Fjord network in Namibia: A snapshot into the dynamics of the late Paleozoic glaciation

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ABSTRACT
Fjords are glacially carved estuaries that profoundly influence ice-sheet stability by draining and ablating ice. Although abundant on modern high-latitude continental shelves, fjord-network morphologies have never been identified in Earth’s pre-Cenozoic glacial epochs, hindering our ability to constrain ancient ice-sheet dynamics. We show that U-shaped valleys in northwestern Namibia cut during the late Paleozoic ice age (LPIA, ca. 300 Ma), Earth’s penultimate icehouse, represent intact fjord-network morphologies. This preserved glacial morphology and its sedimentary fill permit a reconstruction of paleo-ice thicknesses, glacial dynamics, and resulting glacio-isostatic adjustment. Glaciation in this region was initially characterized by an acme phase, which saw an extensive ice sheet (1.7 km thick) covering the region, followed by a waning phase characterized by 100-m-thick, topographically constrained outlet glaciers that shrank, leading to glacial demise. Our findings demonstrate that both a large ice sheet and highland glaciers existed over northwestern Namibia at different times during the LPIA. The fjords likely played a pivotal role in glacier dynamics and climate regulation, serving as hotspots for organic carbon sequestration. Aside from the present-day arid climate, northwestern Namibia exhibits a geomorphology virtually unchanged since the LPIA, permitting unique insight into this icehouse.

INTRODUCTION
Fjords are long, deep, and narrow glacially carved estuaries that were occupied by outlet glaciers. They play a dramatic role in ice-sheet stability (i.e., drainage and ablation), and sensitive to climate change during icehouse periods, and act as important sediment sinks (Svivitski et al., 1987; Bennett, 2003; Kessler et al., 2008; Briner et al., 2009; Moon et al., 2018). Despite occupying just 0.1% of Earth’s modern oceans, fjords account for >10% of Earth’s organic carbon burial and may thus significantly impact the global carbon cycle (Smith et al., 2015). Fjord morphology and the sedimentary infill more-oveplay an instrumental role in assessing ice-sheet dynamics and climate change (Elmersen et al., 2011; Steer et al., 2012; Normandeau et al., 2019; Bianchi et al., 2020). Despite their present-day abundance across high-latitude continental shelves, fjords from pre-Cenozoic glacial epochs have mostly been inferred from stratigraphic relationships and geological mapping (e.g., Kneller et al., 2004; Tedesco et al., 2016, and references therein), while the existence of paleo-fjord networks have not been rigorously established. The scarcity of ancient fjord morphologies seemingly reflects the intrinsic transient nature of these large-scale geomorphological features (Bianchi et al., 2020), rendering them prone to erosion over geological time scales. In turn, our ability to fully embrace large-scale dynamics of deep-time ice sheets and to assess their sensitivity to climate change is hindered.

We present a geomorphic and sedimentologic analysis of a pristine paleo-fjord network across northwestern Namibia, which formed during Earth’s penultimate and long-lived icehouse, the late Paleozoic ice age (LPIA, 360–260 Ma; Montañez and Poulsen, 2013), and the paleo-ice thickness that once occupied these fjords. Furthermore, we estimate glacio-isostatic adjustment following deglaciation. This work highlights the dynamic nature of the LPIA in southwestern Gondwana and the potential for an under-appreciated deep-time carbon and sediment sink that, if valid, would have had direct climate implications through the impact of Carboniferous–Permian atmospheric CO₂.

RESULTS: FJORD NETWORK IN NAMIBIA
The Kaokoland region of northwestern Namibia is characterized by a prominent bimodal topography where staircase-like plateaus (at ~500 m, ~1000 m, and ~1500 m) separated by NNW-SE–oriented escarpments are deeply dissected by a network of valleys in which modern rivers flow (Fig. 1A). These valleys are 1–5 km in width and 80–130 km in length and have steep, subvertical flanks defining U-shaped cross-profiles (Figs. 1B and 1C) whose depths range between 400 and 1200 m; interfluves occur up to 1.7 km above the thalweg of the Kunene Valley (Fig. 1A). These valleys are carved within hard Archean to Proterozoic lithologies of the Pan-African and Congo craton basement (Goscombe and Gray, 2008).

The valley floors display abundant hardbed glacial erosion features such as striae, scratches, grooves, and crescentic gouges (Fig. 2A) superimposed on whalebacks and roches moutonnées (see also Martin, 1953, 1981; Martin and Schalk, 1959). Scratches and striae are also developed on subvertical walls that flank the U-shaped valleys as well as on the subvertical westernmost (Purros; Fig. 1)
escarpment, indicating westward and northward paleo-ice flows, respectively (Fig. 1A). These valleys ubiquitously preserve remnants of partly eroded glaciogenic sediments of the Dwyka Group, forming the base of the Karoo Supergroup (Figs. 1B, 1C, and 2), whose age in the (restored) neighboring Paraná Basin of Brazil and Aranos and Karasburg Basins of Namibia is bracketed between ca. 299 Ma and ca. 296 Ma (Griffis et al., 2021). These glaciogenic sediments consist here of boulder beds (Fig. 2B) encompassing numerous exotic, faceted, and/or striated clasts and discontinuous ridges, patches, and lenses of poorly sorted conglomerates commonly affected by syn-sedimentary ductile deformation (Figs. 1D and 2C), interpreted as ice-contact morainal banks or ridges that experienced glaciotectonic folding (Dowdeswell et al., 2015). Importantly, glaciogenic sediments encompassing numerous and large (1–3 m) glacial erratics are plastered to the sides of these U-shaped valleys and along the escarpment, in association with scratched and striated valley walls (Figs. 2D and 2E). Glaciogenic deposits occur consistently at a height of 100 m above the valley bottom, which are interpreted as marginal moraines.

