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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), are sensitive to climate change during icehouse periods, and act as important sediment sinks (Syvitski 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 moreover play an instrumental role in assessing ice-sheet dynamics and climate change (Eilertsen 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 Earths' penultimate and long-lived icehouse, the late Paleozoic ice age (LPIA, 360–260 Ma; Montañez and Poulsen, 2013). Based on the geomorphology of the paleo-fjord network and its glaciogenic sediment infill, we infer the pace of ice-margin fluctuations 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 CO_2.

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-SSE–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 hard-bed 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 striations are also developed on subvertical walls that flank the U-shaped valleys as well as on the subvertical westernmost (Purros; Fig. 1)

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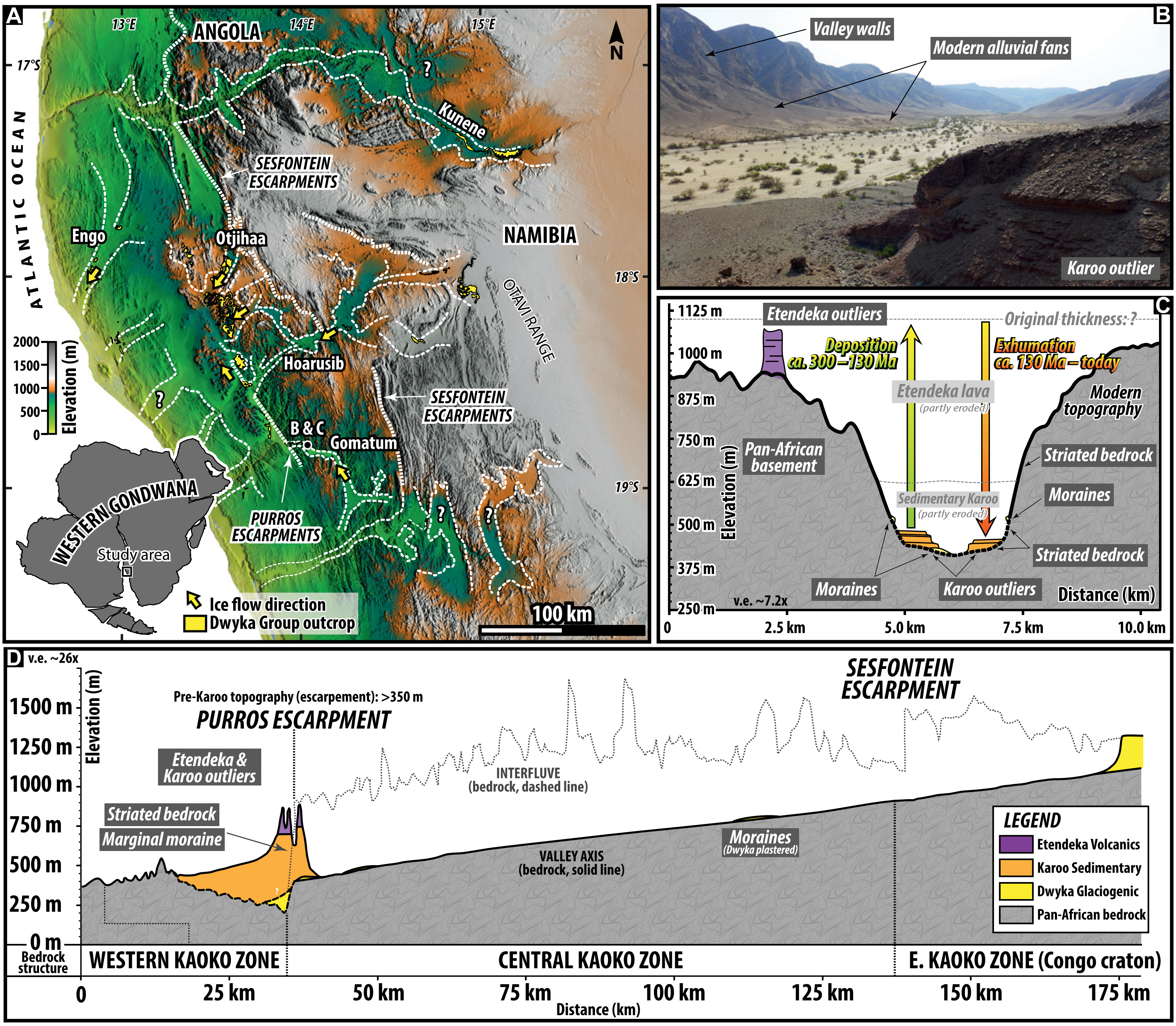

