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Isotopes to ice: Constraining provenance of glacial deposits and ice centers in west-central Gondwana

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ABSTRACT

The timing and geographic distribution of glaciers in high-latitude southern Gondwana during the Late Paleozoic Ice Age remain poorly constrained, ultimately precluding our ability to estimate ice volume and associated climate teleconnections and feedbacks during Earth's penultimate icehouse. Current aerial extents of glaciers, constrained by sedimentary flow directions, near exclusively infer paleo-glaciation to be highland-driven and may underestimate potential ice sources in continental regions from which ice sheets may have emanated. Here, we report new U-Pb ages and Hf isotope compositions of detrital zircons recovered from diamictites in two key mid- to high-latitude Gondwanan basins (Paraná, Brazil and Tepuel, Argentine Patagonia). The results indicate regional sediment sources for both basins during the early period of late Paleozoic glaciation evolving into more distal sources during the final deglaciation along southern and western Gondwana. Similar age sediment sourced from diamictites in the Congo Basin, that require an ice center in eastern Africa suggest the possibility of a large ice sheet in this area of Africa proximal to the Carboniferous-Permian boundary, which may have sourced sediments to the Paraná Basin. An inferred distal southern source of glacial sediment for the Tepuel Basin argues for the presence of an ice sheet(s) in the Ellsworth Block of Antarctica towards the end of the glaciation history in Patagonia. These findings indicate an evolution during the Late Paleozoic Ice Age from proximally to extra-basinally sourced sediment reflecting continental-scale glaciation and subsequent drainage from the Windhoek Highlands, Ellsworth Block and an east African source in west-central Gondwana. Coincidence with a long-term fall in atmospheric pCO_2 during the Pennsylvanian to a minimum across the Carboniferous-Permian boundary and a subsequent rise in the early Permian suggests a primary CO_2-driver for deglaciation in the Paraná Basin. Additional boundary conditions including availability of moisture and paleogeography likely further contributed to the timing of nucleation, growth and demise of these Gondwanan glaciers.

1. Introduction

Earth's penultimate icehouse (late Devonian - late Permian) was the time of invasion of animal life onto land, the global expansion of Earth's earliest tropical forests, and widespread glaciation in the Southern Hemisphere (Gondwana), all under unique atmospheric O_2:CO_2 levels (Montañez et al., 2016). Reconstructions of ice distribution in Gondwana have evolved from early models of an expansive ice sheet (> 50,000 km^2) centered over polar Gondwana (Veevers and Powell, 1987; Crowley and Baum, 1991; Frakes et al., 2005) to empirical and

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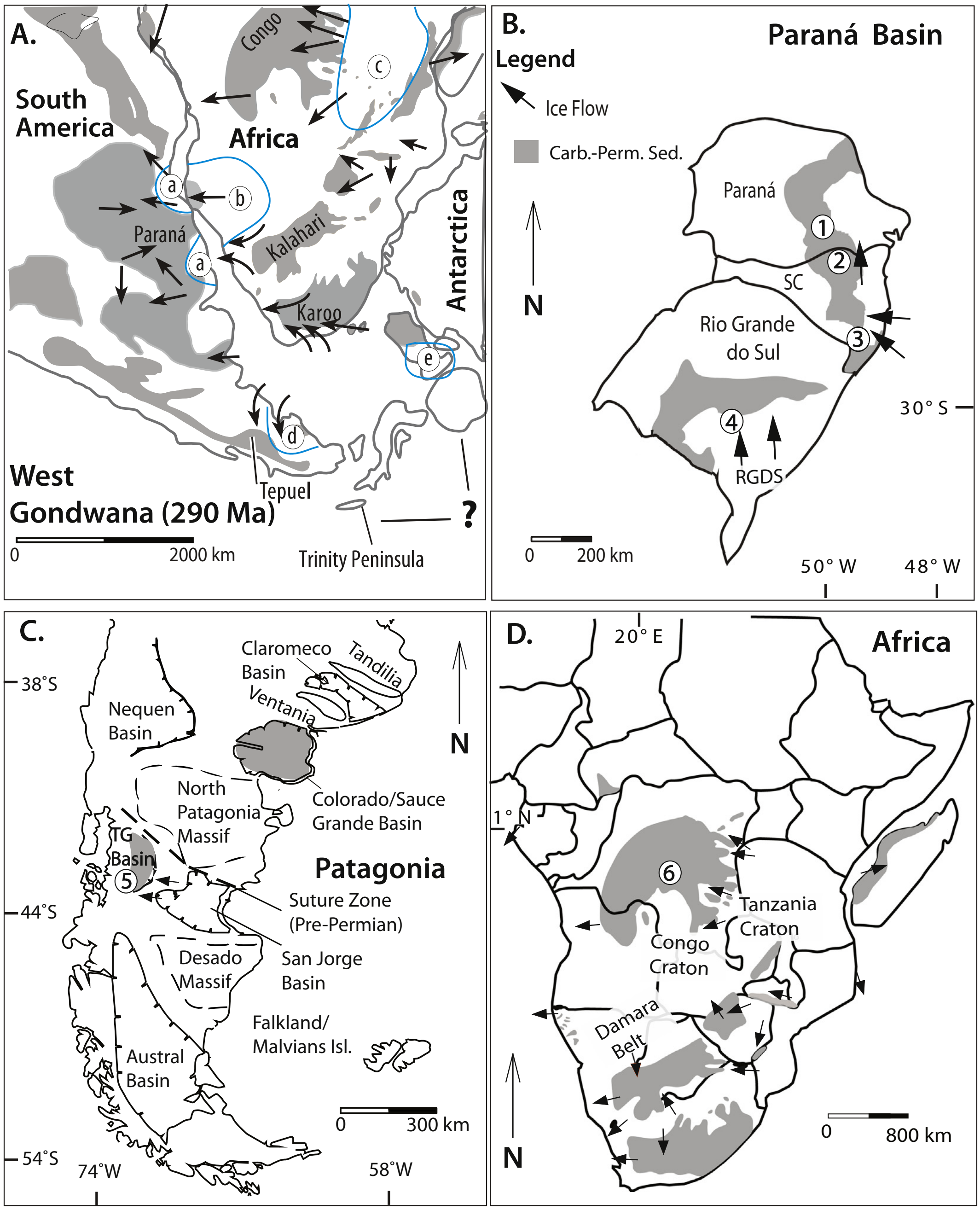

Fig. 1. Generalized maps of depositional basins, cratonic blocks, and sample distribution in west-central southern Gondwana. (A) Distribution of major depositional basins in general study area. Paleo-ice flow directions (black arrows) modified from Isbell et al., 2012. Proposed source terranes supplying glaciogenic sediments outlined in blue a) local granite basement b) Damara Orogenic belt c) Congo and Tanzania cratons d) Deseado Massif and e) Ellsworth Block (B) Generalized map of three states in the central and southern Paraná Basin showing distribution of Carboniferous-Permian deposits. SC- Santa Catarina State; RGDS- Rio Grande Do Sul Shield. Encircled numbers are locations of samples used in this study: 1- Lagoa Azul (BASS), 2- Taciba (east; PTL-D this study) 3- Rio Do Sul, Taciba (east, equivalent; Canile et al., 2016 samples CW22 and 21B) 4. Taciba (south STR-PAV; this study) formations (Fms). (C) Simplified map of basins hosting Carboniferous-Permian deposits (gray shading), cratonic blocks, and paleo-ice flow directions for Patagonia (modified from Pankhurst et al., 2006; Pagani and Taboada, 2010). Encircled '5' = samples from Pampa de Tepuel (HAPD) and Mojón do Hierro (AG) fms. (D) Map of southern Africa showing basins hosting Carboniferous-Permian deposits (gray shading) and cratonic blocks (noted). Encircled '6' = Dekese Core. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

modeling arguments for multiple small- to moderate-size ice sheets (> 50,000 km^2), ice caps (< 50,000 km^2), and alpine glaciers emanating from multiple ice centers (e.g., Crowell, 1995; Visser, 1997; Isbell et al., 2003, 2012; Fielding et al., 2008; Montañez and Poulsen, 2013). Notably, estimates of total ice volume inferred from more recent reconstructions are less than half of those based on the presence of an extensive continental ice sheet(s) (Isbell et al., 2012). Thus, improved constraints on ice source regions and the spatial and temporal distribution of glaciers through the Late Paleozoic Ice Age (LPIA) are much needed. Such constraints are critical for resolving disparity in inferred magnitudes of paleo-glacioeustasy (Rygel et al., 2008; Montañez and Poulsen, 2013). They are further important given that continental ice distribution, through feedbacks, influences atmospheric and ocean circulation, surface conditions, continental weathering rates, and regional hydroclimates and, in turn, the nature and resilience of marine and terrestrial ecosystems (Montañez and Poulsen, 2013).

West-central Gondwanan basins are rich archives of the Southern Hemisphere glaciation during the LPIA (Fig. 1A). Multiple ice centers have been proposed for these basins with vastly differing implications for inferred ice extent and volume in west-central Gondwana over the course of the glaciation history. With minimal exception, these hypothesized reconstructions of ice centers are mechanistically linked to paleo-topographic highlands consistent with the hypothesis of multiple small- to moderate-size glaciers, up to small ice sheets emanating from the highlands (Dos Santos et al., 1996; Isbell et al., 2012; Montañez and Poulsen, 2013; Vesely et al., 2015; Fallgatter and Paim, 2018). Furthermore, most of Antarctica, which remained within the Polar Circle, is postulated to have remained ice-free until the early Permian (Isbell et al., 2008, 2012). Hypothesized large-scale (1.0×10^6 to $> 2.0 \times 10^7$ km^2) ice sheets in west-central southern Gondwana are scarce to nonexistent. We build on this aforementioned framework and suggest larger ice sheet(s) in low elevation settings were feasible during cold/cooler periods of this glaciation history and contrast with warmer intervals when glaciation was compartmentalized, existing in more high latitude or high-elevation settings.

