Late Paleozoic Glaciation

Eduardo LM Rosa and John L Isbell, Department of Geosciences, University of Wisconsin-Milwaukee, Milwaukee, WI, United States

Introduction 1
Evolution of the Concept of LPIA Glaciation 2
The Glacial Stratigraphic Record 2
South America 5
Africa 6
Arabian Peninsula 7
Asia 8
Antarctica 8
Australia 9
Laurasia 9
Glacial Paleogeography and Ice Volume 9
Climatic Drivers 10
Concluding Remarks 11
References 11
Further Reading 12

Glossary

Cyclothems Repetitive stratigraphic successions of marine and nonmarine strata that are indicative of cyclic depositional regimes due to sea-level variations.
Diamictite Textural descriptive term for poorly sorted rocks containing gravel in a sand or mud matrix.
Equilibrium line altitude Theoretical altitude on a glacier that separate an upper area of annual net accumulation from a lower area of annual net ablation. Modern equilibrium line altitudes are at the sea-level in the poles and about 5 km in the tropical latitudes.
***Eurydesma* fauna** Gondwanan cold-water marine fauna mainly composed of brachiopods that occur in deglaciation strata of Sakmarian age.
Glacioeustasy Global sea-level changes resulting from terrestrial ice-volume changes.
***Glossopteris* flora** Temperate, wet flora that expanded on Gondwana in the early Permian succeeding the last late Paleozoic glaciation peak.
Greenhouse Earth Warm, deep-time intervals when Earth's polar to tropical temperatures are slightly different and the surface is ice free.
Hercynian orogeny Mountain-building event that resulted from the continental collision between Euramerica and Gondwana to form Pangea.
Ice stream Corridors of fast flowing ice within an ice sheet.
Icehouse Earth Cooler, deep-time intervals where temperatures at the poles are much colder than they are at the Equator and some areas of the planet are covered by ice sheets for long intervals of time.
Tillite Genetic term for a rock emplaced directly by or in contact with glacial ice.

Introduction

The late Paleozoic was an interval when large-scale tectonic reconfigurations, biotic evolution, and important climatic changes influenced Earth's land surfaces, oceans, and atmosphere. Long-term cooling during this time culminated in icehouse conditions that started in the latest Devonian (362 Ma), extended throughout the Carboniferous, and ended in the early late Permian (256 Ma) ~106 Myr later when global climate transitioned back into a greenhouse mode. This icehouse interval is known as the Late Paleozoic Ice Age (LPIA) and this glaciation is known as the Late Paleozoic Glaciation or Gondwana(n) Glaciation. The LPIA was the longest, most severe, and most widespread icehouse interval of the Phanerozoic. It consisted of multiple, million year-scale glacial episodes that alternated with interglacial/nonglacial conditions of approximately the same duration. Atmospheric CO_2 is estimated to have reached the lowest levels and O_2 the highest levels of the Phanerozoic.

During the late Paleozoic, the supercontinent Gondwana drifted around and across the South Pole providing high latitude sites that allowed for the requisite temperature and precipitation conditions for the initiation of extensive ice masses. In contrast, equatorial landmasses, such as Euramerica and crustal blocks presently constituting much of southern Asia, recorded the expansions

https://doi.org/10.1016/B978-0-08-102908-4.00063-1

of the oldest widespread tropical forests, warm arid belts, and tropical carbonate shelves. Northward drift of Pangea placed the leading edge of the continent in what is now northeastern Asia within the North Polar Circle by 310 Ma.

The bulk of the stratigraphic record for late Paleozoic glaciation is within sedimentary basins of the former supercontinent Gondwana in the form of glacial strata and ice-sculptured landforms generated as ice masses nucleated, advanced, retreated, dwindled, and reformed over various ice centers scattered across the supercontinent (Fig. 1). Controversial evidence for low-latitude glaciers has been reported from North America as well as boreal glaciation in eastern Siberia. Beyond the glacial record left directly by the expansion and shrinkage of Gondwanan ice masses, an indirect, far-field, cyclic record occurs in tropical to subtropical sedimentary basins of Euramerica and Asia. These cyclothems are widely interpreted as high frequency (less than 1 Myr in duration) regressive-transgressive sequences that resulted from glacioeustatic fluctuations as high-latitude southern ice sheets grew and decayed.

Evolution of the Concept of LPIA Glaciation

Permo-Carboniferous glacial deposits were first documented in the second half of the 1800s across India, Australia, and South America. Since then the idea of the LPIA has been constantly evolving as glacial successions are better understood and the resolution of chronostratigraphic models are improved. In the beginning of the 1900s, the correlation of such glacial deposits and their estimated high latitude occurrences were a key argument of Alfred Wegener's hypothesis of continental drift and the reconstruction of Pangea. It was suggested that a great ice cap covered much of Gondwana when the supercontinent was centered over the South Pole during the Permo-Carboniferous (Du Toit, 1937). The "fixists," opposed to the continental drift hypothesis, explained the distribution of late Paleozoic glacial deposits in their current low latitude positions as having been emplaced by an ancient catastrophic glaciation in the Southern Hemisphere that extended from polar to tropical latitudes.

The first extensive investigation of the late Paleozoic glaciation across the regions that were part of Gondwana was performed in the late 1960s and 1970s by Lawrence Frakes and John Crowell. They identified numerous regions of Gondwana where continental ice sheets, ice caps, and mountain glaciers formed and emanated into adjacent sedimentary basins. These ice centers expanded and contracted asynchronously as Gondwana drifted around and across the South Pole. The onset of the ice age was attributed to local glaciation in the Serpukhovian (Upper Mississippian), which culminated around the Carboniferous-Permian boundary with ice sheets spreading out across Gondwana and disappeared in the middle Permian.

During the 1980s, the available temporal and spatial information on the Gondwana glacial record was summarized and correlated with the Euramerican cyclothems. Three glacial episodes within the late Paleozoic were defined. While the first two episodes were short and local during the Upper Devonian (Famennian) and Middle Mississippian (Visean), the third was a long, protracted episode that started with localized nucleation of ice centers on tectonically uplifted margins of Gondwana during the Upper Mississippian (Serpukhovian). These glaciers then expanded to cover much of Gondwana around the time of the Permo-Carboniferous boundary, before shrinking and disappearing during the early Permian (Sakmarian). A similar synthesis was conducted in early 2000s and three nonoverlapping glacial episodes of 10–25 Myr duration, separated by nonglacial periods, were defined (Isbell et al., 2003). Furthermore, the calculations of the previously proposed ice volumes on Gondwana demonstrated an inconsistency with the magnitude of the resulting glacioeustatic fluctuations estimated from the study of Euramerican cyclothems. In this synopsis, the first two episodes took place during the Frasnian-Tournaisian and during the Serpukhovian-Bashkirian, respectively, and were characterized by local alpine glaciation, which would not have been able to produce significant sea-level fluctuations. The third episode was constrained from the Upper Pennsylvanian to early Permian (Sakmarian) and was the only episode in which ice sheets could have been present on Gondwana and produced eustatic changes assumed large enough for the Euramerican cyclothems.

The most recent and up to date scheme for the late Paleozoic glaciation established shorter glacial episodes of 1–8 Myr in duration, alternating with nonglacial/interglacial phases of similar duration (Fielding et al., 2008a). This scheme provided an emergent view that defines the glaciation as a more dynamic icehouse interval, as opposed to the single protracted event traditionally assumed. This view posits that the icehouse epoch started with restricted episodes of mountain glaciation at the Famennian-Tournaisian boundary and in the Visean. Episodes of ice expansion across wider areas of Gondwana ensued at the start of Serpukhovian, Bashkirian, and Moscovian. Subsequently to a warmer period in the Upper Pennsylvanian, a massive expansion of ice across Gondwana took place near the Pennsylvanian-Permian boundary with peak glacial conditions in the early Permian (Asselian-Sakmarian). Widespread polar ice collapsed on Gondwana and local discrete glaciation continued intermittently outside of the South Polar Circle throughout the middle and early late Permian.

