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The Late Palaeozoic of Western Gondwana: New insights from South American records

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INTRODUCTION

Late Palaeozoic basins of southern South America offer an excellent opportunity to study sequences deposited in contrasting tectonic regimes, shifting climatic conditions and different sea level positions. From the tectonic point of view, these Late Palaeozoic basins developed in three scenarios (Limarino and Spalletti, 2006): arc-related or Proto-Pacific basins, retroarc or peripheral basins, and large intracratonic or intraplate basins (Fig. 1). Arc-related or Proto-Pacific basins formed along the westernmost and highly mobile area of Gondwana, in which volcanism played a fundamental role. In turn, retroarc or peripheral basins which are characterized by a thick fossiliferous Late Mississippian up to Late Permian record, registered less magmatic activity and minor deformation. Finally, large intracratonic or intraplate basins developed under more stable tectonic regimes and their sedimentary record was mainly controlled by significant climatic and eustatic oscillations (e.g. Paraná Basin).

The effects of dramatic climatic changes and/or eustatic oscillations on Late Palaeozoic basins have been widely studied. Alternating glacial and interglacial periods as well as processes of progressive aridification towards the Middle and Late Permian times have been recognized (Fig. 2). Moreover, a complete record of sea level changes was defined in the intracratonic basins from the Pennsylvanian to the Latest Permian (Fig. 2).

Despite the importance of the aforementioned issues, the stratigraphic and sedimentological information obtained from South American basins has been frequently overlooked in regional or global-scale studies. Although this may be attributed to the lack of knowledge about the Carboniferous and Permian Systems in southern South America, there is abundant literature on the sedimentary and palaeontological record of these basins. This is clearly documented in specific papers and in comprehensive compilations, such as those of Bigarella et al. (1966), Archangelsky (1987, 1996), and Veroslavsky et al. (2006), among others.

CONTRIBUTION OF LATE PALAEOZOIC BASIN STUDIES TO THE UNDERSTANDING OF THE EVOLUTION OF GONDWANA

Several remarkable aspects of the western Gondwana geology can contribute to an improved understanding of the history of the whole Gondwana supercontinent. Four major issues can be highlighted: 1) the Late Palaeozoic orogenic evolution of the western Gondwana margin, 2) the effect of the widespread Permian-Triassic volcanism, 3) the timing of the Late Palaeozoic glacial event, and 4) the Late Palaeozoic bioestratigraphic record.

Late Palaeozoic orogenic evolution of the western Gondwana margin

According to Ramos et al. (1984, 1986) the Chilenia Terrain accreted to the western margin of southern Gondwana during the Middle to Late Devonian. Limarino

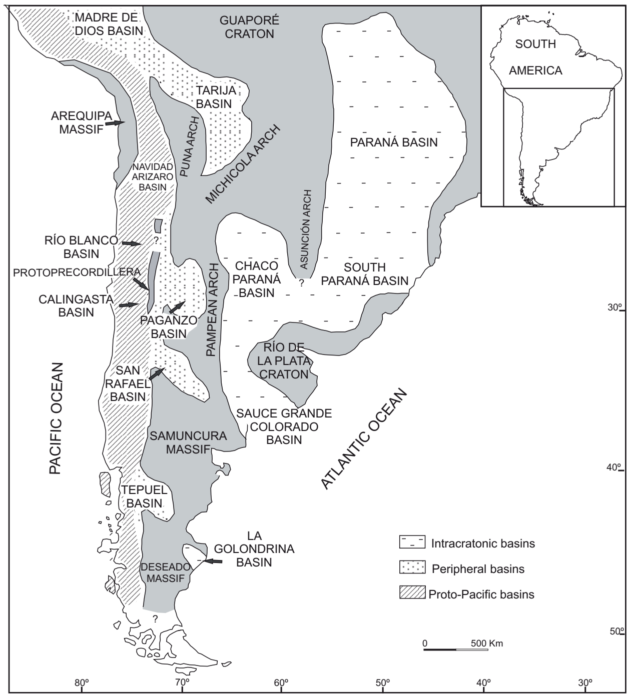

FIGURE 1 | **Major palaeogeographic features of southern South America in the general framework of Gondwana (modified from Limarino and Spalletti, 2006).**