Sediments immediately covering the coarse glaciogenic deposits, infilling the valleys (Figs. 1C and 3) and abutting against the striated valley walls (Figs. 1B and 2D), are made up of a 5–20-m-thick shallowing-upward sequence of medium-grained sandstones with rhythmic climbing ripples and sand-mud couplets (Fig. 2F) interstratified with diamicite layers.
characterized by scattered outsized clasts and highlighted by impact structures reflecting ice-rafted debris (Fig. 2G). We interpret this succession to represent ice-proximal subaqueous fan deposits (Dowdeswell et al., 2015), implying a glaciomarine depositional environment.

Facies characteristic of intertidal processes (truncated, leveled, and breached wave ripples; Fig. 2H) were deposited in a postglacial context, 20 m above the striated floors, well below valley interfluves (Figs. 1D and 3). The fjords were subsequently drowned and accumulated non-glaciogenic sedimentary units of the Permian–Cretaceous Karoo Supergroup, ultimately culminating with the Etendeka basalt flows at 130 Ma, whose remnants occur in valley axes topping both the sedimentary succession and valley interfluves (Fig. 1).

The presented glaciogenic sediments and geomorphic features preserved within and along the sides of these U-shaped valleys and escarpments indicate that they were occupied by ice masses during the LPIA. Ice retreat was accompanied by postglacial marine incursion that therefore turned the valleys into fjords; the observed valley network therefore corresponds to the original fjord network, here mapped for the first time in Figure 1A.
**INTERPRETATION: RECONSTRUCTED LPIA DYNAMICS AND ICE THICKNESSES IN NORTHWESTERN NAMIBIA**

The glacial (fjord) geomorphology and its associated sedimentary infill record a snapshot of the dynamics of the LPIA ice masses (Fig. 4). The deep (as deep as 1.7 km) fjord incisions and the presence of numerous and large glacial erratics (e.g., Fig. 2E) transported by ice across major drainage divides imply the presence of an ice sheet largely overflowing the valleys during an early glaciation acme phase (Fig. 4; Martin and Schalk, 1959; Staiger et al., 2005; Kessler et al., 2008; Steer et al., 2012; Livingstone et al., 2017), with ice of at least 1.7 km thick flowing likely westward toward southeastern Brazil. During the subsequent waning phase, an estimated ice thickness of 100 m existed within the valley, as extrapolated directly from the elevation difference between the valley bottom and the highest observed marginal moraine sediments plastered on the valley flanks (Figs. 1 and 3). As indicated by such an ice thickness, topographically constrained, westward-flowing outlet glaciers occupied the valleys, and some (such as the glaciers that occupied the Gomatum and Hoarusib valleys; Fig. 1) bifurcated or fed into a bigger, northward-flowing ice stream (Fig. 4). These outlet glaciers are therefore regarded as having drained a residual ice sheet located to the east of the study area, possibly over the Otavi Range (Fig. 1A) or the Owanbo Basin further east (Miller, 1997). Our findings therefore demonstrate that both a large ice sheet and highland glaciers existed over northwestern Namibia during particular intervals of the icehouse. As is the case for the Quaternary period, however, for which only the last cycle is preserved in the sedimentary and geomorphic record, this acme-waning succession may be representative of only an ultimate ice growth and decay cycle, and perhaps the most important one, of a period that encompassed several cycles that were erased by subsequent ice advance.

Throughout this acme-waning cycle, during ongoing deglaciation and ice-margin retreat, the postglacial sea invaded the valleys and turned them into fjords. Ice-contact fans and deformed morainal banks indicate that sedimentation took place at the front of retreating glaciers during periods of episodic ice-margin stillstands or minor readvance (Fig. 4). Throughout this deglacial cycle, ice-contact and glaciomarine sedimentation was strictly confined within the topographic depression (the fjords) in a setting likely devoid of tectonic subsidence.

