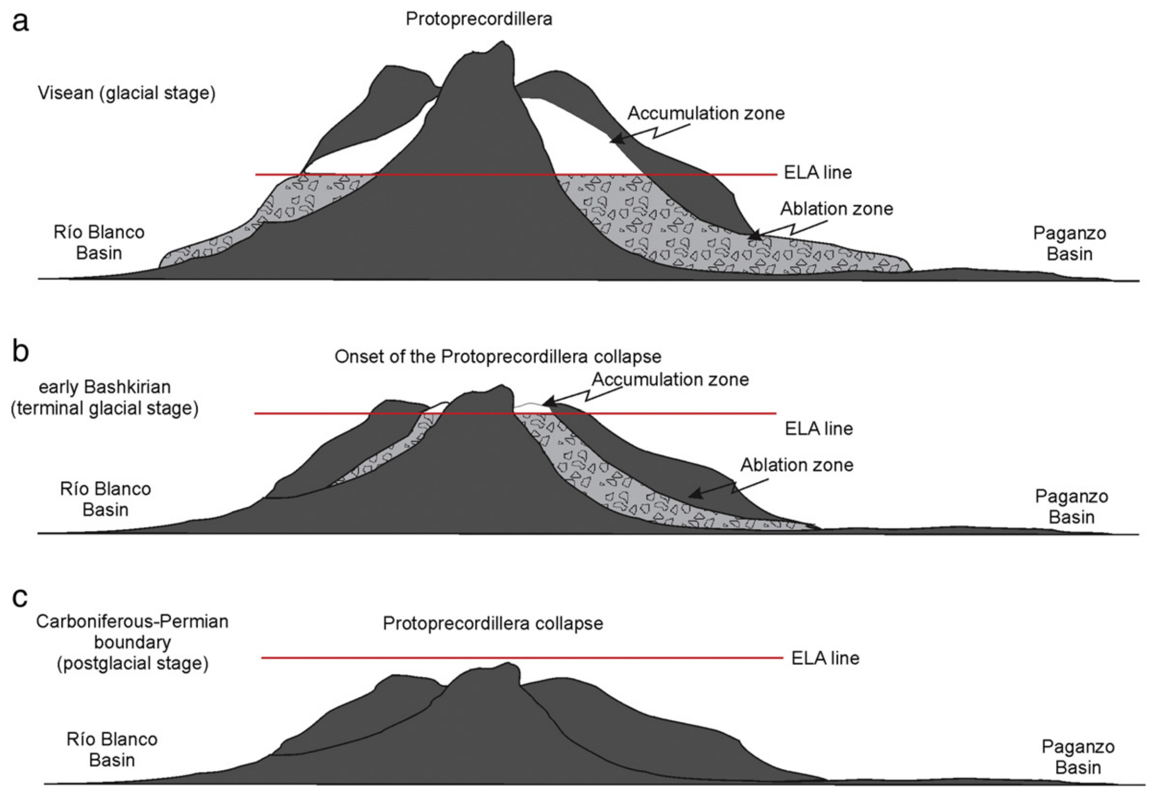

Fig. 15. Hypothetical relation between the ELA line and the collapse of the Protoprecordillera.

2000; Retallack, 2005; Horton et al., 2007; Montañez et al., 2007; Isbell et al., 2008b; Grossman et al., 2008; Shi and Waterhouse, 2010; among others). Although glacial climates have been recognized from the latest Devonian to the earliest Carboniferous (Isaacson et al., 1999; Isbell et al., 2003a; Grader et al., 2007; Caputo et al., 2008; Grader et al., 2008; Isaacson et al., 2008) the most severe and largest glacial period on a worldwide scale seems to have begun in the late Visean and continued into the earliest Permian (Isbell et al., 2008a; Shi and Waterhouse, 2010). This period corresponds to the glacial (late Visean–early Bashkirian) and terminal glacial (Bashkirian–earliest Cisuralian) stages defined in this paper. However, it is important to bear in mind that glacial conditions did not span all this time but rather comprised discrete intervals on the order of 1–10 M.y. alternating with non-glacial intervals (Fielding et al., 2008b; Holz et al., 2008). This is clearly exposed in the Paganzo and Río Blanco basins from Argentina where glacial diamictites of the Upper Member of the Cortaderas Formation (Late Visean) are succeeded by non glacial deposits containing remains of the Paraca flora indicating warm temperate conditions (Early Serpukhovian). In turn, the overlying Guandacol Formation (Serpukhovian–Bashkirian) bears one of the most complete records of the Gondwanic glaciation in the Andean region. Using the worldwide scale models for the late Paleozoic glaciation proposed by Isbell et al. (2003a) and Fielding et al. (2008b), the glacial deposits of the Cortaderas Formation could fit with the C1 glacial interval in the eastern Australia basins (glacial 2 by Isbell et al., 2003a), while the glacial tillites described in the Guandacol Formation would correspond to the C2, and also probably the C3, glacial intervals (Fielding et al., 2008a).

