# The Glacial Paleolandscapes of Southern Africa: the Legacy of the Late Paleozoic Ice Age

**Pierre Dietrich[1,2,3*], François Guillocheau[1], Guilhem A. Douillet[2], Neil P. Griffis[4], Guillaume Baby[5], Daniel P. Le Héron[6], Laurie Barrier[7], Maximilien Mathian[8], Isabel P. Montañez[9], Cécile Robin[1], Thomas Gyomlai[1,7], Christoph Kettler[6], & Axel Hofmann[3]**

[1] Univ Rennes, CNRS, Géosciences Rennes, UMR 6118, 35000 Rennes, France

[2] Institut für Geologie, Universität Bern, Baltzerstrasse 1+3, Bern, CH 3012, Switzerland

[3] Department of Geology, Auckland Park Kingsway Campus, University of Johannesburg, Johannesburg, 2006, South Africa

[4] Department of Earth and Planetary Sciences, University of California, Davis, California 95616, USA

[5] Physical Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

[6] Department of Geology, University of Vienna, Vienna, Austria

[7] Université Paris Cité, Institut de Physique du Globe de Paris, CNRS, UMR 7154, Paris, France

[8] Université de la Nouvelle-Calédonie, ISEA, EA 7484, BPR4, 98851, Noumea, New Caledonia, France

[9] Department of Earth and Planetary Sciences, University of California, Davis, California 95616, USA

*Correspondence to: Pierre Dietrich (pierre.dietrich@univ-rennes.fr)*

**Keywords:** paleorelief, glacial erosion, Africa, Late Paleozoic Ice Age, paleofjords

## Abstract

The modern relief of Southern Africa is characterised by stepped plateaus bordered by escarpments. This morphology is thought to result from stepwise uplift and ensuing continental-scale erosion of the region as it rode over Africa's mantle 'superplume' following the break-up of Gondwana, i.e. since the mid-Mesozoic. We show in this contribution that the modern topography over large parts of Southern Africa bears glacial relief inherited from the Late Paleozoic Ice Age (LPIA) that occurred between 370 and 280 Myr ago and during which Gondwana – which included Southern Africa – was covered in thick ice masses. Southern Africa hosts vast (up to $10^6$ km²) and thick (up to 5 km) sedimentary basins ranging from the Carboniferous, represented by glaciogenic sediments tied to the LPIA, to the Jurassic-Cretaceous. These basins are separated by intervening regions largely underlain by Archean to Paleoproterozoic cratonic areas that correspond to paleohighlands that preserve much of the morphology that existed when sedimentary basins formed, and particularly glacial landforms. In this contribution, we review published field and remote data and provide new large-scale interpretation of the

geomorphology of these paleohighlands of Southern Africa. Our foremost finding is that over Southern Africa, vast surfaces are exhumed glacial landscapes tied to the LPIA. These glacial landscapes manifest in the form of cm-scale striated pavements, m-scale fields of *roches moutonnées*, whalebacks and crag-and-tails, narrow gorges cut into mountain ranges, and km-scale glacial erosion surfaces and large U-shaped valleys, overdeepenings, fjords and troughs up to 200 km in length. These forms are frequently found covered or filled with coarse-grained, glaciogenic sediments (frontal and lateral moraines, grounding zone wedges, IRD-bearing muds etc.) and whose distribution largely follows the pattern of glacial forms. Importantly, these glacial forms still today control many modern aspects of the surficial processes, such as glacial valleys funnel the modern drainage network of some transects of the main rivers of Southern Africa.

To explain how the glacial landscape has survived for such an extended period, we argue that its preservation and modern exposure may be attributed to burial under substantial layers of Karoo sediments and lavas for approximately 120 to 170 million years, followed by its exhumation since the middle Mesozoic, linked to the uplift of Southern Africa. Owing to strong erodibility contrasts between resistant Precambrian bedrock and softer sedimentary infill, the glacial landscapes have been exhumed and re-exposed. This remarkable preservation allows us to reconstruct the paleogeography of Southern Africa in the aftermath of the LPIA, consisting of highlands over which ice masses nucleated and from which they flowed through the escarpments and toward lowlands that now correspond to sedimentary basins.

Moreover, we propose that in many instances, glacial erosion processes have superimposed an older, non-glacial landsystem whose original form is still expressed in the modern geomorphology of Southern Africa. Notably, some escarpments that delineate high-standing plateaus from coastal plains could be surficial expressions of crustal-scale faults which offset likely operated before the LPIA, and on which glacial processes are marked under the form of striae. Additionally, some hill or mountain ranges may have already existed during LPIA times, potentially reflecting remnants of Pan-African orogenic belts. Whether these features were later reactivated or persisted unchanged since that time is uncertain, but they were shaped by glacial erosion. We further propose that a network of pre-existing alluvial valleys could have existed before the LPIA, possibly formed during an extended period of exhumation and erosion in Southern Africa. These valleys may have later facilitated ice flow from highlands to lowlands, although the extent and configuration of such features remain speculatives.

The exhumed pre-LPIA landforms may in some cases be taken for pediments, pediplains and pedivalleys and interpreted as recording the topographic evolution of Southern Africa after the dislocation of Gondwana during the Mesozoic. Some glacial valleys are also taken for rift structures. We therefore emphasise the need of considering the legacy of LPIA geomorphology when assessing the topographic evolution of Southern African and its resulting modern aspect, as well as inferences about climate changes and tectonic processes.

# 1. **Introduction**

Glacial erosion processes profoundly shape the relief of glaciated continents and continental shelves. For instance, areal scouring, U-shaped valleys and fjords, overdeepenings and cross-shelf troughs that dominate the current morphology of northern North America, Greenland, Scandinavia and Antarctica largely result from glacial erosion occasioned by the expansion and demise of Cenozoic and Quaternary ice sheets (see contributions in this special issue; Sugden and Denton, 2004; Steer et al., 2012; Dowdeswell et al., 2016; Paxman et al., 2018; Couette et al., 2022; Vérité et al., 2021, 2023, 2024). Southern Africa was also covered in continental-scale ice masses, twice over the Phanerozoic during icehouse climate periods, on the occasion of the Ordovician (445-443 Myr ago) and Late Paleozoic ice ages (ca. 370-280 Myr ago, Ghienne et al., 2007; Le Heron et al., 2009; Montañez, 2021). However, considering these ice ages happened hundreds of millions of years ago, it is generally thought that their morphological expression has long been erased. Therefore, long-term evolution of the Southern African topography and the resultant modern-day landscapes are viewed as originating from erosion-sedimentation processes and lithospheric uplifts in response to tectonic and non-glacial climate forcings over the Cenozoic and the Mesozoic (Burke and Gunnell, 2008; Feakins and Demenocal, 2012; Kamp and Owen, 2013; Paul, 2021). The high-standing plateau, pediments and coastal plains separated by intervening escarpments and valleys that characterize the peculiar morphology of Southern African are indeed interpreted as mostly originating from Atlantic rifting and continental break-up processes (Dauteuil et al., 2013; Salomon et al., 2015). Such phenomenon are denudation, fluvial erosion and scarp retreat paced by anorogenic uplifts tied to the polyphase activity of the African mantle plume since 130 Myr (Moucha and Forte, 2011; Braun et al., 2014; Goudie and Viles, 2015; Mvondo Owono et al., 2016; Braun, 2018; Guillocheau et al., 2018; Margirier et al., 2019; Baby et al., 2018, 2020). Yet, many regions of Southern Africa bear glacial erosion surfaces, U-shaped valleys and m- to km-scale landforms that happen to be glacially-scoured paleorelief tied to the Late Paleozoic Ice Age (Lister, 1987; Visser, 1987a; Andrews et al., 2019; Dietrich and Hofmann, 2019; Le Heron et al., 2019, 2022, 2024; Dietrich et al., 2021), suggesting that the contribution of glacial erosion processes in shaping the modern morphology of Southern Africa has largely been underestimated. Indeed, although the morphologic footprint of glacial erosion processes in tectonically-active terrains is generally considered largely transient at geological time scales, prone to be rapidly erased over a few million years (Prasicek et al., 2015), glacial landforms may survive over long geological period if buried and fossilized under sediments in tectonically-quiescent or subsiding areas.