Figure 1. (A) Digital elevation model of Kaokoland (northwestern Namibia) highlighting glacial valleys (white dashed lines). Circle labeled "B & C" represents geographic position of panels B and C. (B) U-shaped Gomatum valley. Note subvertical valley walls at background above modern alluvial fans, and Karoo Supergroup outliers. Valley is ~2 km wide. (C) Topographic transect of U-shaped Gomatum valley, showing position of sedimentary and Etendeka Volcanics successions. (D) Longitudinal profile of Hoarusib valley and its interfluve (dashed line), and Karoo and Etendeka outliers. Note bedrock structures (Goscombe and Gray, 2008). v.e.—vertical exaggeration. Background topography is from SRTM3 (USGS 2006), Shuttle Radar Topographic Mission, 3 Arc Second scene SRTM_n47w053_n54w074, Filled Finished B 2.0, Global Land Cover Facility, University of Maryland, College Park, Maryland, February 2000) available at https://www2.jpl.nasa.gov/srtm/. Map was generated using GlobalMapper® GIS software.

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 synsedimentary 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 diamictite layers

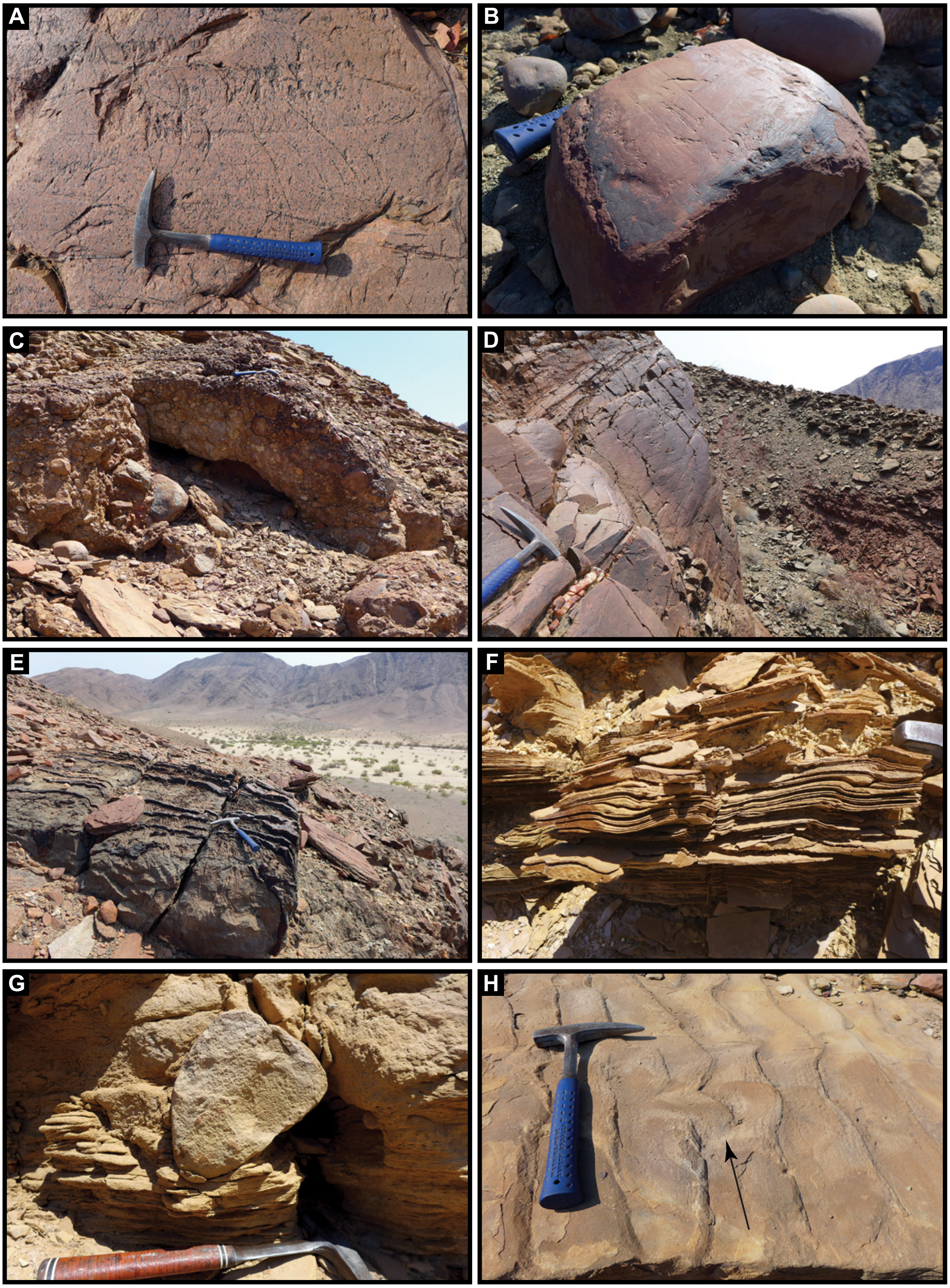

