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Paleogeography of the upper Paleozoic basins of southern South America: An overview

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Abstract

The paleogeographic evolution of Late Paleozoic basins located in southern South America is addressed. Three major types of basins are recognized: infracratonic or intraplate, arc-related, and retroarc. Intraplate basins (i.e., Paraná, Chaco-Paraná, Sauce Grande-Colorado, and La Golondrina) are floored by continental or quasi-continental crust, with low or moderate subsidence rates and limited magmatic and tectonic activity. Arc-related basins (northern and central Chile, Navidad–Arizaro, Río Blanco, and Calingasta–Uspallata basins and depocenters along Chilean Patagonia) show a very complex tectonic history, widespread magmatic activity, high subsidence rates, and in some cases metamorphism of Late Paleozoic sediments. An intermediate situation corresponds to the retroarc basins (eastern Madre de Dios, Tarija, Paganzo, and Tepuel-Genoa), which lack extensive magmatism and metamorphism but in which coeval tectonism and sedimentation rates were likely more important than those in the intraplate region. According to the stratigraphic distribution of Late Paleozoic sediments, regional-scale discontinuities, and sedimentation pattern changes, five major paleogeographic stages are proposed. The lowermost is restricted to the proto-Pacific and retroarc basins, corresponds to the Mississippian (stage 1), and is characterized by shallow marine and transitional siliciclastic sediments. During stage 2 (Early Pennsylvanian), glacial–postglacial sequences dominated the infracratonic (or intraplate) and retroarc basins, and terrigenous shallow marine sediments prevailed in arc-related basins. Stage 3 (Late Pennsylvanian–Early Cisuralian) shows the maximum extension of glacial–postglacial sediments in the Paraná and Sauce Grande-Colorado basins (intraplate region), whereas fluvial deposits interfingering with thin intervals of shallow marine sediments prevailed in the retroarc basins. To the west, arc-related basins were dominated by coastal to deep marine conditions (including turbiditic successions). In the Late Cisuralian (stage 4), important differences in sedimentation patterns are registered for the western arc-related basins and eastern intraplate basins. The former were locally dominated by volcaniclastic sediments or marine deposits, and the intraplate basins are characterized by shallow marine conditions punctuated by several episodes of deltaic progradation. Finally, in the Late Permian (stage 5), volcanism and volcaniclastic sedimentation dominated in basins located along the western South American margin. The intraplate basins in turn were characterized by T–R cycles composed of shallow marine, deltaic, and fluvial siliciclastic deposits.
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1. Introduction

During the Late Paleozoic, the Gondwana supercontinent plausibly reached its maximum expansion, encompassing Australia, India, Antarctica, part of South Africa, the southern half of South America, and a poorly defined group of perigondwanic basins (for a review, see Veevers and Powell, 1994). The western margin of Gondwana, represented in the vast Upper Paleozoic basins of South America, is an important link in the reconstruction of Gondwanan history for several reasons. First, South American basins exhibit a complete Late Paleozoic stratigraphic record, including thick successions of Early Carboniferous age, a time interval often poorly represented in Gondwana.

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Second, important data pertinent to the paleoclimatic evolution of Gondwana can be found in several South American basins. Thus, sedimentological studies reconstruct not only the timing of different glacial episodes but also the transition to semiarid and arid climatic conditions toward the Permian (Bigarella et al., 1967; Rocha-Campos, 1967; Limarino and Spalletti, 1985; López Gamundí, 1986, 1997; López Gamundi et al., 1992; Isaacson et al., 1999). The extensive magmatic activity registered in the western margin of southern South American basins during the Late Paleozoic (Breitkreuz et al., 1989; Kontak et al., 1990; Bahlburg and Breitkreuz, 1991; Llambías, 1999) is among the most important recorded in the Gondwana supercontinent. The rich paleontological record many of these basins have yielded makes them even more significant. Different biostratigraphic schemes have been developed from the study of fossiliferous assemblages and used in regional correlations among different Gondwana basins, because they constitute essential tools to constrain the age of major geologic events (Archangelsky et al., 1996a,b; Díaz Martínez et al., 2000; Azcuy et al., 2002; Gutiérrez et al., 2003; Souza and Marques-Toigo, 2003).

Despite the importance of the Late Paleozoic basins of southern South America, the considerable deficit of regional-scale studies has limited the integration of the evolution of different basins through the few detailed studies or attempts to correlate the depositional records of the basins of the western Andean region and those on the eastern flat of South America. In recent years, this lack of information has begun to be resolved by valuable research focusing on the analysis of the Late Paleozoic record at the regional scale (Isaacson et al., 1995a,b; Starck, 1995; Díaz Martínez, 1996; Sempere, 1996). These papers supply new stratigraphic information, correlation models for adjacent basins, and information about the evolution of depositional environments. Following these contributions, we present an overview of the paleogeographic and paleoenvironmental evolution of the Late Paleozoic basins of South America between 15°S and 46°S (Fig. 1). Our contribution is intended as a first approach to regional paleogeographic models, though some differences in basin treatment reflect uneven knowledge about the South American basins. We use Dickinson's (1978) classification for basin terminology.

2. Upper Paleozoic basins of southern South America

Two major groups of Late Paleozoic basins, separated by a large, continuous upland area, are traditionally recognized in this part of South America (Fig. 2): (1) intraplate basins located to the east and (2) basins along active margin of Gondwana, almost entirely in the western (Andean) region. These two types of basins are separated by a large upland area. To the south, this positive feature is represented by the Somuncura Massif (northern Patagonia), which enlarges to the north to form the Pampean Arch, which remained a paleogeographic highland during Late Paleozoic sedimentation. The basement of the Pampean Arch is divided in two major portions (Ramos et al., 1986; Gamundí et al., 1994), the eastern, formed by Late Precambrian high-grade metamorphic rocks intruded by Early Paleozoic granitoids, and the western portion, which comprises medium- to low-grade schist intruded by Ordovician and Devonian granitoids. At about 24°S, the Pampean Arch splits in two branches, the Puna Arch to the west and the Michicola Arch to the east, which northward is welded to the Guaporé Craton (Fig. 1).

The division between infracratonic (Dickinsin, 1976) or intraplate (Ingersoll and Busby, 1995) and active margin basins reflects not only the paleogeographic location of the depositional areas but also the very different tectonic, magmatic, and sedimentary history that these types of basins show. Overall, intraplate basins are floored by continental or quasi-continental crust (e.g., Guaporé, Brasiliano, and Río de La Plata cratons). They show limited magmatic and tectonic activity. Subsidence rates are relatively low or moderate, making the thickness of the Upper Paleozoic sequences much thinner than their equivalents in the western region. Likewise, the major part of the intraplate basins opened at the beginning of the Late Carboniferous. Therefore, Early Carboniferous rocks are missing or their occurrence is so limited that they have not been studied in depth. The main basins of the intraplate region are the Paraná, Chaco-Paraná, Sauce Grande-Colorado, and La Golondrina. The Paraná Basin is the largest Upper Paleozoic basin of South America, covering approximately 1,700,000 km^2 (Milani and Zalán, 1999; Holz et al., 2000). It is bounded to the north by Precambrian crystalline rocks of the Brasiliano and Guaporé cratons and the south by the Río de La Plata Craton. The Asunción Arch separates the Paraná and Chaco-Paraná basins (Fig. 1). However, the southward extension of the Asunción Arch is still uncertain. According to paleogeographic reconstructions, two major depocenters, Alhuampa and Las Breñas (Fig. 1), are recognized in the Chaco-Paraná Basin (Fig. 1; Russo et al., 1987; Fernández Garrasino, 1996). Despite several facies changes among depocenters, the stratigraphic record of the Chaco-Paraná Basin can be correlated with the Paraná area in Brazil. To the south occurs a small but interesting group of outcrops and subsurface sequences known as the Sauce Grande-Colorado Basin (Gamundí et al., 1994; Andreis and Japas, 1996; Limarino et al., 1999; Chebli et al., 1999). Finally, in the Patagonian region, the La Golondrina Basin (Fig. 1) represents the southernmost record of Late Paleozoic rocks in the cratonic area (Fig. 1). This small basin, flanked and floored by Proterozoic metamorphic rocks and Paleozoic granitoids belonging to the so-called Deseado Massif (Leanza, 1958), shows a very interesting succession of fossil-rich latest Carboniferous–Early Permian deposits (Archangelsky et al., 1996b).

In contrast with the intraplate area, the basins located along the western Gondwana margin are floored by different types of crustal rocks, from an Early-Middle Paleozoic oceanic and quasi-oceanic crust to Precambrian and Early

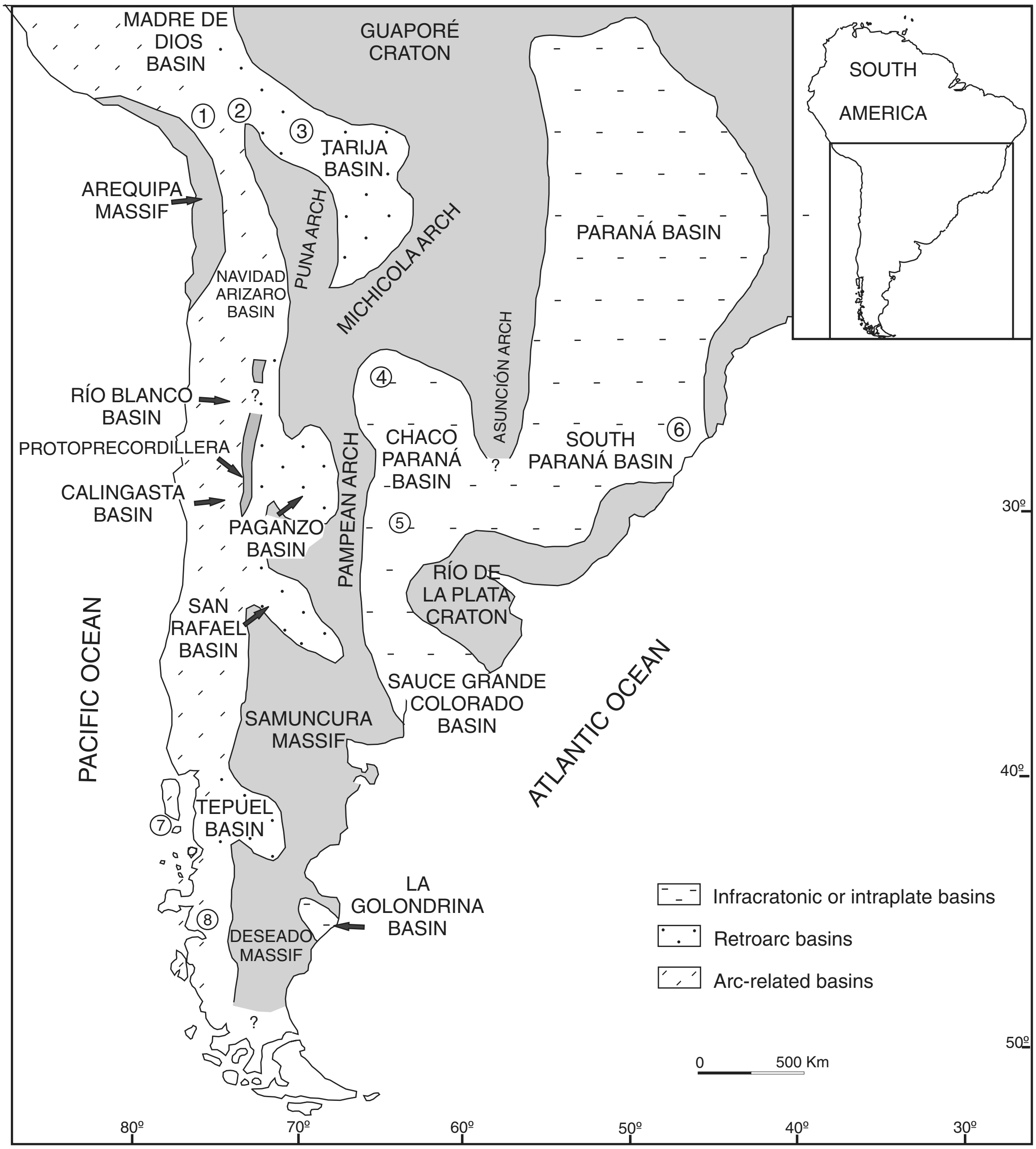

Fig. 1. Major paleogeographic features of southern South America. (1) Altiplano of Perú and Bolivia, (2) Huarina fold-and-thrust belt, (3) Potosí low subsidence area, (4) Alhuapampa depocenter, (5) Las Breñas depocenter, (6) Perimbó fault zone, (7) Los Chonos, and (8) Bahía La Lancha.