Here we test the idea that some of the current relief and landscapes of Southern Africa are inherited from late Paleozoic glacial erosion processes. For doing so, we present new field and remote sensing geomorphic observations along with a compilation of existing studies and geological and GIS-based mapping, which we integrate with sedimentologic studies to test the origin of landscapes scattered across Southern Africa and apprise their origin (Fig. 1). This combined approach revealed the presence

of vast ($10^3$-$10^5$ km²) relief carved by glacial processes during the Late Paleozoic Ice Age, that sometimes superimposed and re-exploited older relief. Glacial relief is in fact mostly encountered on Archean to Paleoproterozoic terrains forming the three cratons situated in Southern Africa, the Kaapvaal, Zimbabwe and Congo cratons. Our study therefore revives the concept of ancestral exposed land surfaces over Southern African cratons (the 'Gondwana Surface' of King, 1948, 1949, 1982; see also Twidale, 2003; Doucouré and de Wit, 2003; Guillocheau et al., 2018). We also address the preservation of these relict glacial landscapes -how they escaped being erased for over hundreds of millions of years- through an early burial and geologically recent re-exposure. Based on these findings, we also propose a paleogeographic reconstruction of Southern Africa in the immediate aftermath of the LPIA. We discuss the heritage of pre-LPIA non-glacial morphological features and surficial expression of tectonic structures preserved, reactivated or enhanced through glacial erosion and whose imprint is still expressed in the landscapes of Southern Africa, discussing the potential polyphased nature of the pre-Karoo surface. We also emphasise the need to consider ancient glacial erosion morphological features as a major component of the modern-day Southern African landscapes and emphasize the different forms of the sub-Dwyka glacial erosion surfaces and their use to reconstruct Mesozoic and Cenozoic topographic evolution of the African surfaces and to infer post-LPIA base level variations and tectonic processes (Gilchrist et al., 1994; Rouby et al., 2009a; Kamp and Owen, 2013; Mvondo Owono et al., 2016; Baby et al., 2018a, 2018b, 2020a; Grimaud et al., 2018).

# 2. The relief and geology of Southern Africa and the record of ice ages

## 2.1. General physiography

We refer here to Southern Africa as a *ca.* 4.000.000 km² region shared by South Africa, Namibia, Botswana, Zimbabwe, Mozambique, Lesotho and Eswatini (Fig. 1a). The morphology of this region is characterized by high-standing plateaus lying above 1000 m.a.s.l. and frequently above 2000 m.a.s.l. (Fig. 1a). These plateaus are surrounded by steep escarpments leading downward to stepped plateaus (planation surfaces) of lower elevation and ultimately to the coastal plains (see Braun et al., 2014; Guillocheau et al., 2018; Baby et al., 2018a, 2018b, 2020 and references therein for details). The escarpments are dissected by valleys focusing the river drainage network, such as the Orange-Vaal-Fish and Ugab and Kunene rivers flowing to the West in the Atlantic, Zambezi and Limpopo to the East in the Indian Ocean and endorheic system at the center (Baby et al., 2020).

## 2.2. Geological setting and pre-LPIA events

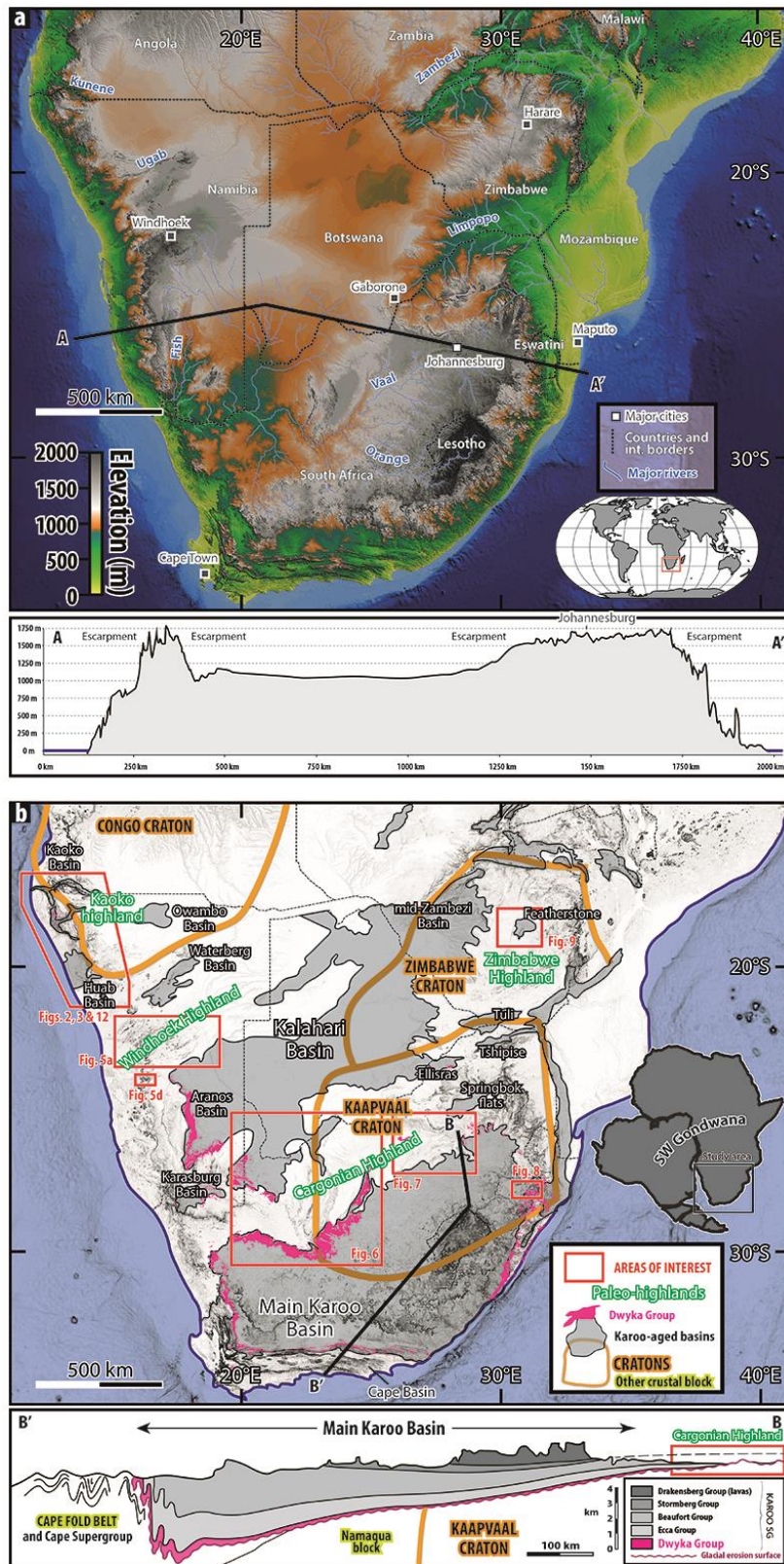



Fig. 1: (a) Modern relief of Southern Africa shown by Digital Elevation Model (DEM) from Shuttle Radar Topographic Mission (https://www2.jpl.nasa.gov/srtm/) along with major river networks, international borders and main cities. The transect highlights the high-standing plateaus. (b) Southern Africa with regions of interest discussed in the text shown by red frame. The Archean to Paleoproterozoic Congo, Kaapvaal and Zimbabwe cratons are evidenced by thick orange lines and Karoo basins are represented by grey shaded area. The glaciogenic Dwyka group is represented by pink colour. The four paleohighlands discussed in the text are evidenced in green. Inset map shows western Gondwana formed by Africa and South America. Transect displays the thickness and sedimentary succession of Main Karoo Basin (MKB) of South Africa, the glaciogenic Dwyka Group in pink, the glacial erosion surface (wavy pink line) at the base of the Karoo Supergroup and the underlying basement structure (cratons vs. accreted terranes). Transect modified after Johnson et al., 1996 and Karoo basins after Catuneanu et al., 1998.