Here we present U-Pb and Hf isotope detrital zircon results for late Paleozoic successions in two key ice proximal basins, the Paraná Basin, Brazil and Tepuel Basin, Argentinean Patagonia (Fig. 1A). The new detrital zircon isotope data, integrated with previously published U-Pb zircon ages from the Paraná Basin (Canile et al., 2016), time-equivalent glacial deposits from the Lukaga Group, Congo Basin (Linol et al., 2016), and possibly reworked glacial sediments of the Trinity Peninsula Group (TPG), Antarctica (Bradshaw et al., 2012), constrain the provenance of Carboniferous-Permian sediments in the region. Although these results accommodate the possibility of a small ice sheet/cap centered on the Windhoek Highlands, western Africa. They may also suggest the possibility of a much larger ice sheet emanating out of eastern Africa similar to an ice center first hypothesized by Crowell and Frakes (1970). Moreover, our findings indicate a possible ice center emanating out of the Ellsworth Block of western Antarctica during the Carboniferous-Permian period. Together, the presented provenance study highlights a dynamic glacial record, with periods of ice minima and maxima that are controlled by atmospheric concentrations of pCO_2, continental configuration, and paleotopography over the glaciation history.

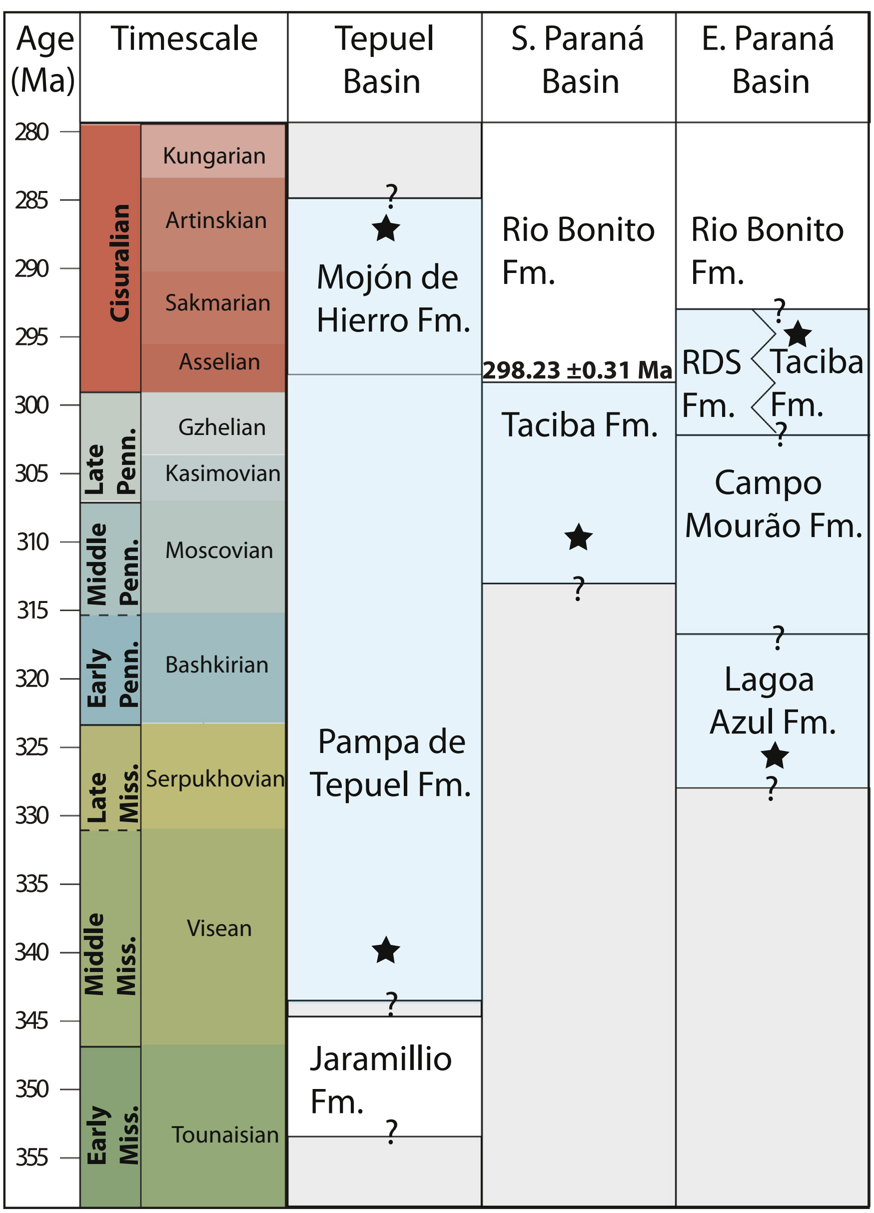

Fig. 2. Simplified stratigraphy for the Paraná and Tepuel basins, South America. The Paraná Basin (east) is separated into three stratigraphic units: the Lagoa Azul, the Campo Mourão and Taciba Fms. The Taciba Formation in southern Santa Catarina State is referred to locally as the Rio Do Sul Fm. Timing of deglaciation in the southern Paraná Basin is well constrained by CA-TIMS single zircon U-Pb age (Weighted Mean age of 298.23 ± 0.31 Ma; Griffis et al., 2018). Absolute age control is lacking for the Tepuel Basin where current age control is constrained by biostratigraphy. Current biostratigraphic constrains suggest the deglaciation may be diachronous from the east to the south in the Paraná Basin. Glacial occurrence denoted by light blue color. Stars indicate samples used in this study. Timescale from Ogg et al., 2016. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

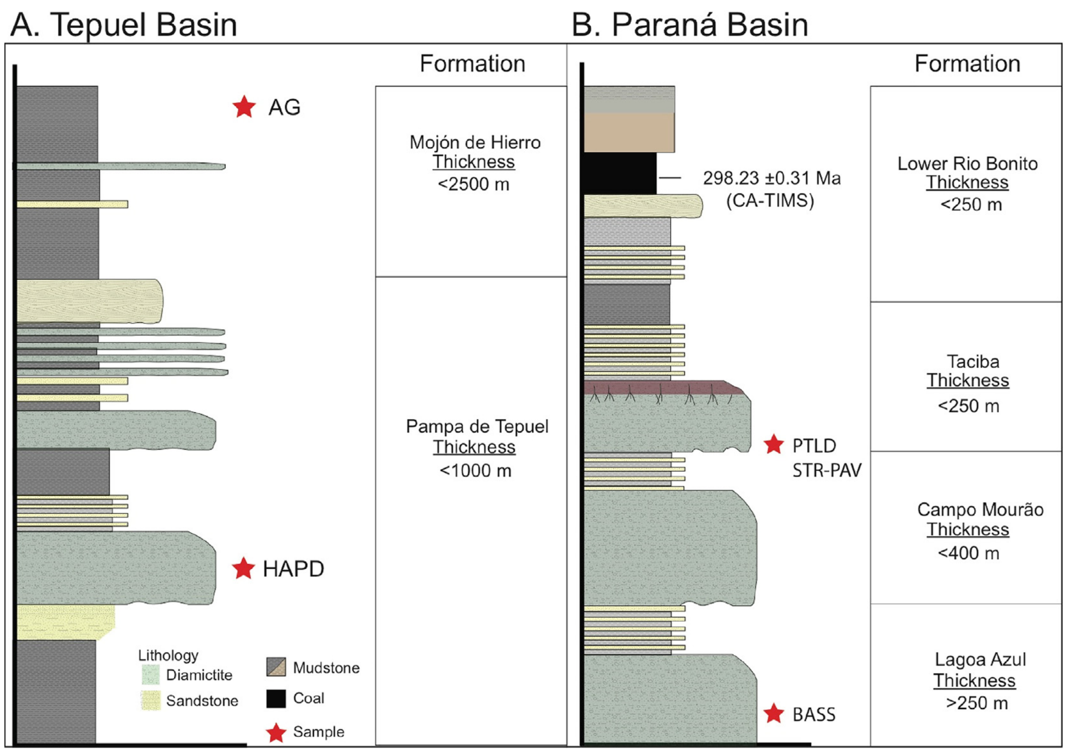

Fig. 3. Simplified lithostratigraphic sections for the Tepuel (A) and Paraná (B) Basins and formation thickness. Red stars indicate sampled facies. U-Pb radioisotope age control for the Paraná Basin (south) comes from a tonstein sampled in a coal. Tepuel Basin formation thicknesses from Freytes, 1971. Paraná Basin formation thicknesses from Vesely and Assine, 2006; Holz et al., 2006; Holz et al., 2008. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Geologic setting and methodology

The Paraná and Tepuel basins occupied mid- and high-latitude Gondwana, respectively with the surrounding hinterlands experiencing minimal to minor amounts of topographic development, respectively, across the late Carboniferous-early Permian (Fig. 1A). The intracratonic Paraná Basin (1.7×10^6 km^2) hosts an ~1300 m thick Carboniferous-Permian succession that archives up to five ice advance-retreat cycles in the Lagoa Azul through Taciba formations (Figs. 1B, 2, 3B; Rocha-Campos et al., 2008; Vesely et al., 2015). Striated paleo-glacial pavements suggest ice flow along the eastern basin margin, with a hypothesized source in the Windhoek Highlands of the Damara Belt, Namibia and extending north into the western edge of the Congo Craton (Fig. 1B,D; Dos Santos et al., 1996; Vesely et al., 2015; Carvalho and Vesely, 2017; Fallgatter and Paim, 2018). Along the southern margin, inferred paleo-ice flow directions indicate sediment dispersal from the south, with a proposed ice center on the Rio Grande do Sul Shield or farther south in Uruguay (Fig. 1B; Tomazelli and Soliani, 1997; Rocha-Campos et al., 2008; Fedorchuk et al., 2018). In the southern Paraná Basin, single crystal U-Pb chemical abrasion thermal ionizing mass spectrometry (CA-TIMS) zircon ages for the post-glacial Rio Bonito Formation, which overlies the Taciba Formation, constrains the terminal deglaciation near the Carboniferous-Permian boundary (Griffis et al., 2018). Herein we refer to areas above Rio Grande do Sul State, along the eastern margin, as the east Paraná Basin (Fig. 2). In the eastern Paraná Basin, an earliest Permian age of deglaciation is suggested by biostratigraphic constraints (Souza, 2006), and suggests the possibility of diachronous deglaciation across the Paraná Basin. High-resolution U-Pb zircon ages are needed to confirm the possibility of diachronous deglaciation across the Paraná Basin.

