Pennsylvanian glacial cycles in western Gondwana: an overview

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Abstract: The Pennsylvanian on the western rim of Gondwana can be considered a time of significant contrasts in terms of environments, revealing a unique translatitudinal disposition of the South American continent, where glaciomarine deposits and peat-forming environments, situated further south, coexisted with marine carbonate platforms and aeolian dune fields, in terrains further north. This peculiar record creates an opportunity to better understand the teleconnections of glaciation and deglaciation during the Late Paleozoic Ice Age (LPIA) between mid and low latitude regions. In the last decade, radiometric dating together with marine microfossils (mostly conodonts) has enabled a better understanding of the timing and duration of deposition of different sedimentary environments found in the climate belts that originated from a global ice-house regime. These advances in the chronostratigraphical positioning of sedimentary deposits also allow a more precise correlation between them, making it possible to estimate cause–effect patterns arising from the growth and decay of glaciers in this portion of Gondwana. This contribution aims to present an overview of the main climatic–environmental events that took place during the Pennsylvanian and to associate them with the floristic changes that occurred in the emergent lands based on palaeobotanic and palynological information. The record from the west rim of Gondwana could be roughly divided into Early, Middle and Late Pennsylvanian, exactly as proposed in the geological time-scale.

The Late Paleozoic Ice Age (LPIA) is one of the most important climate events on Earth, as it is one of two icehouses that took place since plants colonized the continents and represents the longest and most widespread glacial interval of the Phanerozoic (synthesis in Montañez 2021). The LPIA was characterized by a major restructuring of the flora and fauna that accompanied and was likely influenced by global climate changes (e.g. Clapham and James 2008; DiMichele *et al.* 2009). Therefore, it was an event of significant importance for the evolution of Earth's biota. Regarding terrestrial vegetation, the transition from a long icehouse phase (=LPIA) to a greenhouse phase marked the beginning of the turnover from Paleozoic to Mesozoic floras, composed of a series of modern plant groups.

Studies of Gondwanan basins located at medium to high palaeolatitudes have documented a climatically dynamic ice age that was characterized by a series of short glacial intervals (1 to 8 Ma), separated by ice minimum intervals of equal duration (Stollhofen *et al.* 2000, 2008; Isbell *et al.* 2003; Fielding *et al.* 2008; Gulbranson *et al.* 2010). Carboniferous–Permian sequences containing these million-year-long glaciogenic and non-glaciogenic intervals have been accurately delimited in Australia, where a robust chronostratigraphical framework has previously been established (Fielding *et al.* 2008) and recently updated (Fielding *et al.* 2022). Therefore, a time–space framework for eastern Gondwana documents the occurrence of eight glacial phases in the late Paleozoic, four of which are not limited to the Carboniferous whereas three of them lie in the Pennsylvanian. For the western rim of Gondwana (=South America), Carboniferous–Permian sequences have been geochronologically constrained by high-precision U–Pb ages only recently (Gulbranson *et al.* 2010; Césari *et al.* 2019; Griffis

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et al. 2019). These radiometric dates are generally limited to basins that were directly under glacial influence, i.e. Paganzo and Paraná basins, with the exception of the Cochabamba sub-basin, where almost all strata are Permian (di Pasquo *et al.* 2014). Although there are studies that seek to delineate the glacial intervals and palaeoclimatic evolution on this margin of Gondwana, they are restricted only to the basins of the south-central portion of South America (Césari *et al.* 2011; Limarino *et al.* 2014), in addition to establishing general correlations with African and Australian glacial deposits.

In this contribution, we summarize the existing knowledge about the Pennsylvanian sequences that contain glacial and non-glacial intervals, in order to establish more specific intervals that allow correlating them: (i) with the time-equivalent Australian sequences, as well as (ii) with the sequences from the basins of northern South America, located at that time in subtropical latitudes. This last focus will seek to verify whether there is a correspondence (teleconnection) between the glacial cycles verified in southern basins, and those sea-level changes recorded in the platform shelf and coastal deposits present in the northern basins, even if we are analysing million-year-long intervals.

Geological setting

Basins

Among all sedimentary basins mentioned in this review (Fig. 1), there are only two that have relatively well-dated Pennsylvanian sequences, either by radiometric methods (i.e. Paganzo Basin, Argentina) or through biostratigraphical correlations using Euramerican (Midcontinent) index taxa of conodonts and fusulinid foraminiferans (i.e. Titicaca Basin, Bolivia). Fortunately, these two mentioned basins were at quite different latitudes during the Pennsylvanian, with the Paganzo Basin located at mid-latitudes and relatively close to glacial centres, *c.* 40–50°S, and the Titicaca Basin located in subtropical latitudes, *c.* 30°S. In this way, they can be used to check the correlation between events recorded in low and medium latitudes, triggered by the warming and cooling phases, in order to demonstrate the existing teleconnections between the subtropics and temperate areas. In addition to these two basins, two other basins are used to help establish the succession of events and their correlation between the Paganzo Basin and the Titicaca Basin, namely the Paraná Basin and the Parnaíba Basin. These four are the target basins of this contribution. However, throughout the text, other basins, such as the Solimões, Amazonas and Calingasta-Uspallata, are used as auxiliaries in order to complement the analysis.

The best chronostratigraphical control of this interval comes from the high-precision U–Pb ages obtained from sections of the Paganzo Basin by Gulbranson *et al.* (2010). But it was Césari *et al.* (2011) who correlated these ages with the macro- and microfloristic record of the basin, in addition to discussing the climatic and environmental evolution associated with flora succession. These authors also proposed correlations with macro- and microfloras from South America and Gondwana that are used here to establish relative ages with the Paraná Basin deposits. Recently, Cisterna and Sterren (2022) analysed the succession of marine faunas of these radiometrically dated sections and others, proposing correlations with South American basins, plus others from Gondwana. These marine transgressive events in association with their respective faunas are used here as ‘correlation events’ (*sensu* Event Stratigraphy; Iannuzzi and Shen 2013) that allow long-distance correlations between sedimentary basins.

The age control of this interval in the northwestern Bolivia Titicaca Basin comes from the high-precision relative dates by fusilinids and conodont assemblages obtained in sections that were chronostratigraphically studied by Grader (2003) and Grader *et al.* (2008). In the Parnaíba Basin, only conodont-based ages are known (Medeiros *et al.* 2019; Dias *et al.* 2022; Mantilla *et al.* 2022), whereas palynofloras are used in southern Bolivia Tarija Basin (di Pasquo *et al.* 2017 and references therein) in the absence of other fossils except for two marine intervals that allowed their correlation with other South American (SAM) basins (Grader *et al.* 2008; di Pasquo *et al.* 2017, 2019; Cisterna and Sterren 2022).

Results

In this contribution, the main intervals of climatic cooling and warming that can be determined from the sedimentary record of the South American basins (Fig. 1) are addressed. However, it is important to note that these intervals represent periods that span a few million years each one. Therefore, several orbital-scale events of Milankovich Cycles that occur on a scale of thousands of years are involved despite the fact that it is not easy to delimite their influence with such accuracy in view of the current knowledge of sedimentary sequences in SAM due to the lack of high resolution absolute dates such as those obtained by Davydov *et al.* (2010) for the Pennsylvanian chronostratigraphy of the Donets Basin. This subject is out of the scope of this work.

It must also be said that there is a vast literature referring to the topic discussed here, but for this synthesis only a few publications were selected, and it was not within the scope of this contribution to cite all of it (regardless of the authors being fully aware