et al. (2006) postulated that the deformation caused by this event continued into the Early Carboniferous, resulting in significant palaeogeographic changes and in the formation of the North-South trending Protoprecordillera fold and thrust belt. This orogenic belt was probably uplifted during the Late Visean and split western South America into two separate areas, the eastern one characterised by limited tectonic activity and negligible magmatism, and the western one that presented important tectonics and magmatism (Caminos, 1972; Llambías, 1999, Limarino and Spalletti, 2006). The Late Mississippian orogeny, probably the most important one during the Late Palaeozoic in western Gondwana basins, is represented by a remarkable stratigraphic discontinuity close to the Early - Late Carboniferous boundary. This discontinuity clearly separates two tectono-sedimentary cycles. Bahlburg and Breitkreuz (1991) recognised intracarboniferous tectonism (“Toco Orogeny”) in northern Chile, while Suárez Soruco (1989) and Grader et al. (2008) pointed out a (notable) stratigraphic discontinuity between the Ambo (Mississippian) and Titicaca (Mississippian-Permian) Groups in the Cordillera Oriental of Bolivia. In short, an important orogenic event took place along the western margin of Gondwana close to the Mississippian - Pennsylvanian boundary and produced not only dramatic palaeogeographic changes but also significant environmental modifications. Based on these relationships, Veevers and Powell (1987) suggested that the initiation of glacial events during the Mid Carboniferous could have been controlled by the uplift of orogenic highlands in eastern Gondwana. In the same way, the tectonic uplift related to the Mississippian - Pennsylvanian orogeny could account for the Visean and Namurian glacial events recorded in western Gondwana.

Global effect of the Permian - Triassic volcanism in the western Gondwana margin

The global effect of the large volumes of volcanic rocks erupted from the end of the Carboniferous to the earliest Triassic along the western margin of Gondwana has been overlooked in global-scale environmental reconstructions. This volcanism, which is known by a variety of stratigraphic names along the present day Andean region (Choiyoi Group in Argentina, Peine Group in Chile, Mitu Group in Bolivia, etc.), accumulated several thousands of meters of volcanic and volcaniclastic strata over vast areas of western South America. In the case of the Choiyoi magmatic event two major associations were proposed by Llambías (1999): 1) an Early Permian calc-alkaline association (Lower Choiyoi section) and 2) a Latest Permian-Early Triassic silicic association (Upper Choiyoi section). Although the orogenic significance of this volcanism should be analyzed in detail in the future, Sato and Llambías (1993) and Llambías (1999) established the main genetic characteristics. In this way the calc-alkaline association would correspond to the latest stages in the evolution of the Late Palaeozoic magmatic arc in this part of the Andes. By contrast, the silicic association would represent the transition from subduction-related to intraplate volcanism driven by extensional tectonism.

This volcanism exerted an influence on the development of latest Carboniferous and Permian floras. Recently, Césari et al. (2009) reported the presence of an Andean fossil forest of the Carboniferous-Permian boundary intercalated between volcanic rocks and sediments deposited in flooded environments (probably coastal lagoons). The authors considered that the ecological strategy used by the vegetation to survive in such adverse environmental conditions was regeneration via nurse logs. On the other hand, the effect of this Late Palaeozoic volcanism on the atmosphere, life and depositional environments together with its potential contribution to the Permian-Triassic mass extinction have been poorly evaluated.

The Late Palaeozoic glacial event

The Late Palaeozoic glacial event has been a paradigmatic model for geologists working in Gondwana since the beginning of the 20th century. In particular, the timing and number of glacial episodes were topics under debate during the last decades. One of the first global models dealing with the chronology of the glaciation was proposed by Veevers and Powell (1987) who recognized two major glacial events, the older one (Visean in age) involving local alpine glaciation, and the younger one (Latest Pennsylvanian - Early Permian) characterised by widespread ice sheets. This model was later refined by different contributions, and Isbell et al. (2003a and b) identified three principal glacial intervals in the Tournasian, Namurian - Early Westphalian and Late Pennsylvanian - Cisuralian.