139  Southern Africa is rooted by three Archean to Paleoproterozoic cratons -the Kaapvaal, Zimbabwe and

140  Congo cratons (Fig. 1b)- that amalgamated via younger terranes during orogenic events throughout the

141  Proterozoic (Tankard et al., 2009; Begg et al., 2015; Torsvik and Cocks, 2016). The assembly of

142  Gondwana, which Southern Africa was part of, occurred through the Pan-African orogeny, at the end of

143  the Proterozoic and early Paleozoic. In Southern Africa, this orogeny involved the Congo and Kalahari

144  cratons, the later comprising the already-coalesced Kaapvaal and Zimbabwe cratons, to form the Damara

145  branch of the Pan-African orogeny. The collision between the Rio de la Plata and Congo cratons formed

146  the Kaoko branch, whilst the Gariep and Saldania Belts reflect the Kalahari and Rio de la Plata closure,

147  between ca. 580 and 510 Ma (Begg et al., 2009; Lehmann et al., 2016; Goscombe et al., 2017). This

148  period of acute tectonic activity and its aftermath is reflected by a continuous exhumation since at least

149  600 Ma over orogenic terrains (Krob et al., 2019) and since 1 Ga over the cratons (Baughmann &

150  Flowers, 2019) until ca. 300 Ma, as expressed by thermochronology data. Localised subsidence marked

151  the Cape region from the Cambrian to the lower Carboniferous with deposition of the Cape Supergroup,

152  ca. 3.000 m-thick, deposited likely due to rifting and lithospheric deflection due to subduction-driven

153  mantle flow (Fig. 1b, Theron, 1972; Streel and Theron, 1999; Shone and Booth, 2005; Thamm and

154  Johnson, 2006; Tankard et al., 2009; Fourie et al., 2011, Penn-Clarke et al., 2020). The Cape Basin has

155  then been deformed and inverted during the Cape orogeny and today crops out over ca. 90.000 km² in

156  the Cape Fold Belt at the Southern tip of South Africa. This orogeny, the only orogenic event that

157  affected the rest of Southern Africa throughout the Phanerozoic, initiated during the Permian-Triassic

158  and was induced by the subduction of the Panthalassic Ocean (Hansma et al., 2016).

159  From the Late Paleozoic (Carboniferous) to early Mesozoic, large regions of Southern Africa

160  over which erosion previously prevailed, were then subsiding, which promoted the deposition of thick

161  sediment piles in large sedimentary basins named 'Karoo basins'. These basins lie over the basement

162  and the Cape Basin and occupy vast areas, $10^3$-$10^6$ km², and are named after the Main Karoo Basin

163  (MKB) of South Africa, the thickest (5-6 km), largest (ca. 700.000 km²), and most studied of these

164  basins, investigated since at least the mid-XIXth (see Linol and de Wit, 2016). Together, the Karoo basins

165  of Southern Africa cover an area of ca. 1.600.000 km², among which ca. 800.000 km² are subcrop,

166  mostly covered by younger sediments of the Kalahari Desert (Fig. 1b, Catuneanu et al., 2005; Haddon,

167  2005). The volcano-sedimentary pile that forms these Karoo basins -the Karoo Supergroup- can be up

168  to 5 km thick and ranges in age from Carboniferous to Jurassic (in South Africa and Zimbabwe) or

169  Cretaceous (in northern Namibia) (Stratten, 1977; Smith, 1990; Smith et al., 1993a; Johnson et al., 1996;

170  Catuneanu et al., 2005; Milani and De Wit, 2008; Franchi et al., 2021). Depositional environments

171  within the Karoo Supergroup range, from base to top, from glacial (the Dwyka Group), marine (Ecca

172  and Beaufort groups), continental and aeolian (Stormberg Group) and finally subaerial lava outpouring

173  (Drakensberg and Etendeka Groups) (Fig. 1b; Johnson et al., 1996). Two subsidence mechanisms are

proposed for the Main Karoo Basin of South Africa. Johnson et al. (1997), Catuneanu (2004), Catuneanu et al. (2005) and Isbell et al. (2008) postulated isostatic and flexural deflection tied to the Cape Orogeny. However, as the orogeny likely initiated around the Permian-Triassic boundary, ca. 250 Myr ago, date at which the MKB started to function as a foreland, it has been proposed that the MKB originated from a lithospheric deflection pulled down by subduction-driven mantle flow, dynamic subsidence (Pysklywec and Mitrovica, 1999; Pysklywec and Quintas, 1999; Tankard et al., 2009). This dynamic subsidence was first marked by foundering of rigid crustal blocks along pre-existing crustal structures such as faults and then by long-wavelength subsidence (see details in Tankard et al., 2009). During the late Mesozoic and Cenozoic, after the dislocation of Gondwana responsible for the emission of the Drakensberg Lavas, anorogenic uplift related to Indian and Atlantic oceans break-ups and post-rift mantle dynamics led to the inversion of these sedimentary basins and widespread, continental-scale erosion and planation, as detailed in section 2.4 (Veevers et al., 1994; Lithgow-Bertelloni and Silver, 1998; Moulin et al., 2010; Braun et al., 2014; Linol and Wit, 2016a; Braun, 2018; Guillocheau et al., 2018).

## 2.3. The record of the ice ages

During the Neoproterozoic, four ice ages developed over Southern Africa, among which the two 'Snowball Earth' episodes, and all left behind a wealth of sedimentary archives (Hofmann et al., 2014; Hoffman, et al., 2021). As Pan-African tectonic processes strongly overprinted these deposits in numerous regions, leaving little geomorphic remnants of the glacial episodes preserved over Southern Africa. Later, during the Paleozoic, Southern Africa as part of SW Gondwana experienced two distinct and extensive glaciations, the short-lived Late Ordovician episode (ca. 443-445 Ma, Deynoux and Ghienne, 2004; Ghienne et al., 2007; le Heron and Dowdeswell, 2009; Le Heron et al., 2009) and the protracted LPIA (ca. 370-260 Ma, Isbell et al., 2012, 2021; Montañez and Poulsen, 2013; Griffis et al., 2019a, 2019b, 2021, 2023; Montañez, 2021). Southern Africa preserved these two glacial episodes under the form of glaciogenic sedimentary successions within the Cape and Karoo supergroups, respectively, and/or relict glacial erosion features carved on the bedrock.

### 2.3.1. The Late Ordovician glacial episode

The Ordovician glacial episode is recorded within the Cape Supergroup under the form of a 5-20 m-thick layer of diamictite, corresponding to an unsorted mixture of fine- and coarse-grained sediments, named the Pakhuis Pass Formation, and interpreted as having been deposited under a flowing ice sheet (Thamm and Johnson, 2006; Blignault and Theron, 2010). The Pakhuis Pass Formation is well-known for topping the iconic Table Mountain overhanging the city of Cape Town. A single outcrop displays a striated glacial pavement at the Pakhuis Pass of the Cederberg region (Deynoux and Ghienne, 2004). High-amplitude (50 m) folds are present below the Pakhuis Pass formation and are linked to the activity

of a glacier flowing over waterlain soft sediments (Backeberg and Rowe, 2009; Blignault and Theron, 2010, 2017; Rowe and Backeberg, 2011). No major relict glacial erosion landforms are associated to this glacial episode, and the sedimentary record of the Ordovician glaciation is spatially restricted to the Cape Fold Belt in South Africa (Thamm and Johnson, 2006; Ghienne et al., 2007; Fourie et al., 2010; Meadows and Compton, 2015; Davies et al., 2020).