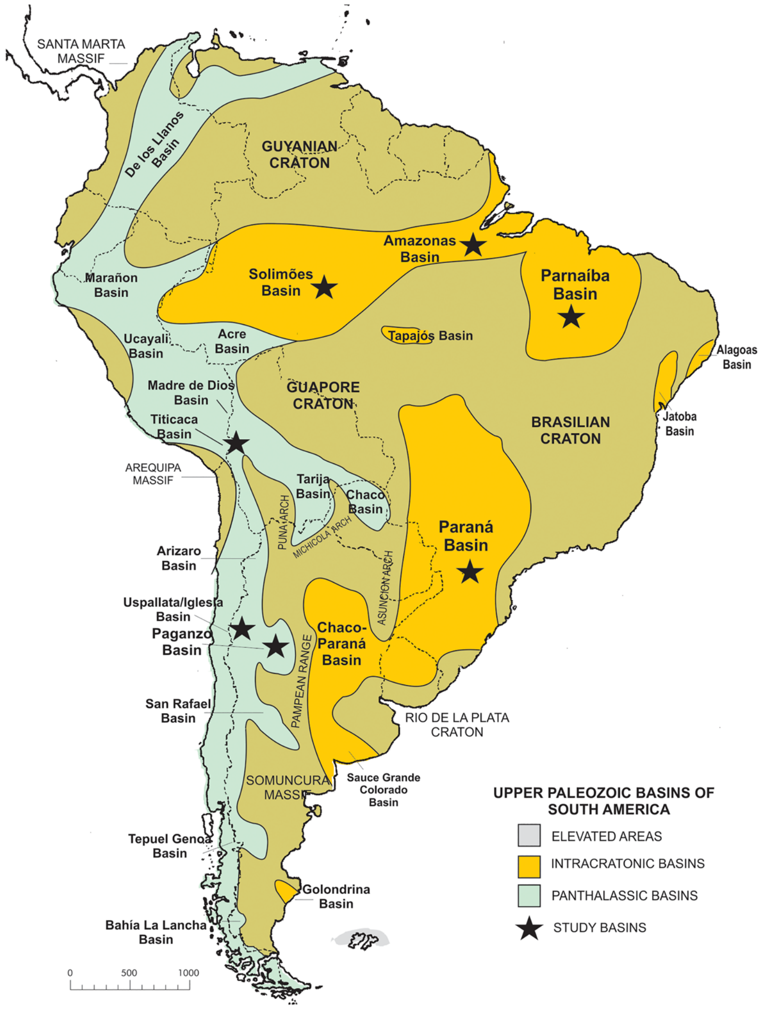


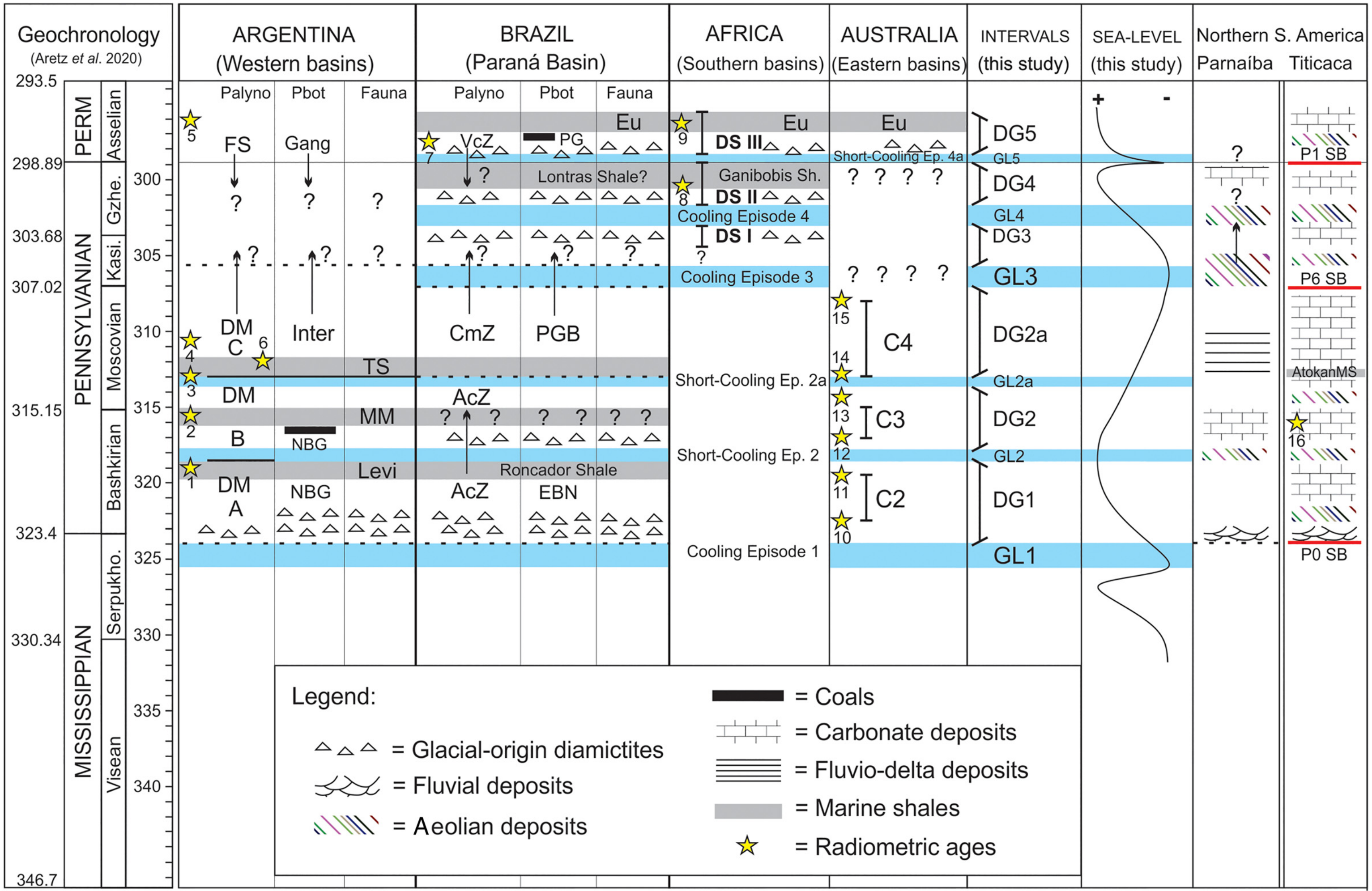
Fig. 1. Location map of main South American sedimentary basins containing late Paleozoic deposits. Note the four target basins highlighted with black stars: Paganzo, Paraná, Titicaca and Parnaíba basins. Besides, three other basins used herein are also marked with black stars: Calingasta Uspallata, Solimões and Amazonas. Source: modified from Azcuy *et al.* (2007).

of the existence of these articles). Within this context, an attempt was made to use the most up-to-date contributions possible that summarized the information accumulated on that topic or time interval. It can be said that we have benefited from the fact that in recent years there has been a significant increase in this type of contribution, as will be seen below. Sometimes specific publications were used given their relevance in clarifying specific points.

Cooling and warming intervals

We assumed the criteria addressed below in the elaboration of this integrative synthesis that attempts to establish correlations based on cause–effect patterns of glacial–deglacial cycles. Hence, Figure 2 summarizes the Glaciation (GL) and Deglaciation (DG) intervals and correlations using the sedimentary record and radiometric and biostratigraphical ages obtained in the selected Paganzo, Paraná, Titicaca and Parnaíba basins during latest Mississippian–earliest Permian LPIA interval.

(a) During the ‘Cooling Intervals’, the base level gradually dropped until significant lowstand conditions were achieved. Consequently, these intervals comprise significant subaerial exposure, aeolian dune fields, ice cover, erosive events and a relative low thickness of preserved stratigraphic


Geochronology
(Aretz et al. 2020)
ARGENTINA
(Western basins)
BRAZIL
(Paraná Basin)
AFRICA
(Southern basins)
AUSTRALIA
(Eastern basins)
INTERVALS
(this study)
SEA-LEVEL
(this study)
Northern S. America
Parnaíba
Titicaca
Palyno
Pbot
Fauna
293.5
298.89
303.68
307.02
315.15
323.4
330.34
346.7
PERM
PENNSYLVANIAN
MISSISSIPPIAN
Asselian
Gzhe.
Kasi.
Moscovian
Bashkirian
Serpukho.
Visean
300
305
310
315
320
325
330
335
340
FS
Gang
DM C
Inter
DM B
DM A
NBG
TS
MM
Levi
Eu
VcZ
PG
CmZ
PGB
AcZ
EBN
Lontras Shale?
Roncador Shale
DS III
DS II
DS I
Ganibobis Sh.
Cooling Episode 4
Cooling Episode 3
Short-Cooling Ep. 2a
Short-Cooling Ep. 2
Cooling Episode 1
Short-Cooling Ep. 4a
C4
C3
C2
DG5
GL5
DG4
GL4
DG3
GL3
DG2a
GL2a
DG2
GL2
DG1
GL1
+
-
P1 SB
P6 SB
AtokanMS
P0 SB
Legend:
= Glacial-origin diamictites
= Fluvial deposits
= Aeolian deposits
= Coals
= Carbonate deposits
= Fluvio-delta deposits
= Marine shales
= Radiometric ages

showing commonly breaks and gaps in the sedimentary successions.

(b) During the 'Warming Intervals', the sea level gradually rose until highstand conditions were achieved. Consequently, these intervals represented positive accommodation (including transgressive events) that allow for the preservation of thicker and more extensive stratigraphy, mainly represented by glaciomarine facies and post-glacial organic-rich shales in southern basins whereas carbonates, shales and, coastal aeolian dunes dominated in northern basins. Thus, these warming intervals correspond to most of the records preserved along the depositional sequences of these basins.

Although, precaution is mandatory whether the correlation of deposits is based on stratigraphically-similar litho-facies successions lacking biostratigraphical and/or isotopic data and they should not be included in correlation charts. A good example of this situation is related to the recent re-interpretation of the previously Permian red beds of the Patquía Formation by Césari *et al.* (2019) based on a new U–Pb age of 311.89 ± 0.21 Ma obtained at the base of the De La Cuesta Formation. Contrary to previous palaeogeographical interpretations in which this early Permian red bed interval succeeded the coal-bearing deposits of the Late Pennsylvanian Tupe Formation as synchronic intervals across Paganzo Basin (cf. Limarino *et al.* 2014), the transition from variegated to red beds successions should not be considered synchronous all along the Paganzo Basin, despite the fact that a progressive warming and drying in environmental conditions since the Moscovian is still valid (Gulbranson *et al.* 2010; Césari *et al.* 2011) with lithological differences depending on environmental conditions of SAM basins as well.

Latest Mississippian–Early Pennsylvanian

Southern records

During the latest Mississippian (=late Serpukhovian)–Early Pennsylvanian (=early Bashkirian), there is a long-term record of deglaciation during which the sea level rose significantly. This deglaciation sequence (DG1) is represented by glaciomarine diamictites and shales with dropstones at the base, and organic shales towards the top, extending from the east to west in the Paganzo Basin (Césari *et al.* 2011). Recently, Valdez *et al.* (2020) suggested an age of approximately 320 Ma for these organic shales, i.e. early Bashkirian, based on medium resolution radiometric U–Pb dates (errors around 5 Ma). These authors also established the correlation of this sequence with the deposits of the Lagoa Azul Formation, the basal unit of the Itararé Group in the Paraná Basin. Therefore, this sequence represents a geographically extensive deglaciation/transgressive event, and its maximum flooding can be traced across