How can Late Palaeozoic South American basins contribute to these models? Firstly, although the oldest record of the Late Palaeozoic glaciation is well documented in South American basins as demonstrated by Díaz-Martínez et al. (1993), Isaacson et al. (1999) and Caputo et al. (2008), among others, it is not clearly recognized across the rest of Gondwanaland. These authors described Late Devonian - Early Carboniferous glacial diamictites in the Andean Altiplano Belt of Bolivia and in the Paraná, Solimoes and Parnaíba basins of Brazil. Secondly, the chronology of the glacial event is currently being refined from radiometric ages obtained from the Paraná Basin (Brazil). Rocha Campos et al. (2008) reported SHRIMP ages from 295 ± 2.6 Ma to 299.1 ± 2.6 Ma on zircons found in the Río Bonito Formation, deposited on top of glacial diamictites included in the Itararé Group. These data not only provide a better constraint on the ages of a glacial maximum in western Gondwana, but also suggest that the end of the glaciation in Brazil was older than previously considered. This problem must be examined in detail in the near future, as well as the implications of these ages for the glacial chronology, when the glacial deposits of the Paraná and Karoo basins are considered together and compared.

The biostratigraphic record in western Gondwana

The complete biostratigraphic record found in western Gondwana basins must be highlighted. In fact, there are few places in Gondwana that show a continuous fossiliferous record from the Early Carboniferous to the Late Permian. South American basins provide abundant fossil floras, marine invertebrates and palynological material from the earliest Carboniferous to the latest Permian. By contrast, the fossiliferous record of central Gondwana (South Africa and Antarctica) is mainly restricted to the Permian or the Latest Carboniferous.

The Mississippian time interval, which is not well represented in Gondwana, is composed of thick sequences with abundant marine and continental fossiliferous assemblages in Bolivia and Argentina. This is the case of the Early Carboniferous *Archaeosigillaria-Frenguellia* flora (Arrondo et al., 1991; Archangelsky, 1996), and the recently defined *Frenguellia eximia - Nothorhacopteris*

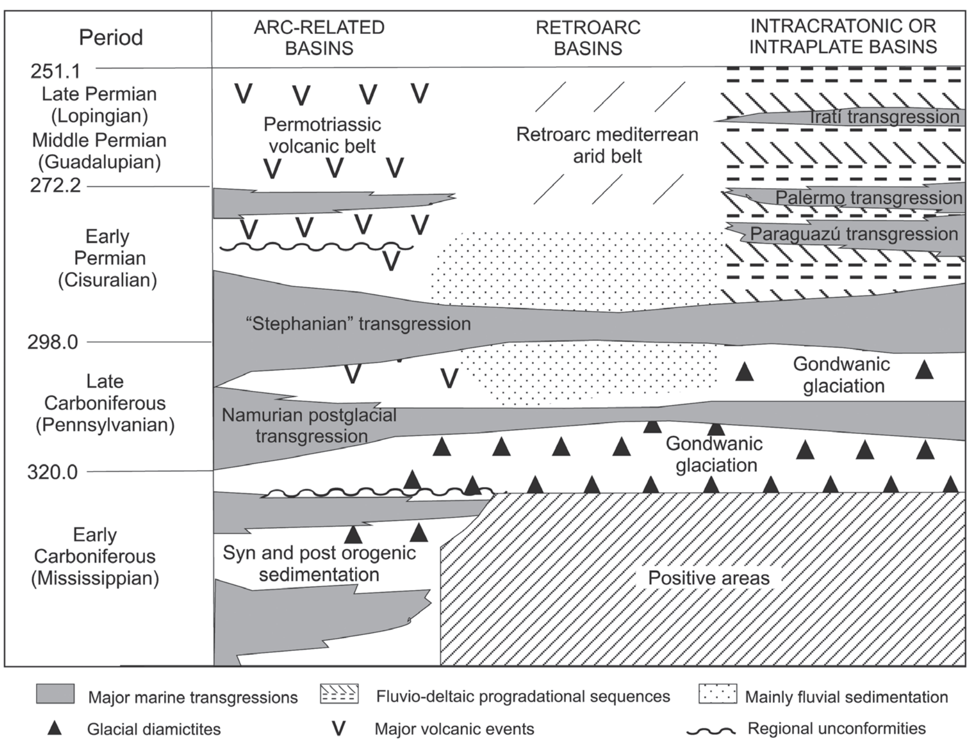

FIGURE 2 | **Palaeoenvironmental evolution of the Upper Palaeozoic basins of South America (modified from Limarino and Spalletti, 2006).**

kellaybelenensis - Cordaicarpus cesarii flora (Balseiro et al., 2009). This flora is one of the best known Mississippian palaeofloristic records of Gondwana.