### 2.3.2. The Late Paleozoic Ice Age (LPIA)

The lowermost sedimentary unit of the Karoo Supergroup, directly lying on the basement, is Carboniferous-Permian in age and has a glaciogenic origin, deposited by ice sheets during the LPIA is the Dwyka group (the pink layer within Fig. 1b; Visser, 1990; Johnson et al., 1996; Cairncross, 2001; Catuneanu et al., 2005; Griffis et al., 2018, 2019a, 2021). The Dwyka Group is extensively present in Southern Africa and crops out or has been identified through drilling in all Karoo basins (Fig. 1b, Smith, 1994; Catuneanu et al., 2005). The Dwyka Group within the MKB is named after the Dwyka River crossing the Cape Mountain in the Western Cape Province (Dunn, 1886; Pfaffl and Dullo, 2023) and its equivalents within other Karoo basins have different, locally-sourced names such as Dukwi, Waterkloof, Gibeon, Malogong or Tshidzi (Haughton, 1963; Smith, 1994; Johnson et al., 1997; Modie, 2002, 2008; Catuneanu et al., 2005; Bordy, 2018). For sake of clarity, we will refer to it as the Dwyka Group throughout the manuscript, independently of the basin considered. The Dwyka Group within the MKB and the Aranos Basin of Namibia is typically several hundreds of meters thick but has been found as thin as a few cm in some other Karoo basins (Visser, 1987a, 1987b, 1997; Isbell et al., 2008; Stollhofen et al., 2008; Miller, 2011; Dietrich and Hofmann, 2019). The lithologies and facies encountered within the Dwyka Group are very diverse, but commonly consist of diamictites, clast-bearing mudstones and conglomerates, interpreted as representing various glacial-related depositional environments, and have been the focus of a plethora of studies (Martin and Schalk, 1959; Crowell and Frakes, 1972; Stratten, 1977; Visser, 1982, 1983, 1987a, 1987b, 1994, 1997; Visser and Kingsley, 1982; Visser and Hall, 1985; Visser and Loock, 1987; Smith et al., 1993b; Brunn et al., 1994; Veevers et al., 1994; Johnson et al., 1996, 2006a; Von Brunn, 1996; Haldorsen et al., 2001; Werner and Lorenz, 2006; Fielding et al., 2008; Isbell et al., 2008; López-Gamundí and Buatois, 2010; Miller, 2011; Linol and Wit, 2016; Dietrich and Hofmann, 2019; Dietrich et al., 2019, 2021; Menozzo da Rosa et al., 2023; Fedorchuk et al., 2023; Fernandes et al., 2023). Glacial striae, grooves and lineations carved by sliding glaciers within soft sediments are common features of the Dwyka Group (Dietrich and Hofmann, 2019; Le Heron et al., 2019). Interestingly, these coarse-grained deposits associated with glacial pavements have long been attributed a glacial origin (Sutherland, 1868, 1870; Dunn, 1886, 1898; Molengraaf, 1898; Cloos, 1915; Wagner, 1915; Du Toit, 1921; Pfaffl and Dullo, 2023). Also, the glaciogenic Dwyka Group and its South American equivalent, the Itararé Group on the other side of the Atlantic Ocean in Southern Brazil, largely led South African geologist Alexander L. Du Toit (1878-1948) and German geologist Henno Martin (1910-1998) to be early supporters of Wegener's theory of continental drift (Du Toit, 1921, 1927,

244    1933, 1937; Martin and Schalk, 1959; Martin, 1961, 1973b, 1973a; see also Haughton, 1949; Milani

245    and De Wit, 2008; Miller, 2011; Linol and de Wit, 2016; Pfaffl and Dullo, 2023)

246        The Karoo basins are separated by cratonic regions over which no or very thin Dwyka and Karoo

247    deposits lie. Wedging out and onlap of Karoo strata against these regions, depositional environments of

248    the Dwyka Group pointing toward a continental ice sheet and the presence of high glacial relief together

249    indicate that these areas correspond to highlands that already existed during the deposition of the Dwyka

250    Group, and hereafter referred to as *paleohighlands* (Fig. 1b, Visser, 1985, 1987a, 1987b, 1997; Smith et

251    al., 1993a; Catuneanu et al., 1998, 2005; Isbell and Cole, 2008). Four paleohighlands exist over Southern

252    Africa: the Kaoko, Windhoek, Cargonian and Zimbabwe, underlain by resistant Archean to

253    Paleoproterozoic basement rocks that form craton and/or shield areas (Fig. 1b). It is over these

254    paleohighlands or on their rims marked by escarpments that most of the glacial landforms and erosion

255    surfaces are observed. These morphological features encompass a range of landform types and shapes

256    ranging from small ($10^{-2-0}$ m: striae and grooves) to intermediate ($10^{0-3}$ m: *roches moutonnées*, cirques,

257    whalebacks, and crag-and-tails), and large scale ($10^{4-6}$ m: fjords, troughs, overdeepenings and area

258    scouring) glacial forms and landsurfaces (Benn and Evans, 2010; Dietrich et al., 2019, 2021). These

259    glacial erosion surfaces have been named 'ancestral glacial pre-Karoo peneplain' (Wellington, 1937),

260    'pre-Dwyka topography' (Du Toit, 1954; von Gottberg, 1970b) or 'Pre-Karoo Surface' (Lister, 1987).

261    It is indeed generally assumed that they were carved during the LPIA, immediately before the deposition

262    of the Karoo Supergroup that started with the glaciogenic Dwyka Group, although their potential pre-

263    LPIA origin has been recognised previously and is discussed below (section 5.1). These glacial erosion

264    forms are the main focus of the present contribution for which a review and new constraints are provided

265    below (section 3 and figures 2 to 8).

266    As no major orogenic event affected the region after the deposition of the Karoo Supergroup

267    (Torsvik and Cocks, 2016), except for the localized Permian-Triassic Cape orogeny, glacial paleorelief

268    have preserved their original shape and orientation and Dwyka strata lie mostly horizontally. Though

269    there is slight and local tilt of the Karoo strata in regions which are attributed to vertical motions of the

270    lithosphere induced by the activity of the African superplume or isostatic processes linked to the Atlantic

271    passive margin.

272        ## 2.4. Post Gondwana-breakup history of the Southern Africa Plateau

273    Following the break-up of Gondwana which is defined by the opening of the Indian and Atlantic oceans

274    in the early Jurassic and early Cretaceous (Frizon De Lamotte et al., 2015; Thompson et al., 2019; Roche

275    et al., 2021; Roche and Ringenbach, 2022), lithospheric movements were mostly vertical in response to

276    the African mantle 'superplume'. Pulses in the activity of this plume led to episodes of swelling and

277    uplift of Southern Africa. This stepwise uplift induced multiple phases (polycyclic) of erosion and

planation of the interior of the continent, including the inversion of the Cape and Karoo basins, retreat of the passive margin escarpments and export of sediments thus produced to the continental margins (e.g., Partridge and Maud, 1987, 2000; van der Beek et al., 2002, Braun, 2010, 2018; Braun et al., 2014; Baby et al., 2018a, 2018b, 2020; Guillocheau et al., 2018; Stanley et al., 2021). By quantifying and budgeting onshore erosion (through geomorphology and thermochronometry) and offshore sediment accumulation (through seismic stratigraphy), sediment fluxes have been reconstructed which together with other inferences e.g., assessment of sediment routing, characterization of kimberlite pipes allowed to reconstruct the post Gondwana-breakup history of the Southern African Plateau, as summarized thereafter.

● During the lower Cretaceous, erosion of the Southern African plateau was spatially restricted and erosion products were funneled eastward through a proto Orange River system in the South and eastward through the proto Zambezi-Limpopo drainage in the North (De Wit, 1999; Moore and Larkin, 2001; Baby, 2017; Ponte, 2018; Baby et al., 2020; Stanley et al., 2021).

● A first period of accelerated denudation of the margins of the plateau followed, at ~150-120 Ma, tied to continental breakup and post-rift erosion of the rift shoulders, as indicated by thermochronometric data (e.g., Gallagher and Brown, 1999; Brown et al., 2002; Tinker et al., 2008b; Kounov et al., 2009, 2013; Stanley et al., 2013, 2015, 2021; Wildman et al., 2016, 2015a; Green et al., 2017). A second pulse of denudation took place at ~100-70 Myr and coincides with acceleration of offshore sediment flux (Walford et al., 2005; Tinker et al., 2008a; Rouby et al., 2009; Guillocheau et al., 2012; Said et al., 2015; Baby et al., 2020). This second pulse of denudation likely resulted from the tilting of the plateau to the west that steepened the slopes across the sub-continent and enhanced a widespread and fast erosion response, notably of the passive margins escarpments (Braun et al., 2014; Baby et al., 2018b; Ding et al., 2019; Stanley et al., 2021). In this context, Wellington (1955) and Braun et al. (2014) highlighted the importance of the erodibility contrast between the soft Karoo sedimentary cover and the underlying harder basement.