Fig. 2. Glaciation (GL) and deglaciation (DG) intervals related to the LPIA delimited using the sedimentary record and radiometric and biostratigraphical ages known from Western Argentinean (mostly Paganzo), Paraná, Parnaíba and Titicaca basins during the latest Mississippian–earliest Permian interval. References of radiometric ages: 1, Lower section of the Río del Peñon Formation and Guandacol Formation, 319.57 ± 0.09 and 318.79 ± 0.10 Ma (Gulbranson *et al.* 2010); 2, Tupe Formation, 315.46 ± 0.07 Ma (Gulbranson *et al.* 2010); 3, Tupe Formation, 312.82 ± 0.11 Ma; 4, Patquía Formation, 310.71 ± 0.11, 309.89 ± 0.08 Ma, middle Rio del Peñón Formation 310.63 ± 0.07 Ma (Gulbranson *et al.* 2010); 5, La Colina Formation, 296.09 ± 0.08 Ma (Gulbranson *et al.* 2010); 6, de la Cuesta Formation, 311.89 + 0.21 Ma (Césari *et al.* 2019, =Upper Tupe Formation in Césari and Pérez Loinaze 2021); 7, Lower Rio Bonito Formation, 298.23 + 0.31, 297.77 + 0.35/–0.59, 297.58 + 0.68/−1.4 and 296.97 + 0.45/–0.72 Ma (in Griffis *et al.* 2019); 8, lower Ganibobis Shale, 300.0 ± 0.45 and 299.31 + 0.35 Ma (Griffis *et al.* 2023); 9, *Hardap Shale*-equivalent, in Klaarstroom, 296.41 + 0.27/–0.35 Ma (Griffis *et al.* 2019); 10, Base of C2, 322.5 Ma (Fielding *et al.* 2008, 2022); 11, Top of C2, 319.5 Ma (Fielding *et al.* 2008, 2022); 12, Base of C3, 317.0 Ma (Fielding *et al.* 2008, 2022); 13, Top of C3, 315.0 Ma (Fielding *et al.* 2008, 2022); 14, Base of C4, 313.0 Ma (Fielding *et al.* 2008, 2022); 15, Base of C4, 308.0 Ma (Fielding *et al.* 2008, 2022); 16, Copacabana Formation, 316.0 ± 0.4 Ma (Carvajal *et al.* 2018). Macrofloras (Pbot): NBG, *Nothorhacopteris–Botrychiopsis–Ginkgophyllum* Zone; Inter, Interval Zone; Ganga, *Gangamopteris* Zone; EBN, *Eusphenopteris–Botrychiopsis–Nothorhacopteris* Taphoflora; PGB, *Paranocladus–Ginkgophyllum–Brasilodendron* Taphoflora; PG, *Phyllotheca–Gangamopteris* Flora. Microfloras (Palyno): DM (subzones A, B, C), *Raistrickia densa–Convolutispora muriornata* (DM Biozone); FS, *Phakapites fusus–Vittatina subsaccatta* Zone; AcZ, *Ahrensisporites cristatus* Zone; CmZ, *Crucissacites monoletus* Zone; VcZ, *Vittatina costabilis* Zone. Macrofaunas (Fauna): Levi, *Levipustula levis* Zone; MM, *Marginovatia peregrina–Maemia tenuiscostata* Zone; TS, *Tivertonia jachalensis–Streptorhynchus inaequiornatus* Zone; Eu, *Eurydesma* Fauna. Sequences: C2–4, Glacial Intervals or Phases (Fielding *et al.* 2008, 2022); DS I–III, Deglaciation Sequences (Stollhofen *et al.* 2000, 2008). Sequence surfaces: AtokanMS, 'Atokan Marker Shale'; P0 SB, Pennsylvanian 0 Sequence Boundary (='mid-Carboniferous erosive event'); P6 SB, Pennsylvanian 6 Sequence Boundary; P1 SB, Permian 1 Sequence Boundary (Grader *et al.* 2008). Abbreviations: Serpurkho, Serpukhovian; Kasi, Kasimovian; Gzhe, Gzhelian. Horizontal lines: solid black line, zone boundary; dashed black line, imprecise or indeterminate stratigraphic boundary; solid red line, erosive unconformity.

up to the Paraná Basin, where it would be documented through the 'Roncador Shale' (França and Potter 1988; Valdez *et al.* 2020). Above this deglaciation sequence, conglomerates, sandstones, and carbonaceous mudstones and coals (Césari *et al.* 2011) document terrestrial environments that fill the accommodation space generated in the basin by the sea-level rise caused by the previous deglaciation event. These deposits extend to the end of the Bashkirian/ beginning of the Moscovian according to the ages obtained by Gulbranson *et al.* (2010).

Based on palynological content, a correlation between the deglaciation sequences of the Paganzo Basin (Guandacol and Água de Jagüel formations) and Paraná Basin (Lagoa Azul and Campo do Tenente formations) is supported where the *DM* Zone (Subzones A–B) would be equivalent to the *Ahrensisporites cristatus* (Ac) Zone because they have several species in common. Regarding the macrofloristic record in NW Argentina, the *Notorhacopteris–Botrychiopsis–Ginkgophyllum* (NBG) *Flora* in the terrestrial strata of this interval is documented, being a typical flora of western Gondwana associated with peat-accumulation environments (coals and carbonaceous facies) (Césari *et al.* 2011). In the Paraná Basin, floristic records are very scarce in this interval. The *Eusphenopteris–Botrychiopsis–Nothorhacopteris Taphoflora* (in Bernardes-de-Oliveira *et al.* 2016), recovered from a single locality (Itapeva, SP) stratigraphically located in the Lagoa Azul Formation, is correlatable to the *NBG Flora* in Paganzo Basin. It is worth mentioning that the floral remains of the informal zone named as *Frenguellia eximia–Nothorhacopteris kellaybelenensis–Cordaicarpus cesarii* assigned to the Serpukhovian *sensu lato* by Balseiro *et al.* (2009) were recently reassigned to the late Bashkirian based on the first palynological study carried out by Di Pasquo and Milana (2021). The palynoassemblage obtained from three samples of dark shale interval below the flora-containing deposits of the mentioned unit yielded two key species of the early–late Bashkirian Subzone B of the *Raistrickia densa–Convolutispora muriornata* Zone (Césari and Pérez Loinaze 2021), the spore *Spelaeotriletes ybertii* and a well-preserved specimen of the striate bisaccate pollen *Illinites unicus.* Also, Cordaitean and Coniferalean pollen grains are well represented (*c.* 25–34%). Therefore, this information allowed their re-allocation of the flora remains bearing *Tomiodendron*, *Nothorhacopteris kellaybelenensis*, *Frenguellia*, *Bumbudendron*, and especially, seeds of *Cordaicarpus* (Cordaitalean affinity), to the NBG Zone, and supports the correlation of the Loma de Los Piojos with the widespread postglacial shales that have been dated locally between *c.* 320 and 316 Ma (Fig. 2).

It is interesting to note that the *Ac Zone* covers two lithostratigraphical units in the Paraná Basin, i.e. the Lagoa Azul and Campo do Tenente formations (Vesely *et al.* 2021), which means that within the range of occurrence of this palynozone there were two deglaciation intervals (interspersed by a glaciation interval). Undoubtedly, the first deglaciation event (DG1), represented by the strata of the Lago Azul Formation, was more widespread than the second, recorded through the Campo do Tenente Formation. This second event (=DG2) is not as well delimited in the Paganzo Basin as it is in the Paraná Basin, but the related transgression can be inferred by mudstones and shales that are intercalated in the upper portion of the Tupe Formation (Césari *et al.* 2011; Valdez *et al.* 2020; Césari and Pérez Loinaze 2021). Towards the west of the continent, in the Calingasta–Uspallata Basin, transgressions related to these two deglaciation events can be better characterized by the records of the marine faunas included in the *Levipustula levis* Zone and *Marginovatia peregrina–Maemia tenuiscostata* (MM) Zone, respectively (Cisterna and Sterren 2022).

Deglaciation events (DG1 and DG2) could be tentatively correlated with the C2 and C3 Glacial Intervals (GI) or Phases (=glaciations) proposed by Fielding *et al.* (2008, 2022) based on recognized glacial deposits in eastern Australia, which are stratigraphically repositioned there in the earliest and late Bashkirian, respectively, based on the originally proposed radiometric ages and the boundaries of the Pennsylvanian ages currently accepted by the Geological Time Scale (Aretz *et al.* 2020). Considering that the fauna of *Levipusla levis* was originally described in Australia (in Cisterna and Sterren 2022), it can be inferred that the presence of this fauna in western South America indicates that the first deglacial transgressive event mentioned above reached a great extent, enabling the dispersion of elements of this fauna across the epicontinental seas of Gondwana.

Northern records

The far-field effects of glaciation and deglaciation events recorded in basins to the south of the continent can be seen in the sedimentary successions of the aforementioned northern basins. Initially, the existence of a huge stratigraphic gap (represented by an erosive unconformity) between the Mississippian and Pennsylvanian deposits (='mid-Carboniferous erosive event' of Grader *et al.* 2008) of basins in northern South America (i.e. Amazonas and Solimões basins) is a direct consequence of the aforementioned strong glacial event (GL1) that had its peak approximately at the end of the Serpukhovian (Fig. 2). Apparently, the basins located to the north suffered more strongly the consequences of the effective fall in sea level associated with this event that generated gaps, non-deposition and erosive and/or pedogenically modified surfaces around the globe (Grader *et al.* 2008; di Pasquo *et al.* 2019).

The DG1 deglaciation process that followed brought a progressive rise in sea level and, therefore, increased accommodation at the beginning of the Pennsylvanian. The beginning of this sedimentary sequence is represented mainly by sandstones and mudstones intercalated with conglomerates, cherts and carbonates that range from terrestrial to coastal environments (Yaurichambi Formation) in the Titicaca Basin (Díaz-Martínez and Dalenz 1995; di Pasquo *et al.* 2019). Overlying these coastal deposits there are marine limestones that represent geographically widespread carbonate homoclinal ramps. These carbonates represent transgressive systems tracts of the Copacabana Formation in Bolivia that deepen upward (Grader *et al.* 2008). All these Pennsylvanian basal deposits filled local incisions in the post-Mississippian palaeotopography left by the 'mid-Carboniferous erosive event' (Grader *et al.* 2008) caused by the significant sea-level drop during the late Serpukhovian glacial event (=GL1 in Fig. 2). In fact, during the Bashkirian, there was a progressive advance through time (punctuated by several high-resolution cycles of sea-level rise–fall) of marine sedimentation/environments from west to east, starting in the Peruvian depositional basins (=Tarma Formation), passing through the Bolivian ones (Grader *et al.* 2008; di Pasquo *et al.* 2019), until reaching the Brazilian intracratonic basins (i.e. Solimões, Amazonas and Parnaíba basins), located further inland (Fig. 1). This is supported by conodont-based ages (Dias *et al.* 2022; Mantilla *et al.* 2022). Recently, the time span established for the carbonate deposits of the Brazilian Amazonas and Parnaíba basin (Monte Alegre Formation – top, Itaituba and Nova Olinda formations – base) based on conodont assemblages was refined, ranging from late Bashkirian to early Moscovian (Dias *et al.* 2022; Mantilla *et al.* 2022). In the Parnaíba Basin, the conodont-bearing carbonates of the Piauí Formation (='Mocambo Carbonates') seem to be restricted to the late Bashkirian (Dias *et al.* 2022), which shows a shallow carbonate platform system adjacent to a coastal dune field (Medeiros *et al.* 2019) similar to what is seen in the Yaurichambi–Copacabana depositional system in Bolivia (Grader *et al.* 2008). Underlying the carbonates there are sandstones interpreted as fluvial at the base and as aeolian at the top (Medeiros *et al.* 2019). These same facies are found earlier in the Yaurichambi Formation in Bolivia, showing that the sedimentary succession from terrigenous to carbonate deposits was similar in different areas where carbonate platforms were developed and adequately dated.