At the same time, the well known Pennsylvanian and Permian fossiliferous sections of Brazil, Peru, Chile and Argentina allow correlation at a large-scale on the basis of biostratigraphic tools. The correlation between western and central Gondwana is based on palynological zones defined in Argentina, Brazil and South Africa (Césari, 2007).

NEW CONTRIBUTIONS FROM WESTERN GONDWANA

The papers included in this special publication refer to different South American regions and basins (Fig. 3) and are good examples of new and continued research on the Late Palaeozoic. In this way, one of the most controversial questions about the palaeogeographic evolution of western Gondwana is the position occupied by Patagonia during the Late Palaeozoic (Ramos, 1984; von Gosen, 2003; Rapalini, 2005, Pankhurst et al., 2006; Gregori et al., 2008). The paper by Rapalini et al. explores this issue based on new geophysical information obtained in northern Patagonia.

Geuna et al. focus on two important questions: 1) the relationship between the tectonic evolution of the retroarc basins (i.e. Paganzo Basin) and the magnetic remanence, and 2) the comparison between the palaeomagnetic poles obtained in the Paganzo Basin and the palaeomagnetic record of Gondwana during the Late Palaeozoic. This last issue is essential for understanding the palaeogeographic evolution of western Gondwana in space and time.

The effect of sea level changes on coastal and continental environments has been poorly documented in the Late Palaeozoic basins of western South America. This contrasts with well-researched cycles of sea level fall and rise recorded in the Late Palaeozoic Paraná Basin (Holz, 1999; Holz et al., 2008). Focusing on the fluvial deposits of the Paganzo Basin (Upper Palaeozoic of San Juan province), Tedesco et al. synthesize the major transgressive events in the western retroarc basins of southern South America and analyze the response of the fluvial systems to shifts in the shoreline position during the Pennsylvanian and Early Permian.

The climatic conditions during the Middle and Upper Permian seem to have been dramatically different from those prevailing during the Gondwanan glaciation. Semiarid and arid climates were inferred for the Permian of southern South America by Limarino and Spalletti (1986), López Gamundí et al. (1992), de Santa Ana et al. (2006) and Nardi Dias and Scherer (2008). The paper by Spalletti et al. presented in this volume extends the known record of the erg system of the Paganzo Basin to the north, which would have reached an approximate area of 85,000 Km^2. As regards to this Permian erg, Kaprovickas et al. focus on fossil traces preserved in terrestrial deposits and identify tetrapod footprints which represent the oldest record of these vertebrates in Argentina.

The Late Palaeozoic basins of South America show the oldest record of the Gondwanan Glaciation (Glacial interval 1, Isbell et al., 2003a and b). Mississippian and even latest Devonian glacial deposits have been described at Madre de Dios (Bolivia), Río Blanco (Argentina), Amazon and Parnaíba Basins of Brazil (Limarino and Césari, 1993; Díaz Martínez and Isaacson, 1994; Caputo et al., 2008). The present issue provides the first description of Late Visean glacial deposits in Argentinean basins (Pérez Loinaze et al., a) and compares them with the classical Serpukhovian - Bashkirian glaciation in the same region. The authors integrate palynological and sedimentological study of both Mississippian and Pennsylvanian glacial deposits of the Río Blanco and Paganzo Basins**.** Moreover, the palynology of postglacial deposits found in the southeastern Paraná Basin (Uruguay) is described in Beri et al.

The incomplete biostratigraphic information as well as the scarcity of radiometric ages have delayed the development