The Glacial Stratigraphic Record

Primary evidence for glaciation in the stratigraphic record includes the occurrence of: (1) landforms carved by glaciers (e.g., roches moutonnées, whalebacks, glacial valleys, grooved and striated surfaces); (2) poorly sorted rocks (e.g., tillites and diamictites); (3) pebbles, cobbles, and boulders that display evidence for glacial transport (e.g., striations and facets); and (4) erratic clasts within laminated strata (dropstones) interpreted as ice-rafted debris that sank through the water column after melting out of icebergs or sea/lake ice (Fig. 2).

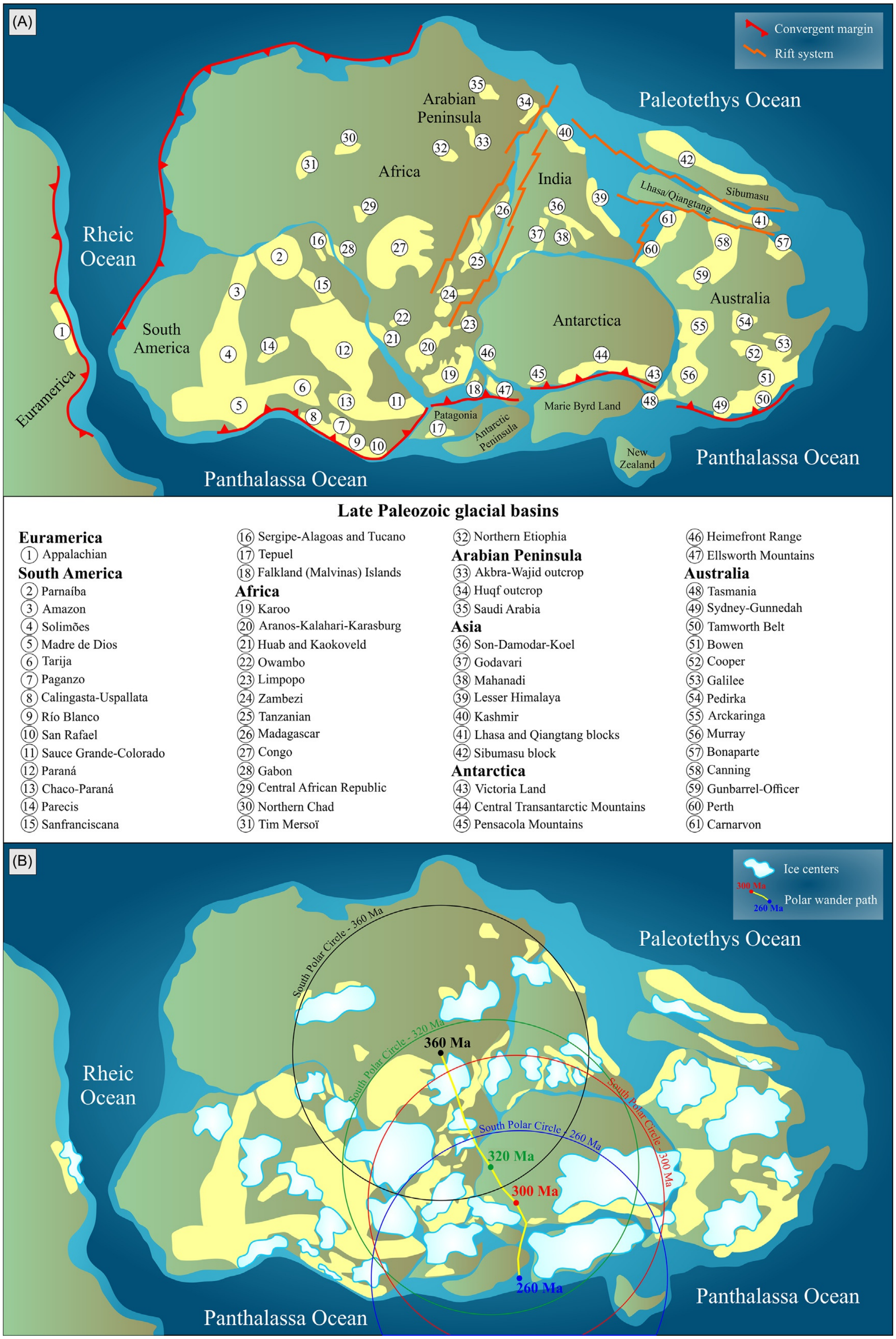

Fig. 1 (A) Paleogeographic reconstruction of Gondwana with late Paleozoic glacial sedimentary basins and major tectonic structures. Position of Euramerica in relation to Gondwana is at the Upper Devonian. (B) Distribution of inferred late Paleozoic ice centers and migration of the South Pole and South Polar Circle during the latest Devonian to late Permian. Gondwana reconstruction and polar wander path from Lawver LA, Dalziel IWD, Norton IO, Gahagan LM and Davis JK (2014) *The PLATES 2014 Atlas of Plate Reconstructions (550 Ma to Present Day).* PLATES Progress Report No. 374-0215, University of Texas Technical Report No. 201, p. 220; Basin configuration modified from Isbell JL, Miller MF, Wolfe KL and Lenaker PA (2003) Timing of late Paleozoic Glaciation in Gondwana: Was glaciation responsible for the development of northern hemisphere cyclothems? In: Chan MA and Archer AW (Eds.), *Extreme Depositional Environments: Mega End Members in Geologic Time*. Geological Society of America Special Paper, vol. 370, Geological Society of America, pp. 5–24.

Fig. 2 Examples of sedimentary facies and ice-sculptured landforms across Gondwana. (A) Striated and faceted boulder within a tectonically tilted subglacial diamictite, Hoyada Verde Formation, Calingasta-Uspallata Basin, Western Argentina; (B) Erratic boulder piercing laminated offshore sediments, Itararé Group, Paraná Basin, Brazil; (C) Grooved surface on Devonian sandstones at the Itararé Group basal unconformity, Paraná Basin, Brazil; (D) Polished surface with cross-cutting striation at the Kaokoveld glacial valleys, northwestern Namibia; (E) Dwyka Group glaciogenic diamictites, northwestern Namibia; (F) Massive glaciomarine diamictites of the Pagoda Formation, central Transantarctic Mountains, Antarctica.

In the latter half of the 1900s significant advances in the field of sedimentology showed that poorly sorted rocks (diamictites) are also generated by processes other than just glacial action (tillites). Such processes include deposition from sediment gravity flows (debris and density flows) and mass transport activity (slides and slumps), both of which form due to re-sedimentation following collapse of unconsolidated to semi-consolidated sediments, thus, raising the question that any given diamictite, which may have been originally interpreted as glacial in origin (tillite), could have been generated by other nonglacial processes. Therefore, the occurrence of diamictites does not necessarily indicate the former occurrence of a glacier. Similarly, any rhythmically laminated mudstones and fine-grained sandstones traditionally interpreted as generated by annual cyclical deposition in glaciolacustrine lakes (varves), are now known to occur due to tidal activity, and deposition from low-density turbidity currents deposited in offshore environments, among other processes. Admittedly, the evidence for glaciation in some sedimentary basins relies solely on the occurrence of diamictites and laminated sediments, suggesting potential ambiguous interpretations.

More than 150 years of research has documented evidence for late Paleozoic glaciations within Gondwanan sedimentary basins across South America, the Falkland (Malvinas) Islands, Africa, Arabian Peninsula, Antarctica, Australia, the Indian subcontinent, and Southeast Asia. Laurasian successions interpreted as of a glacial origin have also been described in the United States and eastern Siberia. Most of the late Paleozoic glacial record consists of glacially influenced marine and glaciomarine deposits as glaciers advanced into and retreated out of the various marine sedimentary basins. Deposits emplaced directly by ice masses, such as those generated or transported in subglacial, ice-marginal, or proglacial environments also occur, but such records are less common. Glacioterrestrial sediments have a low preservation potential due to erosion by subsequent glacial advances and post-glacial isostatic rebound.