The late Paleozoic paleogeography of Patagonia is debated, with Patagonia interpreted as an allochthonous terrane that was accreted to the South American continent during the early Paleozoic (Ramos, 2008; Ramos and Naipauer, 2014) or para-autochthonous in origin (Pankhurst et al., 2006; Pankhurst et al., 2014). We utilize the reconstruction of Pankhurst et al. (2006, 2014 and references therein) that proposes Patagonia as a para-autochthonous terrane accreted to the South American continent during the early Carboniferous. Acceptance of the Pankhurst model is supported by a lack of volcanism associated with Carboniferous ocean closure, which would support the idea of Patagonia as an allochthonous terrane (see Pankhurst et al., 2014). The Tepuel Basin occupies a foreland basin setting on the convergent edge of the South Patagonia Massif and the north Patagonia margin, proximal to the paleo-polar circle (Fig. 1A,C; Limarino and Spalletti, 2006; Pankhurst et al., 2006; Ramos, 2008; Pagani and Taboada, 2010). The Pampa de Tepuel Formation hosts glacial deposits, interpreted as ice proximal, melt-water plume sediments, glacial marine deposits with minor amounts of ice-rafted debris as well as non-glacial marine and shore-face strata (Fig. 3A; Survis, 2015). The Mojón de Hierro Formation conformably overlies the Pampa de Tepuel Formation and consists of glacially influenced deeper-marine deposits that include debris flows (diamictites) interpreted as mass transport deposits beyond the shelf edge. Sediment transport into the Tepuel Basin is broadly from the east (Figs. 1C & 3A; González-Bonorino, 1992). Brachiopod assemblages indicate a broadly Carboniferous-Permian age of glaciation for the Pampa de Tepuel Formation and the Mojón de Hierro Formation (Pagani and Taboada, 2010). The Mojón de Hierro Formation was sampled between beds bearing Glossopterids floral remains, above the Cimmeriella fauna (late Sakmarian) and the Kochiproductus-Costatumulus fauna (earliest Artinskian) (Figs. 2 & 3A; Taboada and Pagani, 2010; Pagani and Taboada, 2010).

We present a broad distribution of U-Pb zircon ages from glaciogenic sediments in the Paraná and Tepuel basins sampled through the LPIA sedimentary packages. The eastern margin of the Paraná Basin consists of plutonic and metamorphic rocks that are broadly defined by Neoproterozoic U-Pb zircon ages (950–550 Ma) associated with the

Table 1
Likeness and K-S statistical results.

	Likeness*											
	STR-PAV	PTLD	RDS (21B)	RDS (CW22)	BASS	U. Lukuga	L. Lukuga	AG	HAPD	DJ.1412.2.	DJ.1433.3.	DJ.1405.2.
STR-PAV		45.5	37	43.2	65.9	37.1	40.6	41.5	24.5	39	34.8	28.4
PTLD	0.004		48.5	65.8	42	68.3	57.6	42	41.1	36.2	34.5	33.6
RDS (21B)	0.002	0		62.1	43.4	43.7	40.4	47.7	32.7	42.5	44.7	38.4
RDS (CW22)	0.05	0.017	0.021		47.6	60.7	61.8	47.4	37.9	43.7	44.8	34.7
BASS	0.002	0	0.005	0		36.5	38.7	60.4	31.7	54.8	53.7	40.6
U. Lukuga	0.002	0.882	0	0.006	0		65.2	35.9	36.1	34.6	26.1	27.8
L. Lukuga	0.04	0.703	0	0.063	0	0.328		37.6	32.5	38.7	31.3	28.4
AG	0	0	0.048	0	0.008	0	0		50.9	66.8	62.2	53.4
HAPD	0	0	0	0	0	0	0	0		29.3	29.8	32.8
DJ.1412.2.	0.002	0	0.118	0.009	0.701	0	0	0.585	0		56.7	51
DJ.1433.3.	0	0	0.225	0	0.018	0	0	0.957	0	0.297		48.9
DJ.1405.2.	0.005	0	0.5	0.004	0.077	0	0	0.916	0	0.746	0.758	
	K-S Test											

* - 10 My Bin; Yellow boxes denote statistically significant values.

Pan-African Orogen (Fig. 1A). The Damara Orogenic belt, a long proposed source for the Paraná Basin glacial sediments, is similarly dominated by Pan-African age zircons, with minor late Mesoproterozoic (1.0–1.3 Ga) and Paleoproterozoic (1.8–2.1 Ga) age components (Fig. 1A; Dos Santos et al., 1996, Foster et al., 2015). North and east of the Damara belt are the Congo and Tanzania cratons (Fig. 1A). These regions are enriched in early Neoproterozoic–late Mesoproterozoic age zircons (1.0–1.2 Ga), as well as minor amounts of Paleoproterozic age zircon (2.1–1.8 Ga) (Fig. 1A; Linol et al., 2016 and references therein). In the Tepuel Basin of Patagonia, plutonic rocks to the east south-east provide a source of Silurian-Carboniferous age zircons, with minor amounts of Cambrian–late Neoproterozoic age components (Fig. 1A; Pankhurst et al., 2006; Ramos, 2008). Further to the east and southeast of Patagonia is the Ellsworth block of Antarctica, which is dominated by Neoproterozoic age plutonic and metasedimentary rocks (Fig. 1A; Elliot et al., 2015; Elliot et al., 2016).

Five diamictites were sampled from the stratigraphically lowest and highest glacially influenced deposits in the eastern Paraná (Lagoa Azul and Taciba formations) and Tepuel basins (Pampa de Tepuel and Mojón de Hierro formations) and from the latest Carboniferous Taciba Formation in the southern Paraná Basin (Figs. 2 & 3A). Zircons were separated using conventional separation techniques (Fedo et al., 2003) and were collected from the matrix to avoid over representation associated with larger clasts. Grains were mounted in epoxy disks and backscatter imaged using a Cameca SX-100 electron microprobe at the UC Davis Electron Microprobe Facility in order to screen for inherited cores, metamict zonations or inclusions prior to laser ablation (Supplementary Fig. S1). A summary of zircon standards, analytical approach, rejection criteria and Tera-Wasserburg plots are presented in the data supplement (Supplementary Table S1; Fig. S2). In addition, we provide a matrix of statistical results that include likeness and two-sample Kolmogorov-Smirnov test (K-S) in order to aid with sample comparison (Table 1). Likeness values > 0.60 are considered significant (Satkoski et al., 2013; Bonich et al., 2017). The two-sample K-S tests is used to evaluate the null hypothesis, which we defined as the two samples being derived from the same population (95% confidence level; p-values > 0.05; see Bonich et al., 2017). In addition, we also use multi-dimensional scaling (MDS) to better assess K-S dissimilarity (Fig. 4; see Vermeesch, 2013; Vermeesch et al., 2016).

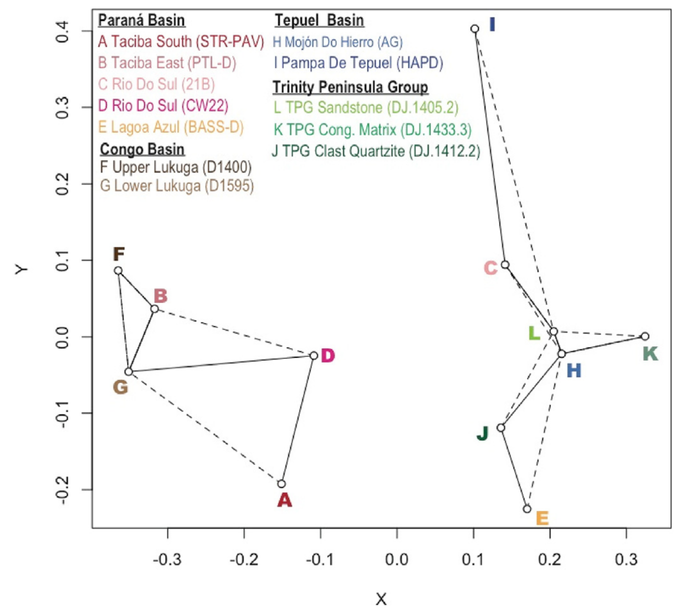

Fig. 4. Plot of multi-dimensional scaling of detrital zircon samples from LPIA glacial deposits (see text for details). Solid black lines connect nearest neighbors and dashed lines represented second nearest neighbors in Kolmogorov-Smirnov space and plotted in R using *Provenance* (Vermeesch et al., 2016). X and Y scales are a dimensionless representation of K-S space between samples. Samples that plot closest to one another are least dissimilar and interpreted to share a similar source. Note the overlap between the Lukaga Group (Congo Basin) and Taciba Formation (east Paraná Basin; PTL-D and Canile et al., 2016 sample CW22). A similar overlap of fit exists between the Mojón de Hierro Formation (Tepuel Basin) and TPG (Antarctic Peninsula) samples. Sample numbers are in parenthesis. Congo Basin samples (Linol et al., 2016). Trinity Peninsula Group samples (Bradshaw et al., 2012). Rio Do Sul samples (Taciba Formation (east) equivalent) (Canile et al., 2016).