This significant marine transgression from west to east recorded in the northern basins can be directly correlated to sea-level rise associated with the DG1 and DG2 deglaciation events recorded in southern basins, independent of other regional tectonic and/or geomorphological controls that may have acted in the different basins and regions where sedimentation took place. It is a clear case of teleconnection, where a trend in the raise of the global eustatic level is maintained on a million-year-scale, i.e. between the Bashkirian and early Moscovian, despite a fall in sea level that must have occurred between the DG1 and DG2 events.

In all northern basins, the floristic record is very rare in this interval. Only in the Parnaíba Basin is the presence of a *Calamites*-like sphenopsid and *Pecopteris*-like fern reported, which was interpreted by Iannuzzi and Rösler (2000) as an indication of the presence of flora with Euramerican affinity. In the Amazonas Basin, a well-established palynozonation for this interval was defined by Playford and Dino (2000), with two zones *Spelaeotriletes triangulus* and *Striomonosaccites incrassatus*, according to ages calibrated by conodonts and fusulinids for the Monte Alegre and Itaituba formations. Due to the predominance of elements exclusively from Gondwana, these authors considered that the flora that gave rise to the palynological assemblages studied was eminently of Gondwanan affinity. However, they recognized a significant contribution from cosmopolitan elements, as well as others from western Euramerica (i.e. US Midcontinent). Those two palynozones can be correlated approximately to the assemblage named A1 by Di Pasquo (2009) for the basal portion of the Copacabana Formation in the Madre de Dios Basin, northern Bolivia. An age of 316.0 ± 0.4 Ma (^{206}Pb/^{238}U CA-ID-TIMS method, Hamilton *et al.* 2016) obtained from an overlying ash bed (Fig. 2) constrained fossiliferous information, such as palynology (di Pasquo *et al.* 2016), calcareous foraminifera, fusilinids and conodonts recognized in this lower Copacabana Formation, and demonstrated a Bashkirian through middle Moscovian age for this interval (Carvajal *et al.* 2018 and references therein). In the palynological successions of both basins, i.e. Amazonas and Madre de Dios, those assemblages present a dominance of some spores and pollen grains related to Cordaitaleans and Coniferales, indicating relatively more humid local conditions.

Middle Pennsylvanian

Southern records

The subsequent Middle Pennsylvanian (*MidPenn*), approximately equivalent to the Moscovian, is an interval characterized by a quiescence of glacial events. Deposits of clear glacial origin are not recognized in the South American basins. In the Paganzo

Basin, there are no more records of glacial influence (i.e. glaciomarine diamictites, dropstone-bearing shales, etc.). Even the climatic conditions under which the deposits were formed during this interval are considered relatively warm and dry (Césari *et al.* 2011). The *MidPenn* begins with the record of a transgressive event that extends through the basins of NW Argentina (i.e. Paganzo, Rio Blanco, Calingasta–Uspallata) and contains a characteristic fauna assigned to the *Tivertonia jachalensis–Streptorhynchus inaequiornatus* (TS) Zone (Césari *et al.* 2007, 2011; Valdez *et al.* 2020; Cisterna and Sterren 2022). This means that the *MidPenn* begins as a relatively humid interval, but increasingly progresses to conditions of greater aridity that can be seen initially through the absence of coals and presence of calcisols on alluvial plains and, subsequently, extensive red beds in the terrestrial deposits overlying the transgressive horizons (Césari *et al.* 2011). The palynological content these Moscovian shallowing-upward sequences from Paganzo is included at the top of the *DM Zone* (subzone C), which is correlated to the *Crucissacites monoletus* (Cm) *Zone* found in the Campo Mourão Formation of the Itararé Group in the Paraná Basin (Césari *et al.* 2011; Valdez *et al.* 2020). The Campo Mourão Formation is the only one among the other formations of the Itararé Group (which is recognized as the unit that concentrates all the overwhelming evidence of the LPIA occurrence in the Paraná Basin) that does not present direct evidence of glacier action, except for subglacial tunnel valleys associated with its basal unconformity (Vesely *et al.* 2021). This unit is sandy-gravelly, contains few and thin diamictite interbeds and is dominated by fluvio-delta systems formed when ice margins retreated further landward. The scarce diamictites seem to be products of debris flows on subaqueous delta slopes (Carvalho and Vesely 2017).

A deglaciation event (DG2a) was responsible for the sedimentation and re-sedimentation processes that gave rise to the Campo Mourão Formation deposits, as well as the transgressive event recorded in the basins of northwestern Argentina and southern Bolivia (di Pasquo *et al.* 2019). The melting of ice caps located far from the Paraná Basin sedimentation area led to a rise in the base level and the creation of accommodation to be filled by fluvial deposits. Therefore, there is no evidence for glaciers occupying depositional basins in South America during this interval, except perhaps for records in the Tarija Basin (Fig. 1), between Argentina and Bolivia, where extensive diamictite deposits are interpreted to still have a glacial origin (di Pasquo *et al.* 2017 and references therein), possibly due to their closer position to some active glacial centres. A modern example to explain this apparent incongruence would be the active glacial Perito Moreno in the Santa Cruz province of Argentina, but this should be checked in the future.

In floristic terms, the *Interval* (Int) Flora is registered in the basins of northwestern Argentina that were further away from the glacial centres, located probably in southern Africa. The Int Flora is characterized by the appearance of conifers and ferns and by the occurrence of several taxa present in the underlying *NBG* Flora (Césari *et al.* 2007, 2011) and its elements lived under humid conditions evidenced by the studies carried out on wood (Césari *et al.* 2007 and references therein). In the Paraná Basin, the *Paranocladus–Ginkgophyllum–Brasilodendron* (*PGB*) Flora known from one locality (i.e. Monte Mor) referred to the Campo Mourão Formation (Vesely *et al.* 2021), is correlated to the Int Flora based on some elements in common with the *NBG* Flora and conifers (Bernardes-de-Oliveira *et al.* 2016). Ferns are not present in the *PGB* Flora. This absence may be associated with the greater proximity of this flora to glacial centres located in Africa, indicating that different climatic and environmental conditions, probably colder than those found in northwestern Argentina were developed. The appearance of ferns in the Paraná Basin occurs only in the Asselian and has been linked to post-glacial warming (Rischbieter *et al.* 2022), in contrast to more humid conditions that would have prevailed in western Argentina under the more maritime-weather influence during the Early Pennsylvanian. From the palynological point of view, the associations of the subzone C of the *DM* Zone (Fig. 2) show both a qualitative and quantitative increase in taeniate-bisaccate pollen grains with respect to the previous *DM* Zone – subzones A and B, which is associated with the occurrence of warmer and seasonally arid climate conditions in this interval (Césari *et al.* 2011). Consistently, the coeval associations of the *Cm* Zone from the Paraná Basin, closer to the African glacial centres, present less abundance and diversity of taeniate-bisaccate grains (Souza 2006).

The South American DG2a deglaciation event could be approximately correlated with the C4 Glacial Interval (GI) or Phase (=glaciation) as proposed by Fielding *et al.* (2008) for glacial deposits in eastern Australia. A Moscovian age can be attributed to C4 GL (313–309.4/308 Ma) using the Pennsylvanian ages currently accepted by the geological timescale (Aretz *et al.* 2020).

Northern records

As a consequence of the DG2a deglaciation, there is a concomitant transgressive event that maintains the carbonate platforms that were geographically widely distributed across the basins in the north of the continent, occurring from Peru, passing through Bolivia, until reaching more inland areas such as northern Brazil, i.e. Amazonas Basin (Cunha *et al.* 2007; Grader *et al.* 2008; Mantilla *et al.* 2022). In fact, it seems that the peak in the geographical expansion of the carbonate platforms took place in the early-to-middle Moscovian (Fig. 2). In the Titicaca Basin, the thick 'Atokan Marker Shale' that overlies carbonate banks and is positioned near the top of the lower Copacabana Member, corresponds to the maximum flooding that can be directly correlated to a transgression at the beginning of the aforementioned DG2a deglaciation event. This is an important biostratigraphical datum that allows connecting cause – deglaciation (DG2a) – and effect – transgression ('Atokan Marker Shale') – demonstrating the teleconnection between the events that occurred in the basins to the south and north of the continent.

The three deglaciation events (DG1, 2 and 2a) recorded in the southern basins, from the beginning of the Bashkirian to the middle of the Moscovian, generated transgressive events in the northern basins that, despite the rises and falls of sea level, kept the base level relatively high during this interval, leading to the generation and expansion of carbonate platforms. After this last transgressive event of Moscovian age the carbonate platforms gradually retracted and there was an increase in terrestrial siliciclastic deposits (aeolian, lagoon, fluvial facies). The development of subaerial exposures in Brazilian inland basins is also recorded (Cunha *et al.* 2007). In fact, in the sequences of the area encompassing the Titicaca Basin, the deposits of the carbonate slopes of the Copacabana Formation are interfingered with the evaporitic lagoons and terrigenous facies (fluvial, aeolian dunes) of the shallow plains of the Yaurichambi Formation, from the beginning of the Bashkirian until the end of the Moscovian (Grader *et al.* 2007, 2008; Di Pasquo 2009; Di Pasquo *et al.* 2017), reflecting the repeated rises and falls of sea level in shallow-water conditions. In the Parnaíba Basin, above the single carbonatic interval, there are terrigenous sediments interpreted as delta fronts indicating wet conditions (Medeiros *et al.* 2019). However, stratigraphically higher, evaporites and aeolian dunes appear, indicating drying and warming conditions (Lima Filho 1991).