The waxing and waning of LPIA glaciers within sedimentary basins typically produced fining-upward successions as tidewater glaciers retreated out of the basins. These deglaciation successions are defined by basal ice-proximal, coarse sedimentation that gradually transitions to offshore mudstones with or without glacial influence. However, other types of sedimentary successions are also possible due to isostatic rebound, proximity to basin margins, and the amount of sediment discharge from the retreating glacier. Moreover, landforms generated by glacial erosion on bedrock establish a lower boundary for the late Paleozoic glacial strata. The paleo-ice pathways and inferences on the position and size of ice centers are mainly reconstructed based on the ice kinematics retrieved from these erosive landforms. Recently, reassessment of striated surfaces generated on soft sediment surfaces, routinely explained as generated below glaciers, have been linked to scour by icebergs or sea/lake ice, thus caution must be exercised in determining true ice flow direction of glaciers (e.g., Rosa et al., 2016).

South America

Late Paleozoic glaciers left an extensive temporal and spatial record throughout South America within basins developed along tectonic active margins and in intraplate positions (Fig. 1A). The best preserved and understood latest Famennian to Mississippian glacial record in Gondwana is in northern Brazil and the Andean region of western South America. In northern Brazil, the intracratonic Parnaíba, Amazonas, and Solimões basins contain striated surfaces on bedrock, diamictites, striated clasts, and dropstones that distinguish three glacial episodes in the latest Famennian, middle Tournaisian, and late Visean (Caputo et al., 2008) (Fig. 3). Latest Famennian, Mississippian, and Pennsylvanian glacial evidence also occur in the late Paleozoic retroarc foreland Peru-Bolivia Basin (Di Pasquo et al., 2019). Orogeny along the Panthalassa margin favored local alpine glaciation with ice

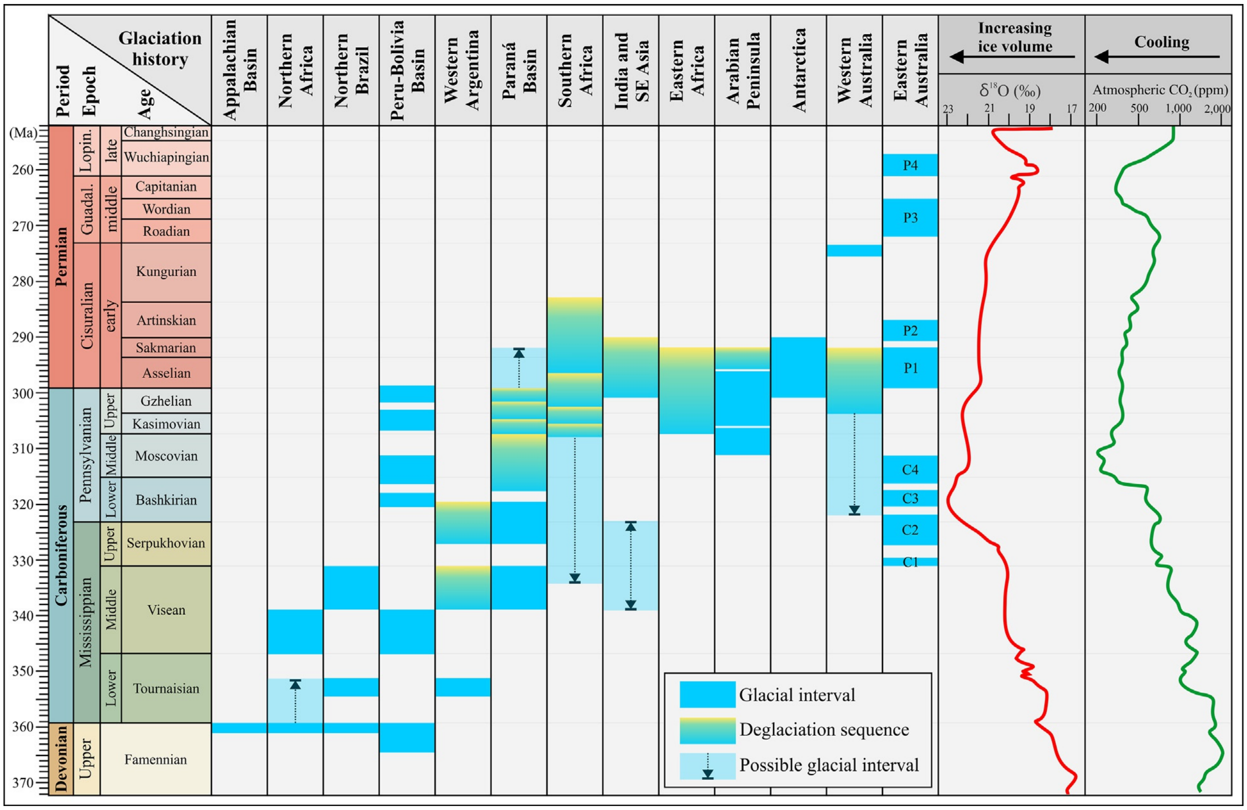

Fig. 3 Spatial and temporal distribution of the main record of the late Paleozoic glaciation. Relative ice volume trends from $\delta^{18}O$ and relative global cooling from atmospheric CO_2 levels. Modified from Isbell JL, Miller MF, Wolfe KL and Lenaker PA (2003) Timing of late Paleozoic Glaciation in Gondwana: Was glaciation responsible for the development of northern hemisphere cyclothems? In: Chan MA and Archer AW (Eds.), *Extreme Depositional Environments: Mega End Members in Geologic Time*. Geological Society of America Special Paper, vol. 370, Geological Society of America, pp. 5–24; Fielding CR, Frank TD and Isbell JL (2008a) The late Paleozoic ice age—A review of current understanding and synthesis of global climate patterns. In: Fielding CR, Frank TD and Isbell JL (Eds.), *Resolving the Late Paleozoic Ice Age in Time and Space*. Geological Society of America Special Paper, vol. 441, Geological Society of America, pp. 343–354 and references throughout the text, modified from Qie W, Algeo TJ, Luo G and Herrmann A (2019) Global events of the Late Paleozoic (Early Devonian to Middle Permian): A review. *Palaeogeography, Palaeoclimatology, Palaeoecology* 531(A): 109259.

fields spawning valley glaciers into the epicontinental Peru-Bolivia foreland. In addition, ice sheets are estimated to have covered northern Brazil, northwestern South America, and parts of northern Africa during the latest Famennian. The age of these South American glaciomarine successions is well constrained by palynostratigraphy. However, some units show strong glacial evidence whereas others only contain diamictites that were correlated to adjacent known glacial successions. Thus, the potential misinterpretation of diamictites could lead to inaccuracies concerning the presence and extent of glaciers in this Gondwana domain. Much of the overlying Upper Mississippian-Pennsylvanian successions in these basins comprise successions deposited under warmer climates due to the northward displacement of these regions towards lower latitudes, making these strata more comparable to those in Euramerica.

In western Argentina, several smaller basins developed along the Panthalassa active margin of Gondwana such as the Paganzo, Calingasta-Uspallata, Río Blanco, San Rafael, and Navidad-Arizaro. These basins show a well-constrained record of two glacial episodes spanning about 8 Myr each, the oldest in the late Visean and the youngest during the late Serpukhovian-early Bashkirian (Césari et al., 2011) (Fig. 3). In addition to these episodes, middle Tournaisian glaciomarine sequences were recently recognized in the Río Blanco Basin (Agua de Lucho Formation). The glacial strata in western Argentina are sometimes confined to glacial valleys radiating from paleotopographic highs interpreted as a fjord network draining out from adjacent ice fields. Deposits include terrestrial to glaciomarine successions with well-defined deglaciation successions and ice-contact facies (Fig. 2A). Glaciation in this region is interpreted as the result of tectonic uplift and elevation of the mountain range above an equilibrium line altitude allowing the nucleation of glaciers. Moisture that nourished the ice fields likely came from the Panthalassa Ocean.