Isbell et al. (2003a) considered widespread ice sheets during late Moscovian–middle Sakmarian coinciding with the terminal glacial paleoclimatic stage defined in this paper, and local alpine glaciation during the Serpukhovian and early Bashkirian (The glacial stage in this paper). Montañez et al. (2007) pointed out a maximum expansion of Gondwana continental ice-sheets during the earliest Permian when the lowest paleoatmospheric CO_2 levels were reached. This conditions correlates with the glacial deposits described in the Parana Basin included here in the Bashkirian–earliest Cisuralian terminal glacial stage. Frank et al. (2008) studied intensity of glaciation using fluctuations in atmospheric pCO_2 suggesting the onset of the glaciation in the middle to upper Visean and maximum glacial conditions during the Early Permian. The Visean onset for glaciation in Gondwana was

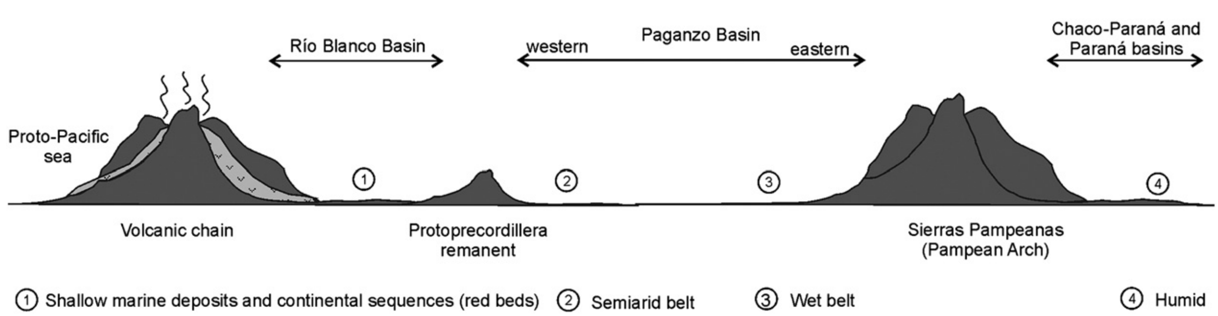

Fig. 16. North–south climatic belts controlled by uplift of the Andean volcanic chain to the west and the Sierras Pampeanas to the east.

also postulated by Mii et al. (1999) using $\delta^{13}C$ and $\delta^{12}O$ excursions on brachiopod shell calcite from North America and by Smith and Read (2000) based on carbonate stratigraphic studies.

Glacial deposits younger than Sakmarian have only been reported from the eastern basins of Australia (Guadalupian–early Lopingian, Fielding et al., 2008b) and possibly from the Siberian platform (Zharkov and Chumakov, 2001). In this last case, Epshteyn (1981) argues that diamictites were the result of surface (sea ice). Evidence by Biakov et al. (2010) suggests that these were not glacial in origin but were mass movements and sediment gravity flows assoicated with the Okhotsk–Taigonos Volcanic Arc. Anyway, the paleogeographic position of east Australia and Siberia were close to the South and North Poles, respectively, which explains the presence of limited ice masses rather than global cooling. Therefore, the glacial and terminal glacial stages reported here approximately correlate with the age of icehouse conditions throughout the global scale and encompass the late Visean–Asselian interval in South America (Fig. 17).