Basin type	***Stratigraphic record***	***Magmatic activity***	***Tectonic activity***	***Deformation and Metamorphism***
Infracratonic or intraplate Basins	Middle Carboniferous to Late Permian	Absent to very low	Very low	Very scarce Late Paleozoic deformation. Metamorphism absent
Retroarc Basins	Early Carboniferous to Late Permian	Low	Low	Localized Late Paleozoic deformation. Metamorphism absent
Arc-related Basins	Early Carboniferous to Late Permian	High	Moderate to high	Metamorphism present in highly deformed successions

Fig. 2. Principal characteristics of intraplate, retroarc, and arc-related basins.

Paleozoic granitic rocks. Moreover, the westernmost basins of southern South America exhibit a very complex tectonic history associated with widespread magmatic activity encompassing a large extensional episode along the active margin of Gondwana during the Permian and Early Triassic (Nasi et al., 1985; Breitkreuz et al., 1989; Kontak et al., 1990; Bahlburg and Breitkreuz, 1991; Llambías, 1999). Subsidence rates were high, leading to the accumulation of several thousands of meters of Late Paleozoic rocks. Despite their similar paleogeographic location and common features, we divide the basins located at the active margin of Gondwana into two subtypes following the classification of Dickinson (1978): arc-related (including fore-, intra-, and backarc) and retroarc basins (Fig. 2). The former encompass northwestern and central Chile, western Argentina, and West Patagonia, with intensive deformation during the Late Paleozoic, extensive magmatism, and in some cases metamorphism of Carboniferous sediments (Gohrbandt, 1992; Sempere, 1996; Jacobshagen et al., 2002; Thomson and Hervé, 2002). In contrast, retroarc basins suffered a minor degree of deformation, less magmatic activity characterized by basic lava flows, and a complete lack of metamorphism of Carboniferous deposits. The main retroarc basins are the eastern sector of the Madre de Dios, Tarija, Paganzo, and Tepuel-Genoa basins (Fig. 1). Arc-related basins include westernmost Madre Dios, Navidad–Arizaro, Río Blanco, and Calingasta–Uspallata, as well as several disperse Late Paleozoic outcrops in the central, coastal, and Patagonian regions of Chile (Fig. 1). In one particular case, the San Rafael Basin can be divided in two sectors, with the western margin as an arc-related basin showing volcanic and volcaniclastic sedimentation and the eastern flank as a more stable retroarc environment.

The Madre de Dios Basin corresponds to the northernmost outcrops we analyze in the western area. This basin, mainly developed in the southeast of Perú and north of Bolivia, is bounded to the east by the Guaporé Craton and to the west by the Arequipa Massif (Fig. 1). The Madre de Dios Basin exhibits a complete Late Paleozoic record, beginning in the Early Carboniferous and ending during the Late Permian, when volcanic and volcaniclastic sequences accumulated (Isaacson et al., 1995a,b; Díaz Martínez, 1996; Giusiano et al., 1998; Zapata et al., 2004).

Southward, the Navidad–Arizaro Basin forms a narrow, north-south elongated depocenter, bounded by two major structural arches, the Puna Arch to the east and the Arequipa Massif to the west (Fig. 1). The regional extension of the Navidad–Arizaro Basin is not well known, but its importance lies in its service as a link between the Madre de Dios Basin in Perú/Bolivia and the northwestern basins of Argentina and Chile. The record of this basin is fragmentary, comprising mainly Late Carboniferous–Early Permian sediments (Aceñolaza et al., 1972; Donato and Vergani, 1985; Niemeyer et al., 1985). Although sufficient paleogeographic information is lacking, we assume that outcrops of the Salar de Navidad (Chile), Salar de Arizaro (Argentina), and Bolivian Puna could have formed a continuous basin between the Arequipa Massif and Puna Arch. Several Late Paleozoic sediments occur as disperse outcrops along the Andean Cordillera, longitudinal valley, and the coastal region of Chile (Thiele and Hervé, 1984; Rivano and Sepúlveda, 1983, 1985; Bell, 1987; Díaz Martínez et al., 2000). They likely are related with similar age sequences in northwest Argentina (Río Blanco and Calingasta–Uspallata, Fig. 1), but the continuity of the outcrops is interrupted by a large volcanic chain developed during the Early Permian–Middle Triassic along the Andean Cordillera.

The so-called Protoprecordillera (Fig. 1) separates the western Río Blanco and Calingasta–Uspallata basins from the eastern Paganzo area (Salfity and Gorustovich, 1983; González Bonorino, 1991). The Paganzo Basin shows an almost continuous sedimentary record from the latest Early Carboniferous to the Late Permian (Salfity and Gorustovich, 1983; Pérez et al., 1993; Limarino et al., 1996). The Río Blanco and Calingasta–Uspallata basins began to subside during the Early Carboniferous, and sedimentation was progressively replaced by volcanism by the latest Early Permian (Fernández Seveso et al., 1993; Limarino et al., 1996; Llambías, 1999). The Protoprecordillera was uplifted in the Late Devonian–Earliest Carboniferous and is basically composed of Late and Middle Paleozoic folded and faulted marine sediments. The Protoprecordillera is likely to continue toward the northeast, welded to the Puna Arch, which basically consists of deformed Lower–Middle Paleozoic sedimentary rocks (Salfity et al., 1975). In this way, the Protoprecordillera and Puna Arch may have acted as important structural elements separating the highly mobile arc-related basins from the retroarc basins. The Tarija Basin appears as a southerly embayment between the Puna Arch and Michicola–Guaporé Craton that grades northward into the eastern margin of the Madre de Dios Basin. Tarija exhibits a complete record from Early Carboniferous to Late Permian sediments (López Gamundí, 1986; Starck et al., 1993; Schulz et al., 1999).

To the south, the paleogeography of the Late Carboniferous–Late Permian San Rafael Basin is not accurately understood. In the northwest, the relation with the Calingasta–Uspallata Basin has been clearly established by Gamundí et al. (1994) but its relation to the southwestern sector of the Paganzo Basin remains poorly known. The eastern extension of the San Rafael Basin has been considerably extended in recent years (Melchor, 1990; Azcuy and di Pasquo, 1999).

In the Patagonian region, the Tepuel-Genoa Basin is flanked by the Somoncura and Deseado massifs (Fig. 1), exhibiting a continuous sequence from the Early Carboniferous to the Early Permian (Andreis et al., 1987; Archangelsky et al., 1996a; Limarino et al., 1999). This basin likely is related in the west to metamorphic rocks outcropping in the Cordillera de La Costa of Chile (Duhart et al., 2001). The belt of Late Paleozoic metamorphic rocks continues along the Patagonian Cordillera of Argentina and

Chile toward the south to 48°30′ (Riccardi, 1971; Godoy et al., 1984; Bell and Suárez, 2000).

3. Paleogeographic models in southern South American basins

On the basis of the distribution of Late Paleozoic sediments, the existence of regional-scale discontinuities (unconformities or correlative conformities), and changes in sedimentation patterns, we divide the paleogeographic evolution of southern South America into five major stages (Fig. 3): (1) Mississippian, (2) Early Pennsylvanian, (3) Late Pennsylvanian–Early Cisuralian, (4) Late Cisuralian, and (5) Middle–Late Permian (geological time scale of Gradstein et al., 2004). Each of these paleogeographic stages is separated by different bounding surfaces that, according to their stratigraphic expression, are grouped into two major hierarchies (Fig. 3). Type 1 corresponds to regional unconformities, frequently related to orogenic events or tectonic activity strong enough to cause substantial paleogeographic changes. Type 2 bounding surfaces appear as local unconformities, significant erosive surfaces, or planes that represent sedimentary truncations resulting from substantial changes in sedimentary facies patterns. Type 1 bounding surfaces are frequently found in the western, highly mobile, arc-related basins, whereas type 2 surfaces prevail in more stable areas (i.e., intraplate basins, Fig. 3). The lateral relations between type 1 and 2 bounding surfaces appears in Fig. 3.

Although at first sight, the paleogeographic time stages may seem somewhat arbitrary, each reflects a particular situation in the paleogeographic evolution of South America. For example, Early Carboniferous times (stage 1) were marked by active tectonism in the basins located along the active margin of Gondwana and a lack of significant sedimentation in the rest of southern South America. Deposits of Early Pennsylvanian age (stage 2) occur throughout the analyzed region, with limited evidence of tectonism and magmatism and separated by unconformities from the Early Carboniferous successions. The Late Pennsylvanian–Early Cisuralian stage 3 corresponds to the maximum extension of glacial accumulations in the cratonic region while fluvial deposits, interfingered with shallow marine sediments, prevailed in the basins of the active margin of Gondwana. Stage 4 (Late Cisuralian) shows considerable contrast in the pattern of the western basins and those in the cratonic area. Whereas the former were locally dominated by volcaniclastic sediments or marine deposits, including carbonate-terrigenous successions, in the cratonic area, transgressive-regressive cycles composed of shallow marine, deltaic, and fluvial siliciclastic deposits prevailed. The Middle–Late Permian (stage 5) elapsed with extensional tectonic conditions associated with the beginning of the Gondwana break-up. Sedimenta-

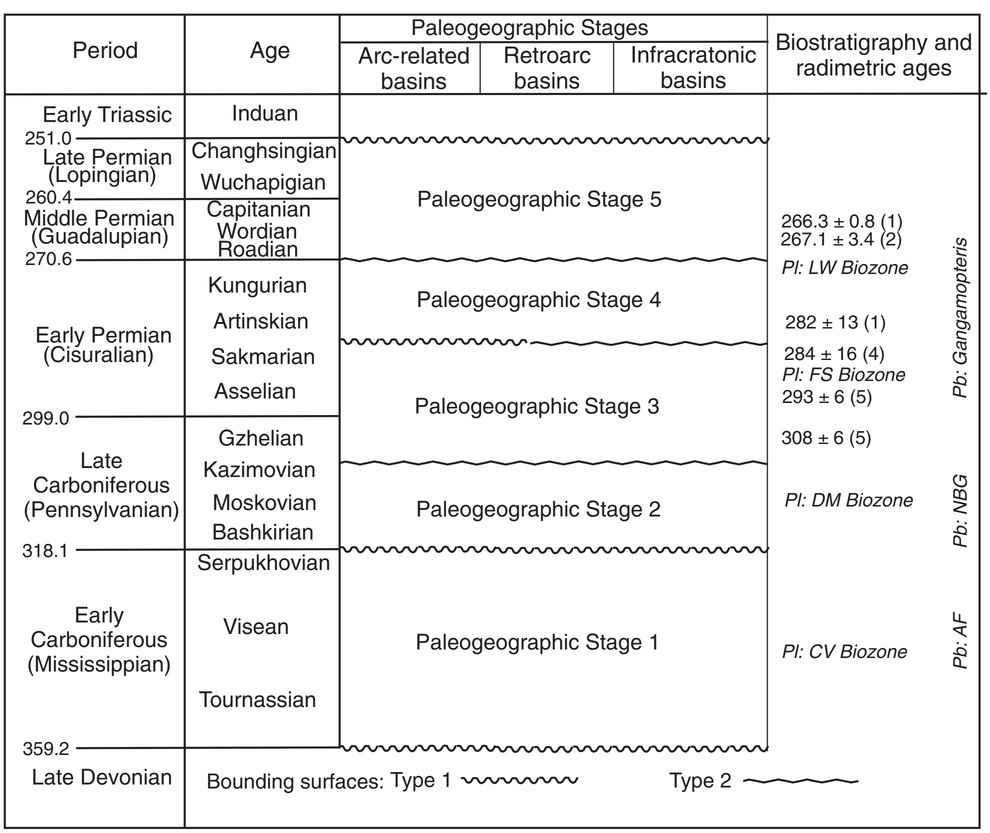

Fig. 3. Defined paleogeographic stages (time scale from Gradstein et al., 2004). Bounding surfaces separating paleogeographic stages are divided into two types (see text). Thompson and Mitchell (1972).

tion continued with two contrasting patterns: widespread volcanism linked to volcaniclastic and fluvial–eolian sedimentation in the western region, and shallow marine, deltaic, and fluvial deposition in the intraplate domain.