Patagonia and the Falkland (Malvinas) Islands are allochthonous terranes to South America and their exact location during the late Paleozoic is estimated to have been in the junction between southern Africa, South America, and Antarctica (Fig. 1A). The Tepuel Basin in Patagonia contains the thickest (up to 5 km) record of the late Paleozoic glaciation contained in the Tepuel Group. The succession is dominated by a glacially-influenced marine succession containing shales with dropstones and diamictite beds that span from the Tournaisian to Artinskian and were deposited when Patagonia was in a polar to subpolar setting, potentially amalgamated with the Antarctic Peninsula block. In the Falkland (Malvinas) Islands, diamictites with boulders up to 7 m long and pebbly mudstones have been described and dated using palynostratigraphy from the late Visean to the early Permian.

The bulk of the Pennsylvanian to early Permian glacial successions in South America occurs within the intracratonic Sauce Grande-Colorado, Paraná, Chaco-Paraná, and Sanfranciscana basins. The glacial record in the Sauce Grande Formation (Sauce Grande-Colorado Basin) includes about 1 km of massive diamictites, some interpreted as glacial and some that resulted from slumping, interbedded with ice-rafted horizons. The age for the glacial successions is poorly constrained and is defined as Upper Carboniferous to Sakmarian since a post-glacial transgressive shale contains early Permian *Eurydesma* fauna and *Glossopteris* flora remnants. In the Sauce Grande-Colorado Basin, the basal unconformity between the glacial strata and older Devonian strata is marked by an angular unconformity that resulted from a Panthalassa margin folding phase predating glaciation.

The Paraná Basin in Brazil, Paraguay, Argentina, and Uruguay is the largest late Paleozoic depocenter in South America. The Itararé Group and its correlative units from other margins of the basin (Aquidauana, Aquidabán, and Coronel Oviedo formations) have an estimated age based on palynology ranging from the middle Visean to early Sakmarian (Rosa et al., 2019). Recent U-Pb dating of ash fall layers at the base of the post-glacial, coal-bearing Rio Bonito Formation in the southernmost Paraná Basin, however, suggest that glaciation ceased at the Carboniferous-Permian boundary (Fig. 3). In this view, the post-glacial succession in the Paraná Basin is the result of sea-level fluctuations linked to early Permian glaciations occurring across other regions of Gondwana (Griffis et al., 2019). The stacking of up to 1.3 km of glaciomarine strata records deglaciation successions usually composed of glaciogenic to proglacial deposits at the base with fining-upward deltaic and offshore sedimentation, including thick shale packages with dropstones (Fig. 2B) and mass-transport complexes (Vesely and Assine, 2006). Estimated sources for ice masses in the Paraná Basin are based on the kinematics retrieved from subglacial erosive landforms (Fig. 2C) and include multiple portions in southwest Africa for the eastern and southern Paraná Basin and in central South America for the western portion of the basin (Rosa et al., 2016).

The Chaco-Paraná Basin is a continuation of the Paraná Basin, occurring essentially as a subsurface basin. It is distributed along northern Argentina and Uruguay. A thick (about 1.1 km) succession in northern Argentina, referred as the Ordoñez Formation, is reported to be dominated by diamictites, sandstones, and some horizons containing dropstones with an estimated age around the Carboniferous-Permian boundary.

In Brazil, late Paleozoic successions in other sedimentary basins as the Parecis, Sanfranciscana, Tucano, and Sergipe-Alagoas have not been studied in detail but are reported to contain glacial erosive landforms, diamictites with striated clasts, and laminated facies with dropstones. No detailed age constrains for these basins have been published, but the glacial strata are correlated with the ages proposed for the glacial succession in the Paraná Basin.

Africa

The best-known African late Paleozoic glacial successions occur in the main Karoo Basin in South Africa where they are known as the Dwyka Group. The Dwyka Group strata attain a maximum thickness of 900 m and record four deglaciation sequences dominated by stratified and massive diamictites and secondary sandstones and shales with dropstones (Visser, 1997). At the base of the Dwyka strata there is a widespread unconformity marked by several paleovalleys carved on Precambrian basement rocks to the North and on the Devonian to Mississippian pre-glacial strata to the South. Whereas the age of the end of glaciation is constrained at the Artinskian-Kungurian boundary using U-Pb geochronology dating of ash-fall layers in the basal post-glacial succession (e.g., Griffis et al., 2019), the age of onset of glaciation in the Karoo Basin is poorly defined and controversial. Postulated initiation ranges from Visean to Lower and Middle Pennsylvanian (Fig. 3). The Dwyka strata are believed to have accumulated in a developing foreland basin that resulted from active tectonism in a southern highland region along the subducting Panthalassa margin. The subduction resulted in the elevation of a Southern Highlands and the Cargonian Highlands to the North of the Karoo Basin. These adjacent uplands and portions of Antarctica are believed to have been the source for valley glaciers and ice streams that entered and merged in the marine depocenter.

Dwyka-equivalent strata occur throughout the southern portion of Africa in smaller basins than that of the main Karoo Basin. In the Aranos-Kalahari-Karasburg Basin, Namibia, the Dwyka Group shows similar deglaciation sequences correlative with the Karoo Basin and ice pathways indicating a source from the Cargonian Highlands in South Africa and the Windhoek Highlands in northeastern Namibia (Visser, 1997). The Windhoek Highlands are also a likely region for ice nucleation responsible for glaciers that emanated from the upland extending into the eastern Paraná Basin, Brazil. In northern Namibia, Dwyka Group glaciogenic and post-glacial strata occur as a thin veneer in the Huab Basin, in the subsurface in the Owambo Basin, and confined within ice-carved valleys in the Kaokoveld (Fig. 2D and E). These valleys and basins are hypothesized to have been extensions of the Paraná Basin located on the present African continent.

Small basins with an elongated shape predominantly to the northeast-southwest contain Dwyka-equivalent strata across Zambia, Mozambique, Zimbabwe, Tanzania, and Madagascar. These basins are considered to have been connected and formed major sedimentary basins. Strata are tilted and preserved in faulted blocks suggesting that post-glacial faulting gave rise to the preservation of the Dwyka beds. The development of these basins and adjacent uplands is related to the inception of the Malagasy Trough intracratonic rift system along east Africa and the Arabian Peninsula during the early Permian (Wopfner, 2002) (Fig. 1A). In these basins, the glacial beds attain a maximum thickness of 160 m and contain diamictites, sandstones, conglomerates and laminated rhythmites with ice-rafted debris as well as striated pavements cut on bedrock. Deposition in these basins is interpreted as glacioterrestrial in which glaciers spawned in the adjacent rift-generated highlands entered proglacial lakes coming from local ice centers, incising valleys on the bedrock. Depositional ages for these basins of Dwyka-equivalent strata are scant and their age relies on lithologic correlations to the Dwyka Group and are attributed to Upper Carboniferous-early Sakmarian glacial activity (Fig. 3). Post-glacial beds occurring on top of the Dwyka strata are fluvial sandstones with coal beds.

The Congo Basin was a large intracratonic depocenter in the current Democratic Republic of Congo and northern Angola. Outcropping of late Paleozoic glacial strata is restricted to the eastern margin of the basin. Valley glaciers dissecting an eastern upland are interpreted to have flowed westwards into the Congo Basin. These valleys are U-shaped and exhibit internally striated surfaces and roches moutonnées. Glacial beds attain a maximum thickness of 450 m in the subsurface in the center of the basin and are referred as the Lukuga Group. Two deglaciation sequences are identified in the basin and their age is roughly correlated with Upper Carboniferous-early Permian, based on lithologic correlation with the Dwyka Group in the Karoo Basin.