● By the end of the Cretaceous, the western side of the plateau was uplifted, as suggested by offshore stratigraphic observations (Aizawa et al., 2000; Paton et al., 2008; Baby et al., 2018b) and onshore kimberlites pipes ages distribution (Jelsma et al., 2004; Braun et al., 2014). This could have resulted in a symmetrical configuration of the Southern African plateau (similar to the modern one), which would have strongly reduced the erosion potential by reducing the slope of a large portion of the sub-continent interior (Braun et al., 2014; Baby et al., 2020; Stanley et al., 2021). This scenario is supported by a drop in offshore sediment flux (Baby et al., 2020), the preservation of crater-lake sediments in ~75-65 Myr kimberlite pipes (Moore and Verwoerd, 1985; Scholtz, 1985; Smith, 1986), and the onset of the Kalahari Basin aggradation (Haddon and McCarthy, 2005).

● Thermochronometric data and offshore sediment fluxes point to limited erosion of the plateau during the Cenozoic (Stanley et al., 2021 and references therein). Recent low-temperature

314 thermochronological data show that Cenozoic erosion focused along the present-day river valleys rather

315 than being broadly distributed as during the Middle Cretaceous (Stanley and Flowers, 2023).

316 Although each pulse of uplift and therefore erosion is thought to be recorded as a planation surface,

317 it has been suggested that very ancient, possibly Jurassic or older, landsurfaces are preserved across

318 Southern Africa, older than the initiation of uplift of Southern Africa and predating the dislocation of

319 Gondwana, and called the 'Gondwana surface' (Du Toit, 1933; King, 1949a, 1949b, 1982; Doucouré

320 and de Wit, 2003).

# 3. Glacial paleorelief of Southern Africa

321

322 In the following section, we describe and review the geomorphology and sedimentary infill of

323 glacial landforms preserved across the paleohighlands of Namibia (the Kaoko and Windhoek highlands,

324 section 3.1 and 3.2), South Africa and Botswana (the Cargonian Highland, section 3.3) and Zimbabwe

325 (the Zimbabwe Highland, section 3.4) (Fig. 1). This is done by combining novel field and aerial/satellite

326 observations, digital elevation model (DEM) from Shuttle Radar Topographic Mission (SRTM,

327 https://www2.jpl.nasa.gov/srtm/) and geological maps analysis as well as an assessment of existing

328 literature. We provide morphostratigraphic transects evidencing the presence of glacially-carved relief

329 and the presence of glaciogenic Dwyka sediments based on geological maps and digital elevation models

330 (fig. 3 to 9).

331 Based on these data, we provide description and interpretation of the glacial paleorelief and the

332 glaciogenic sedimentary rocks hosted within glacial relief wherever present. Possible pre-glacial origin

333 (surficial expression of tectonic structures enhanced by glacial erosion or older non-glacial erosional

334 forms later re-exploited by glacial erosion) is discussed in section 5.1. For each study site, we present

335 evidence for glacial processes (plain pink line on transects on fig. 2 to 9) or, for suspected glacial

336 landscapes, we provide supporting data and discuss their potential glacial origin (dotted pink line on

337 transects on fig. 2 to 9). For these latter cases, additional field-based examinations targeting striated

338 pavements or other evidence for glacial activity would be required to confirm their glaciogenic nature.

339 Erosion and resulting landforms of mountain glaciers that existed locally during the Quaternary will not

340 be considered in this study (Hall and Meiklejohn, 2011; Knight and Grab, 2015).

## 3.1. The Kaoko Highland

341

342 The Kaoko region of NW Namibia is formed by a plateau that stands at ~1000 m.a.s.l. and is located at

343 the boundary between the Congo Craton and the Kaoko branch of the Pan-African orogenic belt (Figs.

344 1 and 2). This plateau is bordered to the west by a succession of stair-like escarpments (that may

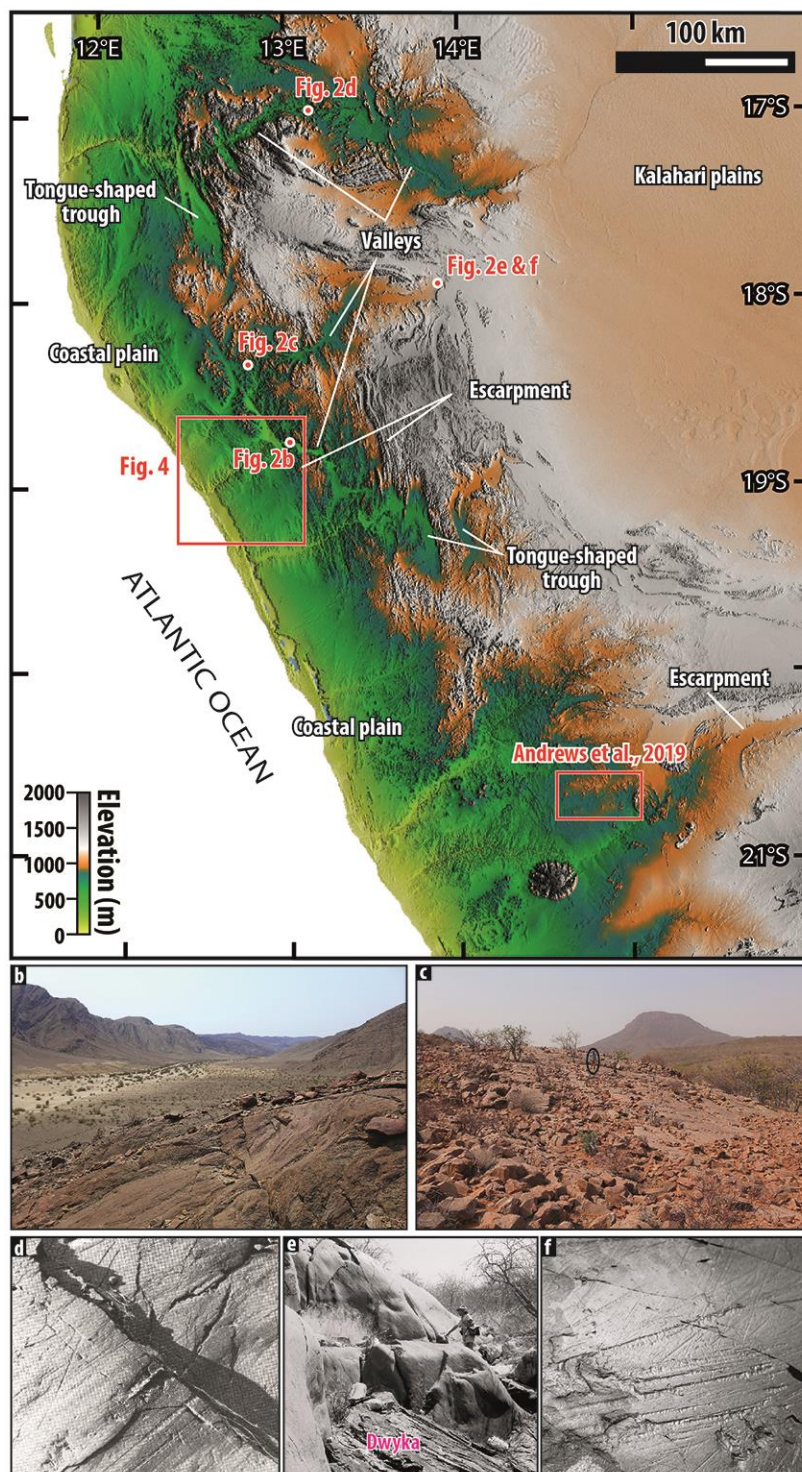
345 correspond to surficial expression of crustal-scale faults, see below) leading to the Atlantic Ocean

346

Fig. 2: (a) DEM of the Kaoko region of Northern Namibia, corresponding to the Kaoko paleohighland. The escarpments, valleys and tongue-shaped troughs discussed in the text are arrowed. Location of the pictures are also indicated. Figure 1b for location. (b) the Gomatum valley corresponds to a fjord carved during the LPIA, later sealed and exhumed in recent times. See Dietrich et al., 2021 for further details. Valley is ca. 2.5 km wide and 550 m deep. (c) A field of roches moutonnées and whalebacks characterized by glacial striae and grooves and polished floors covered in places by boulder pavement, evidencing a westward ice movement. Circled geologist for scale, see Le Heron et al. (2024) for details. (d) Striated floor in the Kunene valley, plucking at the joint shows ice movement from east to west. Picture from Martin, 1961; (e) Glacially polished walls and (f) floor in NE Kaoko. Pictures taken by K.E.L. Schalk, geologist Henno Martin for scale, see Miller (2011).