Figure 2. Facies. (A) Striae and crescentic gouges superimposed on roches moutonnées; 18°11′00″S, 12°45′40″E, vertical view. (B) Striated boulder bed covering roches moutonnées; 18°10′46″S, 12°45′45″E, vertical view. (C) Discontinuous and deformed ridge of poorly sorted conglomerate; 18°30′00″S, 12°49′10″E, view toward west. Note hammer near top for scale. (D) Striated vertical wall against which Karoo Supergroup strata abut in background; 18°47′56″S, 13°01′49″E, view toward northwest. (E) Marginal moraine plastered on valley wall, encompassing large erratic boulder; 18°47′53″S, 13°01′45″E, view toward northwest. (F) Rhythmites and sand-mud couplets; 18°29′59″S, 12°49′05″E, view toward south. (G) Lonestone encompassed within sand-sized, rippled sediments; 18°29′59″S, 12°49′05″E, view toward south. (H) Intertidal depositional environment (breached wave ripples) reworking underlying ice-contact fan; 18°29′59″S, 12°49′05″E, view toward south.

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.

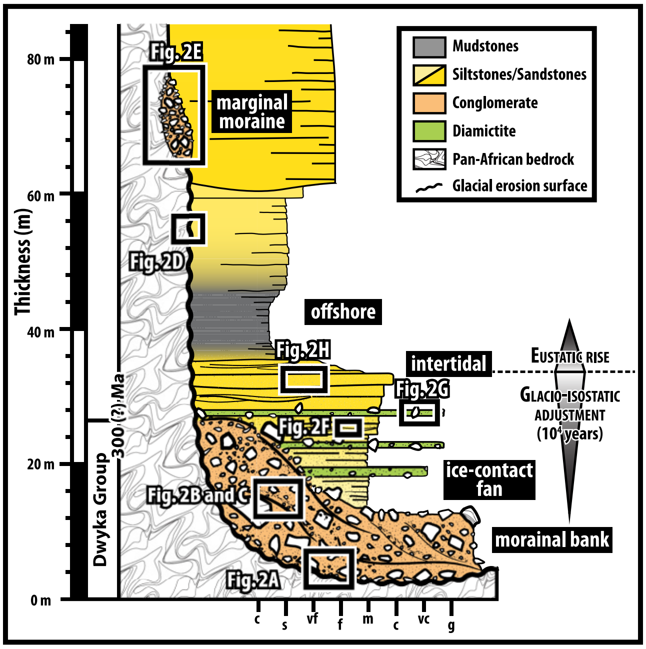

Figure 3. Stratigraphic log of lower fjord infill from the Hoarusib valley (from Karoo Supergroup outliers of Fig. 1D), depositional environments, and relative sea-level changes. c—clay; s—silt; vf—very fine-grained sandstone; f—fine-grained sandstones; m—medium-grained sandstone; c—coarse-grained sandstone; vc—very coarse-grained sandstone; g—gravel.

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 Owambo 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.