In the northern basins, the palaeobotanical record is practically non-existent, and even the palynological record becomes rare towards the end of this interval. In the Amazonas Basin, Playford and Dino (2000) established three palynozones for time-equivalent Moscovian strata, according to the fusulinid and conodont ages obtained for the (upper) Itaituba and Nova Olinda formations, namely: *Illinites unicus*, *Striatosporites heyleri* and *Raistrickia cephalata*. These three palynozones are approximately correlated to assemblage A2 described by Di Pasquo (2009) for the Copacabana Formation, considered as Moscovian in age on the basis of calcareous microfossils obtained from the same profile. In all these assemblages, except for those belonging to the *Illinites unicus Zone* (where taeniate grains are inconspicuous), taeniate-bisaccate pollen grains related to new groups of pteridosperms become more abundant and diverse, which is interpreted as a decrease in humidity and/or an increase in seasonally arid conditions under warmer climate that prevailed in the terrestrial environments surrounding the 'Copacabana Sea' (Playford and Dino 2000; Di Pasquo 2009).

Late Pennsylvanian–earliest Permian

Southern records

The last interval, corresponding to the Late Pennsylvanian (*c.* Kasimovian–Gzhelian = *LPenn*), is characterized by the return of glacial cycles in a similar way to those that have been recorded in the Early Pennsylvanian (*EPenn*). The interval begins with a more significant cooling event (GL3) due to a new intensification of the glaciation (cause) and an accentuated fall in sea level (effect) that started at the end of the *MidPenn*. As aforementioned, the apogee of the aridization process probably corresponds to a progressive warming and drying in climate conditions that begins in the Paganzo Basin from the middle Moscovian (Césari *et al.* 2011). This process of progressive aridization is well documented in the Patquía Formation that overlies the Tupe Formation, where the succession of Pennsylvanian events presented so far is well recorded. The Patquía Formation begins with fluvial deposits that become lacustrine and alluvial, with the predominance of calcisols and development of red beds, aeolian dunes and evaporites toward the top of unit (Andreis 1988). According to the existing radiometric ages below and above this unit (Gulbranson *et al.* 2010; Césari *et al.* 2011, 2019), the Patquía Formation sediments were mainly deposited during the middle to late Moscovian, possibly reaching the Kasimovian. Césari *et al.* (2019) supported this age based on their U–Pb age of 311.89 ± 0.21 Ma obtained at the base of the De La Cuesta Formation (Fig. 2) from where the disappearance of coal beds, the predominance of calcisols in alluvial plains and the formation of red bed sequences were documented.

In the Paraná Basin, the Taciba Formation, which may have even started at the end of the Carboniferous (=late Gzhelian, see discussion below) sits unconformably on the Campo Mourão Formation (Vesely *et al.* 2021), considered to be of Moscovian age based on palynological correlation with radiometrically calibrated palynozones in Argentina (Césari *et al.* 2011). This unconformity represents a stratigraphic gap that may even extend across the entire basin (Vesely *et al.* 2021). There is even a significant change in sediment dispersal patterns. Whereas in the Campo Mourão Formation the palaeocurrents point to the north, in the Taciba Formation sediment transport changed to the SSW (Mottin *et al.* 2018; Vesely *et al.* 2021; Mottin 2022). Finally, the deposits of the Rio do Segredo Member, the lowest of the Taciba Formation, can be found embedded in palaeovalleys formed at the top of the Campo Mourão Formation (Vesely *et al.* 2021). All this evidence argues in favour of the occurrence of a significant gap between these two formations, which as a first approach, would correspond mainly to the Kasimovian age.

Interestingly, there is no palaeontological record in NW Argentina within the *LPenn* interval, neither macro nor microfossils, plants nor invertebrates (Césari *et al.* 2011; Cisterna and Sterren 2022). The biozones (palaeobotanical, palynological and invertebrate) from northwestern Argentina that were previously believed to be temporally positioned in the *LPenn* (Kasimovian–Gzhelian) have been repositioned in the *MidPenn*, i.e. Moscovian, based on radiometric age calibration of fossiliferous horizons (Gulbranson *et al.* 2010; Césari *et al.* 2011). This still poorly documented or potentially absent fossil record could be due to the aforementioned accentuated aridity and oxidation of sediments assigned to the *LPenn* (i.e. Patquía Formation and correlative units). In the upper portions of these sequences there are also recurrent subaerial exposures, indicated by the occurrence of palaeosols and aeolian dunes, in addition to the occasional presence of evaporites. Furthermore, the sedimentary sequence of the Patquía Formation ends abruptly, on an erosive surface, indicating the occurrence of a stratigraphic hiatus that was positioned within the Gzhelian (Césari *et al.* 2011), but which could have even started in the Kasimovian, covering all the *LPenn*. All these facts point to a significant drop in the base level in the Paganzo Basin (and in other neighbouring ones) that can reflect an intense cooling event that marks the transition from *Mid*- to *LPenn*, named here as the 'Kasimovian glacial event' (=GL3 in Fig. 2).

In fact, the sedimentary rocks or fossil record of the Kasimovian across Gondwana is not clear as addressed below, whereas there are more records of deglaciation sequences in the Gzhelian. In Australia, where the Carboniferous rocks are better understood and also radiometrically dated, there is also no confirmation of the existence of deposits in the Kasimovian (and even Gzhelian). Instead, there is a gap in the vast majority of sedimentary sequences of the basins (Fielding *et al.* 2008, 2022). This confirms that there is a generalized drop in sea level in the basins along Gondwana, probably caused by the intensification of glaciation over this continent during the Kasimovian.

Subsequently in Gzhelian time, the beginning of a deglaciation process likely derived in the increase of the record of glacial-marine sequences and a progressive rise in sea level in the southernmost basins. The sections that present the best record of this deglaciation interval, which have radiometric dates, some of which are of high precision, are those belonging to the Dwyka Group in Namibia and South Africa. In the Karoo and Kalahari basins, four deglaciations have been established, named as Deglaciation Sequences (DS) I to IV (Stollhofen *et al.* 2000, 2008). The timing of DS II and III has been better circumscribed due to U–Pb radiometric dates carried out on tuffs found in marine shales (=maximum floods) located in the upper portion of each of those deglaciation sequences, from base to top, *Ganigobis Shale* and *Hardap Shale*, respectively. Earlier, tuffs at the base of the *Ganigobis Shale*, in Namibia, were dated by SHRIMP (SIMS) U–Pb zircon to 302.0 ± 3.0 to 299.5 ± 3.1 Ma (in Stollhofen *et al.* 2000, 2008). High-resolution U–Pb zircon CA-TIMS ages for the same tuffs provided ages of 300.0 ± 0.45 to 299.31 ± 0.35 Ma (Griffis *et al.* 2023), confirming a late Gzhelian age for the top of DS II. The tuff horizon obtained from the *Hardap Shale*-equivalent mudstone, in Klaarstroom, South Africa, yielded a SHRIMP (SIMS) U–Pb zircon age of 297.1 ± 1.8 Ma (in Stollhofen *et al.* 2000, 2008). A new U–Pb zircon CA-TIMS age of 296.41 ± 0.27/−0.35 Ma from the same tuff horizon was recently obtained (Griffis *et al.* 2019), indicating a middle Asselian age for the top of DS III. In Namibia, the *Hardap Shale* is characterized by containing elements of the *Eurydesma Fauna* and, consequently, relates to the Gondwana-widespread '*Eurydesma Transgression*' (Stollhofen *et al.* 2008).

In the northeastern Paraná Basin, there are records of *Eurydesma Fauna* elements in shales positioned in the upper portion of the Taciba Formation (Itararé Group) named as the *Passinho Shale* (Neves *et al.* 2014; Taboada *et al.* 2016). Therefore, it is possible to correlate those mudstones of the *Passinho Shale* with those of the *Hardap Shale*, assuming that both correspond to the '*Eurydesma Transgression*'. Recently, based on the occurrence of glacial diamictites above and below the *Eurydesma* Fauna-bearing *Passinho Shale*, it has been proposed that the upper Taciba Formation in the northeastern rim of the basin corresponds directly to DS III and DS IV of Visser (1997), according to Mottin (2022). Furthermore, the *Lontras Shale*, a fossiliferous horizon positioned below the Passinho, is correlated with the *Ganigobis Shale* based on the facies, its positioning within the sedimentary sequence and its wide geographical distribution throughout the basin, indicating the occurrence of a significant transgressive event (Holz *et al.* 2010). The *Lontras Shale* contains the first (oldest) records of palynomorphs belonging to the *Vittatina costabilis* (Vc) Zone (Souza 2006) considered to indicate the beginning of the Permian. Because of this, the Carboniferous–Permian boundary has been positioned in the *Lontras Shale* (Holz *et al.* 2008, 2010). However, if this equivalence with the *Ganigobis Shale* is correct, the base of the *Vc* Zone should be extended back to the late Gzhelian (Souza *et al.* 2021).

Based on the 4–5 Ma difference between DS II and DS III sequences, it can be assumed that DS I started between the end of the Kasimovian and the Kasimovian–Gzhelian boundary (Fig. 2). Therefore, we suggest herein to re-evaluate the Kasimovian palaeontological and sedimentary record in SAM and elsewhere in Gondwana because a significant sea-level drop occurred in this interval that could have precluded their preservation and a considerable gap should be more likely documented. After this interval, the sedimentation restarted and four major deglaciation sequences lasting a few million years each were deposited, two during the *LPenn* (=Gzhelian) and two during the early Permian, as proposed in the Kalahari and Karoo basins (see Stollhofen *et al.* 2000, 2008). Interspersed with these deglaciation sequences documented in southern Africa, it is assumed that there must have been short periods of cooling. Hence, a glaciation event between the DS I and DS II sequences, named here GL4, and another between DS II and DS III, named GL5 would have developed (see Fig. 2). It is interesting to note that given the aforementioned radiometric ages for the DS sequences, the ICS Carboniferous–Permian boundary (aged 298.9 $\pm$ 0.15, according to Aretz *et al.* 2020) may even be physically lying on top of DS II (=*Ganagobis Shale*), but the beginning of the Permian would be marked by a drop in sea level due to the beginning of a cooling phase (=glacial event GL5, Fig. 2), consequently generating breaks or sequence boundaries in most sedimentary successions (i.e. non-deposition, subaerial exposure, and unconformities).