3. Results

This section presents U-Pb zircon ages of glacial diamictites and glacially influenced mudstones, which represent the oldest through youngest glacially influenced deposits in the Paraná and Tepuel basins. In addition, we present previously published Hf data from the Rio Do Sul Formation (east; Canile et al., 2016 samples CW22 and 21B), which is the equivalent of Taciba Formation (east), as well as new Hf data from the Mojón do Hierro Formation. Hafnium isotope data are presented in order to discriminate between source terrains with different crustal histories (Hawkesworth and Kemp, 2006) and overlapping U-Pb zircon ages (Weber et al., 2012).

3.1. Paraná Basin

3.1.1. Eastern Paraná Basin

The Lagoa Azul Formation (BASS), the lowermost stratigraphic unit in the eastern Paraná Basin, which contains diamictites (Figs. 2 & 3B), was sampled in proglacial delta facies (#1 on Fig. 1B) exposed on a fresh mine surface in Bassiani Quarry, Paraná State, Brazil. Vesely et al. (2015) interpreted these deposits as evidence for direct ice contact based on ice-shove structures (e.g., ice-thrusted sediment blocks and striated pavements). A total of 169 zircon grains were analyzed of which 117 are included in the analysis. The remaining grains were excluded because they deviate from the acceptable criteria outlined in the data supplement. Kernel density estimates reveal a primary U-Pb age peak at 600 Ma and secondary peaks at 820, 1060, 1990 and 2200 Ma (Figs. 5 & 6).

The Taciba Formation (PTL-D), the uppermost stratigraphic glacial deposit in the eastern Paraná Basin was sampled (#2 on Fig. 1B) from a muddy diamictite located in a gravel mine proximal to Mafra, in northern Santa Catarina State (Figs. 2 & 3B). The Taciba Formation in this area of the basin is largely recognized as a deglaciation sequence, with no evidence of ice-proximal subglacial deposits. In this location, there is an erosional unconformity between the glacial deposits and the underlying mudstone deposits of the Lontras Shale. 140 grains were analyzed and 105 are included in the analysis. Kernel density estimates reveal primary U-Pb age peaks at 550, 1030, 1880 and 2030 Ma. Secondary peaks occur at 890, 1730 and 2600 Ma (Figs. 5 & 6). Twenty-four out of twenty-seven previously published Hf isotope measurements from the Rio Do Sul Formation (Taciba Formation (east) equivalent) in southern Santa Catarina State, plot below the chondritic uniform reservoir (CHUR) (#3 on Fig. 1B; Fig. 2; Canile et al., 2016). Cambrian age grains and younger plot between −6.5 and −17.5 ε^{176}Hf. Neoproterozoic grains plot from near the depleted mantle value to −20 ε^{176}Hf and grains older then Neoproterozoic plot from CHUR to −11 ε^{176}Hf.

3.1.2. Southern Paraná Basin

In the southern Paraná Basin, the Taciba Formation (STR-PAV) was sampled from a conglomerate associated with a glacially striated pavement (#4 on Fig. 1B) near Cachoeiro do Sul, Rio Grande do Sul State (Figs. 2 & 3B). A total of 84 zircons were analyzed of which 57 were included in the analysis. Kernel density estimates reveal a primary age peak at 610 and secondary peaks at 840, 1790, 2080 and 2350 Ma (Figs. 5 & 6).

3.2. Tepuel Basin

The Pampa de Tepuel Formation (HAPD), the lowermost glaciogenic diamictite interpreted to be of glaciomarine origin, was collected (#5 on Fig. 1C) from fresh outcrop 94 m above an unconformable contact with the underlying Jaramillio Formation (Figs. 2 & 3A). A total of 157 grains were analyzed of which 134 are included in the analysis. Kernel density estimates reveal a primary U-Pb age peak at 420 Ma with secondary peaks at 900, 1040, 1180, 2110 and 2630 Ma (Figs. 5 & 6).

The Mojón de Hierro Formation (AG) hosts the youngest glacially influenced marine deposit in the Tepuel Basin. A pebbly mudstone, interpreted as a submarine debris flow, was sampled (#5 on Fig. 1C). A total of 228 grains were analyzed from this sample of which 183 were included in the analysis. Kernel density estimates reveal primary age peaks at 570 Ma, and 1060 Ma and a secondary peak at 420, 1190 and 2700 Ma (Figs. 5 & 6).

Hf isotopes of the youngest zircons (Cambrian-Carboniferous) are less enriched in radiogenic Hf, with values ranging from 3.1 to −5.7 ε^{176}Hf, suggesting a juvenile magmatic source. The majority of the subpopulation of detrital zircons of Cambrian-Silurian age plot close to CHUR with values ranging from 4.2 to 5.7, with the exception of one highly enriched zircon of Ordovician age that has a ε^{176}Hf value of −22.2. The Neoproterozoic age fraction of detrital zircons reveals the largest range of Hf isotopic values ranging from 2.8 to −25.7 ε^{176}Hf. The 550–650 Ma fraction of detrital zircons have the most negative values (−12.7 to −25.7). All detrital zircons with Mesoproterozoic ages (1.0–1.2 Ga) have ε^{176}Hf values ranging from 3.8 to −14.3.

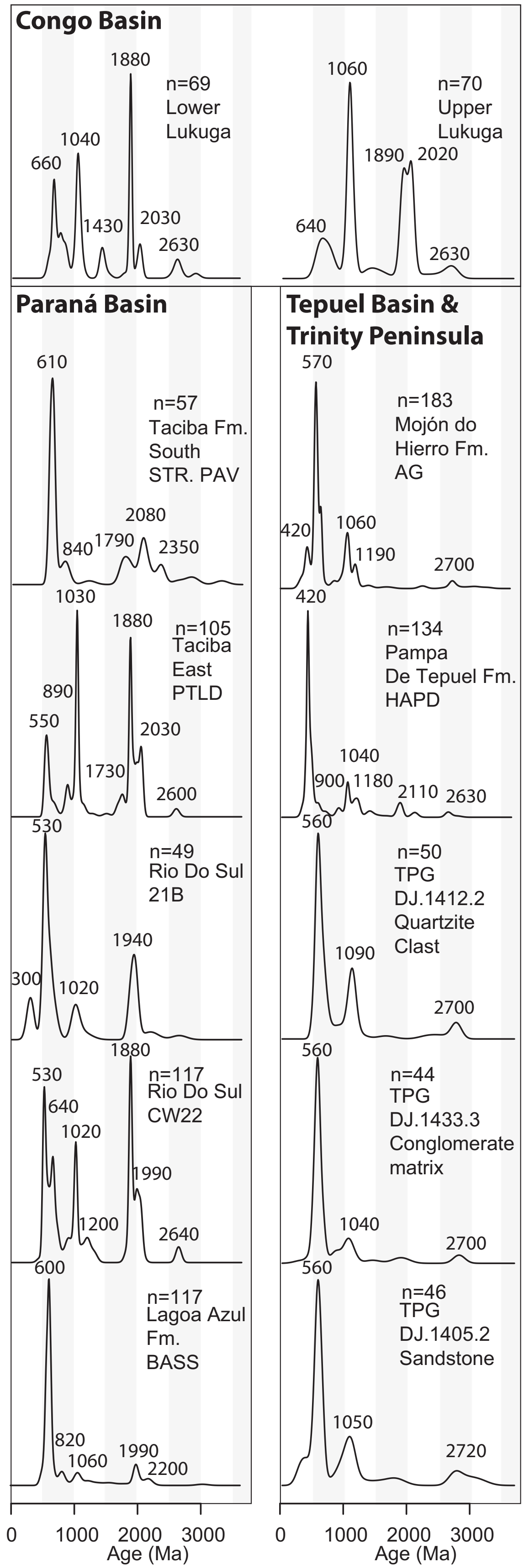

Fig. 5. Kernel Density estimates used to obtain ages in this study. Samples are grouped by geographic region. ^{206}Pb/^{207}Pb ages are presented for grains older than 1.4 Ga. ^{206}Pb/^{238}U ages presented for grains younger than 1.4 Ga. Gray bars separate 500 My increments.