From the present Equator towards the Northern Hemisphere portion of Africa, the glacial record is scarce and occurs scattered across wide regions (Fig. 1A). Ice streams draining an ice sheet of a probably Visean age were recently documented in Chad (Le Heron, 2017). This Visean ice sheet was interpreted on the basis of time-equivalent glacial diamictites, striated pavements, and dropstones of the same age in the Aïr Plateau (Tim Mersoï Basin) in Niger, which also possibly comprises latest Devonian to Tournaisian diamictites (Fig. 1B). In the southwestern Central African Republic, the Mambéré Glacial Formation contains diamictites and its age is attributed to the Famennian to Mississippian. N'khom-Angoula Permian diamictites occur in coastal Gabon and are interpreted as of a glacial origin due to strata containing striated clasts as well as laminated mudstones with erratic blocks, which possibly correlate to the northeastern Brazilian Sergipe-Alagoas Basin. Carboniferous diamictites are also reported in southwestern Egypt and northwestern Sudan and latest Famennian diamictites were documented from a core in the Murzuq Basin in Libya. Proven Upper Carboniferous-early Permian glacial deposits are reported form northern Ethiopia (Bussert, 2014). The glaciogenic and resedimented beds indicate two glacial advances and retreats in a subaqueous body overlying an undulating unconformity composed of valleys and ridges with superimposed striated pavements and roches moutonnées.

Arabian Peninsula

Glacial deposits are distributed in the Arabian Peninsula across Oman, Yemen, and Saudi Arabia. The Al Khlata Formation reaches up to 800 m in the subsurface and is well defined in the Huqf area in Oman. Its beds are interpreted as glaciofluvial to glaciodeltaic grading laterally into ice-contact lacustrine strata. Evidence for glaciation during sedimentation of this unit is very strong and comprises erosive landforms on bedrock, ice-rafted debris within laminated beds and diamictites with striated clasts (Martin et al., 2012).

The age of the Al Khlata Formation and coeval facies in Saudi Arabia are defined by palynomorphs as latest Moscovian to middle Sakmarian (Fig. 3). In the region close to the Arabian Gulf in Saudi Arabia the time equivalent Unayzah Formation is defined only in the subsurface. The background for sedimentation in the Arabian Peninsula involves Carboniferous uplift due to the Hercynian Orogeny and later rifting and thermal doming associated with the Tethyan rifting (Malagasy Trough). Estimated areas for nucleation of ice masses in the Arabian Peninsula are local and related to paleotopographic highs generated by tectonism.

Asia

Successions of the LPIA in Asia formed along the Tethyan margin of eastern Gondwana. These areas rifted and drifted away from the supercontinent at various times. Glacial strata are found in sedimentary basins from Peninsular India and within fold belts across the Himalayan range encompassing northern India, Kashmir, Nepal, Bhutan, and Tibet, as well as in fold belts in Myanmar, Thailand, Malaysia, and Sumatra.

The Talchir Formation is the name given to the late Paleozoic glacial deposits within sedimentary basins present in Peninsular India and it represents the base of the late Paleozoic to Mesozoic Gondwana Group. These sedimentary basins are distributed along three major modern river valleys (Godavari, Mahanadi, and Son-Damodar-Koel). Strata are largely unfolded but faults are common and believed to have occurred concomitantly with deposition due to early rifting around the Gondwanan Tethyan margin. The several basins comprised along these three axis are believed to have been part of the same basin in the interior of Gondwana and possibly connected to portions of East Antarctica. The glaciomarine Talchir Formation attains a maximum thickness of 300 m and it is bounded by a glacial unconformity evidenced by a few erosive landforms. Striated clast-bearing diamictites interpreted as tillites or debris flow deposits occur at the base of the Talchir Formation and are succeeded by a deglaciation sequence composed of rhythmites with dropstones, open shelf deposits, and topped by black shales. Repeated glacial advances and retreats led to multiple, fining-upward deglaciation cycles (Bhattacharya and Bhattacharya, 2015). The age of the Talchir strata is assumed as Upper Carboniferous to Sakmarian based on palynomorphs and the presence of the *Eurydesma* fauna within the final deglaciation strata (Fig. 3). Within fold belts in the Kashmir and Lesser Himalaya, there are thin successions of boulder diamictites, pebbly mudstones, and shales. They show a similar deglaciation fining-upward trend as the Talchir Formation, though these beds were deposited in Tethyan passive margin of the Indian subcontinent.

Several tectonic blocks (Cimmerian blocks) detached from the Tethyan margins of eastern Gondwana during the Permian (Fig. 1A) and later collided with other terranes making up part of current southeast Asia. These blocks (i.e., Lhasa, Qiangtang, Sibumasu) contain the typical threefold Upper Carboniferous to Sakmarian deglaciation sequences composed of basal diamictites, pebbly mudstones, and upper shales containing cool-cold water marine faunas. Besides being broadly considered Upper Carboniferous to Sakmarian, some diamictites and dropstones successions in southern Tibet and Malaysia are dated as Visean-Serpukhovian (e.g., Hassan et al., 2014), implying that the onset of glacial conditions began earlier in these basins when they were still attached to Gondwana.

Antarctica

Most of the Antarctica is currently covered by ice and late Paleozoic deposits are described from ranges protruding from the modern ice sheet. Sequences are known from the Transantarctic, Pensacola, and Ellsworth mountains, but also occur in the Shackleton and Heimefront ranges (Fig. 1A).

In the central Transantarctic Mountains, the glacial strata are identified by different names according to the region where they were first described (e.g., Pagoda, Scott Glacier, and Buckeye formations, Darwin Tillite) and occur unconformably over basement and Devonian strata with relief on the unconformity exceeding several hundred meters locally (Isbell et al., 2008). Along basin margins, both glaciogenic and post-glacial black shales lap onto the basement. The top of the basement occurs as either a polished and striated surface or as a deeply weathered contact. The glaciogenic beds are up to 450 m in thickness and occur in two narrow trough-shaped basins cut sub-parallel to oblique to the trend of the modern Transantarctic Mountains. The glacial succession consists of massive (Fig. 2F) and stratified diamictites with striated debris, conglomerates, sandstones, dropstone-bearing mudrocks, and thick, black, dropstone-free post-glacial shales at the top. The succession is interpreted as deposited in glaciomarine ice-proximal to distal to open-marine settings as temperate glaciers waxed and waned during the early Permian (Asselian-Sakmarian), with the black shales representing withdrawal of the glaciers from the depositional basins. Upward, the middle and upper Permian consist of thick coal-bearing fluvial strata containing an abundant *Glossopteris* fossil flora.

Glaciogenic complexes from the Metschell Tillite in southern Victoria Land are composed of sheared subglacial diamictites, thrust moraines containing thick plucked rafts of Devonian bedrock and Permian glaciogenic beds, and massive and striated diamictites (Isbell, 2010). The glaciogenic facies are associated with subaqueous strata and interpreted as generated from ice masses that advanced and retreated into a marine/lacustrine realm. The orientation of glaciotectonic structures are evidence for temperate glaciers coming from the East Antarctic Craton and from that of the present Ross Sea converging into an elongated basin with a parallel long-axis to the present mountain range trend (Fig. 1B). The glaciogenic strata are conformably to disconformably overlain by up to several hundred meters of *Glossopteris*-bearing, fluvial coal measures. In northern Victoria Land, a succession that represents the linkage between Antarctica and basins in Tasmania and eastern Australia, consists of subglacial terrestrial to glaciolacustrine strata deposited under two advance and retreat cycles during the Asselian (Cornamusini et al., 2017).

In the Pensacola and Ellsworth mountains, successions reaching up to 1200 m in thickness are dominated by diamictites with minor interstratified mudstones with dropstones and sandstones (Whiteout Conglomerate and Gale Mudstone). These successions contain striated clasts and boulder pavements and are interpreted as have been deposited under a fluctuating grounding zone in a glaciomarine setting. Diamictites are interpreted as glaciogenic as well as the result of gravity-driven resedimentation. The basal contact between the glaciogenic Whiteout Conglomerate in the Ellsworth Mountains is attributed as transitional, raising questions there that the glacial succession could have been deposited throughout the Carboniferous and early Permian. These successions resemble the ones from the Falkland Islands and Karoo Basin in South Africa and could have been deposited in a similar geotectonic and paleoclimatic context prior to the dispersal of the various Gondwanan crustal blocks.