According to paleoclimatic models, the reduction of continental land-masses during the latest Carboniferous–earliest Permian led to a progressive warming in tropical regions of Pangea which was controlled by a reduced global albedo and an increase in greenhouse conditions due to an increase in global specific humidity (Poulsen et al., 2007). Also by low latitudes, Peyser and Poulsen (2008) identified two main mechanisms capable of causing aridification during the Permian, the retreat of continental ice on Gondwana and the increasing atmospheric CO_2.

The progressive aridity observed in the whole of the southern South American basins from the late Guadalupian is in keeping with the transition to extremely severe climates that produced the worldwide Permo-Triassic extinction (Erwin et al., 2002; Clapham et al., 2009; Metcalfe and Isozaki, 2009). According to Raup and Sepkoski (1982) and Clapham et al. (2009), high extinction rates in marine environments started at the end of the Guadalupian, which began the onset of the prolonged end-Permian crisis. In South America, the semiarid–arid stage was characterized by fluvial, ephemeral lacustrine and eolian deposits in the Paraná Basin (upper Rio do Rasto Formation, Rohn et al., 2005; Holz et al., 2010) that were replaced by dominantly eolian successions during the Lopingian and Early Triassic (Pirambóia and Sanga do Cabral formations). This transition from semiarid to arid environments also occurred in the western basins where fluvial deposits of the Talampaya Formation are replaced by playa lake and alternating fluvial and eolian successions during the latest Permian (top of the Talampaya Formation).

The origin of the dramatic environmental changes that occurred during the late Permian cannot be unequivocally identified. However, there seems to exist a general agreement that high output of volcanic activity played a principal role in the changing conditions (Campbell et al., 1992; Kamo et al., 2003; Metcalfe and Isozaki, 2009). The Siberian Traps volcanism, which occurred close to the Permian–Triassic boundary (251.7 ± 0.4 Ma and 251.1 ± 0.3 Ma), extruded a ~6500 m thick volcanic succession injecting large amounts of CO_2 and H_2SO_3 into the atmosphere (Kamo et al., 2003). However, southern South American basins show arid to semiarid climates, indicating continental-scale environmental deterioration, at least in the early Lopingian, and probably from as early as the late Guadalupian. Therefore, the onset of semiarid–arid conditions in South America fits better with the end Guadalupian faunal crisis, which has been linked to volcanism of the Emeishan Igneous Province in the southwest China dated into the middle Capitanian (Zhou et al., 2002; Sun et al., 2010).

The environmental effect of the Permo-Triassic volcanism that developed along the western margin of South America during the middle and late Permian (Fig. 17) has been overlooked in global-scale reconstructions. However, taking into account the volume of eruptive rocks that accumulated along the Andean Cordillera, the effect of this volcanism should not be ignored. Strazzere et al. (2006) calculated that Permo-Triassic volcanic rocks, and subsidiary intrusions of the Choiyoi Group, covered an estimated area of ~500,000 km^2 with thickness ranging up to 2000 m in Argentina and Chile. Moreover, Permian volcanism exceeds the Choiyoi province, and to the north, very thick volcanic sequences appear in the Peine Group in Chile,