3.1. Stage 1: Mississippian (Early C,arboniferous)

Intraplate basins lack Early Carboniferous sediments or form such thin accumulations that they have not been extensively considered in the literature. On the contrary, the basins of the active margin of Gondwana show very thick Early Carboniferous successions dominated by siliciclastic marine deposits that gradually pass upward to continental, facies. Fig. 4 displays a paleogeographic scheme for the Early Carboniferous that emphasizes the important distribution of these sediments in the western region and the dominance of continental to transitional siliciclastic facies.

In the northern region, the Peruvian Madre de Dios Basin shows well-exposed Early Carboniferous sediments composed of shales and sandstones of the Ambo Group (Newell et al., 1949; Isaacson et al., 1995a,b; Zapata et al., 2004). This unit takes different formational names according to its position in the basin; for example, in the Ambo region (slightly north of the analyzed area), it has been divided into the Buena Vista, Yanaj, and Chunomaja formations (Zapata et al., 2004). The Buena Vista Formation, composed of coarse-grained conglomerates, breccias, and sandstones, has been interpreted as an alluvial fan system succeeded by transgressive shales and mudstones. Wave-dominated shallow marine, coastal, and fluvial (deltaic?) systems are represented in the Yanaj Formation, which is overlain by mainly high-sinuosity fluvial deposits of the Chunomaja Formation (Zapata et al., 2004).

To the south, in the Altiplano of Bolivia, the Ambo Group is composed of the Cumaná (Late Devonian–Earliest? Carboniferous), Kasa, and Siripaca formations (Fig. 4). Recent publications note the existence of glacial deposits in the lowermost Cumana Formation and other Famennian–Earliest Carboniferous sections of the Madre de Dios Basin (Díaz Martínez et al., 1993; Isaacson and Díaz Martínez, 1995; Isaacson et al., 1999). Moreover, glacial diamictites were mentioned by Isaacson and Díaz Martínez (1995) in the overlying Kasa Formation. The rest of the Kasa Formation is dominated by deposits of continental and transitional environments in which the development of swamp, small water bodies and deltaic settings favor organic-rich sediment accumulation (Fig. 4). Surrounding Titicaca Lake, the Kasa Formation is characterized by marine shales, mudstones, and sandstones stacked in progradational sequences that represent a transition from storm-dominated marine conditions to fan delta settings (Díaz Martínez et al., 1993). The overlying Siripaca Formation is considered deposited in delta plain environments succeeded by distal fluvial plains (Díaz Martínez et al., 1993). A similar pattern of facies occurs southeast of the Madre de Dios Basin (northern Subandean of Bolivia), where Giusiano et al. (1998) describe shallow marine and deltaic facies in the Toregua and Kaka formations (Latest Devonian?–Tournasian).

Early Carboniferous sediments occur in the north and center of the Tarija Basin (Bolivia), but its existence in outcrops has not been recognized in Argentina despite having been reported in the subsurface by Villa et al. (1984), Suárez Soruco (1989), and Palma (2004). In Bolivia, Latest Devonian–Early Carboniferous sediments appear in the Saipurú and Itacua formations (Suárez Soruco, 1989; Díaz Martínez, 1996; Schulz et al., 1999; Palma, 2004). The former is composed of sandstones, mudstones, and some diamictites interpreted as deposited in continental and transitional (deltaic) environments punctuated by glacial episodes (Fig. 4). Itacua is dominated by shales, mudstones, diamictites, and some intercalations of sandstones likely deposited in prodeltaic settings (Schulz et al., 1999; Palma, 2004).

North of Chile, Early Carboniferous marine deposits have been identified in the upper member of the Zorritas Formation (Isaacson et al., 1985) and probably the Lila Formation (Ramírez and Gardeweg, 1982, Fig. 4). Although "Zorra Beds" were originally considered Silurian or Devonian, Isaacson et al. (1985), on the basis of invertebrate faunas, relocated the upper member to the Tournaisian, likely reaching the Visean. These rocks, up to 1600 m thick, form a coarsening-upward sequence composed of mudstones at the bottom with increasing shales and sandstones upward (Isaacson et al., 1985). The upper member of the Zorritas Formation is composed of fine-grained sandstones, mudstones, shales, and some conglomerates deposited in different marine environments from offshore to deltaic settings (Isaacson et al., 1985).

Farther south, between 25° and 29°S, a very thick (up to 2500 m) lacustrine record is reported from the Chinches Formation by Bell (1985), Fig. 4. It forms a low-grade metasedimentary succession distributed in two north–south elongated belts, the western one appearing in the coastal region of Chile and the eastern belt located in the Andean Cordillera. According to Bell's studies, three major depositional facies occur, and the first is composed of shales and laminated fine-grained sandstones interpreted as deep-water lacustrine deposits. Upward, siltstones and ripple-marked sandstones represent shallow lacustrine environments (Bell, 1985). The third facies corresponds to cross-bedded sandstones and different limestones attributed to a wave-dominated lakeshore (Bell, 1985). Despite the lacustrine interpretation, a marine influence for at least part of the Chinches Formation should not be ignored.

In neighboring areas, other interesting Middle Devonian–Early Carboniferous deep marine successions are the Quebrada de Las Arcas, Las Tórtolas, Sierra del Tigre, and Arrayán formations (Rivano and Sepúlveda, 1985; Sepúlveda and Naranjo, 1982; Bell, 1985; Bahlburg and Breitkreuz, 1991). These units were deposited mainly in deep marine environments, including different types of turbiditic deposits.

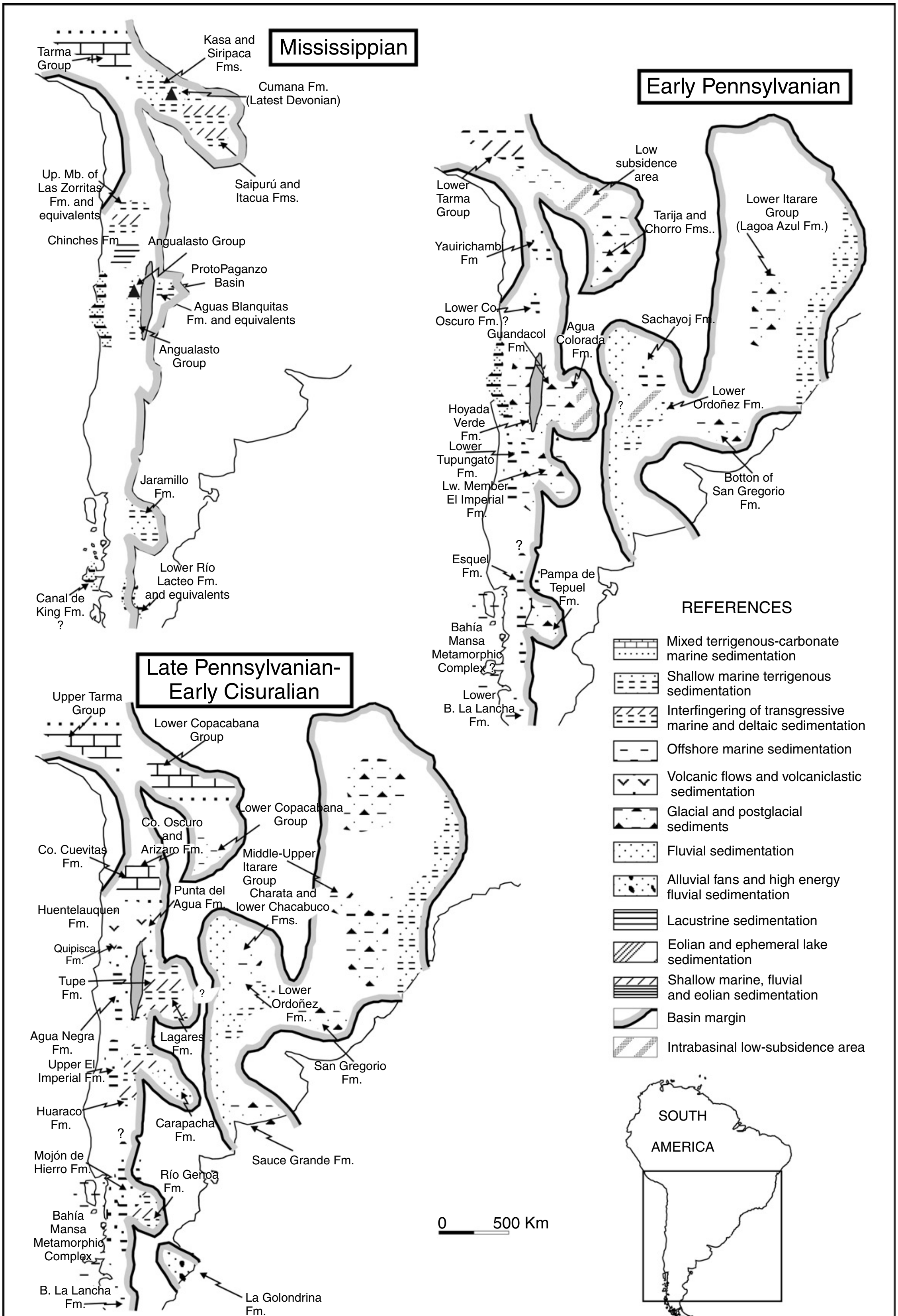

Fig. 4. Suggested paleogeographic evolution of southern South America during the Carboniferous and Earliest Permian.

The Calingasta–Uspallata and Río Blanco basins (Fig. 1) exhibit well-exposed Early Carboniferous successions of the Angualasto Group (Limarino and Césari, 1993). In this case, offshore shales and coastal fine-grained sandstones prevailed in the lower Malimán Formation (Tournasian), while deltaic (including fan-delta sequences), fluvial, and diamictitic deposits occur in the upper Cortaderas (Fig. 4). A remarkable feature of the Malimán Formation is the presence of some coal beds bearing plant remains of the Early Carboniferous *Archaeosigillaria–Frenguellia* biozone (Arrondo et al., 1991; Archangelsky et al., 1996a). Moreover, the existence of glacial-related diamictites bearing palynomorphs of Visean age at the top of the Angualasto Group ensures the existence of glacial climates during at least part of the Early Carboniferous (Limarino and Césari, 1993).