Australia

The record of eastern Australia provides important evidence for the late Paleozoic glaciation as a dynamic icehouse comprising discrete (1–8 Myr in duration) glacial and interglacial intervals (Fielding et al., 2008b). Eight glacial events spanning an interval from the Upper Mississippian (Serpukhovian) to the early late Permian (Wuchiapingian) are identified, with four in the Carboniferous (C1 to C4) and four in the Permian (P1 to P4) (Fig. 3). C1 to C4 glacial episodes in eastern Australia are preserved within the southern New England (Tamworth) Fold Belt and in the Galilee Basin. Depositional systems are predominantly glacioterrestrial, and the strata formed under glacial influence are interbedded with strata with little or no evidence of glaciation. Carboniferous glaciation in this region is interpreted to have been local and to have been controlled by the uplift of the land surface above the equilibrium line altitude as a continental volcanic arc formed along the eastern Australian continental margin. The glaciers formed in these uplands and flowed into adjacent forearc basins. In contrast to the Carboniferous strata, the Permian strata were deposited in a shallow open-marine environment with glacial influence.

In addition to the Tamworth Fold Belt and Galilee Basin, the Permian glacial record is widespread in the Sydney-Bowen-Gunnedah Basin system, Cooper Basin and in Tasmania. The oldest Permian episode (P1) took place in the earliest Permian and was related to widespread ice sheets that expanded throughout Australia. Differently, the P2, P3, and P4 glacial episodes are recorded mainly in glaciomarine facies in the form of outsized clasts in mudstones and the occurrence of glendonites, a mineral indicative of cold-water conditions. At that time of P3 and P4 episodes, polar Gondwana was under ice-free conditions as evidenced by widespread coal measures in Antarctica and southern Africa. It is suggested that these late-phase events in eastern Australia were driven by the presence of uplands allowing nucleation of glaciers and local climatic conditions.

In Western Australia the record for glaciation is widespread in the surface and subsurface of the Carnarvon, Perth, Canning, Gunbarrel-Officer, and Bonaparte basins (Fig. 1). These basins were formed according to inception of rifting in the Tethyan margin as differences in thickness in the strata in these basins suggest. Most of what is known about these basins come from narrow outcrop belts along the margins of these basins and from shallow subsurface data. Striated surfaces on bedrock and tunnel valleys indicate multiple ice sheets entering the marine basins. The Western Australian basins commonly show a deglaciation succession composed by basal glacial diamictites and mudstones with dropstones, succeeded by a marine mudstone succession and topped by coal-bearing, fluvio-deltaic sandstones (Mory et al., 2008). The biostratigraphy and stratigraphic context of these basins suggest that extensive glaciation occurred in Western Australia during the Upper Pennsylvanian (Gzhelian) to middle Sakmarian. Dubious glaciation sequences could have been emplaced in these basins since the Bashkirian as reported subsurface data from the Perth and Carnarvon basins, but it is poorly defined by sedimentological data. Late early Permian (Kungurian) floating ice is evidenced by erratic pebbles and boulders in the Carnarvon and Perth basins and may represent transport of clasts by sea ice (Fig. 3).

Laurasia

Even though the bulk of the record for late Paleozoic glaciation is from Gondwana, glacial deposits are also described from Laurasia such as in the United States and in eastern Siberia. Latest Famennian sheared to massive diamictites and laminated mudstones with dropstones occur in the central Appalachian Basin in an outcrop belt that extends from Pennsylvania, to West Virginia (Brezinski et al., 2008) (Fig. 1). The strata contain evidence of a single glacial advance and retreat in a glacioterrestrial setting of glaciers that also reached sea level as evidenced by dropstones in laterally equivalent marine shales. The glaciation occurred adjacent to the Acadian Highlands, which is interpreted as the source for glaciers that entered the Appalachian Foreland Basin. In Colorado, Permo-Pennsylvanian upland glaciation on the Ancestral Rocky Mountains of equatorial Pangea is postulated accordingly to the presence of poorly sorted deposits, voluminous paleoloess deposits, and a valley assumed to have been carved by glaciers (Soreghan et al., 2014).

Diamictites and outsized clasts interpreted as products of glacial processes, ice rafting or debris flow have been reported from Carboniferous-Permian strata in eastern Siberia. During the late Paleozoic, Siberia corresponded to northernmost Pangea and was placed close to the North Polar Circle. The affirmation of these diamictites as product of glacial processes implies the presence of ice at the North Pole and a bipolar glaciation model for the LPIA. However, this bipolar glacial model has been challenged and attested that part of these strata are related to subaqueous debris flows off volcanic arcs and not the result of glacial processes (Isbell et al., 2016).

Glacial Paleogeography and Ice Volume

The spatial and temporal distribution of ice masses on Gondwana, the estimated ice volume, and the glaciation peak are still controversial topics. These premises rely on information obtained from different geologic sources and from diverse methods, such as direct analysis of the stratigraphic record, geochemistry, and climate modeling.

Initially, the late Paleozoic glaciation was represented by a single, perennial, massive ice sheet that waxed and waned covering much of Gondwana with a significant ice volume (Du Toit, 1937). The extent and configuration of this ice sheet was determined by encircling all known evidence for glaciation on paleogeographic maps and assumed that the most outward occurrences of glacial facies indicated the terminal position of the Gondwanan ice sheet. This ice sheet configuration can still be seen in paleogeographic maps and climate models today. Our knowledge of the regions where ice must have nucleated and the maximum extent has been improving in resolution by assessing glaciers pathways and their terminal positions via ice-sculptured landforms, glaciogenic facies, and more recently, through high-resolution provenance studies. Several ice centers with distinct sizes (ice sheets, ice caps, and mountain glaciers) and configurations are distinguished throughout Gondwana (Fig. 1B). They are believed to have been asynchronous within the LPIA, that is, some Gondwana regions were not glaciated at the same time as the other regions. First-order controls for this lack of synchroneity are attributed to Gondwana's position in relation to the South Pole and the role of local tectonic topographic buildup above the equilibrium line altitude allowing ice centers to nucleate. The local role of oceanic currents, moisture sources, and atmospheric circulation are believed to have contributed to the local nucleation of ice centers as well.

Assessments of late Paleozoic ice volume are done by considering the glacioeustatic sea-level changes estimated for the paleotropical cyclothems, by the abundance and areal extent of glacial successions, and by climate models employing estimated atmospheric $p\mathrm{CO}_2$ concentrations. It is important to determine whether there was one immense ice sheet or whether there were multiple smaller ice sheets, ice caps, and mountain glaciers on Gondwana because the two alternatives have a profound impact on the ice volume during glaciation episodes and consequently on the glacioeustasy (Isbell et al., 2003).

The glaciation climax corresponding to the maximum ice volume on Gondwana is presumed to have happened around the Carboniferous-Permian boundary, more precisely in the early Permian (Asselian-Sakmarian). This view prevails in the literature and relies on the greater abundance and areal occurrence of early Permian glacial deposits and ice-rafted debris across much of the Gondwanan basins. An early Permian glacial peak is also shown in positive excursions of $\delta^{18}O$ and $\delta^{13}C$ isotopes obtained from late Paleozoic tropical successions as well as by estimated magnitude of glacioeustatic fluctuations from the study of paleotropical cyclothems. Another hypothesis suggests that peak glacial conditions during the LPIA occurred around the Mississippian-Pennsylvanian boundary (González-Bonorino and Eyles, 1995). This hypothesis poses an inverse relationship between ice volume and abundance of glacial deposits.

Although different hypothesis exist, extreme climaxes within the LPIA are recognized around both the Mississippian-Pennsylvanian and Pennsylvanian-Permian boundaries as indicated by glacioeustatic fluctuations, the glacial record on Gondwana, and positive isotopic excursions. Nonetheless, $\delta^{18}O$ and $\delta^{13}C$ isotopic positive excursions reported from Euramerican successions also show intense glacial activity in the Mississippian (Visean). There is little direct evidence for glaciation at this time and it is poorly constrained, as Visean glaciation is considered to be of local occurrence and related to topographically elevated regions in South America and northern Africa. However, recent documentation of Visean ice-contact sedimentation in the Paraná Basin and erosive landforms, such as a network of channels interpreted to be the result of paleoice streams in Chad, radiating outside the Visean South Polar Circle, are raising questions on the occurrence of polar ice sheets during early stages of the LPIA (e.g., Le Heron, 2017; Rosa et al., 2019).