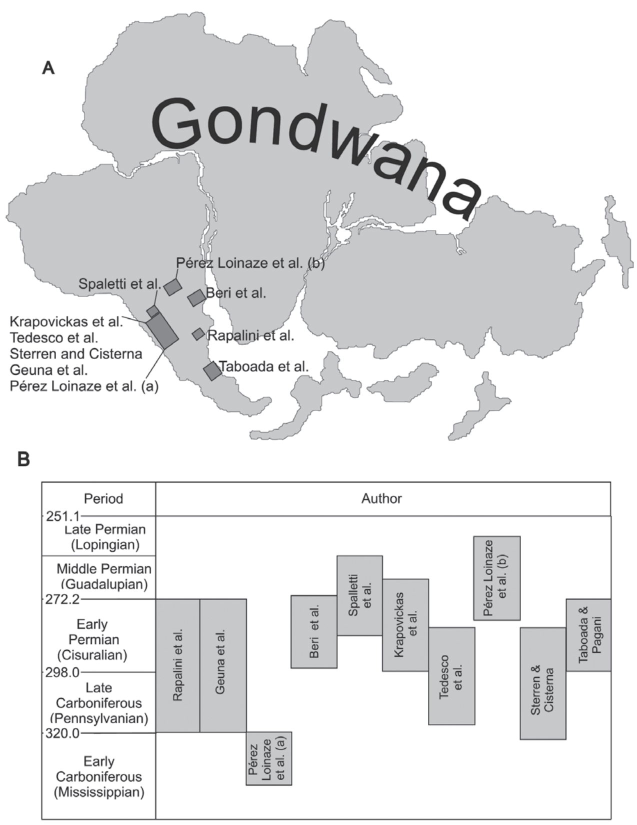

FIGURE 3 | **A) Sketch map of Gondwana showing the principal locations and B) stratigraphic framework of the work covered in this issue.**

of large-scale correlations among different Late Palaeozoic basins of western Gondwana. The Paraguayan sector of the Paraná Basin is a good example of this situation. Thus, the paper on the palynology of the Permian San Miguel Formation in Paraguay (Pérez Loinaze et al., b) seeks to fill this gap. The results are used to develop a regional correlation with sequences outcropping in Brazil and Argentina.

Also of biostratigraphic interest, the paper by Sterren and Cisterna describes the bivalve and brachiopod faunal succession found in the western Andean basins of Argentina and compares biodiversity changes and diversification patterns with major global events. Finally, Taboada and Pagani report the occurrence of a brachiopod assemblage (*Cimmeriella-Jakutoproductus*) in Patagonia and discuss how this assemblage can be used to correlate high to middle palaeolatitude marine sequences of the Early Permian.

CONCLUDING REMARKS

All the contributions of this special publication were presented during the V Simposio Argentino del Paleozoico Superior which was held in Buenos Aires on April 21-23, 2008. The papers represent a collection of case-studies on different Late Palaeozoic basins of southern South America. They address the major issues discussed above from different perspectives:

The orogenic evolution of the western Gondwana margin is considered from geophysical (Rapalini et al.), palaeomagnetic (Geuna et al.), sedimentological (Tedesco et al., Spalletti et al., Krapovickas et al.) and biostratigraphic (Sterren and Cisterna) viewpoints. The contributions provided by these papers highlight two major aspects: 1) the need for integrating information derived from different disciplines in order to obtain reliable stratigraphic, palaeogeographic and palaeoenvironmental models used in orogenic reconstructions and 2) the improved knowledge of the western Gondwana active margin to gain a better understanding of the evolution of Gondwana.

Spalletti et al. and Sterren and Cisterna reach different conclusions on the possible effects of the Permian-Triassic volcanism in the sedimentological record and faunas. According to Spalletti et al. the existence of a significant arid phase during the Permian could have been related to the Permian-Triassic volcanism. By contrast, Sterren and Cisterna suggest that the volcanic activity and relatively warmer marine currents could have controlled the bivalve and brachiopod distribution during the Late Carboniferous-Early Permian.

From palynological dating Pérez Loinaze et al. (a) point out that at least two glacial intervals are recognized in the western Andean Paleozoic basins of Argentina. These two glacial events can be correlated with others in central and eastern Gondwana yielding new information on global-scale palaeoclimatic reconstructions.

Finally, Beri et al., Pérez Loinaze et al. (b) and Taboada and Pagani provide new palaeontological data to contribute to the South America Late Palaeozoic bioestratigraphic record. The results of these studies will enable us to enlarge the biochronological-chronostratigraphic dating of glacial, interglacial and postglacial events in South America. These papers make an important contribution to the biostratigraphic schemes and palaeoclimatic models in the region. They also address the similarities and differences not only with other places in South America but also in Gondwana.

The intention of the guest editors of this special issue of Geologica Acta has been to report new advances in the knowledge of the western Gondwana geology. This work will contribute to our understanding of the history of the whole Gondwana supercontinent.

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