.

377     through a gently inclined, ~50 km-wide coastal plain. Eastward, the plateau leads toward the low relief

378     of the Kalahari plains. On the northern half of the Kaoko region, a network of E-W-oriented valleys, in

379     which modern rivers flow toward the Atlantic, deeply dissect both the plateau and the escarpments.

380     Tongue-shaped troughs, N-S-oriented, are also incised within the highland or at the feet of the

381     escarpments. These troughs either connect with the river network or are endorheic. The Southern half

382  of the Kaoko region is characterized by a plateau separated on its western side from the coastal plain by

383  a single escarpment.

384

385  In the northern half of the Kaoko Highland, a network of E-W oriented valleys between the

386  Kunene River to the North and the Hoanib River to the South has been interpreted by Dietrich et al.

387  (2021) as an exhumed glacial landscape (Figure 3). These valleys are U-shaped and their floors and

388  subvertical flanks commonly display abundant small-scale hard-bed glacial erosion features such as

389  striae, grooves, whalebacks and *roches moutonnées* (Fig. 2, see also Fedorchuk et al., 2023).

390  Paleovalleys in Angola that cut through the escarpment may also correspond to glacial valleys (Moragas

391  et al., 2023). In places, these glacial erosion features are covered with remnants of glaciogenic sediments

392  of the Dwyka Group (Fig. 3), including frontal and lateral moraines and glaciomarine sediments such

393  as ice-rafted debris scattered in shales (Fig. 2; see also Martin and Schalk, 1959; Dietrich et al., 2021;

394  Menozzo da Rosa et al., 2023), and fig. 16.1 in Miller, 2011). These glaciogenic sediments are typically

395  found abutting against the valley walls (Fig. 3; Le Heron et al., 2024). Based on the relict glaciogenic

396  forms and associated sedimentary rocks, these modern valleys were interpreted as exhumed paleofjords

397  whose modern U-shaped profiles reflects their original glacial morphologies (Dietrich et al., 2021, see

398  also Martin, 1953, 1961, 1968, 1973b, 1981; Martin and Schalk, 1959). As the bottoms of the valleys

399  are frequently covered in recent alluvium, however, it is difficult to observe potential overdeepenings.

400  Moreover, Dietrich et al. (2021) demonstrated that the Purros escarpment separating the high standing

401  plateau to the coastal plain already existed by the LPIA as indicated by glacial striae found on the

402  escarpments (Fig. 2). In this same region, at the downstream end of some of the aforementioned U-

403  shaped valleys are deep and encased bedrock canyons, such as the Purros and Khowarib canyons.

404  Geological maps indicate scattered glaciogenic sedimentary rocks within these canyons (Fig. 4). We

405  therefore suggest that these canyons forming the downstream continuation of exhumed glacial valleys

406  may correspond to gorges similar to those characterizing the base of Quaternary glacial valleys found

407  in almost all terrains that experienced repeated Quaternary glaciations (e.g., Lajeunesse, 2014;

408  Livingstone et al., 2017). Such an interpretation, however, awaits confirmation by further

409  sedimentological and geomorphological characterization. Moreover, the N-S-oriented tongue-shaped

410  troughs, such as the Omarumba-Omutirapo, the Sesfontein and Warmquelle at the head of the glacially-

411  carved Hoanib valley, and the Otjinjange (Fig. 2 and 3) were interpreted as glacial cirques by Martin

412  (1953, 1961, 1968, see also Hoffman et al., 2021 pages 105-106). These troughs are endorheic or connect

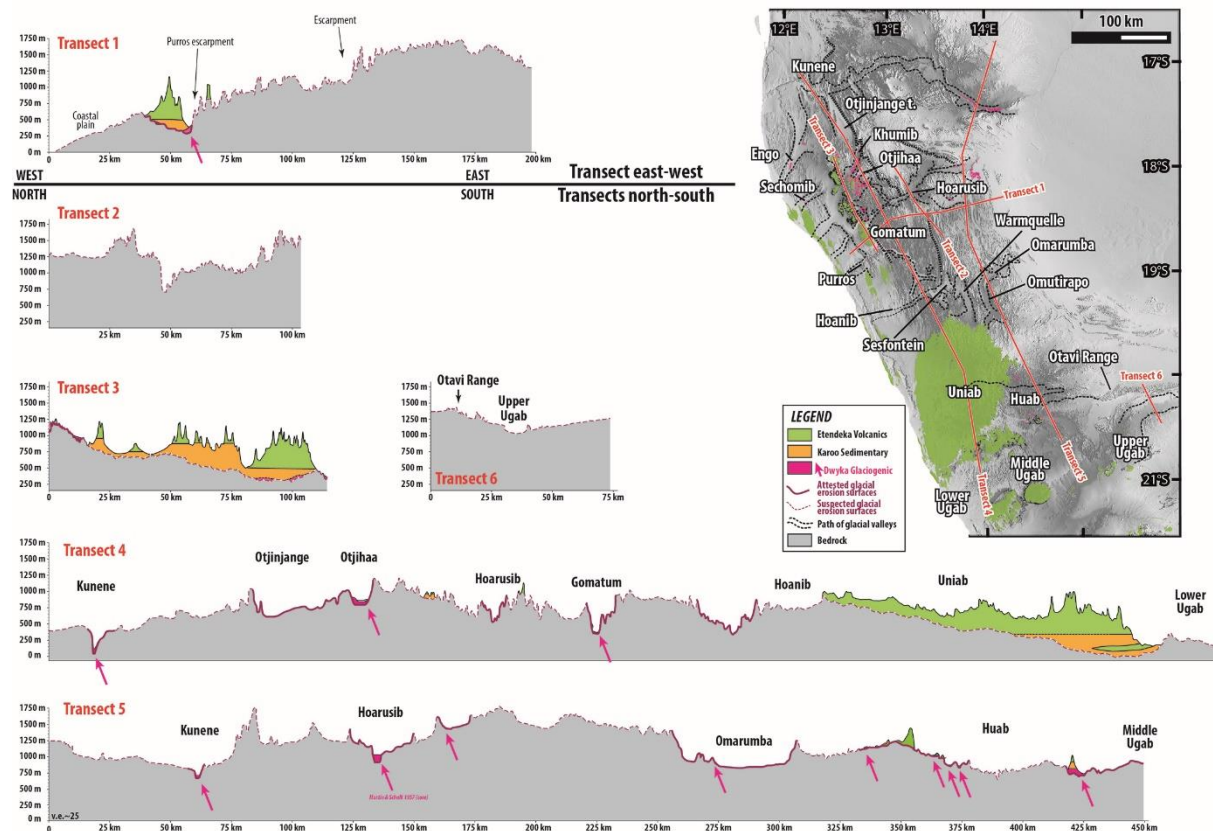
413  to the river systems through narrow ravines encased within mountain reliefs, which might suggest glacial

414  overdeepening and subglacial gorge (Dürst Stucki et al., 2012). Here though, no glaciogenic sediments

415  or morphological features have so far been described or reported, hindering a definitive interpretation.