A similar pattern of facies occurs farther south in Patagonia, where the lower part of the Jaramillo Formation (Tournaisian–Visean) is composed mainly of continental sandstones and mudstones (Andreis et al., 1987; González Bonorino, 1991; Limarino et al., 1999). These rocks are followed by shallow marine fine-grained sandstones, which in turn are overlain by offshore shales (Fig. 4). To the west, in the Los Chonos region of Chile, Early Carboniferous sediments may appear in metamorphosed turbiditic sequences of the Canal de King Formation (Chonos metamorphic Complex). The age of this unit is controversial. In some cases, it has been correlated with the Triassic beds of the Potranca Formation, whereas other authors interpret the Canal de King Formation as considerably older on the basis of unpublished fossil remains (see Bell and Suárez, 2000).

Near the Chile–Argentina border, the Andean metamorphic Complex (Hervé, 1993) includes two units of probable Late Paleozoic age. The northernmost Río Lácteo Formation (Leanza, 1972) comprises medium-grade, metamorphosed, fine-grained sediments and some pyroclastic intercalations. According to stratigraphic relationships and radiometric data, Bell and Suárez (2000) propose a pre-Late Carboniferous age for the Río Lácteo Formation. To the south, in the Patagonian Andean Cordillera, marine fine-grained sediments form the Bahía La Lancha Formation (Riccardi, 1971) have been considered Middle(?) or Late Carboniferous in age, though the possibility of an older age (Early Carboniferous?) does not seem improbable.

3.2. Stage 2: Early Pennsylvanian

During the Bashkirian–Moscovian, the oldest Late Paleozoic record in the intraplate basins of southern South America appears. The Paraná Basin shows diamictites and marine postglacial transgressive shales belonging to the lowermost Itararé Group (Lagoa Azul Formation, in the sense of França and Potter, 1991; Campo do Tenente Formation according to Schneider et al., 1974; Fig. 4). Palynological information suggests that these rocks would have been deposited during the Late Bashkirian–Early Moscovian (Souza, 2003; Souza and Marques-Toigo, 2003). Lithologically, the Lagoa Azul Formation is composed of different types of diamictites (true tillites and gravity-flow resedimented diamictites), sandstones, shales with dropstones, and some levels of conglomerates deposited in an overall glacial–postglacial succession (Barros Franca et al., 1996; Fig. 4). The southernmost part of the Paraná Basin in Uruguay shows a similar association of glacial diamictites and transgressive deposits in the San Gregorio Formation. Although the unit was dated by palynological studies as Late Carboniferous or Early Permian (De Santa Ana et al., 1993; Beri, 2003), the unfossiliferous diamictites at the bottom of the San Gregorio Formation may represent the Bashkirian–Moscovian glacial episode (Fig. 4).

In the Alhuampa depocenter, the subsurface record of the Chaco-Paraná Basin shows Late Carboniferous pre-Kasimovian strata in the Sachayoj Formation. This unit is formed by alternating beds of sandstones and mudstones deposited in marine and transitional environments (for a review, see Fernández Garrasino, 1996). Southward, in the Las Breñas depocenter, the lower half of the Ordóñez Formation, likely Moscovian in age (Gutiérrez et al., 2003), is composed of sandstones, carbonaceous mudstones, diamictites, and shales deposited in continental and shallow marine transitional settings (Fernández Garrasino, 1996). Moreover, Winn and Steinmetz (1998) interpret the diamictitic levels in cores of the Ordóñez Formation as subglacial tills or subaerial ice-related mudflows (Fig. 4).

Early Pennsylvanian sediments occur in the Tarma Group (Madre de Dios Basin), where offshore to shallow marine deposits are composed of shales, limestones, interbedded sandstones and mudstones, and cross-bedded sandstones (Newell et al., 1949; Díaz Martínez et al., 1993). The Tarma Group has been assigned, on the basis of marine invertebrates, to the Late Carboniferous (*sensu lato*), but more recent palynological studies constrain the age of the uppermost Tarma levels to the Moscovian (Azcuy et al., 2002). Toward the Altiplano in Bolivia, Early Pennsylvanian sedimens are represented by the Yaurichambi Formation, which filled an irregular topography formed after Middle Carboniferous tectonic movements (Isaacson and Díaz Martínez, 1995). The lower part of the Yaurichambi Formation is composed of fluvial, transitional, and coastal terrigenous sediments (Fig. 4).

In the Tarija Basin, the Early Pennsylvanian sedimentation began with the Tupambi Formation, composed of sandstones and minor proportions of mudstones interstratified with some thin diamictitic levels (Starck et al., 1993; Starck, 1995; Azcuy and di Pasquo, 1999). Despite the presence of glacial-related horizons, the major part of the unit is attributed to transitional (deltaic) environments that evolved to fluvial, sandy-dominated systems (López Gamundí, 1986). The age of Tupambi is currently under debate. It is considered, at least in part, Early Carboniferous in Bolivia, but in Argentina, palinologycal studies suggest a Late Carboniferous age (Azcuy and di Pasquo, 1999). Glacial deposits of Early Pennsylvanian age occur throughout the Tarija Basin in the sub-Andean regions of Bolivia and northwestern Argentina. Several cycles of glacial and resedimented diamictites are recorded in the Tarija Formation of the Macharetí Group (Salfity et al., 1986; López Gamundí, 1986; Starck et al., 1993; Schulz et al., 1999). At the top of the Tarija Formation, diamictites are overlain by transgressive shales, which are followed by alternating sandstone and mudstone beds (Chorro Formation, Bolivia) interpreted by Starck (1995) as periglacial sandy braided river deposits (Fig. 4).

A similar pattern of Bashkirian–Moscovian glacial–postglacial deposits appears in several places in the Paganzo Basin (Limarino and y Gutiérrez, 1990). Glacial continental facies occur in the eastern Paganzo Basin (Agua Colorada Formation), where tillites and glacilacustrine deposits have been described by Limarino and Césari (1988), Limarino and y Gutiérrez (1990), and Buatois et al. (1990). Continental tillites appear in the Quebrada de Las Gredas locality (northwest Argentina), where two genetic types of diamictites have been recognized: (1) resedimented gravity-flow diamictites within glacilacustrine deposits and (2) true tillites composed of massive matrix-supported diamictites. These outcrops are important because the fine-grained glacilacustrine facies bear abundant palynomorphs of Namurian (Late Serpukhovian–Bashkirian) age (Limarino and y Gutiérrez, 1990). At the western Paganzo Basin, transitional facies including marine moraine accumulations (Guandacol Formation) have been studied by Marenssi et al. (2004) Fig. 4.

In arc-related basins, glacial deposits occur in the eastern margin of the Calingasta–Uspallata Basin, where glacimarine deposits appear in the Hoyada Verde Formation (López Gamundí, 1987; Fig. 4). These accumulations represent an excellent example of an ice-contact glacimarine system formed by striated boulder pavements, massive diamictites (tillites), bedded diamictites (gravity-flow resedimented), and dropstone-bearing shales (López Gamundí, 1987). To the south in the San Rafael Basin, a similar assemblage of glacimarine accumulations composed of tillites, gravity-flow resedimented diamictites, and pebbly mudstones is well exposed in the Lower Member of the El Imperial Formation (Espejo et al., 1996). Although some Late Paleozoic diamictites outcropping in Chile were believed to be glacial deposits, these levels were later considered younger or reinterpreted as gravity-flow deposits (Charrier, 1986). Along the Chilean Cordillera, Early(?)–Late Carboniferous marine sediments crop out, forming intensively deformed turbiditic and deep marine facies of the Chañaral mélange (Bell, 1987). This sequence, largely composed of interbedded sandstones and mudstones, shows some intercalations of basic lavas and siliceous tuffs (Bell, 1987; Breitkreuz et al., 1989; Fig. 4).

In Patagonia, Pennsylvanian glacial-related diamictites are noted by Suero (1953), who also identifies several diamictitic levels encapsulated into fine-grained marine sequences of the Pampa de Tepuel Formation. Subsequently, González Bonorino (1992), González Bonorino and Eyles (1995), and González et al. (2003) characterize the glacial–marine deposits and recognize striated pavements. The sedimentary paleoenvironment of the whole Pampa de Tepuel Formation was studied by López Gamundí and y Limarino (1984), who also identify submarine fans and lobes likely linked to proglacial environments (Fig. 4).

To the south, the Bahía La Lancha Formation (Riccardi, 1971) is composed of partially metamorphosed successions of interbedded sandy and muddy turbidites. As mentioned previously, the age of Bahía La Lancha is uncertain, but the finding of remains of licophytes (Frenguelli, 1935) suggests a Middle(?) or Late Carboniferous age.

3.3. Stage 3: Late Pennsylvanian–Early Cisuralian

During the latest Carboniferous and earliest Permian, different types of glacial and glacial-influenced deposits covered most of the Paraná Basin (Bigarella et al., 1967; França and Potter, 1991; Milani and Zalán, 1999; Rocha-Campos et al., 2000; Fig. 4). According to Castro (1999), five depositional sequences related to glacial–postglacial processes can be identified in the Campo Mourao and Taciba formations (middle and upper parts of the Itararé Group). Each sequence forms fining-upward cycles composed of subglacial tillites at the bottom overlain by resedimented diamictites or conglomerates and sandstones deposited in small outwash fans (Castro, 1999). The top of each fining-upward sequence is formed by transgressive shales, suggesting a sea-level rise during glacial melting. The Folhelho Lontras Member (upper part of the Campo Mourao Formation) likely represents a major postglacial (or interglacial) transgression that can be recognized throughout the eastern flank of the Paraná Basin and serve as a regional-scale correlation level (Castro, 1999). The upper part of the Taciba Formation is dominated by deltaic sandstones and mudstones including delta plain coal beds, though in some cases, glacimarine diamictites occur (Castro, 1999; Castro et al., 2004).

Different types of glacial deposits (from glacimarine sequences to terrestrial tillites) formed the southern sector of the Paraná Basin during the Kasimovian–Asselian interval (Bossi, 1966; De Santa Ana et al., 1993; Andreis et al., 1996). The lower part of the San Gregorio Formation is dominated by resedimented diamictites or tillites (De Santa Ana, 1989; De Santa Ana et al., 1993, Fig. 4), which in some cases bear faceted and striated clasts covering striated pavements (Falconer, 1937; Andreis et al., 1996). The genetic relation between glaciation and gravity-flow processes in the lower part of the San Gregorio Formation was stressed by De Santa Ana et al. (1993), who also relate the abundance of resedimented diamictites to a sea-level rise coupled with high sedimentation rates resulting from glacial melting. Both tillites and resedimented diamictites are covered by shales with dropstones, which are overlain by marine shales and fine-grained sandstones (transition to Melo Formation, in the sense of Andreis et al., 1996). During the Sakmarian, glacial conditions appear to have ceased, and the progradation of deltaic and fluvial successions of the San Gregorio Formation began (Andreis et al., 1996).

In the Chaco-Paraná Basin, diamictites were reported from the Latest Carboniferous Charata Formation (Fernández Garrasino, 1996), which is succeeded by Early Permian shales, mudstones, and fine-grained sandstones deposited in shallow marine and transitional environments (lower part of the Chacabuco Formation, Fig. 4). A similar composition appears in the latest Carboniferous–Early Permian record of the Las Breñas depocenter, where the lower part of the Ordóñez Formation bears some diamictite levels (Fernández Garrasino, 1996; Winn and Steinmetz, 1998).