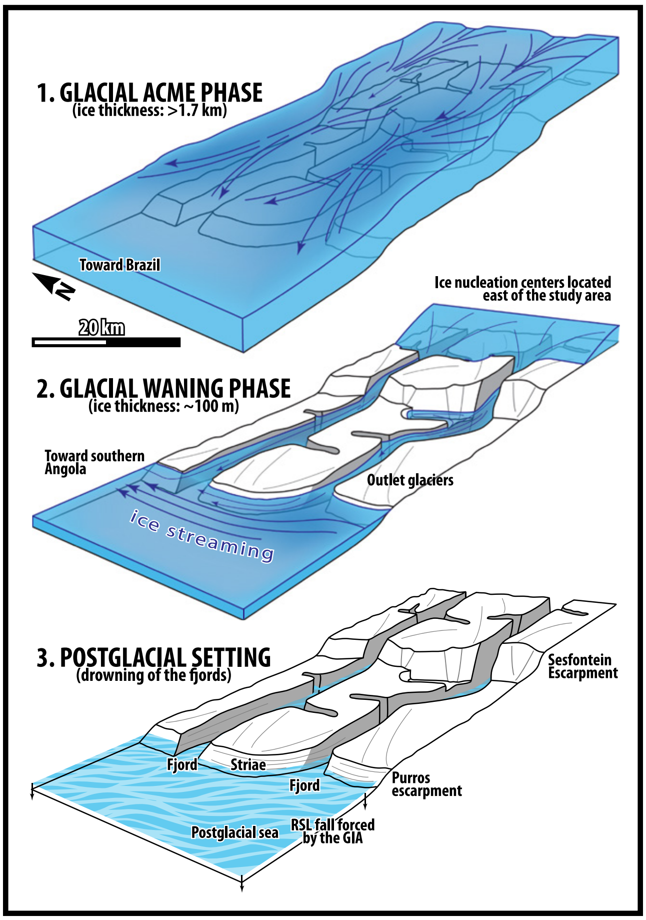

Figure 4. Three-dimensional model of late Paleozoic ice age dynamics on Kaokoland, northwestern Namibia. RSL—relative sea level; GIA—glacio-isostatic adjustment.

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, ~50,000 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 peneplanation (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 CO_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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REFERENCES CITED

Assine, M.L., de Santa Ana, H., Veroslavsky, G., and Vesely, F.F., 2018, Exhumed subglacial landscape in Uruguay: Erosional landforms, depositional environments, and paleo-ice flow in the context of the late Paleozoic Gondwanan glaciation: Sedimentary Geology, v. 369, p. 1–12, https://doi.org/10.1016/j.sedgeo.2018.03.011.

Baby, G., Guillocheau, F., Braun, J., Robin, C., and Dall'Asta, M., 2020, Solid sedimentation rates history of the Southern African continental margins: Implications for the uplift history of the South African Plateau: Terra Nova, v. 32, p. 53–65, https://doi.org/10.1111/ter.12435.

Bennett, M.R., 2003, Ice streams as the arteries of an ice sheet: Their mechanics, stability and significance: Earth-Science Reviews, v. 61, p. 309–339, https://doi.org/10.1016/S0012-8252(02)00130-7.

Bianchi, T.S., et al., 2020, Fjords as aquatic critical zones (ACZs): Earth-Science Reviews, v. 203, 103145, https://doi.org/10.1016/j.earscirev.2020.103145.

Boulton, G.S., 1990, Sedimentary and sea level changes during glacial cycles and their control on glaciomarine facies architecture, *in* Dowdeswell, J.A., and Scourse, J.D., eds., Glacimarine Environments: Processes and Sediments: Geological Society [London] Special Publication 53, p. 15–52, https://doi.org/10.1144/GSL.SP.1990.053.01.02.

Briner, J.P., Bini, A.C., and Anderson, R.S., 2009, Rapid early Holocene retreat of a Laurentide outlet glacier through an Arctic fjord: Nature Geoscience, v. 2, p. 496–499, https://doi.org/10.1038/ngeo556.

Dietrich, P., Ghienne, J.-F., Lajeunesse, P., Normandeau, A., Deschamps, R., and Razin, P., 2018, Deglacial sequences and glacio-isostatic adjustment: Quaternary compared with Ordovician glaciations, *in* Le Heron, D.P., et al., eds., Glaciated Margins: The Sedimentary and Geophysical Archive: Geological Society [London] Special Publication 475, p. 149–179, https://doi.org/10.1144/SP475.9.

Dowdeswell, J.A., Hogan, K.A., Arnold, N.S., Mugford, R.I., Wells, M., Hirst, J.P.P., and Decalf, C., 2015, Sediment-rich meltwater plumes and ice-proximal fans at the margins of modern and ancient tidewater glaciers: Observations and modeling: Sedimentology, v. 62, p. 1665–1692, https://doi.org/10.1111/sed.12198.