416  To summarize, the presence of glacial erosion features within the valleys and on the escarpments

417  indicate this relief already existed by LPIA times and was occupied, and then at least partly carved, by

418   glacial ice, although their older origin is discussed below. It remains unclear however whether the
419   interfluves between the glacial valleys are glacial in origin as no trace of glacial erosion has been
420   reported so far, as they might have been lowered down by erosion in post-LPIA times. In both cases
421   however, this network of U-shaped glacial valleys encased within low-relief, high-elevation plateaus
422   would point toward a selective linear erosion *sensu* Benn and Evans (2010). As discussed below, the
423   selective linear erosion may have followed an already existing non-glacial erosional landforms such as
424   alluvial valleys and pediments or weaknesses in the underlying basement geology.

425

426
427   Fig. 3: Geological map indicating the Karoo Supergroup and morphostratigraphic transects across the Kaoko highland,
      highlighting the morphology of the Kunene, Kaoko, Huab-Ugab regions and the associated glacial valleys and troughs.
428   Etendeka lavas are represented in green, non-glaciogenic Karoo sediments in yellow and glaciogenic Dwyka Group in
429   pink, or indicated by pink arrows. Black dashed lines on the map represent outlines of exhumed glacial reliefs and valleys;
430   solid purple lines on morphostratigraphic transects represent glacial surfaces and dashed purple lines represent suspected
      glacial surfaces. Bedrock in grey indicates substrate older than the Karoo Supergroup Note that this colouration is
431   consistently used throughout the manuscript. Fig. 1b for location.

432

433   Further south, in the Huab-Uniab regions (Figs. 2 and 3), outliers of Karoo sediments and
434   Cretaceous Etendeka lavas topping the Karoo succession form the western part of the plateau, and rest
435   on highly uneven basement rocks dipping southward (transects 4 and 5 on figure 3). This volcano-
436   sedimentary pile, reaching 1000 m in maximum thickness to the south, thins toward the north: the basal
437   sedimentary units are present only in the deepest part of these basins, formed by the Huab and Lower

438    Ugab to the south. The pile of sedimentary rocks wedges out northward to the Unihab Basin where
439    Etendeka lava rests directly on the bedrock. Glaciogenic sedimentary rocks are observed resting directly
440    on the bedrock in the Huab Basin (transect 5 on Fig. 3), whereas none is mapped at the interface between
441    the lavas and the bedrock further north (at the border between the Uniab and Hoanib basins, transect 5
442    on fig. 3). Andrews et al. (2019) argued that profiled, elongated hills of the middle Ugab basin are glacial
443    megalineations and megawhalebacks indicative of paleo ice streams (Fig. 2; see discussions in Le Heron
444    et al., 2022, 2024). Based on these observations, we suggest that this uneven bedrock topography
445    covered by glaciogenic sediments corresponds to an exhumed glaciogenic relief. Given its dimension,
446    i.e. at least 150 km wide and 1000 m deep and the presence of geomorphic evidences for ice streams,
447    we interpreted this glacial topographic depression that form the Huab and Lower Ugab basins (Figs. 2
448    and 3), as a cross-shelf trough, as its dimensions match those of Quaternary ones, as reviewed by
449    Batchelor and Dowdeswell (2014). The deepest parts of this large glacially-carved depression were
450    filled by sediments of the lower Karoo Supergroup (Holzförster et al., 2000), which probably promoted
451    preservation of the glaciogenic sediments and landforms. Shallower parts to the north remained
452    protruding until the outpouring of the Etendeka lavas some 165 Myr after the glaciation, which likely
453    eroded and erased all evidence for glacial activity.

454    ## 3.2 The Windhoek Highland

455    The Windhoek highland lies at the center of Namibia and almost reaches 2000 m above sea level,
456    and is composed of Neoproterozoic age rocks which formed during the Damara Orogeny (Fig. 5; Begg
457    et al., 2009). Numerous valleys dissect and radiate outward from the Windhoek highland. Most of these
458    valleys have been interpreted or inferred as exhumed glacial valleys by Martin (1975, 1981, see also
459    Miller, 2011). However, the only firm evidence for a glacial origin is the N-S-oriented Black Nossob
460    River valley which has a U-shaped cross-profile, 7-km wide and 30-m deep, at the bottom of which are
461    remnants of glaciogenic sediments preserved, as indicated by geological maps (transect 2 on Fig. 5).
462    The other river valleys dissecting the Windhoek highland, the upper and lower Swakop and its tributary,
463    the Okahandja-Windhoek and the Kurikaub, as well as southward-flowing Skaap, Usip and Nausgamab
464    and the westward-flowing Kuiseb have also been interpreted as glacial in origin by Martin (1975, 1981).
465    Although these valleys have conspicuous U-shaped cross-profile (Fig. 5c), no glaciogenic sediments or
466    morphologies have been mapped or described in the literature or observed during our own fieldwork
467    within the thalweg of these valleys. A Dwyka outcrop has been described in the vicinity of the
468    Nausgamab valley (Fig. 5, Faupel, 1974), which would witness at least local glacial processes; we
469    however did not locate these deposits during our own field campaign. The Okahandja-Usip is sometimes
470    interpreted as a graben tied to Mesozoic-Cenozoic extensive processes (the Windhoek graben,
471    Schneider, 2004; Waren et al., 2023) whereas the other valleys seem to follow grain of the underlying

472   basement: N-S-oriented valleys follow a network of faults whilst NE-SW oriented valleys follow

473   lithological boundaries. Further field studies are therefore required to confirm a glacial origin of the

474   network of valleys dissecting the Windhoek Highland.

475       Further south, Korn and Martin (1959) and Martin (1959, 1961) indicate that the encased U-shaped,

476   E-W-oriented Tsondab valley that crosscuts the Naukluft Mountains is a glacial valley, as remnants of

477   Dwyka sediments occur within the valley thalweg (Fig. 5d, e and f). Geological map also indicates

478   glaciogenic sediments on the interfluve of the valley whose form would therefore indicate selective

479   linear glacial erosion (Fig. 5d). Therefore, in this case, the valley and its interfluves where glacial

480   sediments are preserved correspond to a glacial relief. The very name 'Naukluft' means 'narrow gorge'

481   in Namibian German which unintentionally reflects the presence of the glacial valley.