To the south, the Sauce Grande Formation (Sauce Grande-Colorado Basin, Fig. 1) is composed of several levels of diamictites punctuated by thin beds of poorly sorted sandstones, mudstones, and shales (Andreis and Japas, 1996; Andreis and Torres Ribeiro, 2003). Stratigraphically upward, diamictites are gradually replaced by monotonous transgressive sequences of mudstones and very fine sandstones (Piedra Azul Formation, latest Carboniferous–earliest Permian) that represent, at least in part, open marine offshore environments (Andreis and Japas, 1996, Fig. 4). In Patagonia, the lowermost part of the unfossiliferous Laguna Lillo Member (La Golondrina Formation) could have begun to deposit in the Sakmarian. This unit is composed of conglomerates and sandstones deposited in braided alluvial plains (Archangelsky et al., 1996b). Glacial diamictites have not been identified in the Laguna Lillo Member, likely because of its younger age in relation to the other glacigenic deposits.

The sedimentation pattern differed in the basins of the active margin of Gondwana, where glacial diamictites are missing, or if they were present, their glacial origin has not been accurately accounted. For example, in the Altiplano of Bolivia, an important latest Carboniferous–Early Permian transgressive event is recorded (upper Yaurichambi Formation, lower Copacabana Formation; Isaacson et al., 1993; Isaacson and Díaz Martínez, 1995; Fig. 4). The early transgressive stage is represented by shallow marine, deltaic, and fluvial siliciclastic deposits and succeeded by a complex interfingering of terrigenous sediments with marls, limestones, and caliches that belong to the lower section of the Copacabana Formation (cycles 1 and 2 of Isaacson et al., 1993). In the Peruvian sector of the Madre de Dios Basin, this transgressive event occurs in the Tarma Group, composed of sandstones, limestones, shales, and marls.

An interesting continuous sequence of Late Carboniferous–Early Permian sediments crops out in the north Andean region of Argentina (Arizaro), where Late Carboniferous sediments belonging to the Cerro Oscuro Formation are composed of sandstones, conglomerates, and mudstones deposited in alluvial environments (Donato and Vergani, 1985; Andreis et al., 1996; Fig. 4). These rocks are transitionally covered by marine transgressive deposits of the Early Permian Arizaro Formation (Salfity et al., 1986; Donato and Vergani, 1985). The lower half of this unit is dominated by marine terrigenous sediments (sandstones and mudstones) overlain by marine limestones and marls (Aceñolaza et al., 1972). A similar arrangement of facies occurs in the Cerro de Cuevitas Formation (Salar de Navidad area, north of Chile), which shifts from marine fine-grained sandstones and mudstones at the bottom to limestones and marls at the top (Niemeyer et al., 1985; Fig. 4).

A remarkable feature of both the Salar de Navidad and Arizaro records is the presence of several levels of tuffs in the highest stratigraphic levels, pointing to the existence of coeval volcanism. Localized arc-related volcanism of Late Carboniferous–Earliest Permian age was reported from Punta del Agua Formation in Argentina (Río Blanco Basin, Remesal et al., 2004; Fig. 4), and important Late Carboniferous–Earliest Permian volcanic activity appears north of Chile, forming the Quipisca Formation (Galli, 1968). This unit is composed of up to 800 m thick volcanic and volcaniclastic rocks, such as dacitic and rhyolitic tuffs alternating with coarse-grained massive breccias formed by proximal pyroclastic flows. Other thick volcanic–volcaniclastic units north of Chile include the Collahuasi Formation (Vergara and Thomas, 1984), Cas Formation (Ramírez and Gardeweg, 1982), and Peine Group (Bahlburg and Breitkreuz, 1991). The latter comprises ignimbrites, volcanic agglomerates, andesitic flows, and tuffs punctuated by intercalations of volcanic conglomerates and sandstones formed by erosion of the volcanic field during interruptive periods.

In the Tarija Basin, the record of Late Pennsylvanian–Early Cisuralian sedimentation is represented in the Escarpment and San Telmo formations (Starck et al., 1993; Starck, 1995; Schulz et al., 1999; Azcuy and di Pasquo, 1999). The former comprises progradational fluvial and deltaic sandstones and mudstones, whereas the latter has a more complex lithological composition and has been divided into three members (see Azcuy and di Pasquo, 1999). The lower member (Yaguacá) is characterized by shales, mudstones, and very fine-grained sandstones, in our opinion forming a marine transgressive phase (Fig. 4). The middle member (Chimeo) consists of sandstones, conglomerates, and mudstones deposited in coastal alluvial plains and deltaic environments. Finally, the upper member (Caiguami) is composed of diamictitic mudstones deposited in shallow lacustrine areas.

In the Paganzo Basin, fluvial facies predominate along the eastern margin, whereas basinward, they are interstratified with shallow marine deposits (Fig. 4). Fluvial sedimentation is recorded at the top of the Lagares Formation and in the lower member of the La Colina Formation red beds (Limarino et al., 1996; Azcuy et al., 1999). These units are composed of channelized conglomerates, sandstones, and muddy floodplain deposits that have yielded remains of *Gangamopteris* flora (Archangelsky et al., 1996a). An interesting feature of the lower member of La Colina Formation is the presence of some intercalations of alkaline basalts, some of which have been dated to the earliest Permian (Thompson and Mitchell, 1972). On the contrary, in the western sector of the Paganzo Basin, the Tupe Formation shows at least two transgressive events, likely latest Carboniferous–earliest Permian in age.

The neighboring Río Blanco and Calingasta–Uspallata basins are dominated by terrigenous successions deposited from shallow marine to offshore settings (Agua Negra, La Puerta, and equivalent formations, Polanski, 1970; Caballé, 1986; Fig. 4). Recently, Busquets et al. (2005) divided the Agua Negra Formation into two sections separated by an erosional surface on which massive matrix-supported conglomerates were deposited by subaqueous, high-density flows.

Several small outcrops of Late Pennsylvanian–Early Cisuralian sediments appear along the Andean Cordillera of Chile between 29° and 30°S (Chong and Cecioni, 1976; Nasi et al., 1990; Martin et al., 1999). They are composed of marine alternating beds of sandstones and mudstones belonging to the Las Placetas and Hurtado formations. Some Late Paleozoic sediments were metamorphosed during the intrusion of Late Paleozoic–Early Mesozoic batholiths (e.g., Elqui-Limari and Collay batholiths). In the coastal region of Chile, the Huentelauquén Formation comprises alternating beds of limestones and sandstones deposited in shallow marine environments (Thiele and Hervé, 1984; Rivano and Sepúlveda, 1985). Some controversy exists about the age of the Huentelauquén Formation. According to Rivano and Sepúlveda (1983), it is Late Carboniferous, but Díaz Martínez et al. (2000) correlate it with the Artinskian–Kungurian Juan Morales Formation. The Huentelauquén Formation is composed of two stratigraphic members (Rivano and Sepúlveda, 1985): The lower La Higuera Member is made up of black mudstones and sandstones, and the upper La Cantera Member is composed of limestones, calcareous sandstones, marls, and some levels of conglomerates. According to Rivano and Sepúlveda (1985), coarsening-/thickening-upward sequences in the La Higuera Member indicate progradation of deltaic lobes, and the La Cantera Member represents a carbonate platform that periodically received high amounts of clastic sediments.

Mainly continental facies in the east and marine sediments to the west appear in the San Rafael Basin (Fig. 4). Thus, to the east, fluvial and lacustrine sediments bearing remains of *Gangamopteris* flora (Melchor and Césari, 1991) are found in the lower part of the Carapacha Formation (Melchor, 1990). It passes basinward into continental and transitional facies of the Agua Escondida Formation (Azcuy et al., 1999). Farther west, the sedimentary record of the San Rafael Basin is represented by marine sandstones and mudstones belonging to the upper member of the El Imperial Formation (Azcuy et al., 1999).

Southward, the continuity of the Late Pennsylvanian–Early Cisuralian basin appears in the Cordillera del Viento area, where siliciclastic marine and transitional Late Carboniferous–Early Permian sediments were described in the Huaracó Formation (Zöllner and Amos, 1973; Limarino et al., 1999; Fig. 4).

During the Latest Carboniferous, the Tepuel Basin of Patagonia was dominated by inner platform shales and shallow marine mudstones and sandstones (Upper Pampa de Tepuel Formation), though thin levels of fossiliferous limestones appear (López Gamundí and y Limarino, 1984; Fig. 4). Toward the Early Permian, shallow and coastal marine deposits (Mojon de Hierro Formation) were replaced by highly constructive deltaic systems represented in the Río Genoa Formation (Andreis et al., 1987). From the tectonic and paleogeographic viewpoint, an Early Permian magmatic arc (Hervé, 1988) separated the eastern Tepuel Basin from western marine successions in Chile. The Chilean deposits metamorphosed, forming the Complejo Metamórfico de Bahía Mansa (Hervé, 1988; Duhart et al., 2001). This terrigenous marine record extends farther south, where it is known as the Bahía Lancha Formation (and equivalents) of probable Late Carboniferous–Early Permian age (Fig. 4).

3.4. Stage 4: Late Cisuralian

Fluvial sediments corresponding to the lower part of the Río Bonito Formation were deposited in a lowstand system track during the Artinskian and Early Kungurian in the Paraná Basin (Holz et al., 2000). The Río Bonito Formation exhibits a complex pattern of facies associations in both time and space (Zalán et al., 1990; Holz et al., 2000, 2002; Castro et al., 2004). The lower part of the Río Bonito Formation comprises fluvial and estuarine deposits composed of sandstones, mudstones, and thin coal beds forming a thin blanket throughout the basin (Alves and Ade, 1996; Della Fávera et al., 1994; Holz et al., 2000, Fig. 5). At the NNE of the basin, these rocks are succeeded by a succession dominated by marine mudstones and shales of the "Paraguazú" transgression. These deposits grade SSW into lagoonal and barrier island facies, including thick coal beds (Correa da Silva, 1991; Alves and Ade, 1996). Finally, the top of the Río Bonito Formation comprises sandy, shoaling-upward sequences, including some regressive coal seams (Holz et al., 2000; Fig. 5). A radiometric U–Pb age of 267.1 ± 3.4 Ma was obtained by de Matos et al. (2001) from a level of tonstein found in the middle part of the Río Bonito Formation.

Marine conditions also dominated in Uruguay (south of Paraná Basin) during the Late Cisuralian, when fine-grained sandstones and mudstones accumulated in tidally dominated bays and transitional environments (upper Melo Formation, Andreis et al., 1996). Sedimentation evolved to shallow marine and continental conditions (Yaguarí Formation, Fig. 5).