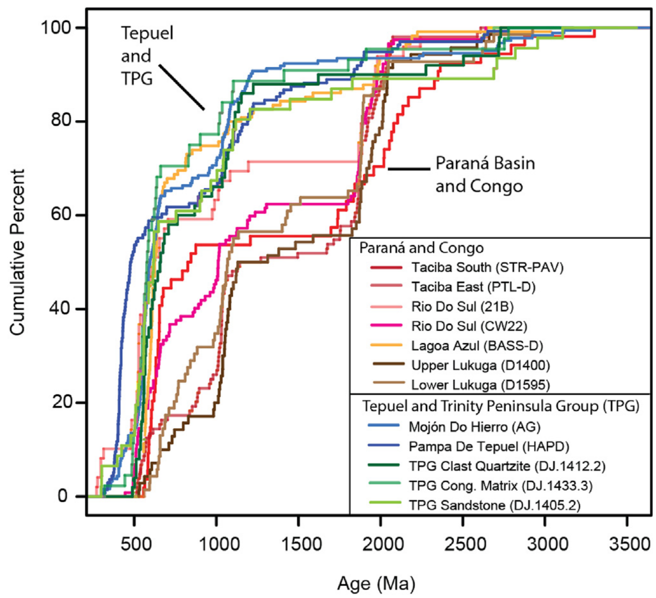

Fig. 6. Cumulative density (%) plot (CDE) for detrital zircons of Carboniferous-Permian glacial deposits, southwest Gondwana. Zircons < 1 Ga characterize ~80% of the Tepuel deposits and Trinity Peninsula Group (TPG) shown in shades of blue and green, with the greatest accumulation occurring at ~500 Ma. Conversely, glacial sediments from the Congo and Paraná basins, shown in shades of red and brown, yield zircon ages of < 1 Ga ages for 40 to 60% of the data. Sparse zircons of ~2 Ga age characterize the Tepuel and TPG diamictites, while this component accounts for up to 50% of the Paraná and Congo glacial deposits. The exception to this trend is the Lagoa Azul and Taciba (south) formations, which suggest a local provenance (see text for discussion). In-steps of trend lines denote individual sample accumulation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Detrital zircons with U-Pb ages older then Mesoproterozoic have negative ε^{176}Hf values ranging from −1.8 to −9.5, suggesting a slightly more evolved magmatic source (Fig. 7). Crustal separation ages (Tdm) reveal two peaks one at 1500 Ma and the other at 2500 Ma, with the 2500 Ma peak comprising 28% of the data.

4. Interpretation of provenance

4.1. Eastern Paraná Basin

The Lagoa Azul Formation (BASS) represents the stratigraphically lowermost ice proximal formation in the Paraná Basin (east). The dominant U-Pb age peak at 600 Ma coincides within uncertainty with U-Pb TIMS ages (580–585 ± 12 Ma; Vlach et al., 2011) of zircons from plutonic rocks that surround the Bassiani Quarry to the south and east, indicating a likely local provenance for the Lagoa Azul diamictite. This detrital zircon result provides further evidence for the presence of locally grounded glaciers on the eastern rim of the Paraná Basin during the Carboniferous. Subsidiary fractions of older zircons, most notably those of Grenvillian age (1.03 Ga), coupled with paleo-ice flow indicators (Canile et al., 2016; Rosa et al., 2016; Carvalho and Vesely, 2017; Fallgatter and Paim, 2018) require an extrabasinal source in western or eastern Africa, as grains of this age are not typically observed in the Paraná Basin and are common to these parts of Africa (Figs. 7 & 8; Roberts et al., 2012; Foster et al., 2015; Linol et al., 2016).

The youngest glacial deposit in the Paraná Basin, the Taciba Formation (east; PTLD) reveals a more complex zircon age inventory despite the relative proximity to the Lagoa Azul Formation diamictite, sampled 80 km to the north (Fig. 1B). Rather, the observed age distribution is similar to the published detrital zircon U-Pb age inventory (Canile et al., 2016) for interglacial deposits of the Rio do Sul Formation, the Taciba Formation (east) equivalent, sampled 250 km to the south, in the eastern Paraná Basin (Table 1; Canile et al., 2016 samples CW22 and 21B; Figs. 1B #3; 5, 6). Herein we refer to the Rio Do Sul Formation as the Taciba Formation (east) unless otherwise specified. The long proposed source for the Paraná Basin glacial deposits are the Windhoek Highlands, associated with the Neoproterozoic-Cambrian age Damara Orogenic Belt of southwest Africa. Large incised valleys were cut through the highlands, running east-west in northern Namibia and are interpreted to host ice centers that drain into the Paraná Basin, slightly to the north of the location of the Taciba Formation (east) sample (PTL-D; Fig. 8; Visser, 1987). U-Pb ages observed in the Damara Belt, an orogenic belt composed of metasedimentary, metamorphic and plutonic rocks that surround the Paraná Basin on the eastern margin contain all of the major age peaks observed in the Taciba Formation (east) samples (PTL-D; Canile et al., 2016 samples CW22 and 21B; Fig. 8). The Pan-African Orogeny along the margin of the Paraná Basin provides a source for 550 Ma zircons (Canile et al., 2016). In addition, U-Pb zircon ages for the Kamanjab Inlier, a felsic plutonic complex located in the northern reaches of the Damara Belt range from 1.83–1.86 Ga (Kleinhanns et al., 2013), providing an additional source for the 1.8 Ga zircons observed in the Taciba Formation (Fig. 8). Reported concordia ages from the Kamanjab Inlier are 20–50 My younger then the age defined by the Kernel Density Estimate (KDE), although they are within uncertainty (2-sigma) of individual spot analysis. A source for the 1.03 Ga zircon is found in the underlying granitic basement of the Damara Belt (Fig. 8). The Hf isotopes of the 1.03 Ga basement show a highly evolved crustal signature (ε^{176}Hf of −13.8 to −23.3; cf. Foster et al., 2015), and are in agreement with similar detrital zircons ages of the Rio do Sul Formation, the Taciba Formation (east) equivalent (Canile et al., 2016 samples CW22 and 21B).

The source rock ages in the Damara Belt are consistent with the ages

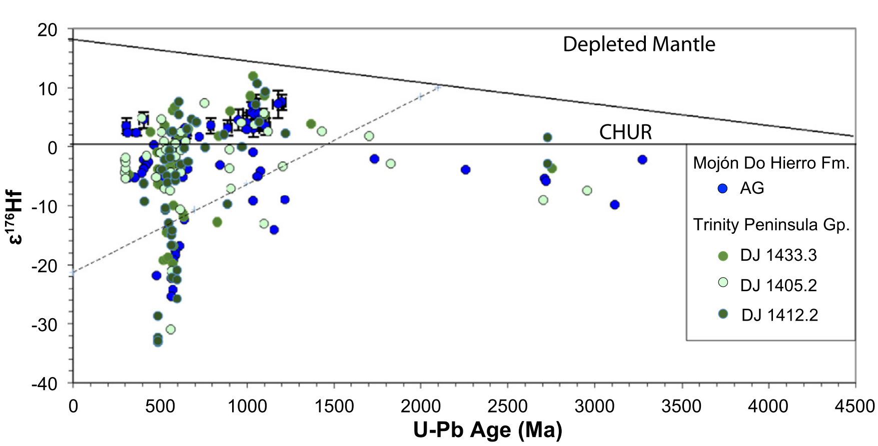

Fig. 7. Plot of ε^{176}Hf values versus U-Pb ages of detrital zircons from diamictites of Carboniferous-Permian Mojón de Hierro Formation, Argentinean Patagonia (AG sample; this study) and Trinity Peninsula Group (DJ samples; Bradshaw et al., 2012). Note overlap in age and Hf isotopes of the two data sets. Highly negative Hf values of late Neoproterozoic in age observed in the Mojon de Hierro Formation and TPG detrital zircons (~500 Ma) are unknown in South American sediment/ice sources. Such highly depleted Hf values occur in plutonic rocks and metasediments of the Ross Orogenic Belt, Antarctica (Flowerdew et al., 2007; Yakymchuk et al., 2015).