Northern records

In the Titicaca Basin, the beginning of the *LPenn* (close to the Moscovian–Kasimovian boundary) is marked by the occurrence of a sequence boundary called 'Penn 6SB' that defines an unconformity and significant stratigraphic gap (Grader *et al.* 2008). This erosive surface confirms the generalized drop in sea level recorded in the basins across Gondwana, probably caused by the aforementioned 'Kasimovian Glacial', coded here as GL3 (Fig. 2). Overlying the 'Penn. 6 SB' transgressive sandstone deposits of the Yaurichambi Formation filled local troughs in post-Atokan (Moscovian) palaeotopography. The first carbonates interfingered with basal siliciclastics and contained a low frequency of 'Missourian' fusulinids, indicating that the sedimentation re-started in the Kasimovian (Grader *et al.* 2008). However, the overlying carbonates of the Copacabana Formation have abundant 'Virgilian' fusulinid intervals, confirming that most of the carbonate interval above was deposited during the Gzhelian (Grader *et al.* 2008). Also, there is a new expansion of carbonate platforms in the Peru–Bolivia basins, probably as a result of sea-level rise related to the aforementioned deglaciation events recorded in southern South America and southern Africa (DS I to DS II). In this context, di Pasquo *et al.* (2017) recorded a short-lived marine event in the San Telmo Formation of southern Tarija Basin (Fig. 1). This sample is characterized by poorly preserved marine brachiopods accumulated between storm wave base and fair weather wave base, where abundant gastropods also occur. It is located slightly over the highest productive palynomorph sample of the Kasimovian/Ghzelian *Marsupipollenites triradiatus–Lundbladispora braziliensis* (TB) Zone of di Pasquo. Hence, this event here correlated with the DG4 in Figure 2 is another evidence of the upward transgressive trend in the Gzhelian, like the carbonate intervals of the Copacabana unit.

A further significant fall in relative sea level near the Carboniferous–Permian boundary is represented by the sequence boundary 'P1 SB' (Grader *et al.* 2008). This sea-level fall is in line with the occurrence of the Glacial Event GL5 (Fig. 2), as proposed hitherto based on the analysis of the DS II and DS III deglaciation sequences from southern Africa basins (see the previous section).

To the east, in the Parnaíba Basin, after the deposition of the late Bashkirian–early Moscovian carbonate interval and the overlying Moscovian fluviodeltaic deposits, apparently extensive aeolian dune fields were established (Kifumbi *et al.* 2022), which may be recording a drier interval at mid-latitudes (*c.* 30°S) driven by the Kasimovian Glacial Event. In fact, a coastal dune system always existed before, during (laterally interfingered) and after the marine carbonate interval (Lima Filho 1991; Medeiros *et al.* 2019). However, there are no sufficient chronostratigraphical (relative or absolute ages) and stratigraphic controls to establish the temporal positioning of the thick aeolian interval (erg-systems) recorded in the Piauí Formation (Kifumbi *et al.* 2022). The contact with the overlying Pedra-de-Fogo Formation seems to occur as a paraconformity, where there is a time gap represented by slightly pedogenically modified and/or deflated surfaces, on which basal shoreface facies of the Pedra-de-Fogo Formation are deposited (Kifumbi *et al.* 2022). A time gap extending from the late Moscovian to early Permian is assumed for the succession of the Amazonas Basin, based on palynological analysis, which is normally also accepted for Pennsylvanian successions of the Solimões Basin, to the west, and the Parnaíba Basin, to the east (Playford and Dino 2000). Nevertheless, the ages of the units based on conodonts indicate the existence of a slightly shorter gap, which would extend from the late Moscovian to the early Gzhelian (Cunha *et al.* 2007). In any case, there is no clear evidence of the presence of Kasimovian strata.

Finally, the time of the onset of sedimentation in the Pedra-de-Fogo Formation and correlated units from the basins of northern Brazil should be mentioned. Taking into account that in the Peru–Bolivia basins: (i) the post lowstand Kasimovian sedimentation started before the end of the Kasimovian itself and (ii) the carbonate platforms were expanding (from west to east) since the beginning of the Gzhelian, it is reasonable to assume that sedimentation could have restarted in the interior basins of NNE Brazil, even at the end of the Gzhelian. The Arari Member, upper portion of the Nova Olinda Formation in the Amazonas Basin, has yielded Virgilian conodonts that indicate a Gzhelian age for this unit (Cunha *et al.* 2007). However, the palynological associations coming from this same member are included in the *Vittatina costabilis* (*Vc*) Zone, considered early Permian in age (Playford and Dino 2000). Considering that the ages based on conodonts are more reliable and precise, it can be assumed that not only did the sedimentation of this unit start in the Gzhelian, but also the *Vc* Zone as well. This is a situation similar to that already reported above for the *Vc* Zone in the *Lontras Shale* in the Paraná Basin, which, if correlated with the *Ganigobis Shale* from Namibia, is Ghzelian in age. From this point of view, other units traditionally considered as Permian based only on palynological content, such as the Pedra-de-Fogo Formation in the Parnaíba Basin, could have started their deposition already in the Gzhelian (Fig. 2).

Final remarks

As a result of the above (summarized in Fig. 2), the following glaciation (GL) and deglaciation (DG) intervals were determined:

- The GL1 interval represents a huge, globally recognized gap that exists between the Mississippian and the Pennsylvanian and must have been generated by a significant drop in sea level. In fact, it seems that this event should be seen as one of the main onsets of glaciation during the entire time span of the LPIA, given its global scope.
- The DG1 interval, which corresponds to the transition from conditions of global cooling to those of post-glacial warming, holds a relatively thick sedimentary succession that documents the entire transition from glacial to non-glacial environments, until reaching the formation of extensive, vegetated coastal plains.
- Subsequent intervals, i.e. GL2, DG2, GL2a and DG2a, can be seen as part of a widespread warming process that lasted for millions of years (starting with DG1 and therefore spanned from the early Bashkirian to the late Moscovian). Despite including two short interspersed cooling intervals (GL2 and GL2a), this period of time documents a change in Earth's climate to relatively warm and humid conditions. Much of the water previously trapped in glaciers was made available to the atmosphere–hydrosphere throughout the demise of the ice cover, which contributed to the maintenance of the highstand sea level.
- The GL3 interval represents a new intensification of glaciation, with a significant fall and retraction of the seas, which basically took place in the Kasimovian. Although, there were already signs of that foreshadowed change since the Moscovian, such as a progressive drop in sea level and an increase in aridity in terrestrial environments. In addition, there was a decrease in sedimentation rates and a concomitant increase in areas prone to subaerial exposure.
- After this GL3 event, which indicates that there was a resumption of severe cooling conditions, probably accompanied by an increase in aridity in terrestrial environments, a new long period of progressive climate amelioration (represented by DG3, GL4, DG4, GL5, DG5) was developed, similar to what happened during the Bashkirian–Moscovian (DG1, GL2, DG2, GL2a, DG2a). This led to a new period of global warming and sea-level rise that culminated at the beginning of the Permian.

It is important to point out that the most complete history of the LPIA is preserved in South America (Fig. 2), even if that requires analysing different basins that preserve distant portions of the record of this long glacial interval. Also, the published compilations containing the sedimentological, palaeontological and geochronological database indicated that LPIA occurred in two main intervals, one centred in the latest Mississippian–early-to-middle Pennsylvanian (*c.* 325–313 Ma) and the other in the Late Pennsylvanian–early Permian (*c.* 307–295 Ma) (Fig. 2). However, not all types of data obtained from the sedimentary sequences have clearly shown this, as in the case of isotopic data, in which only the second interval has been highlighted as the acme of the LPIA (see Montañez

2021). This is a question that deserves to be stressed in forthcoming contributions.

In any case, the LPIA was certainly the main driving force behind the evolution of Earth's biotas during the Late Devonian–early Permian interval. All the changes taking place on the surface of the planet due to the flip-flop of global warming and cooling have inevitably affected life. In the case of plants, in the interval covering the LPIA, there was the emergence of gymnosperms (Late Devonian), the appearance of the first pollen grains (Serpukhovian) and the emergence of new groups of plants, such as callipterids, glossopterids and gigantopterids (Pennsylvanian–Permian transition).

In terms of the cooling and warming intervals outlined here (equivalent to the Glaciation – GL and Deglaciation – DG sequences, respectively), there is a relatively straightforward correlation with documented changes for Euramerican environments and floras. Assuming that during intervals of cooling the global climate tends to become drier, since there is less water in liquid and gaseous state available in the atmosphere–hydrosphere, and in intervals of warming there is more humidity around the world (as seen in the Cenozoic Ice Age), it is possible to roughly to trace a correlation between:

(a) the occurrence of wetlands and peat-accumulating environments, where tree-lycopsids dominated, in Euramerica (DiMichele 2014; Opluštil *et al.* 2013) and transgressive deglaciation sequences during the Bashkirian–Moscovian interval (Fig. 2), when there was an increase in both atmospheric humidity and sea level;
(b) the emergence of more arid environments, with the concomitant expansion of marattialean tree-ferns, in the tropics (DiMichele 2014; Opluštil *et al.* 2013), and the increase in aridity and progressive sea-level fall recorded in Gondwana from the middle Moscovian (= DG2; Fig. 2), which culminates in a likely cooling event in Kasimovian (GL3);
(c) the predominance of arid to semi-arid environments (and significant decrease in environments that accumulate peat), associated with the disappearance of tree-lycopsids and emergence of marattialean tree-ferns, in Euramerica (DiMichele 2014; Opluštil *et al.* 2013), and the 'Kasimovian Cooling Event' proposed here, especially during the early-to-middle Kasimovian (GL3; Fig. 2) that would have caused the drying out of Earth's climate;
(d) the intermittent expansion of peat-accumulating environments, in Euramerica (Opluštil *et al.* 2013), and the deglaciation sequences (DG3, DG4 …), documented in western Gondwana (Fig. 2), during the middle-to-early Kasimovian and early Permian.