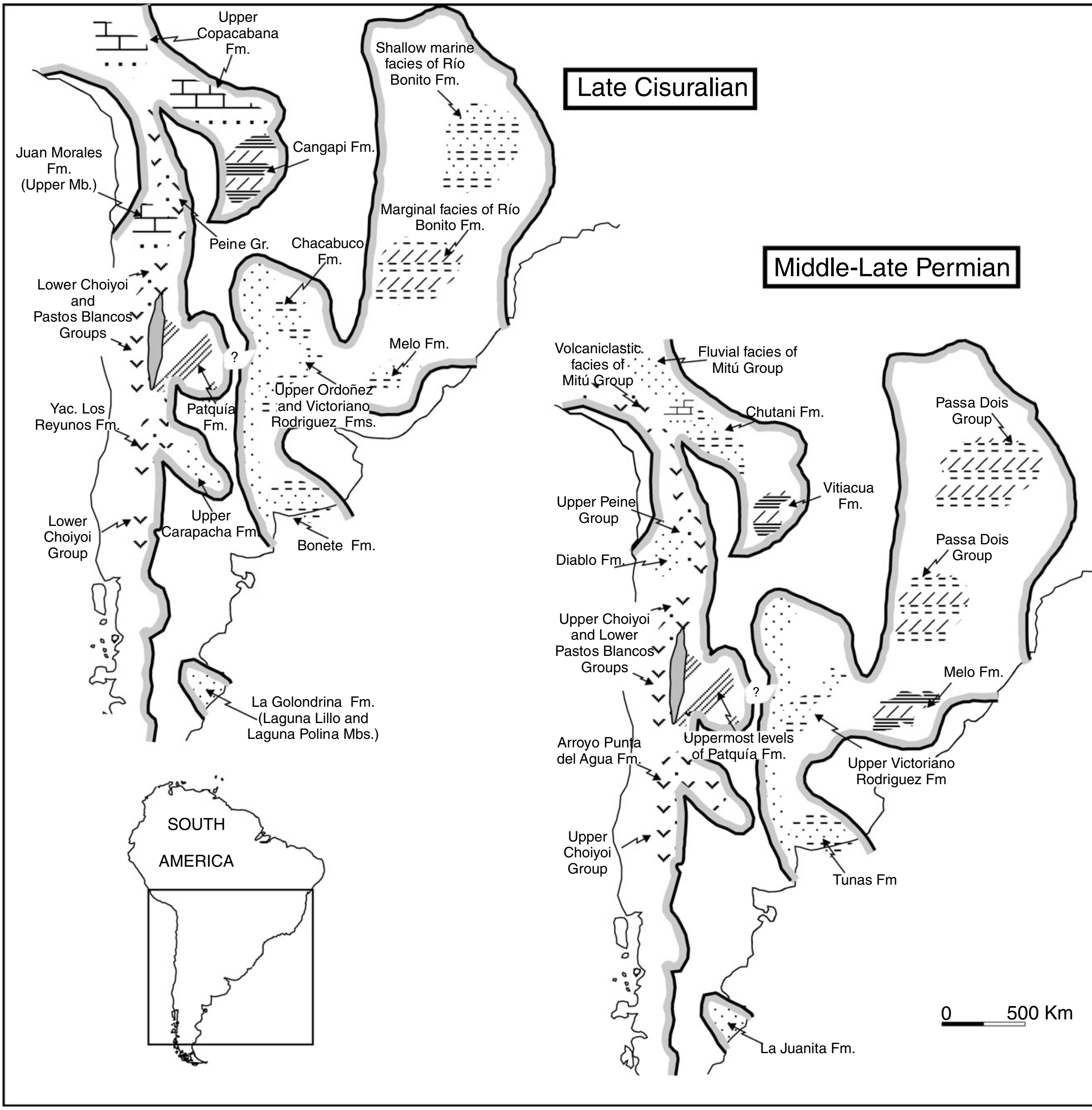

Fig. 5. Suggested paleogeographic evolution of southern South America during the Early, Middle, and Late Permian.

Late Cisuralian rocks occur in both depocenters of the Chaco-Paraná Basin (Fernández Garrasino, 1996; Winn and Steinmetz, 1998; Gutiérrez et al., 2003). At Alhuapampa, shallow marine sediments, in part transitional to continental facies, appear in the upper section of the Chacabuco Formation, which is composed of claystones, siltstones, some intercalations of fine-grained sandstones, and marls (Fernández Garrasino, 1996; Fig. 5). To the south, in the Las Breñas depocenter, the Late Cisuralian interval is represented by shallow marine deposits of the uppermost Ordóñez Formation and lowermost Victoriano Rodríguez Formation (Gutiérrez et al., 2003). In the case of the Sauce Grande-Colorado Basin, the Bonete Formation (supposed Late Cisuralian in age) comprises shallow marine sandstones and mudstones bearing remains of *Glossopteris* and invertebrates of the *Eurydesma* fauna (Andreis and Japas, 1996; Archangelsky et al., 1996a).

Shallow marine conditions were replaced by different kinds of fluvial environments in the eastern Patagonian region (Fig. 5). Strata of Sakmarian–Kungurian age would be represented in the lower and middle members of the La Golondrina Formation (Laguna Lillo and Laguna Polina, respectively; Archangelsky et al., 1996b). The Laguna Lillo Member (650 m thick) comprises massive, cross-bedded conglomerates and sandstones interpreted as braided river deposits. Conglomerates are scarce in the overlaying Laguna Polina Member (800 m thick), where extended muddy floodplain deposits, bearing abundant plant remains, have been attributed to anastomosing fluvial systems (Archangelsky et al., 1996b).

In the western basins of South America, marine sedimentation prevailed. Lagoonal limestones and claystones of the upper Copacabana Formation (cycles 3 and 4 of Isaacson et al., 1993) characterize the sedimentary record in southern Perú and the Altiplano of Bolivia (Fig. 5). In the sub-Andean region of Bolivia and northwestern Argentina (Tarija Basin), the Copacabana Formation pinches out into shallow marine, fluvial, and eolian sandstones and mudstones belonging to the Cangapi Formation (Starck, 1995; Schulz et al., 1999; Fig. 5).

Along the Andean Cordillera of Chile and Argentina, two different lithological associations are identified: (1) interbedded terrigenous-carbonate marine sediments and (2) volcaniclastic and volcanic successions (Fig. 5). The former crop out as the Juan Morales Formation southeast of the Arequipa Massif (Galli, 1968) and are the most representative examples of Late Paleozoic sedimentation along the northern central valley of Chile. According to Díaz Martínez et al. (2000), Juan Morales can be divided into three members. The lower is composed of coarse-grained massive conglomerates and cross-bedded sandstones deposited in alluvial fans flanked by volcanic and high-grade metamorphic rocks. A flooding surface marks the base of the middle member, a series of marine siliciclastic and carbonate sediments interpreted as the deposits of coastal strand plains and open carbonate platform (Díaz Martínez et al., 2000). Finally, the upper member is dominated by terrigenous sediments, probably deposited in an open marine platform subjected to periodic storm events. Díaz Martínez et al. (2000) locate the middle member of the Juan Morales Formation in the Artinskian–Kungurian on the basis of foraminifer biostratigraphy. They also correlate the middle member with the Huentelauquén Formation. If this assumption is correct, the last unit should be relocated to the Late Early Permian. However, the second lithological association composed of volcanic and volcaniclastic rocks is represented by the Peine Group and equivalent units. These successions characterize the Late Cisuralian record along the Andean Cordillera of northern Chile and southern Perú (Ramírez and Gardeweg, 1982; Naranjo and Puig, 1984; Bahlburg and Breitkreuz, 1991; Fig. 5).

In the Paganzo area of Argentina, Late Cisuralian sediments occur in the upper member of the La Colina and Patquía formations, forming an extensive eolian field that covered much of the basin (Limarino and Spalletti, 1985; Pérez et al., 1993; Fig. 5). This desert environment includes not only sand dune deposits but also ephemeral lake and different types of ephemeral river deposits (Limarino et al., 1993).

In the Andean Cordillera, sedimentation in the Río Blanco and Calingasta–Uspallata basins was almost totally replaced by very thick sequences of volcanic rocks belonging to the Choiyoi Group. These rocks were divided into two sections (for a review, see Llambías, 1999), of which only the lower is Late Cisuralian in age. The volcanic rocks of the lower section form a calc-alkaline association composed of ignimbrites, volcanic breccias, andesites, and dacites (Llambías et al., 1993; Sato and Llambías, 1993). Moreover, in the lowermost levels of the Choiyoi Group, up to 400 m thick volcanic agglomerates, conglomerates, and breccias appear. This coarse-grained association resulted from volcanosedimentary flows and fluvial sedimentation during interruptive periods (Llambías, 1999, Fig. 5). The Chilean sector of the Andean Cordillera, at the latitudes of the Río Blanco and Calingasta–Uspallata basins, shows similar volcano and volcanosedimentary deposits in the Pastos Blancos Group (Thiele, 1964; Mpodozis and Cornejo, 1988). According to Martin et al. (1999), the Pastos Blancos Group may be divided in two volcanic-volcaniclastic sequences: Guanaco Sonso (Permian–Early Triassic) and Los Tilos (Middle–Late Triassic–Early Jurassic). Only the Upper Paleozoic Guanaco Sonso sequence results are of interest herein. It comprises rhyolitic welded ashflow tuffs, rhyolitic and dacitic lava flows, volcanic conglomerates, lithic sandstones, and massive breccias (Martin et al., 1999). The Guanaco Sonso sequence was considered the extrusive and epiclastic equivalent of the Permian Ingaguas superunit (Nasi et al., 1985; Martin et al., 1999) that forms an extensive Late Paleozoic batholith along the high Cordillera of Chile.

The San Rafael Basin shows two different lithological associations, a western area dominated by volcanic and volcaniclastic deposits and an eastern sector where siliciclastic sedimentation prevailed (Dessanti and Caminos, 1967; Melchor and Césari, 1991; Azcuy et al., 1999). The western association is represented by the Yacimiento Los Reyunos Formation (lower Cochicó Group), mainly composed of volcanic breccias, coarse-grained volcanic conglomerates, ignimbrites, rhyolites, dacites, and tuffs. These rocks yield palynological assemblages of the *Striatites* zone (Césari et al., 1996), as well as radiometric dating of 272 ± 13 (Dessanti and Caminos, 1967) and 272 ± 10 Ma (Toubes and Spikerman, 1976). Recently, Melchor (2000) recalculated seven radiometric ages previously obtained from the Toba Vieja Gorda Member (upper Cochicó Group) by Polanski (1966), Dessanti and Caminos (1967), Toubes and Spikerman (1976), and Linares et al. (1979). According to Melchor (2000), the age of the upper section of the Cochicó Group ranges from 282 ± 13 Ma (Late Cisuralian) to 266.31 ± 0.82 Ma (Early Guadalupian). In the eastern association, the upper section of the Carapacha Formation comprises fluvial–lacustrine sandstones and mudstones in which plant remains of the *Dizeugotheca* zone were found (Melchor and Césari, 1991).

Volcanic and volcaniclastic rocks extend along an almost continuous belt of outcrops reaching northern Patagonia in the Cordillera del Viento area (Limarino et al., 1999; Fig. 5). There volcanic and volcaniclastic rocks in the lower Choiyoi Group yield radiometric Late Cisuralian ages. Late Early Permian sedimentary rocks have not been identified in the Tepuel-Genoa Basin. It is not clear if the Late Cisuralian sediments were eroded or the basin was closed by this time.

3.5. Stage 5: Middle–Late Permian (Guadalupian–Lopingian)

Middle–Late Permian sediments are represented in the Paraná Basin by a thick, coarsening-upward sequence known as the Passa Dois Group (Rohn, 1994; Canuto, 2000; Simões et al., 2000). Although the Passa Dois Group represents the upper part of the major transgressive-regressive cycle that embraces a great part of the Permian (Simões et al., 2000), detailed studies indicate alternating highstand and lowstand conditions during Passa Dois deposition (Canuto, 2000). For example, the Taquaral Member of the Iratí Formation (lower Passa Dois Group) represents offshore transgressive facies deposited over the Late Kungurian Palermo Formation (Canuto, 2000). Another important flooding is recorded in the Iratí Formation, during which widespread black shales indicate a basinwide euxinic episode (Simões et al., 2000; Fig. 5). Open marine conditions were progressively replaced by coastal and transitional environments represented by carbonaceous shales, very fine-grained sandstones, limestones, and evaporites of the topmost Iratí Formation (Simões et al., 2000). Another transgressive event occurred in the Serra Alta Formation (upper Passa Dois Group). This event was followed by a regressive stage in which shallow marine deposits, including hypersaline conditions (Teresina Formation, Rohn, 1994), were overlain by fluvial and lacustrine red beds (Río do Rasto Formation, Fig. 5).