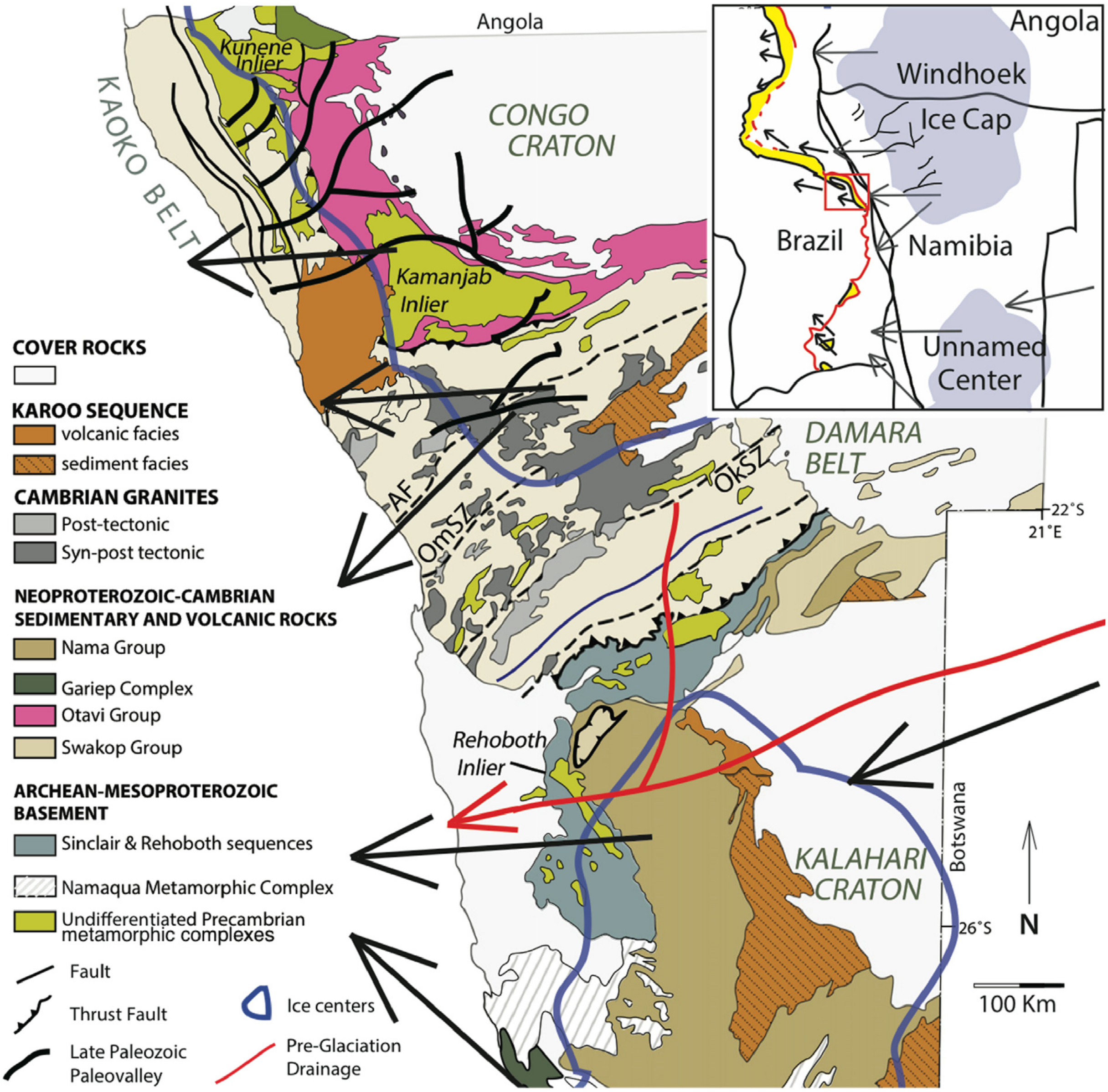

Fig. 8. Geologic basement map of Namibia modified after Foster et al., 2015. Inset map (right) shows general location of the Itararé Group sediments (yellow) and ice flow directions (from Visser, 1987; Rosa et al., 2016), Paraná Basin. Red box is general location of Taciba Fm (east) sample. Windhoek and Unnamed ice center labeled. Main map: proposed ice centers of the Windhoek ice cap (north) and an unnamed ice center (south) outlined in blue (Fallgatter and Paim, 2018). Incised valley orientations (from Visser, 1987) and ice flow directions outlined by black arrows. Red line highlights the pre-glaciation paleo-drainage to the west, in this area of Gondwana (Visser, 1987). Thin black dashed lines refer to shear zones in Foster et al. (2015). AF- Autseib Fault, OmSZ- Omaruru Shear Zone, OkSZ- Okahandja Shear Zone. Red arrow denotes pre-glacial drainage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

observed in the Taciba Formation (east; PTL-D, Canile et al., 2016 samples CW22 and 21B), though not all sources are exposed at surface near the proposed Windhoek ice center (Fig. 8). The inferred paleoflow directions (Visser, 1987) for the Windhoek ice center and the samples surrounding the paleovalley are not in agreement with the U-Pb zircon ages found in the Taciba Formation (east). For example, the 1.03 Ga basement observed in the Damara Belt is not exposed along flow of the paleovalleys of Visser (1987) and is first expressed at the surface 200 km to the south of the Kamanjab Inlier where it first crops out south of the Omaruru Shear Zone (Fig. 8; Foster et al., 2015). The basement is not cored north of the Omaruru Shear Zone, restricting availability of the 1.03 Ga source near the paleovalleys of Visser (1987) (Fig. 8; Foster et al., 2015). Furthermore, the 1.76 Ga grains, which are commonly observed throughout the northern reaches of the Damara Belt, near the paleovalleys, are not common in the Taciba Formation samples (east; PTL-D, Canile et al., 2016 samples CW22 and 21B; Kröner et al., 2010, 2015). In addition, the Neoproterozoic metasediments of the Swakop Group are common along the glacially formed paleovalleys and along inferred paleo-ice flow directions in the Windhoek Highlands (Fig. 8). The U-Pb age inventory from the Kuiseb Schist (Upper Swakop Gp) in the northeast corner of the Damara Belt (southwest of the Dekese core, Fig. 1D) matches reasonably well with that of the Taciba Formation (east) diamictite (Fig. 3). However, for the Taciba Formation (east, PTL-D) sample the Grenvillian peak (1.03 Ga) does not match the Kuiseb Schist (950 Ma) as determined by the KDE. In addition, the Hf isotope composition of the Grenvillian age zircon fractions from the Taciba Fm (east; Canile et al., 2016 samples CW22 and 21B) does not overlap with the Kuiseb Schist (Foster et al., 2015). For the Kuiseb Schist, all

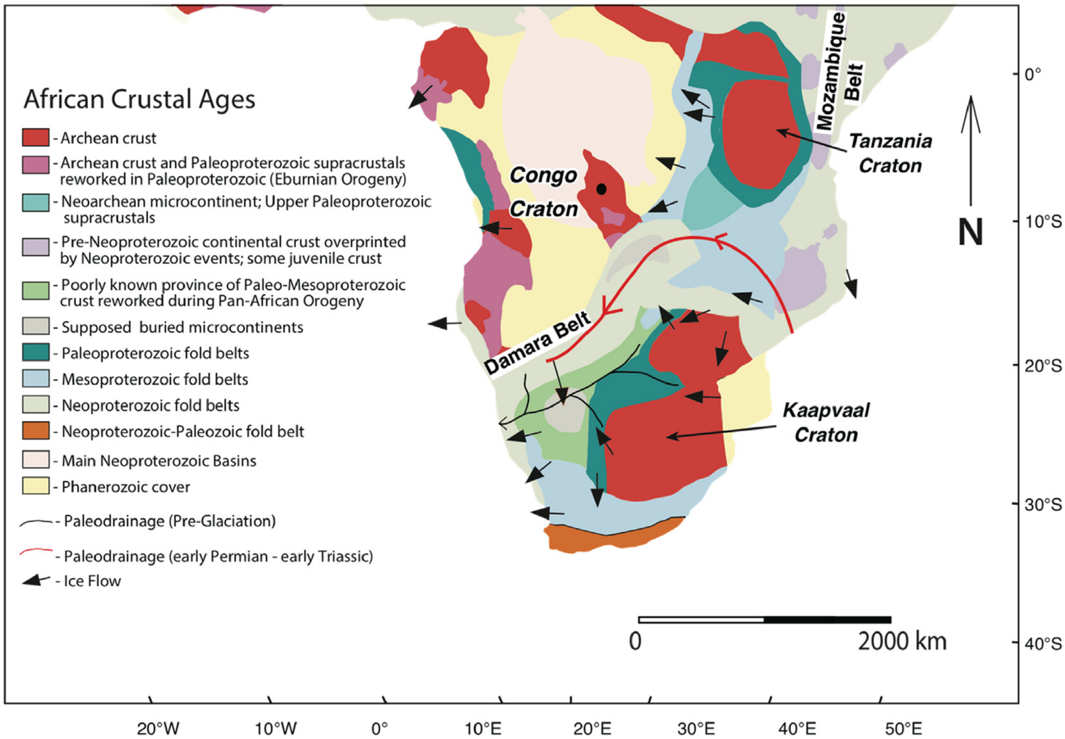

Fig. 9. Simplified geologic Map of Africa (modified after Begg et al., 2009). Ice flow directions associated with LPIA (Visser, 1987; Linol et al., 2016; Milleson et al., 2016). Bold black line highlights the extent of a major pre-LPIA drainage in southern Africa (Visser, 1987). Red lines are proposed paleo-Zambezi River (early Permian through early Triassic) (Bicca et al., 2017). Black dot is location of Dekese core. Sources of Paleoproterozoic and Neoproterpozic grains are common throughout eastern Africa. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Neoproterozoic zircons plot above CHUR, whereas the ε^{176}Hf of the late Neoproterozoic-Cambrian grains in the Taciba Formation (east) plot proximal to -20 (Canile et al., 2016; Foster et al., 2015), indicating that the Kuiseb Schist of the Swakop Group is not a likely source for zircons in the Paraná Basin despite its widespread presence surrounding the paleovalleys of Visser (1987) (Fig. 8).

The zircon U-Pb age distribution of the youngest Taciba Formation (east; PTL-D) diamictite strongly matches that of the Carboniferous-Permian glacial deposits of the upper and lower Lukaga Group, Congo Basin. Detrital zircon ages of these Lukaga Group and Taciba Formation (east; PTL-D) deposits show the statistically closest relationship of all analyzed samples (Table 1; Figs. 1D, 4 & 6; Linol et al., 2016). Thus, it may be possible that the Congo and Tanzanian cratons in eastern Africa (Fig. 1D), a source for the Lukaga Group sediments, also provides a source of zircons for the youngest Taciba Formation (east) glacial deposit of Santa Catarina and southernmost Paraná States in the Paraná Basin. U-shaped glacial valleys, east of the Congo Basin, indicate sediment was sourced from the east (Figs. 1D & 9; Linol et al., 2015, 2016; Milleson et al., 2016). This interpretation is further supported by orientations of U-shaped valleys to the west and southwest in Angola and Namibia that indicate ice flow towards the Paraná Basin (Fig. 1D; Milleson et al., 2016; Linol et al., 2016). Additionally, U-Pb ages of zircons from plutonic rocks, east and southeast of the Congo Basin, contain a source for all of the U-Pb ages of the Lukaga Group, Congo Basin (De Waele et al., 2008; Linol et al., 2016; Thomas et al., 2016) and the Taciba Formation (east) Paraná Basin. Furthermore, recent analysis of gneiss in the Tanzania Craton reveals the presence of 1.0 Ga zircons with a highly evolved crustal signature, and similar to those observed in the Taciba Formation (east; Canile et al., 2016 samples CW22 and 21B; Thomas et al., 2016).