Climatic Drivers

Studies have been deciphering and improving our knowledge of the complex interactions and feedbacks between the geosphere, atmosphere, hydrosphere, and biosphere during the late Paleozoic (Qie et al., 2019). Different controls have been proposed to explain how the late Paleozoic glaciation began and ended, as well as the mechanisms that drove climatic fluctuations within the icehouse. Tectonics is assumed as a first-order driver of late Paleozoic glaciation. Plate movements brought changes in continental landmass arrangements and caused the uplift of regions relative to the equilibrium line altitude. Furthermore, fluctuations of atmospheric $p\mathrm{CO}_2$ were partly driven by uplift-induced weathering, burial of carbon-rich sediments, and volcanic activity. However, the causes and consequences of each of these controls are still not fully understood.

The earliest theories concerning the causes for the onset and demise of glaciation were considered to be Gondwana's migration and positioning in relation to the South Pole (Du Toit, 1937; Caputo and Crowell, 1985). Although the paleoposition of Gondwana provided a base for the nucleation of ice masses during the late Paleozoic, this explanation by itself is insufficient as a first-order control for glaciation since Gondwana at the southern pole was marked by significant warmer epochs in the early to middle Paleozoic. In addition, the middle to late Permian stages of glaciation in eastern Australia occurred at mid-latitudes, and therefore cannot be explained by drifting as polar Gondwana remained ice free (Fig. 1B). The role of supercontinental reconfiguration resulting in the amalgamation of Pangea during the late Paleozoic is also an assumed first-order control of glaciation as this interaction played an important role on closing and opening of marine gateways, thus changing oceanic and atmospheric circulation patterns. Orogenesis and uplift in the Panthalassa margin of Gondwana in the Mississippian through the early Permian is also credited as a second-order trigger for the main phase of late Paleozoic glaciation. In this model, uplift promoted a control by the accumulation of ice on elevated areas that expanded across Gondwana. In a similar fashion, the paleotopography and the position of the equilibrium line altitude for ice accumulation are credited as a local, second-order drivers for initiation and demise of early and latest glacial intervals within the LPIA.

The late Paleozoic was an interval characterized by extensive subduction and collisional events, such as at the Gondwanan Panthalassa margin and the tropical Central Pangean Mountains between Gondwana and Euramerica (Fig. 1A). The role of tectonics in driving the late Paleozoic glaciation is also tied to tectonic uplifting and enhancement of continental weathering. This, in turn, was responsible for perturbations in the carbon cycle by enhancing the consumption of atmospheric CO_2 due to weathering of silicates. Atmospheric CO_2-forcing is a well-established driver of on both long and short-term climate change. Changes in pCO_2 were paced by changing tectonic and biotic conditions (Montañez et al., 2007). Terrestrial vegetation both intensified silicate rock weathering, consuming atmospheric CO_2, and enhanced organic carbon sequestration due to the burial of organic matter. Decreases in pCO_2 levels during the late Paleozoic are linked with the colonization of land by vascular plants and the expansion of extensive tropical forests during the Upper Devonian and Mississippian (Qie et al., 2019) (Fig. 3). Short-term glacial and interglacial variations, in a time scale similar of the Quaternary orbitally-induced solar insolation cycles, are difficult to be assessed from the Gondwanan glacial record due to current low-resolution chronostratigraphy. However, eustatic fluctuations, floral evolutionary trends, and short-term atmospheric pCO_2 fluctuations defined from Euramerican cyclothems have been shown to be linked to ice volume fluctuations in Gondwana.

Concluding Remarks

The late Paleozoic glaciation is the last complete and best detailed icehouse interval and the only recorded icehouse-to-greenhouse turnover on a complex vegetated Earth. Therefore, the LPIA provides a unique perspective on how Earth's physical, chemical, and biological systems respond to icehouse-greenhouse dynamics. This icehouse interval shares many similarities with the current Cenozoic Ice Age as both represent long duration glaciation on a biologically complex Earth experiencing low atmospheric pCO_2 concentrations. However, important differences also occur including atmospheric pO_2 levels, continental positioning, incident solar luminosity, and a biosphere made of different fauna and flora.

Despite the late Paleozoic glaciation being a unique analog for our future deep-time climatic transition, many unanswered questions remain due to the current state of knowledge. These questions concern the spatial and temporal extent of ice centers, the timing of waxing and waning of ice masses, the relative importance of climatic drivers, the relationship between ice volumes and global sea-level changes, the impact and feedbacks of climatic fluctuations on the biosphere, and the nature and timing of the glacial to post-glacial turnover. One factor still precluding a better understanding of the LPIA is the low resolution of chronostratigraphic correlations between glacial and interglacial episodes across and between high-latitude Gondwana glaciated sedimentary basins as well as correlations between Gondwana and the tropical late Paleozoic world. Nevertheless, since the first conclusive evidence of the LPIA record was discovered, our understanding of the dynamics of the ice age has been constantly evolving due to re-evaluation of the record under the improving sedimentology concepts and the advent of new analytical techniques.

References

Bhattacharya HN and Bhattacharya B (2015) Lithofacies architecture and palaeogeography of the late Paleozoic glaciomarine Talchir Formation, Raniganj Basin, India. *Journal of Palaeogeography* 4(3): 269–283.

Brezinski DK, Cecil CB, Skema VW, and Stamm R (2008) Late Devonian glacial deposits from the eastern United States signal an end of the mid-Paleozoic warm period. *Palaeogeography, Palaeoclimatology, Palaeoecology* 268: 143–151.

Bussert R (2014) Depositional environments during the Late Palaeozoic ice age (LPIA) in northern Ethiopia, NE Africa. *Journal of African Earth Sciences* 99(2): 386–407.

Caputo MV and Crowell JC (1985) Migration of glacial centers across Gondwana during Paleozoic Era. *Geological Society of America Bulletin* 96: 1020–1036.

Caputo MV, Melo JHG, Streel M, and Isbell JL (2008) Late Devonian and Early Carboniferous glacial records of South America. In: Fielding CR, Frank TD, and Isbell JL (eds.) *Resolving the Late Paleozoic Ice Age in Time and Space. Geological Society of America Special Paper*, vol. 441, pp. 161–173. Geological Society of America.

Césari SN, Limarino CO, and Gulbranson EL (2011) An Upper Paleozoic bio-chronostratigraphic scheme for the western margin of Gondwana. *Earth-Science Reviews* 106: 149–160.

Cornamusini G, Talarico FM, Cirilli S, et al. (2017) Upper Paleozoic glacigenic deposits of Gondwana: Stratigraphy and paleoenvironmental significance of a tillite succession in Northern Victoria Land (Antarctica). *Sedimentary Geology* 358: 51–69.

Di Pasquo MM, Folnagy HJA, Isaacson PE, and Grader GW (2019) Late Paleozoic carbonates and glacial deposits in Bolivian and northern Argentina: Significant paleoclimatic changes. In: Fraticelli CM, Markwick PJ, Martinius AW, and Suter JR (eds.) *Latitudinal Controls on Stratigraphic Models and Sedimentary Concepts*. vol. 108, pp. 185–203. SEPM Special Publication.

Du Toit AL (1937) *Our Wandering Continents*. Edinburgh: Oliver and Boyd Ltd, p. 366.

Fielding CR, Frank TD, and Isbell JL (2008a) The late Paleozoic ice age—A review of current understanding and synthesis of global climate patterns. In: Fielding CR, Frank TD, and Isbell JL (eds.) *Resolving the Late Paleozoic Ice Age in Time and Space. Geological Society of America Special Paper*, vol. 441, pp. 343–354. Geological Society of America.