South of the Paraná Basin, the Middle–Late Permian is represented by the Yaguarí Formation (Ferrando and Andreis, 1986; Andreis et al., 1996), which conformably covers Late Cisuralian sediments of the Melo Formation. Yaguarí has been divided into two members. The lower is mainly composed of mudstones, marls, and subordinated limestones interpreted as tidal-dominated coastal deposits (Andreis et al., 1996). The upper shows less muddy levels, progressively replaced by cross-bedded sandstones that indicate the passage from shallow marine to fluvial environments (Andreis et al., 1996).

It is not clear if Middle–Late Permian rocks occur in the Chaco-Paraná Basin. According to Gutiérrez et al. (2003), the youngest Late Paleozoic levels of Chaco-Paraná occur in the upper Victoriano Rodríguez Formation (subsurface of Las Breñas depocenter). These sediments, which could reach the Guadalupian, are composed of siltstones, claystones, and fine-grained sandstones deposited in shallow marine settings (Fig 5).

In the Sauce Grande-Colorado Basin, the Tunas Formation (Guadalupian?) is composed of medium- and fine-grained cross-bedded sandstones, siltstones, and some levels of intraformational conglomerates and tuffs. According to Andreis et al. (1996), the Tunas Formation was deposited in shallow marine, tidally influenced environments and transitional settings.

In the Patagonia area, despite the lack of paleontological remains, the age of La Juanita Formation (La Golondrina Basin) can be estimated on the basis of its stratigraphic position. La Juanita Formation covers Late Cisuralian sediments of La Golondrina Formation, which suggests a probable Middle–Late Permian age for La Juanita strata (Archangelsky et al., 1996b). The cross-bedded sandstones and conglomerates of this unit are interpreted as fluvial deposits by Archangelsky et al. (1996b) Fig. 5.

North of the western region, the lowermost sections of the Mitu Group (south of Perú) were deposited during the Middle–Late Permian. For simplicity, it is convenient to divide the lower Mitu Group in two major lithological associations: (1) terrigenous sedimentary and (2) volcanic and volcaniclastic (Fig. 5). Good examples of the terrigenous sedimentary association occur in the Pisac Formation, a thick (up to 400 m) red bed succession composed of coarsening and thickening upward sequences of interbedded mudstones, breccias, and conglomerates that unconformably cover limestones of the Copacabana Formation (Carlotto et al., 2004). Although the Pisac Formation has been considered deposited in alluvial fans, locally muddy intervals deposited in lacustrine environments were also reported (Carlotto et al., 2004). The volcanic and volcaniclastic association of the Mitu Group comprises mesosilicic, acid, and basaltic lavas, as well as different genetic types of breccias. Alkaline signatures of the volcanic rocks have been reported by Kontak (1985) and Kontak et al. (1990).

To the south, in the Tarija Basin, Middle–Late Permian sediments appear mainly in shallow marine facies of the Vitiacua Formation (Fig. 5), a 90 m thick succession of mudstones, marls, limestones, and sandstones (Sempere et al., 1992; Starck, 1995). Starck (1995) reports meter-scale shallowing-upward cycles composed of limestones, cherty limestones, and breccias, as well as lenticular bodies of eolian sandstones. These rocks interfinger in the Altiplano of Bolivia with volcaniclastic shallow marine and continental sequences belonging to the Chutani Formation (Isaacson et al., 1995a,b; Sempere et al., 1992). The Chutani Formation is basically composed of silty dolostones, marls, tuffs, fine-grained sandstones, and mudstones that bear remains of *Glossopteris* flora (Vieira et al., 2004). A semiarid climatic condition likely prevailed during the deposition of the Chutani, considered to have been deposited in shallow marine and fluvial (deltaic) environments (Vieira et al., 2004). The uppermost levels of the Chutani Formation are dominated by basaltic lava flows and red volcaniclastic conglomerates and sandstones (Tiquina Member).

In the Navidad–Arizaro Basin, Middle–Late Permian sedimentation was influenced by Permian–Triassic volcanism (Fig. 5). In this way, high-energy fluvial volcaniclastic deposits composed of coarse conglomerates, sandstones, and shales occur in the Diablo (north of Chile, Díaz Martínez et al., 2000) and Machani (south of Perú) formations.

Coevally, thick volcaniclastic sequences, included in the upper levels of the Peine Group, were deposited in the areas of the High Cordillera and longitudinal valley of Chile.

Although stratigraphic and paleomagnetic evidence suggests a Middle–Upper Permian age for the uppermost levels of the Patquía Formation in the Paganzo Basin, the presence of Middle–Late Permian red beds was not confirmed until the finding of palynomorphs of the *Striatites* biozone (Aceñolaza and Vergel, 1987). During this time, the Paganzo Basin was dominated by eolian and lacustrine (ephemeral) sedimentation (Fig. 5), though it remains uncertain if these red beds reached the end of the Permian (Limarino and Spalletti, 1985). In the Andean sector of the Río Blanco and Calingasta–Uspallata basins, sedimentation was almost entirely replaced by very thick sequences of lava flows belonging to the upper section of the Choiyoi Group. Geochemical data suggest an extensional signature for this upper section that formed the "silicic association" of Llambías (1999) Fig. 5. Middle–Late Permian volcanism was also extensively developed in central Chile, where the Guanaco Sonso sequence (lower part of Pastos Blancos Group, Martin et al., 1999) would have begun to form during the Early Permian and continued through the Middle–Late Permian. Finally, important volcanic flows and volcaniclastic sedimentation occurred in the major part of the San Rafael Basin (uppermost levels of the Cochico Group and Cerro Carrizalito Formation, Azcuy et al., 1999). According to radiometric data obtained from Cerro Carrizalito Formation by Linares et al. (1979) and recently recalculated by Melchor (2000), volcanic activity extended almost entirely along the Middle–Late Permian.

4. Controls on late paleozoic sedimentation

Allocyclic controls, such as tectonism, magmatism, sea-level changes, and climate, exerted considerable control over the sedimentological and paleogeographic evolution of Late Paleozoic basins (Dalmayrac et al., 1980; González Bonorino, 1991; Bahlburg and Breitkreuz, 1991; Gohrbandt, 1992; Sempere, 1996). From a tectonic point of view, different tectonosedimentary schemes have been proposed for the western margin of Gondwana, summarized in Fig. 6. That which we adopt is in close agreement with Sempere's (1996) proposal, which recognizes two supersequences in Late Paleozoic basins of Perú and Bolivia: the Villamontes (Late Famenian–Mississippian) and Cuevo (Pensylvanian–Early Triassic, Fig. 6). This division stresses the existence of two different tectonosedimentary cycles separated by an important stratigraphic discontinuity around the Early–Late Carboniferous boundary. The discontinuity is a central issue in the paleogeographic evolution of the Upper Paleozoic Gondwana basins, not only from a stratigraphic point of view but also for the tectonic reconstruction of southern South America. Bahlburg and Breitkreuz (1991) recognize intracarboniferous tectonism ("Toco Orogeny"), characterized in northern Chile by NW/SE- to N/S-trending folds verging SE. To the east, in Argentinian retroarc basins, similar deformation has been described during the Late Mississippian ("Río Blanco

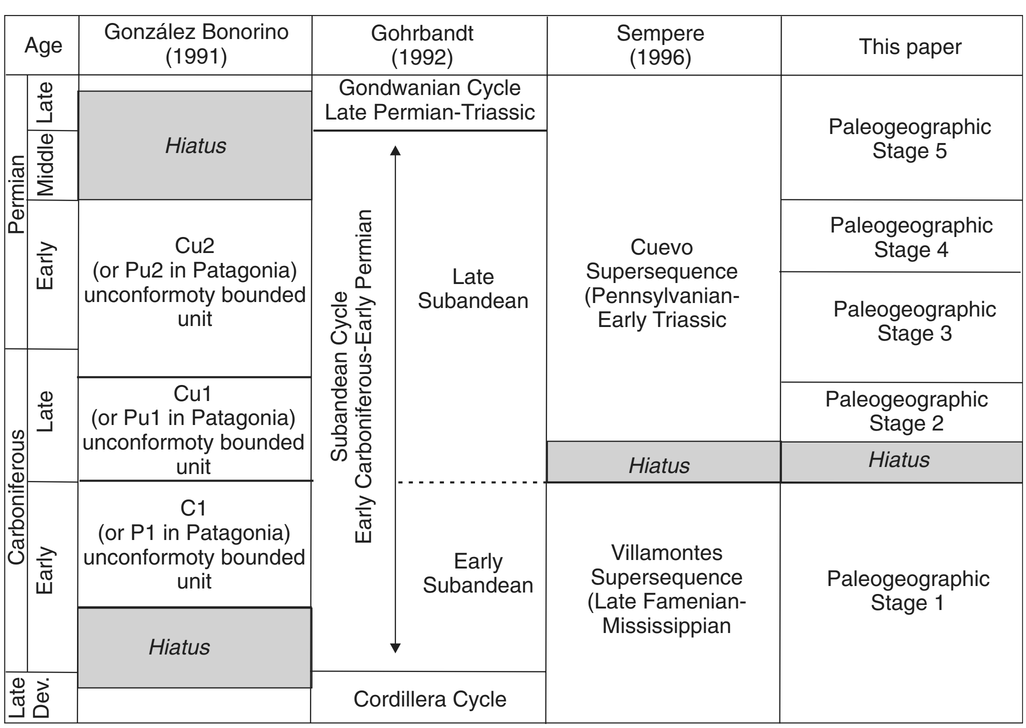

Fig. 6. Synthesis of principal tectonosedimentary schemes proposed for the southwestern Gondwana margin and tentative correlation among different proposals.

movements" of Fauqué and y Limarino, 1989), separating synorogenic Late Devonian–Early Carboniferous sequences (Angualasto Group) from postorogenic arkose suites of the Paganzo Group. Río Blanco movements, as well as the intracarboniferous tectonism of Bahlburg and Breitkreuz (1991), likely represent the last tectonic movements of a Late Devonian–Early Carboniferous orogeny.

According to the preceding authors, tectonism had major control over sedimentation during the Late Devonian–Early Carboniferous (Stage 1, Fig. 7). A continental collision between the Chilenia terrain and the western margin of South America has been proposed by several authors (Ramos et al., 1984, 1986; Gohrbandt, 1992; Davis et al., 2000; Ramos, 2001), which would have resulted in high tectonic instability along the arc-related basins and produced intense deformation (Fauqué and y Limarino, 1989; Bahlburg and Breitkreuz, 1991; Sempere, 1996), coeval magmatism (Breitkreuz et al., 1989; Alemán and León, 2002), and local metamorphism. An important feature of the Late Devonian–Early Carboniferous orogeny was the uplift of the Protoprecordillera fold-and-thrust belt that separated the arc-related basins of Chile and west Argentina from the more stable retroarc Paganzo Basin (Fig. 1). In the same direction, Sempere (1996) considers the probable uplift during the Early Carboniferous of the present-day Huarina fold-and-thrust belt, located close to the eastern border of the Altiplano (Bolivia). It is important to acknowledge that the northern continuity of the Protoprecordillera has not been investigated. At this point, the relationship between the Protoprecordillera and the Huarina fold-and-thrust belt could be critical not only for confirming the Late Devonian–Early Carboniferous orogeny but also for understanding the different deformational styles between arc-related and retroarc basins. Isaacson and Díaz Martínez (1995) highlight a period of uplift followed by intense subaerial erosion and nondeposition in the Altiplano of Bolivia and Perú during the Serpukhovian and Bashkirian. This "Middle Carboniferous hiatus" (Isaacson and Díaz Martínez, 1995) seems to disappear, or at least minimize, to the east in the retroarc basins of Bolivia, Perú, and northwestern Argentina (i.e., Tarija Basin). In the tectonosedimentary scheme of Fig. 6, the Middle Carboniferous unconformity would mark the culmination of important paleogeographic changes that led to the formation of mountain belts, such as the Protoprecordillera and Huarina (see also the Proto-Cordillera of Gohrbandt, 1992). These positive areas would have separated highly mobile basins of the western arc-related area from the eastern retroarc basins, which acted as foreland basins during the Mississippian and earliest Pennsylvanian.