Therefore, a better understanding of how and when the events of the LPIA took place will allow us to understand the evolution of life during the late Paleozoic. This contribution is just a starting point that intends to help in the delineation of future works that seek greater detail of this icehouse interval on Earth.

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References

Andreis, R.R. 1988. *Las fácies verdosa de La Formación Patquía (Pérmico) en el extremo austral de la Sierra de Maz (La Rioja)*. Project 211-IGCP Late Palaeozoic South America, Communication, Buenos Aires, 49–52.

Aretz, M., Herbig, H.G. and Wang, X.D. 2020. The Carboniferous Period. *In*: Gradstein, F.M., Ogg, J.G., Schmitz, M.D. and Ogg, G.M. (eds) *Geologic Time Scale 2020.*

Elsevier, Amsterdam, **2**, 811–874, https://doi.org/10.1016/B978-0-12-824360-2.00023-1

Azcuy, C., Beri, A. *et al*. 2007. *Bioestratigrafía del Paleozoico Superior de América del Sur: primera etapa de trabajo hacia una nueva propuesta cronoestratigráfica*. Asociación Geológica Argentina, Serie D: Publicación Especial, Buenos Aires, **11**, 9–65.

Balseiro, D., Rustán, J.J., Ezpeleta, M. and Vaccari, N.E. 2009. A new Serpukhovian (Mississippian) fossil flora from western Argentina: paleoclimatic, paleobiogeographic and stratigraphic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **280**, 517–531, https://doi.org/10.1016/j.palaeo.2009.07.005

Bernardes-de-Oliveira, M.E.C., Kavali, P.S. *et al*. 2016. Pennsylvanian–early Cisuralian interglacial macrofloristic succession in Paraná basin of the state of São Paulo. *Journal of South American Earth Sciences*, **72**, 351–374, https://doi.org/10.1016/j.jsames.2016.09.004

Carvajal, C.P., Soreghan, G.S., Isaacson, P.E., Ma, C., Hamilton, M.A., Hinnov, L.A. and Dulin, S.A. 2018. Atmospheric dust from the Pennsylvanian Copacabana Formation (Bolivia): a high resolution record of climate and volcanism from northwestern Gondwana. *Gondwana Research*, **58**, 105–121, https://doi.org/10.1016/j.gr.2018.02.007

Carvalho, A.H. and Vesely, F.F. 2017. Facies relationships recorded in a Late Paleozoic fluvio-deltaic system (Paraná Basin, Brazil): insights into the timing and triggers of subaqueous sediment gravity flows. *Sedimentary Geology*, **352**, 45–62, https://doi.org/10.1016/j.sedgeo.2016.12.004

Césari, S.N. and Pérez Loinaze, V. 2021. Update of the Pennsylvanian palynostratigraphy from central-western Argentina. *Journal of South American Earth Sciences*, **106**, 102933, https://doi.org/10.1016/j.jsames.2020.102933

Césari, S.N., Gutiérrez, P. *et al*. 2007. Paleozoico Superior de Argentina: un registro fosilífero integral para el Gondwana occidental. *Asociación Paleontológica Argentina, Publicación Especial*, **11**, 35–54.

Césari, S.N., Limarino, C.O. and Gulbranson, E.L. 2011. An Upper Paleozoic biochronostratigraphic scheme for the western margin of Gondwana. *Earth-Science Reviews*, **106**, 149–160, https://doi.org/10.1016/j.earscirev.2011.01.012

Césari, S.N., Limarino, C.O., Spalletti, L.A., Piñol, F.C., Pérez Loinaze, V.S., Ciccioli, P.L. and Friedman, R. 2019. New U Pb zircon age for the Pennsylvanian in Argentina: implications in palynostratigraphy and regional stratigraphy. *Journal of South American Earth Sciences*, **92**, 400–416, https://doi.org/10.1016/j.jsames.2019.02.010

Clapham, M.E. and James, N.P. 2008. Paleoecology of Early–Middle Permian marine communities in eastern Australia; response to global climate change in the aftermath of the late Paleozoic ice age. *Palaios*, **23**, 738–750, https://doi.org/10.2110/palo.2008.p08-022r

Cisterna, G.A. and Sterren, A.F. 2022. Brachiopod zonation in the late Paleozoic sequences of Argentina and its correlation with other South American basins. *Journal of South American Earth Sciences*, **117**, 103845, https://doi.org/10.1016/j.jsames.2022.103845

Cunha, P., Melo, J.H. and Silva, O. 2007. Bacia do Amazonas. *Boletim de Geociências da Petrobras*, **15**, 227–254.

Davydov, V.I., Crowley, J.L., Schmitz, M.D. and Poletaev, V.I. 2010. High precision U–Pb zircon age calibration of the global Carboniferous time scale and Milankovitch-band cyclicity in the Donets Basin, eastern Ukraine. *Geochemistry, Geophysics, Geosystems*, **11**, Q0AA04, https://doi.org/10.1029/2009GC002736

Dias, S.K.R., Lima Soares, J., Scomazzon, A.K., Medeiros, R.S.P. and Nascimento, S. 2022. Taxonomic revision of conodonts of Piauí Formation, Parnaíba Basin, updating to late Bashkirian age and biostratigraphic – paleoecologic correlation with the Itaituba Formation, Amazonas Basin. *Journal of South American Earth Sciences*, **115**, 103750, https://doi.org/10.1016/j.jsames.2022.103750

Díaz-Martínez, E. and Dalenz, A. 1995. La Formación Yaurichambi (Carbonífero superior): depósitos siliciclásticos costeros y fluviodeltaicos de la base del Grupo Titicaca de Bolivia. 6° Simpósio Sul-brasileiro de Geologia – 1° Encontro de Geologia do Cone Sul. *Boletim de Resumos Expandidos*, **1**, 245–247.

DiMichele, W.A. 2014. Wetland-dryland vegetational dynamics in the Pennsylvanian Ice Age tropics. *International Journal of Plant Sciences*, **175**(2), 123–164, https://doi.org/10.1086/675235

DiMichele, W.A., Montañez, I.P., Poulsen, C.J. and Tabor, N.J. 2009. Vegetation–climate feedbacks and regime shifts in the Late Paleozoic ice age earth. *Geobiology*, **7**, 200–226, https://doi.org/10.1111/j.1472-4669.2009.00192.x

di Pasquo, M.M. 2009. The Pennsylvanian palynoflora from the Pando X-1 Borehole, northern Bolivia. *Review of Paleobotany and Palynology*, **157**, 266–284, https://doi.org/10.1016/j.revpalbo.2009.05.006

di Pasquo, M. and Milana, J.P. 2021. First palynological data from Loma de los Piojos Formation suggesting a reappraisal of its age. *XII Congreso de la Asociación Paleontológica Argentina (CAPA), Simposio 'Actualización del conocimiento de los esquemas palinoestratigráficos del Paleozoico Superior sudamericano', (CABA, noviembre)*. Buenos Aires, Resúmenes, 138–139.

di Pasquo, M.M., Grader, G.W., Isaacson, P., Souza, P.A., Iannuzzi, R. and Díaz-Martínez, E. 2014. Global biostratigraphic comparison and correlation of an early Cisuralian palynoflora from Bolivia. *Historical Biology: an International Journal of Paleobiology*, **27**, 868–897, https://doi.org/10.1080/08912963.2014.910204

di Pasquo, M., Isaacson, P., Grader, G.W., Hamilton, M.A. and Soreghan, G.S. 2016. Palynostratigraphy of the Yaurichambi and Copacabana formations in the Manuripi X-1 core, Madre de Dios Basin, northern Bolivia: first constraints from U–Pb dating of volcanic ash. *XIV International Palynological Congress and X International Organisation of Palaeobotany Conference IPC/IOPC 2016 'Palaeobotany and Palynology: Towards New Frontiers'*, 23–28 October, Salvador de Bahia. *Boletin ALLP*, **16**, 110.

di Pasquo, M.M., Anderson, H. and Isaacson, P. 2017. Record of a Pennsylvanian–Cisuralian marine transgression, southern Bolivia: a short-lived event in western Gondwana? *Palaeogeography, Palaeoclimatology, Palaeoecology*, **485**, 30–45, https://doi.org/10.1016/j.palaeo.2017.05.026

di Pasquo, M.M., Anderson Folnagy, H.J., Isaacson, P.E. and Grader, G.W. 2019. Late Paleozoic carbonates and glacial deposits in Bolivia and northern Argentina: significant paleoclimatic changes. *Society for Sedimentary Geology, SEPM, Special Publication*, **108**, 185–203.

Fielding, C.R., Frank, T.D., Birgenheier, L.P., Rygel, M.C., Jones, A.T. and Roberts, J. 2008. Stratigraphic imprint of the late Palaeozoic ice age in eastern Australia: a record of alternating glacial and nonglacial climate regime. *Journal of the Geological Society, London*, **165**, 129–140, https://doi.org/10.1144/0016-76492007-036

Fielding, C.R., Frank, T.D. and Birgenheier, L.P. 2022. A revised, late Palaeozoic glacial time–space framework for eastern Australia, and comparisons with other regions and events. *Earth-Science Reviews*, **236**, 104263, https://doi.org/10.1016/j.earscirev.2022.104263

França, A.B. and Potter, P.E. 1988. Estratigrafia, ambiente deposicional e análise de reservatório do Grupo Itararé (Permocarbonífero), Bacia do Paraná (Parte 1). *Boletim de Geociências da Petrobrás*, **2**, 147–191, https://doi.org/10.18356/0e75c030-ru

Grader, G.W. 2003. *Carbonate-Siliciclastic Sequences of the Pennsylvanian and Permian Copacabana Formation, Titicaca Group, Andes of Bolivia*. PhD thesis, University of Idaho.