Our hypothesized reconstruction of sediment sourced from eastern Africa is supported by paleo-ice flow interpretations proposed by Visser (1987). Visser (1987) proposed a major ice drainage system, associated with an ice sheet in this region of Africa, originating in Zimbabwe and Botswana, and flowing through the Kalahari basin towards the west and southwest into the Paraná Basin (Fig. 9; Visser, 1987). The proposed LPIA drainage is similar to the pre-glaciation drainage for this region of Africa (Visser, 1987; Squire et al., 2006). In addition, the proposed flow direction for the paleo-Zambezi River drains eastern Africa towards the Paraná Basin starting in the early Permian (Fig. 8; Bicca et al., 2017). Furthermore, the Neoproterozoic and Paleoproterozoic sources are more abundant (spatially) in eastern Africa (Begg et al., 2009). Thus, this scenario would suggest that the Windhoek Highlands may be only one of the sources of glaciogenic sediment in Africa that sourced zircons into the Paraná Basin during the LPIA (Figs. 8 & 9; Visser, 1987). The Neoproterozoic and Paleoproterozic peaks observed in the Taciba Fm (east; PTL-D) persist through the fluvial-deltaic Rio Bonito Formation in this location of the basin, and further support the possibility of fluvial drainage emanating from eastern Africa (Canile et al., 2016). Further evaluation is needed of the late Paleozoic diamictites that exist in Namibia and further east in Africa (see Cairncross, 2001) to test our hypothesis of a continental ice sheet centered in eastern Africa feeding sediment into the Paraná Basin during the LPIA. Lastly, high-precision age control across the LPIA diamictites in Africa and South America are greatly needed in order to assess the temporal and spatial distribution of paleo-glaciers during this time.

4.2. Southern Paraná Basin

The age spectrum of the Taciba Formation (STR-PAV) conglomerate from the southern Paraná Basin overlaps with the ages observed from the Rio Grande do Sul Shield and the Rio de la Plata Craton to the south in Uruguay. The primary 610 Ma peak occurs within the São Gabriel Block hosted in Rio Do Sul Shield and in Neoproterozoic plutonic and recycled sedimentary rocks of the Camaquã Basin (Figs. 1B & 5; Hartmann et al., 2002; de Oliveira et al., 2014). The presence of striated pavements and ice-shove structures on the western side of the Rio Grande do Sul Shield suggest the Taciba Formation (south) was deposited in a sub-glacial to ice-proximal environment. The lack of Grenvillian age detrital zircons and a primary age peak of 610 Ma indicates a separate ice center than the eastern basin. No evidence for an African sediment source, which has been previously suggested (Crowell, 1995), exists in the U-Pb zircon age inventory of this Taciba Formation glacial deposit, which is constrained by high-precision CA-TIMS U-Pb zircon ages to the Carboniferous (Griffis et al., 2018). Additional analysis of the Taciba Formation (south) from other locations in Rio Grande do Sul State, as well as in Uruguay, is needed to confirm a solely local provenance for the Taciba Formation (south).

4.3. Tepuel Basin

The primary Silurian-Devonian U-Pb-age peak of the lowermost diamictite in the Carboniferous-Permian succession of the Pampa de Tepuel Formation (HAPD) overlaps with the zircon U-Pb age (425 ± 4 Ma) of the El Sacrificio Granite of the Deseado Massif, ~500 km to the southeast of the sample location (Figs. 1C & 10; Pankhurst et al., 2003; Vidal et al., 2014). No other Silurian age sources are known from the North Patagonia Massif arguing for a southeastern source for the Pampa de Tepuel Formation diamictite. In addition, the Tepuel Basin was located on a north-verging cratonic block (Deseado Massif), outboard of the South American Craton during the early Carboniferous, thus limiting input from the South American Craton from the north and northeast. Therefore, the Deseado Massif is the most parsimonious interpretation of the sediment source for the earliest phase of late Paleozoic glaciation in the Tepuel Basin.

A significant shift in U-Pb ages of detrital zircons is observed between those from the older Pampa de Tepuel Formation (HAPD) and those in the younger Mojón de Hierro Formation (AG). A primary age peak of 570 Ma and secondary peak of 420 Ma for the Mojón de Hierro Formation detrital zircons is interpreted as a shift during the glaciation history from a more proximal source during deposition of Pampa de Tepuel Formation to a more distal source during deposition of the Mojón de Hierro Formation. One possible local source, the El Jaguelito and Nahuel Niyeu formations to the northeast of the basin (North Patagonia Massif), is dominated by detrital zircon U-Pb age peaks at 515 to 535 Ma, slightly younger then the Mojón de Hierro Formation 570 Ma peak, but does not contain an age component of 420 Ma zircons (Pankhurst et al., 2006; Ramos and Naipauer, 2014). Furthermore, crustal separation ages (Tdm) for the El Jaguelito and Nahuel Nuyeu formations do not match those observed in the Mojón de Hierro Formation zircons (Table S1). This indicates that the North Patagonia Massif is not a viable source for sediments supplied to the Tepuel Basin (Pankhurst et al., 2006). The minor 420 Ma peak is similar to that observed in the underlying Pampa de Tepuel Formation, and interpreted to be sourced from the Deseado Massif (Fig. 10). Outside of Patagonia, Silurian-Devonian sandstones from the Port Stevens and Port Stanly formations of the Falkland Islands provide an additional source for 570 Ma zircons as well as a source for some of the accessory peaks observed in the Mojón De Hierro Formation (Ramos et al., 2017). The highly evolved Hf isotopic signature observed in the Tepuel Basin that are late Neoproterozoic in age are not observed in the Falkland Island sandstones.

We propose an additional Antarctic source for the Mojón de Hierro Formation glaciogenic deposits. The TPG, southwest of the Deseado Massif, is composed of a combination of late Paleozoic age debris flow and turbidities deposits of possible glaciogenic origin (Fig. 10). Detrital zircons recovered from the TPG are interpreted as being sourced from Patagonia (Fig. 10; Bradshaw et al., 2012), though some of the U-Pb ages of detrital zircons and clasts from the Carboniferous-Permian View Point Conglomerate of the Trinity Peninsula Group (Bradshaw et al., 2012) overlap well with those from the Mojón de Hierro Formation. Furthermore, both deposits contain zircons of late Neoproterozoic age that have anomalously negative ε^{176}Hf values, suggesting these two units may share a similar source (Fig. 7). In particular, clasts hosted in the TPG sediments are interpreted as being sourced from felsic rocks of the Ross-Delameran Orogen in Antarctica, which are characterized by U-Pb zircon ages of 490–650 Ma, an age common in the Mojón de Hierro Formation (Bradshaw et al., 2012; Elliot et al., 2015, 2016). U-Pb ages and Hf isotope compositions of detrital zircons in meta-conglomerates from the Ross Orogenic Belt (Swanson Formation) and the Wyatt Earp and Mt. Twiss formations of the Ellsworth Mountains also overlap with the View Point Conglomerate (TPG) and Mojón de Hierro Formation detrital zircon U-Pb age inventories, including the presence of highly enriched ε^{176}Hf of Neoproterozoic-Cambrian age zircons (Figs. 5, 7 & 10; Flowerdew et al., 2007; Bradshaw et al., 2012; Yakymchuk et al., 2015). Additionally, highly enriched εNd values in Cambrian age granites of the Ross Orogen provide an additional support for a source of highly depleted continental crust in this region of Antarctica (Fig. 10; Goodge et al., 2012).

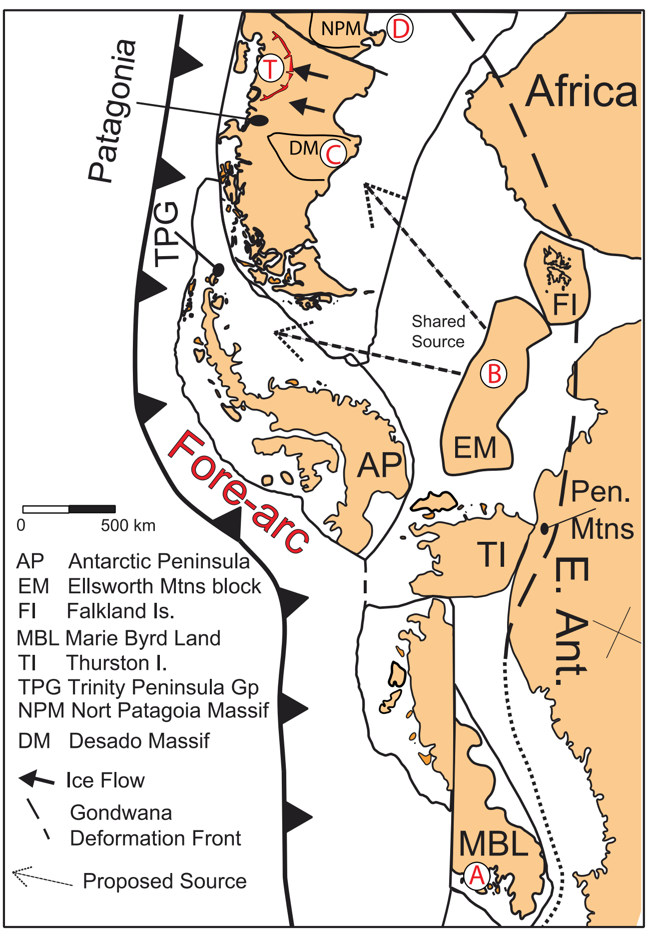

Fig. 10. Reconstruction of polar western Gondwana after Elliot et al. (2016). Letters in figure refer to the possible source terranes of sediments supplied to the Mojón do Hierro Formation. Proposed Tepuel Basin Sources: A. Mary Bird Land (Goodge et al., 2012; Yakymchuk et al., 2015) B. Ellsworth Mountains (Flowerdew et al., 2007) C. Deseado Massif (Pankhurst et al., 2003; Pankhurst et al., 2014; Pankhurst et al., 2006) D. North Patagonia Massif (Pankhurst et al., 2006). T. Tepuel Basin. We propose that recycled Ellsworth Mountain sediments likely provided a source of zircon to the Tepuel and TPG based on similar age distributions and highly evolved Hf isotopic compositions. Solid black arrows interpreted ice-flow direction (González-Bonorino, 1992).