Away from the western region, most of the South American intraplate basins opened during the Early Pennsylvanian (Paraná, Chaco-Paraná, and Sauce Grande-Colorado, Fig. 7). The origin of subsidence in the eastern basins has not been analyzed in detail, but the role of postorogenic relaxation should be borne in mind when analyzing the origin of the intraplate basins.

From the Early Pennsylvanian to the Early Cisuralian (stages 2 and 3), tectonic activity decreased considerably in arc-related basins, and a period of tectonic quiescence seems to have dominated in retroarc basins. As of the latest Carboniferous, volcanism began to expand along the west-

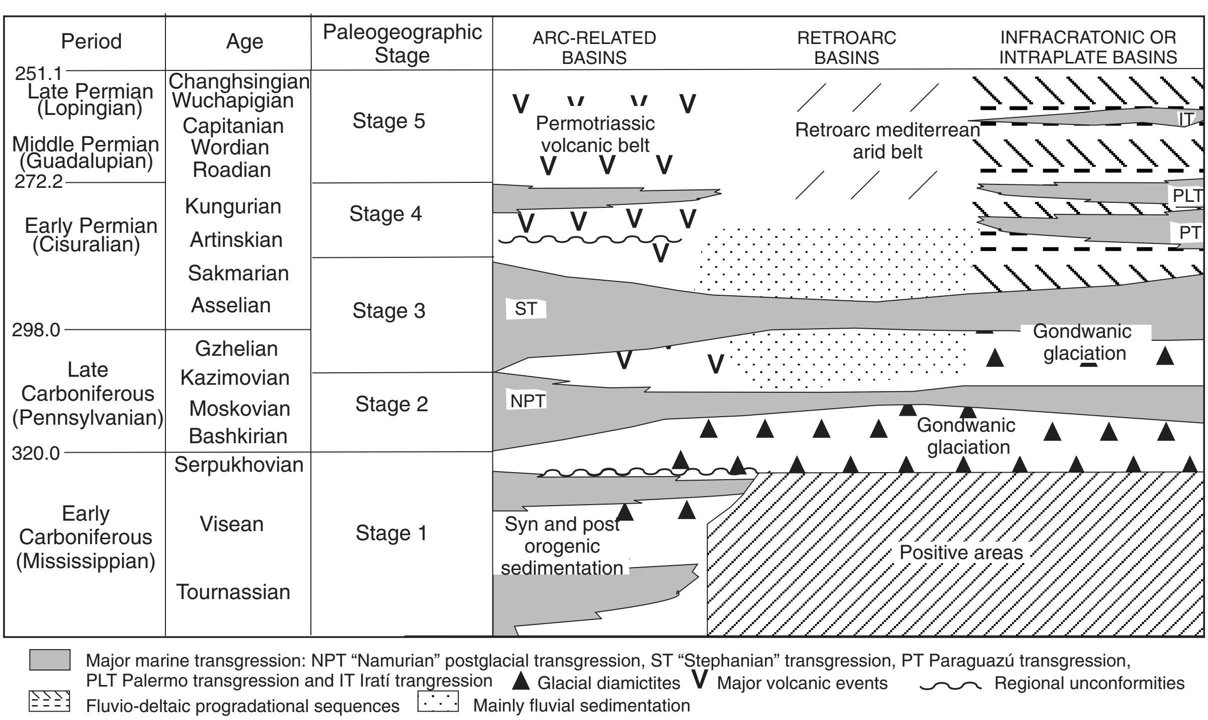

Fig. 7. Paleoenvironmental evolution of Upper Paleozoic basins of South America, according to the paleogeographic stages proposed herein.

ernmost areas, forming very thick volcanic–volcaniclastic successions like those reported from the Peine Group (Bahlburg and Breitkreuz, 1991), Collahuasi Formation (Vergara and Thomas, 1984), and Punta del Agua Formation (Remesal et al., 2004; Fig. 7). The origin of this volcanism is a key question that should be addressed, but modern geochemical studies seem to relate it to the formation of a new active, arc-related margin (Remesal et al., 2004). To the east in the retroarc basins, volcanism was less important or inexistent, and as we discuss subsequently, the transition from glacial to postglacial conditions, coupled with sea-level changes, was the most important control on sedimentation (Fig. 7). Limited tectonic movements in the cratonic area during the Sakmarian–Artinskian were described in the Río Bonito Formation by Holz (2003). These movements, registered in the Candiota coal field, at least partially controlled the base level position and the development of progradational and retrogradational sequences (Holz, 2003).

During the Late Cisuralian (Stage 4), tectonic activity, represented by the San Rafael tectonic phase, was closely associated with volcanism along the arc-related basins (Llambías, 1999; González Bonorino, 1991; Azcuy et al., 1999). This volcanism played a principal role as a control on the extension and nature of sedimentation, producing very important paleogeographic changes (Fig. 7). In some cases, sediments were progressively replaced by volcanic flows, but in others, fine-grained marine deposits were dramatically overlain by coarse-grained volcaniclastic sequences formed at the foothills of the volcanic chains or during intereruptive stages. In the retroarc basins, volcanism was far less important and formed isolated basaltic flows that did not exert a major influence on sedimentation (Limarino et al., 1996).

Extensional tectonism seemingly began to be established in both arc-related and retroarc basins near the Late Permian, favoring local reactivation in sedimentation and extensional magmatism (Kontak, 1985; Llambías, 1999).

The effect of the tectonic activity registered in the western margin of Gondwana on the Paraná Basin was discussed by Milani and Ramos (1998), who argue a phase of increased subsidence occurred in the Late Permian, which may be interpreted as a consequence of the San Rafael movements in the arc-related basins. The true relationship between subsidence acceleration in the cratonic region and tectonic movements in the arc-related basins is not addressed here and should be examined further. One of the main problems in relating Late Permian high subsidence patterns in the Paraná Basin to the San Rafael movements results from the dating of the San Rafael event in the Early Permian in arc-related basins (Caminos and Azcuy, 1996). An alternative interpretation appears in Rostirolla et al. (2003), who examine the Permian activity of the Perimbó fault zone located on the eastern margin of the Paraná Basin (Fig. 1). These authors conclude that Late Paleozoic sediments were deformed by Late Permian oblique extensional movements, generated by in-plane stresses resulting from the convergence of the Sierras Australes of Buenos Aires (Ventania belt, Cobbold et al., 1986; Rostirolla et al., 2003; Fig. 1).

Sea level exerted a major control on sedimentation in both intraplate and active margin Gondwana basins. Early Carboniferous sea-level changes have been scarcely analyzed. In the Argentinean Precordillera a relative sea-level curve has been proposed for the Angualasto Group, in which two major transgressive events were recognized (Limarino and Césari, 1993; Fig. 7). The older one corresponds to the middle member of the Malimán Formation, which bears several invertebrate remains of the Namurian *Protocanites* biozone (Archangelsky et al., 1996b). The younger transgression (Late Tournassian) appears at the top of the Cortaderas Formation covering glacial tillites (Limarino and Césari, 1993). A similar pattern of transgressive events can be identified in the Jaramillo Formation (Tepuel Basin, Patagonia, Fig. 7). However, it is uncertain whether both transgressions should be identified in the north.

The Early Pennsylvanian transgression, which we include in stage 2, occurs in both retroarc and intraplate basins. The "postglacial Namurian transgression" in Argentina (Limarino et al., 2002; Fig. 7) has been correlated with the postglacial marine levels found at the top of the Lagoa Azul Formation (Barros Franca et al., 1996).

From a paleoclimatic point of view, glacial conditions during the Late Devonian and Early Carboniferous have been reported by Díaz Martínez et al. (1993), Limarino and Césari (1993), and Isaacson et al. (1999). Glacial climates favored the formation of diamictitic sequences, followed by postglacial transgressive shales in at least two stratigraphic positions: (1) Latest Devonian (Isaacson et al., 1999) and (2) Late Visean (Limarino and Césari, 1993; Fig. 7).

Paleogeographic stages 2 and 3 show a complete transition from glacial to postglacial conditions (Figs. 4 and 7). In contrast with the conventional wisdom, we consider the maximum glacial in South America was reached during the Early Pennsylvanian, not in the Early Permian. Thus, retroarc and intraplate basins show unequivocal evidence of glacial conditions during the Early Pennsylvannian (paleogeographic stage 2, López Gamundí, 1997; López Gamundi et al., 1992). The situation was modified later, because though glaciation disappeared in most of the retroarc basins toward the Late Pennsylvanian, glacial conditions persisted at least until the Earliest Permian in the cratonic region (Figs. 4 and 7).

As a consequence of recurrent glacial events, different orders of postglacial transgressions can be identified during paleogeographic stages 2 and 3 (França and Potter, 1991; Holz et al., 2000; Limarino et al., 2002). At present, two major third-order transgressions can be followed throughout the region with acceptable confidence (Fig. 7). The older corresponds to the "Namurian postglacial transgression" (earliest Pennsylvanian) and had different effects on sedimentation depending on the paleogeographic setting. Thus, in shallow marine and transitional environments, thick sequences of resedimented diamictites and shales with dropstones formed, covering tillitic deposits or glacial erosive features (Limarino et al., 2002). In continental areas, the transgression flooded a postglacial irregular topography, in some cases forming fjord-type deposits (Buatois et al., 1990; Kneller et al., 2004). The younger postglacial transgression is known in Argentina as "Fauna Intermedia Transgression" and has been referred to the Latest Carboniferous–Early Permian (Archangelsky et al., 1996a). In the western Gondwana basins, this transgression did not cover glacial tillites and cannot be related to glacial evidence. However, in our's opinion, this major transgression may be the equivalent in non-glaciated areas to the postglacial flooding described at the top of the Itararé Group.

Repeated changes in sea level were a very important factor controlling sedimentation patterns in the intraplate basins during the Cisuralian (Figs. 5 and 7). In the case of the Paraná Basin, where the transgressive events have been better studied, three major relative highstands can be recognized (Canuto, 2000; Holz, 2003): "Paraguazu" (Late Sakmarian–Early Artinskian), "Palermo" (Kungurian), and "Serra Alta" (Late Kungurian–earliest Late Permian) (Fig. 7). Each of these transgressions produced retrogradational and progradational cycles recorded in the Río Bonito, Palermo, Serra Alta, and Iratí formations (Alves and Ade, 1996; Canuto, 2000; Simões et al., 2000; Holz et al., 2002). Finally, during the Late Permian, a slow sea-level fall associated with semiarid and locally arid conditions progressively replaced marine sediments by shallower, transitional and/or continental deposits (Rohn, 1994; Figs. 5 and 7). Sedimentation in the western arc-related basins was almost entirely replaced by widespread, mainly acidic volcanism, though coarse-grained breccias composed of volcaniclastic material occur in some places. To the east, behind the magmatic arc, hot climates favored the formation of thick eolian sequences in the Paganzo Basin (Limarino and Spalletti, 1985; López Gamundi et al., 1992; Limarino et al., 1993; Fig. 7), as well as mixed terrigenous-carbonate deposits in transitional and marine settings of the Tarija Basin (Starck et al., 1993; Starck, 1995).

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