Eilertsen, R.S., Corner, G.D., Aasheim, O., and Hansen, L., 2011, Facies characteristics and architecture related to palaeodepth of Holocene fjord-delta sediments: Sedimentology, v. 58, p. 1784–1809, https://doi.org/10.1111/j.1365-3091.2011.01239.x.

Fallgatter, C., and Paim, P.S.G., 2019, On the origin of the Itararé Group basal nonconformity and its implications for the Late Paleozoic glaciation in the Paraná Basin, Brazil: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 531, 108225, https://doi.org/10.1016/j.palaeo.2017.02.039.

Goscombe, B.D., and Gray, D.R., 2008, Structure and strain variation at mid-crustal levels in a transpressional orogen: A review of Kaoko Belt structure and the character of West Gondwana amalgamation and dispersal: Gondwana Research, v. 13, p. 45–85, https://doi.org/10.1016/j.gr.2007.07.002.

Griffis, N., et al., 2021, High-latitude ice and climate control on sediment supply across SW Gondwana during the late Carboniferous and early Permian: Geological Society of America Bulletin, https://doi.org/10.1130/B35852.1 (in press).
Isbell, J.L., Henry, L.C., Gulbranson, E.L., Limarino, C.O., Fraiser, M.L., Koch, Z.J., Ciccioli, P.L., and Dineen, A.A., 2012, Glacial paradoxes during the late Paleozoic ice age: Evaluating the equilibrium line altitude as a control on glaciation: Gondwana Research, v. 22, p. 1–19, https://doi.org/10.1016/ j.gr.2011.11.005.
Le Heron, D.P., Dietrich, P., Busfield, M.E., Kettler, C., Bermanschläger, S., and Grasemann, B., 2019, Scratching the surface: Footprint of a late Carboniferous ice sheet: Geology, v. 47, p. 1034–1038, https://doi.org/10.1130/G46590.1.
Kessler, M.A., Anderson, R.S., and Briner, J.P., 2008, Fjord insertion into continental margins driven by topographic steering of ice: Nature Geoscience, v. 1, p. 365–369, https://doi.org/10.1038/ngeo201.
Kneller, B., Milana, J.P., Buckee, C., and al Ja'aidi, O., 2004, A depositional record of deglaciation in a paleofjord (Late Carboniferous [Pennsylvanian] of San Juan Province, Argentina): The role of catastrophic sedimentation: Geological Society of America Bulletin, v. 116, p. 348–367, https://doi.org/10.1130/B25242.1.
Krob, F.C., Eldracher, D.P., Glasmacher, U.A., Husch, S., Salomon, E., Hackspacher, P.C., and Titus, N.P., 2020, Late Neoproterozoic-to-recent long-term *t–T*-evolution of the Kaoko and Damara belts in NW Namibia: International Journal of Earth Sciences, v. 109, p. 537–567, https://doi.org/10.1007/s00531-020-01819-7.
Livingstone, S.J., Chu, W., Ely, J.C., and Kingslake, J., 2017, Paleofluvial and subglacial channel networks beneath Humboldt Glacier, Greenland: Geology, v. 45, p. 551–554, https://doi.org/10.1130/G38860.1.
Margirier, A., Braun, J., Gautheron, C., Carcaillet, J., Schwartz, S., Pinna Jamme, R., and Stanley, J., 2019, Climate control on Early Cenozoic denudation of the Namibian margin as deduced from new thermochronological constraints: Earth and Planetary Science Letters, v. 527, 115779, https://doi.org/10.1016/j.epsl.2019.115779.
Martin, H., 1953, Notes on the Dwyka Succession and on some Pre-Dwyka Valleys in South West Africa: Transactions of the Geological Society of South Africa, v. 56, p. 37–41.
Martin, H., 1981, The Late Paleozoic Dwyka Group of the South Kalahari Basin in Namibia and Botswana and the subglacial valleys of the Kaokoveld in Namibia, *in* Hambrey, M.J. and Harland, W.B. eds., Earth's Pre-Pleistocene Glacial Record: Cambridge, UK, Cambridge University Press, p. 61–66.