Considering such a succession of deglacial events, the sedimentary succession observed infilling the fjords is therefore thought to archive the glacio-isostatic adjustment (Boulton, 1990). Given that glacio-isostatic adjustment operates over a short (10^4 yr) time scale, i.e., well shorter than the temporal resolution available for such a deep-time record, the unravelling of this process is made by analogy between the fjordal deglacial sedimentary succession showcased here and a Quaternary deglacial succession (Dietrich et al., 2018). Thus, we posit that the basal, 20–40 m-thick shallowing-upward parasequence (glaciomarine capped by intertidal facies) is interpreted as a response to falling relative sea level resulting from the glacio-isostatic adjustment. The subsequent drowning (offshore deposits upon intertidal deposits)
therefore likely corresponds to an eustatic rise during which non-glaciogenic sedimentation occurred (Fig. 3). The glacial dynamic that we envisage is largely comparable to the evolution of post-Last Glacial Maximum ice masses over Canada, Norway, and Greenland, whose post-acme recession saw the confinement of outlet glaciers into fjords, which after glacial demise were invaded by postglacial seas (e.g., Syvitski et al., 1987; Dietrich et al., 2018).

**DISCUSSION AND IMPLICATIONS**

**A Preserved LPIA Glacial Landscape:** A Fjord Network Superimposed on Preexisting Plateaus and Escarpments

The preservation of glaciogenic deposits and erosion features indicates that the U-shaped valley network forms an intact relict geomorphic landscape inherited from the LPIA and complements temporally contemporaneous, though smaller, glacial landscapes and paleo-fjords preserved and exhumed (or still sealed) across southwestern Gondwana (e.g., Visser, 1987; Assine et al., 2018; Le Heron et al., 2019; Fallgatter and Paim, 2019). The presence of incised valleys furthermore implies that the plateaus and intervening escarpments were in place when the glacial topography was carved (Fig. 1D), i.e., before the Atlantic (Cretaceous) rifting. Thermochronological studies (Krob et al., 2020) indicate that little denudation occurred after the LPIA prior to the deposition of the Cretaceous Etendeka basalts, whose remnants are preserved on valley interfluves (Fig. 1C). Therefore, modern valley depths and the whole of the Kaokoland landscape, although uplifted (Baby et al., 2020), are virtually unchanged since LPIA times (Martin, 1953). The observed network of valleys, troughs, and escarpments that currently characterizes the Kaokoland therefore corresponds to an extensive, \( \sim 50,000 \text{ km}^2 \) preserved glacial landscape (Fig. 1A). Our showcased example is unique because it represents the sole example of a pristine fjord network and glacial landscape yet described for a pre-Cenozoic glacial epoch. Furthermore, our work highlights the compatibility of both large ice sheets and highland glaciation across the LPIA in a single location (cf. Isbell et al., 2012).

In the absence of recent (middle to late Paleozoic) major tectonic events antecedent to the LPIA in this region, the preexistence of plateaus and escarpments exploited by glacial erosion that carved fjords is interpreted as follows. The NNW-SSE-oriented escarpments correspond to basement sutures delineating the Congo craton to the west and segments of the Kaoko (Pan-African) orogen to the east (Goscombe and Gray, 2008). Because these plateaus and escarpments had already formed prior to the LPIA, we suggest that this existing topography resulted from substantial rejuvenation of the Kaoko orogenic structures after 200 Ma during post-orogenesis exhumation and penepalana

Krob et al., 2020). A differential response of the Congo craton and the Kaoko orogen to vertical tectonic forces that promoted the initiation of Karoo-aged basins over southwestern Gondwana (Pysklywec and Quintas, 1999) is tentatively invoked to explain this topographic rejuvenation. Alternatively, or complementarily, glacial erosion itself through isostatic uplift may have generated the mountainous relief required to create fjords (Medvedev et al., 2008). After the LPIA and until 130 Ma, this paleo-fjord network was progressively buried by the Karoo sediments and Etendeka volcanics, and subsequently exhumed until the present (Krob et al., 2020; Margirier et al., 2019; Baby et al., 2020). Thus, preservation of a pristine paleo-fjord network, in spite of 130 m.y. of uplift and exhumation, is remarkable. Determining the reasons for this exceptional preservation will be a driver of future research.

**Implications for Global Climate Change**

The Namibian paleo-fjords have major implications for understanding the turnover from the late Paleozoic icehouse to a permanent greenhouse state. Delineating the extent and dynamics of ice masses in northwestern Namibia provides more realistic boundary conditions for the scale of glaciation in this region of Gondwana. In particular, the reconstructed paleo-landscape that requires an ice sheet during the acme followed by upland glaciation through the demise of the LPIA could well be explained by the insertion of fjords that promoted dramatic ice-mass loss through drainage and ablation (Bennett, 2003; Briner et al., 2009), in turn triggering abrupt climate change and enhanced ice-sheet sensitivity to climate change, ultimately leading to ice shrinkage (Kessler et al., 2008). Importantly, the Namibian paleo-fjord network together with its South American (Tedesco et al., 2016, and references therein) and South African (Visser, 1987) counterparts could have facilitated the deposition and long-term sequestration of organic carbon analogous to Quaternary fjords (Smith et al., 2015). If this was the case, then burial of large amounts of glacially derived organic material may have contributed to a 10 m.y. nadir in atmospheric pCO\(_2\) in the earliest Permian that defines a paradox, given the loss of major carbon sinks prior to the close of the Carboniferous (Richey et al., 2020). The potential for paleo-fjords of southwestern Gondwana to have played an important role in atmospheric pCO\(_2\) and climate regulation is thus a worthwhile area of further study and carbon-cycle modeling.

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