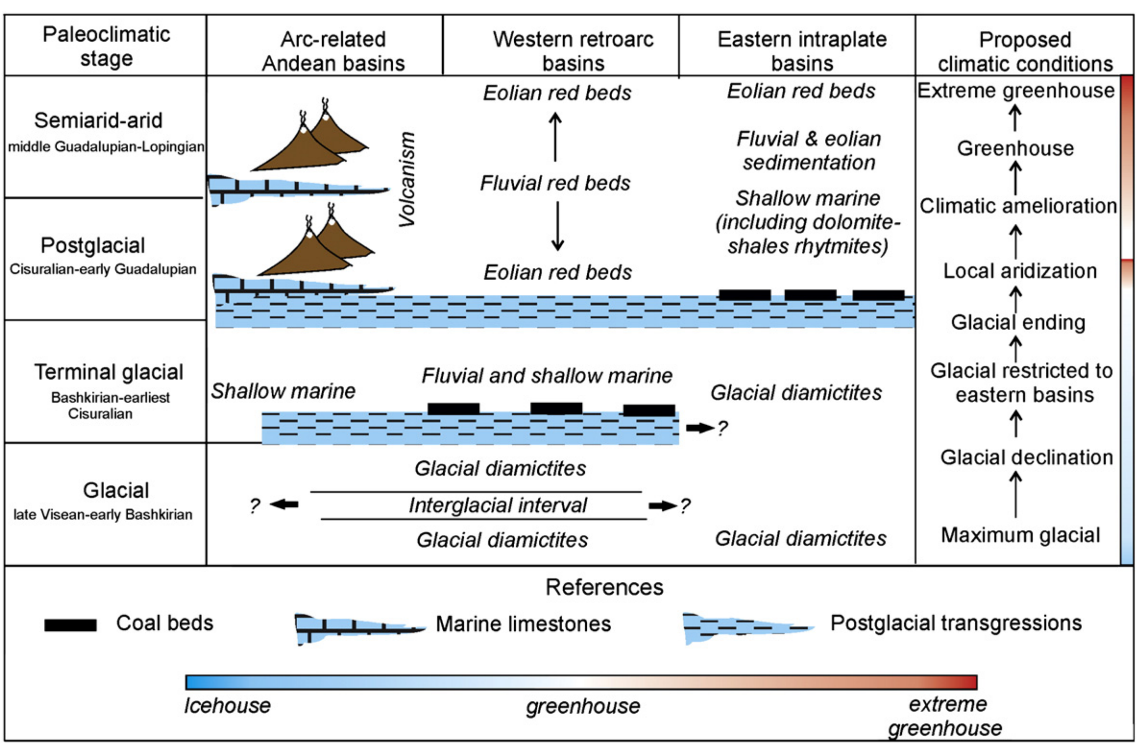

Fig. 17. Schematic representation of the late Paleozoic climatic evolution recorded in strata in the southern South America basins.

Mitú Group in Peru, and the Tiquina Formation in Bolivia. However, the total thickness and areal extent of the Permo-Triassic volcanism have not been accurately estimated yet.

The volcanic activity in the Choyoi Group began at 280 Ma (late Cisuralian) and continued up to 240 Ma (Early Triassic, Llambías, 1999; Kleiman and Japas, 2009). Undoubtedly, this volcanism introduced large volumes of CO_2 and other greenhouse gasses into the atmosphere, for which its influence in environmental deterioration must be considered.

11. Conclusions

The paleoclimatic evolution of the southern South American basins can be synthesized into four paleoclimatic stages: 1. Glacial (late Visean–early Bashkirian), 2. Terminal glacial (Bashkirian–earliest Cisuralian), 3. Postglacial (Cisuralian–early Guadalupian) and 4. Arid–semiarid (late Guadalupian–Lopingian). This scheme provides new evidence for a long-term transition from icehouse (Late Mississippian–earliest Permian) to extreme greenhouse (late Permian) conditions on a global scale.

The glacial stage would have begun in the late Visean in the Paganzo and Río Blanco basins. During the Bashkirian–earliest Cisuralian (terminal glacial stage) glacial deposits disappeared almost completely in the western retroarc basins (Guandacol Formation), but glaciation persisted in the Paraná and Sauce Grande basins (eastern South America).

A progressive climatic amelioration took place during the Permian (postglacial stage) lending to the complete disappearance of glacial deposits in South America and the formation of thick coal beds in the Rio Bonito Formation (Paraná Basin). For this time, north–south climatic belts began to be delineated in the western basins, which were likely controlled by the paleogeography of South America.

Towards the late Permian, climatic belts became less evident and indications of semiarid or arid conditions dominated much of southern South America. Eolian dune, playa lake deposits, and alternating eolian–fluvial successions occur in the Pirambóia and the Sanga do Cabral Formations in the Paraná Basin and in the Talampaya Formation in the Paganzo area.

Although the origin of the extreme greenhouse conditions and the Permian–Triassic extinction are under debate, there is an agreement in the scientific community that volcanism had a principal role. The importance of the Gondwanic volcanism along the western margin of Gondwana (Choiyoi volcanism in Argentina and Chile) has yet to be considered in a similar way as that of the role that the Emeishan igneous province in China and the Siberian Traps played.

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