Martin, H., and Schalk, K., 1959, Gletscherschliffe an der Wand eines U-Tales im nördlichen Kaokofeld, Südwestafrika: Geologische Rundschau, v. 46, p. 571–575, https://doi.org/10.1007/BF01803042.
Medvedev, S., Hartz, E.H., and Podladchikov, Y.Y., 2008, Vertical motions of the fjord regions of central East Greenland: Impact of glacial erosion, deposition, and isostasy: Geology, v. 36, p. 539–542, https://doi.org/10.1130/G24638A.1.
Miller, R.M., 1997, The Owambo Basin of northern Namibia, *in* Selley, R.C., ed., Sedimentary Basins of the World, Volume 3: African Basins: Amsterdam, Elsevier Science, p. 237–268, https://doi.org/10.1016/S1874-5997(97)80014-7.
Montañez, I.P., and Poulsen, C.J., 2013, The Late Paleozoic Ice Age: An evolving paradigm: Annual Review of Earth and Planetary Sciences, v. 41, p. 629–656, https://doi.org/10.1146/annurev.earth.031208.100118.
Moon, T., Sutherland, D.A., Carroll, D., Felikson, D., Kehrl, L., and Straneo, F., 2018, Subsurface iceberg melt key to Greenland fjord freshwater budget: Nature Geoscience, v. 11, p. 49–54, https://doi.org/10.1038/s41561-017-0018-z.
Normandeau, A., Dietrich, P., Hughes Clarke, J., Van Wychen, W., Lajeunesse, P., Burgess, D., and Ghienne, J.-F., 2019, Retreat pattern of glaciers controls the occurrence of turbidity currents on high-latitude fjord deltas (Eastern Baffin Island): Journal of Geophysical Research: Earth Surface, v. 124, p. 1559–1571, https://doi.org/10.1029/2018JF004970.
Pysklywec, R.N., and Quintas, M.C.L., 1999, A mantle flow mechanism for the late Paleozoic subsidence of the Paraná Basin: Journal of Geophysical Research, v. 105, p. 16,359–16,370, https://doi.org/10.1029/2000JB900080.
Richey, J.D., Montañez, I.P., Goddéris, Y., Looy, C.V., Griffis, N.P., and DiMichele, W.A., 2020, Influence of temporally varying weatherability on CO_2-climate coupling and ecosystem change in the late Paleozoic: Climate of the Past, v. 16, p. 1759–1775, https://doi.org/10.5194/cp-16-1759-2020.
Smith, R.W., Bianchi, T.S., Allison, M., Savage, C., and Galy, V., 2015, High rates of organic carbon burial in fjord sediments globally: Nature Geoscience, v. 8, p. 450–453, https://doi.org/10.1038/ngeo2421.
Staiger, J.K.W., Gosse, J.C., Johnson, J.V., Fastook, J., Gray, J.T., Stockli, D.F., Stockli, L., and Finkel, R., 2005, Quaternary relief generation by polythermal glacier ice: Earth Surface Processes and Landforms, v. 30, p. 1145–1159, https://doi.org/10.1002/esp.1267.
Steer, P., Huismans, R.S., Valla, P.G., Gac, S., and Herman, F., 2012, Bimodal Plio-Quaternary glacial erosion of fjords and low-relief surfaces in Scandinavia: Nature Geoscience, v. 5, p. 635–639, https://doi.org/10.1038/ngeo1549.
Syvitski, J.P.M., Burrell, D.C., and Skei, J.M., 1987, Fjords: Processes and Products: New York, Springer-Verlag, 379 p., https://doi.org/10.1007/978-1-4612-4632-9.
Tedesco, J., Cagliari, J., Coitinho, J.d.R., Lopes, R.d.C., and Lavina, E.L.C., 2016, Late Paleozoic paleofjord in the southernmost Parana Basin (Brazil): Geomorphology and sedimentary fill: Geomorphology, v. 269, p. 203–214, https://doi.org/10.1016/j.geomorph.2016.06.035.
Visser, J.N.J., 1987, The influence of topography on the Permo-Carboniferous glaciation in the Karoo Basin and adjoining areas, southern Africa, *in* McKenzie, G.D., ed., Gondwana Six: Stratigraphy, Sedimentology, and Paleontology: American Geophysical Union Geophysical Monograph 41, p. 123–129, https://doi.org/10.1029/GM041p0123.

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