5. Implications of provenance for distribution of paleo-ice centers

The interpreted detrital zircon provenance for glaciogenic deposits that record the LPIA and its demise, when considered within the context of published detrital zircon U-Pb data for southern Gondwana, indicate large changes in surface drainage that can be related to temporal changes in climate and ice distribution in southern Gondwana. The oldest glacial deposits in the Paraná and Tepuel basins, which have been previously interpreted as ice-proximal (Frakes and Crowell, 1969; Dos Santos et al., 1996), yield detrital zircons that indicate local bedrock sediment sources. We interpret these to be sourced from a local grounded glacier with sediments derived from eroded bedrock at the ice front. Only minor fractions of detrital zircons with U-Pb ages indicative of more distal sources are observed in the glaciogenic deposits of the Lagoa Azul and Pampa de Tepuel formations. No distal sediment sources are observed in the Taciba Formation (south). The abundance of thick diamictites with proximal glacial indicators further supports the presence of proximal glaciers at the onset of glaciation in these two regions of west-central southern Gondwana (González et al., 2013; Vesely et al., 2015; Survis, 2015; Aquino et al., 2016). Absolute age constrains are needed to determine the synchroneity of the onset and demise of glaciation in the Tepuel and Paraná basins.

Conversely, the deeper marine and youngest glaciogenic deposits of the Taciba (east) and Mojón de Hierro formations, which both record the final phase of glaciation in these regions of southern Gondwana (Holz et al., 2010; Pagani and Taboada, 2010), are dominated by detrital zircon U-Pb ages populations and Hf isotopic compositions that indicate a mix of local and distal provenance. Sediments that record the deglaciation in both basins exhibit no subglacial evidence and sediment supply is influenced by fluvial systems draining away from a distal ice front which manifest as delta deposits, submarine fans and ice rafted debris (cf. Vesely et al., 2015; Carvalho and Vesely, 2017). We propose that both the Congo and Tanzania cratons in eastern Africa served as distal source regions that fed sediment into the Paraná Basin along with the previously proposed Windhoek Highlands.

The lack of an isolated Damaran isotopic signature in detrital zircons of the Taciba Formation (east; PTL-D, Canile et al., 2016 samples CW22 and 21B) glaciogenic deposits, suggest that the Windhoek Highlands of Namibia, the long proposed source for Paraná Basin glacial deposits, was not the only source supplying sediment into the Paraná Basin during the final stage of late Paleozoic glaciation. Rather, the detrital zircon U-Pb ages of glaciogenic deposits of the Parana and Congo basins argue for an additional sediment sourced from the Tanzania and Congo cratons in east Africa. We propose a scenario where the incised valleys associated with the Windhoek Highlands are carved out during initial ice advance. During the deglaciation of this region of Gondwana, glacio-fluvial and fluvial systems, associated with a diminishing ice center in central to eastern Africa carried sediments into the Paraná Basin. Consistent with this interpretation is the presence of Carboniferous-Permian glacial deposits found throughout southern and central Africa and east of the Windhoek Highlands in the Ovambo Basin, and throughout Zambia, Botswana, and Zimbabwe, with ice-flow directions generally to the west (Figs. 8 & 9; see Cairncross, 2001). Furthermore, the major early Neoproterozoic–late Mesoproterozoic (1.0–1.2 Ga) and Paleoproterozoic age (1.8–2.1 Ga) peaks observed in the Taciba Formation (east) and through the early Permian into fluvial facies of the Rio Bonito Formation in Santa Catarina are consistent through the deglaciation and into post glacial period of the Paraná Basin (Canile et al., 2016). The presence of the aforementioned peaks in both turbidite facies of the Taciba Formation (east) and fluvial facies of the Rio Bonito Formation are in agreement with the proposed paleo-Zambezi river system that operated from the early Permian–early Triassic (Fig. 9; Bicca et al., 2017). Our finding also supports a model of an ice center in east Africa that was first proposed by Crowell and Frakes (1970), but not subsequently considered in the literature. Meanwhile, the U-Pb zircon ages from diamictite in the Taciba Formation (south; STR-PAV) implies a source area for the southern margin of the Paraná Basin that is unrelated to the eastern basin, possibly due to an ice center emanating north out of Uruguay.

The overlap in U-Pb ages and Hf isotopic compositions of detrital zircons from the deglaciation sequences of the Tepuel Basin, Patagonia with the TPG and greater Ross-Orogenic Belt, Antarctica suggests an ice sheet centered over the Ellsworth Mountain Crustal Block during the final stage of glaciation. We interpret this ice center to source sediment to the Mojón do Hierro Formaton as well as the TPG (Fig. 10). In addition, minor amounts of sediment are sourced from recycled sandstones situated in the Falkland Islands and from the Deseado Massif. A late Paleozoic Antarctica-Patagonia connection was previously suggested on the basis of archeocyath fossils. Clasts hosting archeocyath within Carboniferous age glaciogenic deposits in the Sauce Grande Basin, northeast Argentina (González et al., 2013) have been linked to outcrops with archeocyath fossils in western Australia and along the Ross Orogenic Belt, Antarctica. Thus, the detrital zircon data, coupled with inferred paleo-ice flow directions for the Sauce Grande and Tepuel basins (González-Bonorino, 1992; González et al., 2013), further support the hypothesis of an Antarctic ice center with different ice streams feeding into the Sauce Grande and Tepuel basins during the later phase of glaciation. Lastly, the absence of major tectonic uplift during the late Paleozoic, in the areas surrounding the Paraná and Tepuel basins, suggests that tectonism alone cannot be the sole driver of glaciation.

Reconstructions of Pennsylvanian-Permian atmospheric pCO_2 (Montañez et al., 2007, 2016) indicate a long-term fall in CO_2 ($\leq$200 ppm) to a minimum proximal to the Carboniferous-Permian boundary and into the first few million years of the early Permian after which CO_2 concentrations rose through the Permian. We hypothesize that the long-term decrease in atmospheric pCO_2 during the Carboniferous (from a mean of 400 $\pm$ 100 ppm to a sustained minimum of 200 $\pm$ 100 ppm; Montañez et al., 2016) promoted the outward expansion of ice sheets in the Windhoek Highlands and east-central Africa from highlands. An initial short-lived CO_2 rise in the latest Carboniferous, forced proximal glaciers to dissipate and more distal sediment sources appear in the Paraná Basin. Deglaciation of the Tepuel Basin, which is estimated to be early Permian in age based on biostratigraphic constrains, is broadly consistent with the rise in atmospheric pCO_2 across the early Permian (Montañez et al., 2016). A dearth of high-resolution age control prohibits the direct correlation of CO_2 and glaciation in the Paraná Basin (east) and the Tepuel Basin.

6. Conclusions

U-Pb ages of zircons from LPIA glacial deposits of the Parana and Tepuel basins, South America, reveal multiple distinct source signatures, which vary both spatially and temporally throughout the glaciation history for west-central Gondwana. Differences in U-Pb ages are interpreted as changes in ice centers and an inferred dynamic variation in aerial extent and volume of ice through the glaciation history of this region. Peak glaciation is coincident with subglacial features during the Carboniferous in the Paraná Basin and a U-Pb age spectrum enriched in local sources reflecting subglacial erosion. Glacial demise is coincident with deglaciation sequences and significant allochthonous sediment input at the Carboniferous-Permian Boundary in the Paraná Basin record. A similar scenario is also observed in the Tepuel Basin, though determining synchroneity of deglaciation between the Paraná and Tepuel basins is hindered by lack of reliable absolute age control.

This study provides a test of modeled ice distribution in southern Gondwana that mechanistically link ice sources to highlands. The detrital zircon U-Pb ages and Hf isotope compositions provide the first geochemical evidence that suggest continental-scale fluvial and glacio-fluvial drainage systems linked to glaciation in the paleo-high-latitudes during the LPIA. Ice extended into western southern Gondwana and emanated from at least four distinct ice centers that include the Windhoek Highlands, east Africa, an Uruguayan ice center, and the Ellsworth Mountain crustal block of Antarctica. This study provides support for the existence of separate, large ice centers during the late phase of glaciation during the Late Paleozoic. These findings do not preclude the presence of smaller glaciers centered on paleotopographic highlands throughout west-central Gondwana. Rather, our findings indicate a complex glaciation history, where diamictites record drainage from both alpine glaciation and inferred ice caps/sheets in areas of Africa and Antarctica. These findings suggest that some ice centers may have been larger than previously hypothesized during intervals of the LPIA. Glaciation appears to follow the CO_2 record in the Paraná and Tepuel basins suggesting this mechanism is a main driver of ice distribution in this area of Gondwana throughout the Carboniferous and into the early Permian.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2018.04.020.

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