Fielding CR, Frank TD, Birgenheier LP, et al. (2008b) Stratigraphic record and facies associations of the late Paleozoic ice age in eastern Australia (New South Wales and Queensland). In: Fielding CR, Frank TD, and Isbell JL (eds.) *Resolving the Late Paleozoic Ice Age in Time and Space. Geological Society of America Special Paper*, vol. 441, pp. 41–57. Geological Society of America.

González-Bonorino G and Eyles N (1995) Inverse relation between ice extent and the late Paleozoic glacial record of Gondwana. *Geology* 23(11): 1015–1018.

Griffis NP, Montañez IP, Mundil R, et al. (2019) Coupled stratigraphic and U-Pb zircon age constraints on the late Paleozoic icehouse-to-greenhouse turnover in south-central Gondwana. *Geology* 47(12): 1146–1150.

Hassan MHA, Aung A, Becker RT, et al. (2014) Stratigraphy and palaeoenvironmental evolution of the mid- to upper Palaeozoic succession in Northwest Peninsular Malaysia. *Journal of Asian Earth Sciences* 83: 60–79.

Isbell JL (2010) Environmental and paleogeographic implications of glaciotectonic deformation of glaciomarine deposits within Permian strata of the Metschell Tillite, southern Victoria Land, Antarctica. In: López-Gamundí OR and Buatois LA (eds.) *Late Paleozoic Glacial Events and Postglacial Transgressions in Gondwana. Geological Society of America Special Paper*, vol. 468, pp. 81–100. Geological Society of America.

Isbell JL, Miller MF, Wolfe KL, and Lenaker PA (2003) Timing of late Paleozoic Glaciation in Gondwana: Was glaciation responsible for the development of northern hemisphere cyclothems? In: Chan MA and Archer AW (eds.) *Extreme Depositional Environments: Mega End Members in Geologic Time. Geological Society of America Special Paper*, vol. 370, pp. 5–24. Geological Society of America.

Isbell JL, Koch ZJ, Szablewski GM, and Lenaker PA (2008) Permian glacigenic deposits in the Transantarctic Mountains, Antarctica. In: Fielding CR, Frank TD, and Isbell JL (eds.) *Resolving the Late Paleozoic Ice Age in Time and Space. Geological Society of America Special Paper*, vol. 441, pp. 59–70. Geological Society of America.

Isbell JL, Biakov AS, Vedernikov IL, et al. (2016) Permian diamictites in northeastern Asia: Their significance concerning the bipolarity of the late Paleozoic ice age. *Earth-Science Reviews* 154: 279–300.

Le Heron DP (2017) An exhumed Paleozoic glacial landscape in Chad. *Geology* 46(1): 91–94.

Martin JR, Redfern J, and Williams BPJ (2012) Evidence for multiple ice centres during the late Paleozoic ice age in Oman: Outcrop sedimentology and provenance of the Late Carboniferous—Early Permian Al Khlata Formation. In: Huuse M, Redfern J, and Le Heron DP, et al. (eds.) *Glaciogenic Reservoirs and Hydrocarbon Systems*. vol. 368, pp. 229–256. Geological Society of London Special Publication.

Montañez IP, Tabor NJ, Niemeier D, et al. (2007) CO_2-forced climate and vegetation instability during late paleozoic deglaciation. *Science* 315(5808): 87–91.

Mory AJ, Redfern J, and Martin JR (2008) A review of Permian-Carboniferous glacial deposits in Western Australia. In: Fielding CR, Frank TD, and Isbell JL (eds.) *Resolving the Late Paleozoic Ice Age in Time and Space. Geological Society of America Special Paper*, vol. 441, pp. 29–40. Geological Society of America.

Qie W, Algeo TJ, Luo G, and Herrmann A (2019) Global events of the Late Paleozoic (Early Devonian to Middle Permian): A review. *Palaeogeography, Palaeoclimatology, Palaeoecology* 531(A): 109259.

Rosa EM, Vesely FF, and França AB (2016) A review on late Paleozoic ice-related erosional landforms in the Paraná Basin: Origin and paleogeographical implications. *Brazilian Journal of Geology* 46(2): 147–166.

Rosa EM, Vesely FF, Isbell JL, et al. (2019) Constraining the timing, kinematics and cyclicity of Mississippian-Early Pennsylvanian glaciations in the Paraná Basin, Brazil. *Sedimentary Geology* 384: 29–49.

Soreghan GS, Sweet DE, and Heavens NG (2014) Upland glaciation in tropical Pangaea: Geologic evidence and implications for late Paleozoic climate modeling. *The Journal of Geology* 122: 137–163.

Vesely FF and Assine ML (2006) Deglaciation sequences in the Permo-Carboniferous Itararé Group, Paraná Basin, southern Brazil. *Journal of South American Earth Sciences* 22: 156–168.

Visser JNJ (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.

Wopfner H (2002) Tectonic and climatic events controlling deposition in Tanzanian Karoo basins. *Journal of African Earth Sciences* 34: 167–177.

Further Reading

Crowell JC (1978) Gondwanan glaciation, cyclothems, continental positioning, and climate change. *American Journal of Science* 278: 1345–1372.

Crowell JC and Frakes LA (1975) The late Paleozoic glaciation. In: Campbell KSW (ed.) *Gondwana Geology: Papers presented at the Third Gondwana Symposium. Australian National University Press, Canberra* 313–331.

Eyles N (1993) Earth's glacial record and its tectonic setting. *Earth-Science Reviews* 35: 1–248.

Fielding CR, Frank TD, and Isbell JL (2008) *Resolving the Late Paleozoic Ice Age in Time and Space*. *Geological Society of America Special Paper*, vol. 441, Geological Society of America, p. 354.

Frakes LA, Francis JE, and Syktus JI (1992) *Climate Modes of the Phanerozoic*. Cambridge: Cambridge University Press, p. 274.

Hambrey MJ and Harland WB (1981) *Earth's Pre-Pleistocene Glacial Record*. Cambridge: Cambridge University Press, p. 1004.

Isaacson PE, Díaz-Martínez E, Grader GW, et al. (2008) Late Devonian-earliest Mississippian glaciation in Gondwanaland and its biogeographic consequences. *Palaeogeography, Palaeoclimatology, Palaeoecology* 268: 126–142.

Isbell JL, Henry LC, Gulbranson EL, et al. (2012) Glacial paradoxes during the late Paleozoic ice age: Evaluating the equilibrium line altitude as a control on glaciation. *Gondwana Research* 22: 1–19.

Lakin JA, Marshall JEA, Troth I, and Harding IC (2016) Greenhouse to icehouse: A biostratigraphic review of latest Devonian-Mississippian glaciations and their global effects. In: Becker RT, Königshof P, and Brett CE (eds.) *Devonian Climate, Sea Level an Evolutionary Events*. vol. 423, pp. 439–464. Geological Society of London Special Publication.

Limarino CO, Césari SN, Spalletti LA, et al. (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.

Montañez IP and Poulsen CJ (2013) The late Paleozoic ice age: An evolving paradigm. *Annual Review of Earth and Planetary Sciences* 41: 629–656.

Rygel MC, Fielding CR, Frank TD, and Birgenheier LP (2008) The magnitude of late Paleozoic glacioeustatic fluctuations: A synthesis. *Journal of Sedimentary Research* 78: 500–511.

Visser JNJ (1997) A review of the Permo-Carboniferous glaciation in Africa. In: Martini IP (ed.) *Late Glacial and Postglacial Environmental Changes: Quaternary, Carboniferous-Permian, and Proterozoic*, pp. 169–191. Oxford: Oxford University Press.

Veevers JJ and Powell CM (1987) Late Paleozoic glacial episodes in Gondwanaland reflected in transgressive-regressive depositional sequences in Euramerica. *Geological Society of America Bulletin* 98: 475–487.

Wopfner H and Jin XC (2009) Pangea Megasequences of Tethyan Gondwana-margin reflect global changes of climate and tectonism in Late Palaeozoic and Early Triassic times—A review. *Palaeoworld* 18: 169–192.