Grader, G.W., Díaz-Martínez, E., Davydov, V., Montañez, I., Tait, J. and Issacson, P.E. 2007. Late Paleozoic stratigraphy framework in Bolivia: constraints from the Warm Water Cuevo Megasequence. *Cuadernos de Museo Geominero*, **8**, 181–188.

Grader, G.W., Isaacson, P.E., Díaz-Martínez, E. and Pope, M.C. 2008. Pennsylvanian and Permian sequences in Bolivia: direct responses to Gondwana glaciation. *Geological Society of America Special Paper*, **441**, 143–159, https://doi.org/10.1130/2008.2441(10)

Griffis, N.P., Montañez, I.P., Mundil, R., Richey, J., Isbell, J., Fedorchuck, N. and Yin, Q.Z. 2019. Coupled stratigraphic and U–Pb zircon age constraints on the Late Paleozoic Icehouse-to greenhouse turnover in south-central Gondwana. *Geology*, **47**, 1146–1150, https://doi.org/10.1144/0016-76492007-036

Griffis, N., Mundil, R., Montañez, I.P. and Iannuzzi, R. 2023. A Carboniferous apex for the late Paleozoic Icehouse. *Geological Society, London, Special Publications*, **535**, https://doi.org/10.1144/SP535-2022-256

Gulbranson, E.L., Montañez, I.P., Schmitz, M.D., Limarino, C.O., Isbell, J.L., Marenssi, S.A. and Crowley, J.L. 2010. High precision U–Pb calibration of Carboniferous glaciation and climate history, Paganzo Group, NW Argentina. *Geological Society of America Bulletin*, **122**, 1480–1498, https://doi.org/10.1130/b30025.1

Hamilton, M.A., Soreghan, G.S., Carvajal, C.P., Isaacson, P.E., Grader, G.W. and Di Pasquo, M.M. 2016. A precise U–Pb zircon age from volcanic ash in the Pennsylvanian Copacabana Formation, Bolivia. *Geological Society of America Rocky Mountain Section – 68th Annual Meeting*, 2006, Idaho, Moscow, 48, Abstract no. 276278, https://doi.org/10.1130/abs/2016RM-276278

Holz, M., Souza, P.A. and Iannuzzi, R. 2008. Sequence stratigraphy and biostratigraphy of the Late Carboniferous to Early Permian glacial succession (Itararé subgroup) at the eastern-southeastern margin of the Paraná Basin, Brazil. *Geological Society of America Special Paper*, **441**, 115–129, https://doi.org/10.1130/2008.2441(08)

Holz, M., França, A.B., Souza, P.A. and Iannuzzi, R. and Rohn, R. 2010. A stratigraphic chart of the Late Carboniferous/Permian succession of the eastern border of Paraná Basin, Brazil, South America. *Journal of South American Earth Sciences*, **29**, 381–399, https://doi.org/10.1016/j.jsames.2009.04.004

Iannuzzi, R. and Rösler, O. 2000. Floristic migration in South America during the Carboniferous: phytogeographic and biostratigraphic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **161**, 71–94, https://doi.org/10.1016/S0031-0182(00)00118-8

Iannuzzi, R. and Shen, S. 2013. Event Stratigraphy. *Ciências da Terra (UNL)*, **18**, 121–124, https://doi.org/10.21695/cterra/esj

Isbell, J.L., Miller, M.F., Wolfe, K.L. and Lenaker, P.A. 2003. Timing of late Paleozoic glaciation in Gondwana: was glaciation responsible for the development of northern hemisphere cyclothems? *Geological Society of America Special Papers*, **370**, 5–24, https://doi.org/10.1130/0-8137-2370-1.5

Kifumbi, C., Scherer, C.M.S., Souza, E.G., Reis, A.D., Ferronatto, J.P.F. and Michel, R.D.L. 2022 Late Pennsylvanian aridification in Gondwana mid-latitudes contemporaneous to high-latitudes ice cap expansion, upper Piauí Formation, Brazil. *Journal of South American Earth Sciences*, **117**, 103840, https://doi.org/10.1016/j.jsames.2022.103840

Lima Filho, F.P. 1991. *Fácies e ambientes deposicionais da Formação Piauí (Pensilvaniano)*. Bacia do Parnaíba. Master thesis, Instituto de Geociências – USP.

Limarino, C.O., Césari, S.N., Spalletti, L.A., Taboada, A.C., Isbell, J.L., Geuna, S. and Gulbranson, E.L. 2014. A paleoclimatic review of Southern South America during the late Paleozoic: a record from icehouse to extreme greenhouse conditions. *Gondwana Research*, **25**, 1396–1421, https://doi.org/10.1016/j.gr.2012.12.022

Mantilla, A.F.R., Scomazzon, A.K., Nascimento, S., Alvarenga, R.S., Lemos, V.B. and Souza, P.A. 2022. The conodont genus *Neognathodus* Dunn, 1970, lower to middle Pennsylvanian, Amazonas Basin, Western Gondwana: biostratigraphic and paleoenvironmental analysis. *Geobios*, **75**, 17–40, https://doi.org/10.1016/j.geobios.2022.10.002

Medeiros, R.S.P., Nogueira, A.C.R., Silva Junior, J.B.C. and Sial, A.N. 2019. Carbonate-clastic sedimentation in the Parnaiba Basin, northern Brazil: record of carboniferous epeiric sea in the Western Gondwana. *Journal of South American Earth Sciences*, **91**, 188–202, https://doi.org/10.1016/j.jsames.2019.01.018

Montañez, I.P. 2021. Current synthesis of the penultimate Icehouse and its imprint on the Upper Devonian through Permian stratigraphic record. *Geological Society, London, Special Publications*, **512**, 213–245, https://doi.org/10.1144/sp512-2021-124

Mottin, T.E. 2022. *Stratigraphic record of environmental changes during the Late Paleozoic Glacial–Postglacial* *transition in northeastern Paraná Basin, Brazil*. PhD thesis, Graduate Program in Geology, Universidade Federal do Paraná (UFPR), Curitiba.

Mottin, T.E., Vesely, F.F., de Lima Rodrigues, M.C.N., Kipper, F. and de Souza, P.A. 2018. The paths and timing of late Paleozoic ice revisited: new stratigraphic and paleo-ice flow interpretations from a glacial succession in the upper Itararé Group (Paraná Basin, Brazil). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **490**, 488–504, https://doi.org/10.1016/j.palaeo.2017.11.031

Neves, J.P., Anelli, L.E. and Simões, M.G. 2014. Early Permian post-glacial bivalve faunas of the Itararé Group, Paraná Basin, Brazil: paleoecology and biocorrelations with South American intraplate basins. *Journal of South American Earth Sciences*, **52**, 203–233, https://doi.org/10.1016/j.jsames.2014.03.001

Opluštil, S., Šimůnek, Z., Zajíc, J. and Mencl, V. 2013. Climatic and biotic changes around the Carboniferous/Permian boundary recorded in the continental basins of the Czech Republic. *International Journal of Coal Geology*, **119**, 114–151, https://doi.org/10.1016/j.coal.2013.07.014

Playford, G. and Dino, R. 2000. Palynostratigraphy of Upper Palaeozoic strata (Tapajós Group), Amazonas Basin, Brazil: part two. *Palaeontographica Abt B*, **255**, 87–145.

Rischbieter, M., Neregato, R., Iannuzzi, R., di Pasquo, M.M., Alvarenga, R. and Freitas, J. 2022. A new flora from the Rio Bonito Formation (late Asselian) and its implications for the biostratigraphy of the southern Paraná Basin, Brazil. *Journal of South American Earth Sciences*, **119**, 104010, https://doi.org/10.1016/j.jsames.2022.104010

Souza, P.A. 2006. Late Carboniferous palynostratigraphy of the Itararé Subgroup, northeastern Paraná Basin, Brazil. *Review of Paleobotany and Palynology*, **138**, 9–29, https://doi.org/10.1016/j.revpalbo.2005.09.004

Souza, P.A., Boardman, D.R., Premaor, E., Félix, C.F., Oliveira, E.J. and Bender, R.R. 2021. The *Vittatina costabilis* Zone revisited: new characterization and implications on the Pennsylvanian–Permian icehouse-to-greenhouse turnover in the Paraná Basin, Western Gondwana. *Journal of South American earth Sciences*, **106**, 102968, https://doi.org/10.1016/j.jsames.2020.102968

Stollhofen, H., Stanistreet, I.G., Bangert, B. and Grill, H. 2000. Tuffs, tectonism and glacially related sea-level changes, Carboniferous–Permian, southern Namibia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **161**, 127–150, https://doi.org/10.1016/S0031-0182(00)00120-6

Stollhofen, H., Werner, M., Stanistreet, I.G. and Armstrong, R.A. 2008. Single-zircon U–Pb dating of Carboniferous–Permian tuffs, Namibia, and the intercontinental Deglaciation Cycle Framework. *Geological Society of America Special Paper*, **441**, 83–96, https://doi.org/10.1130/2008.2441(06)

Taboada, A.C., Neves, J.P., Weinschütz, L.C., Pagani, M.A. and Simões, M.G. 2016. Eurydesma–Lyonia fauna (Early Permian) from the Itararé group, Paraná Basin (Brazil): a paleobiogeographic W–E trans-Gondwanan marine connection. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **449**, 431–454, https://doi.org/10.1016/j.palaeo.2016.02.022

Valdez, V.B., Milana, J.P. *et al*. 2020. Timing of the Late Palaeozoic glaciation in western Gondwana: new ages and correlations from Paganzo and Paraná basins. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **544**, 109624, https://doi.org/10.1016/j.palaeo.2020.109624

Vesely, F.F., Delgado, D., Spisila, A.L. and Brumatti, M. 2021. Divisão litoestratigráfica do Grupo Itararé no estado do Paraná. *Boletim Paranaense de Geociências*, **78**, 3–23, https://doi.org/10.5380/geo.v78i0.80754

Visser, J.N.J. 1997. Deglaciation sequences in the Permo-Carboniferous Karoo and Kalahari Basins of southern Africa: a tool in the analysis of cyclic glaciomarine basin fills. *Sedimentology*, **44**, 507–521, https://doi.org/10.1046/j.1365-3091.1997.d01-35.x