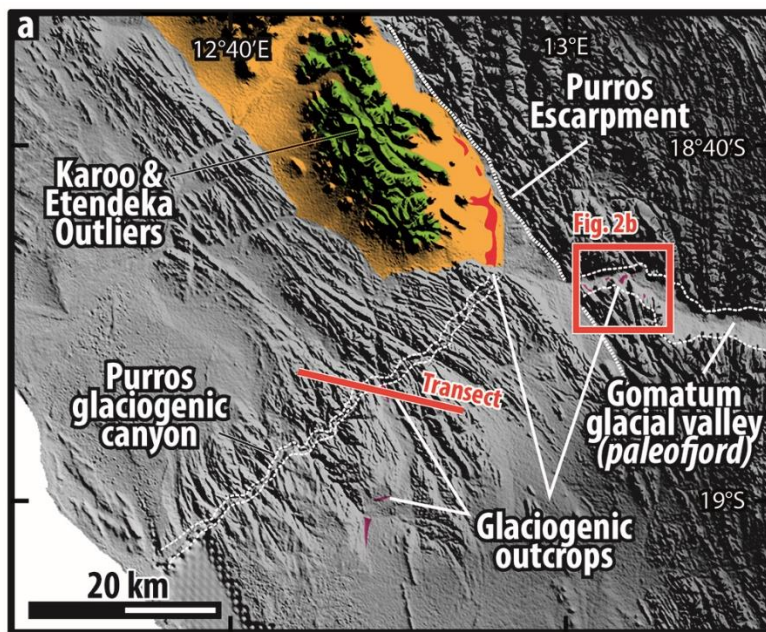
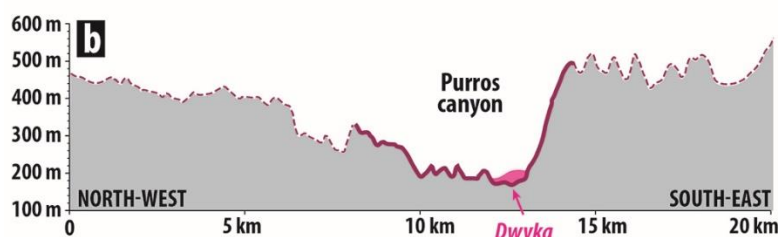
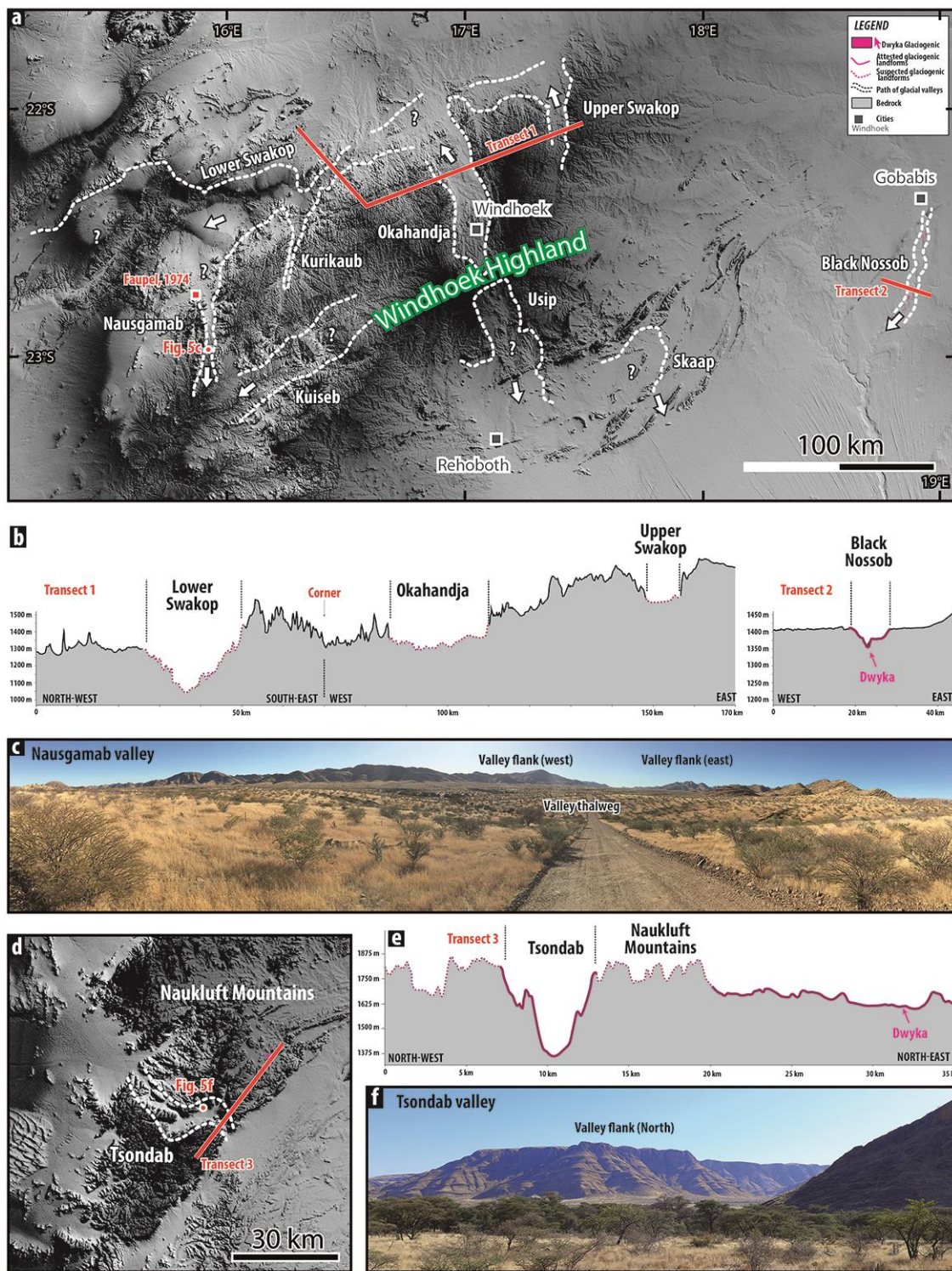



Fig. 4: (a) DEM of the western coastal Kaoko region and (b) morphostratigraphic transect. In the Purros canyon are remnants of glaciogenic sediments, and therefore the canyon is tentatively interpreted here as a relict glacial landform. See Fig. 2 for location.

.

482

483

484

Fig. 5: (a) DEM of the Windhoek highland (central Namibia), (b) their morphostratigraphic transects. And (c) mosaic picture of the U-shaped Nausgamab valley interpreted by Martin (1961) as a potential glacial valley (see also Miller, 2011). Faupel (1974) reported glaciogenic sediments in the vicinity of this valley; (d) DEM of the Naukluft mountain crosscut by the U-shaped Tsondab valley interpreted by Korn & Martin (1959) and Martin (1961) as a glacial valley. (e) morphostratigraphic transect and (f) picture of the Tsondab valley. Fig. 1b for location.

## 3.3. The Cargonian Highland

In South Africa, between the MKB and the Kalahari Basin (Fig. 1), large areas of the Kaapvaal Craton, with the basement formed by Archean to Paleoproterozoic rocks, correspond to exhumed glacial landscapes (Fig. 6, 7 and 8). Portions of the Ghaap plateau and the Kaap-Orange river valleys (Fig. 6) as well as the Highveld, Witbank, Bushveld and Mooi-Harts areas in the Johannesburg-Pretoria region and the Vredefort Dome (Fig. 7) are part of the extensive Cargonian paleohighland. The term 'Cargonian' stands for the contraction between Carboniferous and Gondwanian and was coined by Visser (1987a). The Buffalo-Tugela river valleys, at the southeasternmost edge of the craton, preserve widespread glacial landscapes (Fig. 8). Over these areas, vast erosion surfaces, U-shaped valleys, fjords, inlets, embayments, troughs and canyons were carved by direct glacial action (Visser, 1983b, 1985, 1987a, 1997; von Brunn, 1983, 1994, 1996, Haldorsen et al., 2001; Dietrich and Hofmann, 2019). The preservation of these glacial reliefs spans a large range from poorly-preserved to outstandingly-exposed, whose review based on geological maps, literature and own field investigations is provided below.

The most extensive relict glacial relief occurs in the confluence region between the Orange and Vaal river valleys (Fig. 6). Before joining the Vaal, the Harts River flows in a 20-30 km wide and 280-km long, NNE-SSW-oriented valley, the Kaap valley. DEM and geological maps reveal that the valley cross profile, roughly U-shaped, is asymmetric (transect 2 on fig. 6). The eastern flank of the valley has a shallow slope (1-2%) and is formed by a ridge made up of Archean andesite of the Ventersdorp Supergroup, leading eastward to an uneven relief upon which remnants of Karoo sediments rest. Glaciogenic sediments rest in the valley axis, drape the valley flanks and, on the eastern bank, occur as pockets in paleotopographic lows that develop on the bedrock (Visser and Loock, 1988). Here, the Nooitgedacht glacial pavement records a WSW glacial movement (Fig. 6; Slater et al., 1932; Du Toit, 1954; Visser and Loock, 1988; Master, 2012). The western flank of the valley is steep (slope angles up to 11%), 100-200 m-high and cut into Paleoproterozoic dolomites of the Griqualand West Basin forming the karstified Ghaap plateau, over which no glaciogenic sediments are mapped. The Kaap valley has therefore been interpreted as a relict paleotopography by Visser, (1987a), namely an exhumed glacial valley, and may be interpreted as selective linear glacial erosion *sensu* Benn and Evans (2010). This selective linear erosion may originate from the ice on its southward flow from the Cargonian paleohighland have re-exploited the interface and the lithological contrast between the Griqualand West and the Ventersdorp basins, and possibly an older alluvial valley or pediment (see discussion below). As such, this exhumed glacial valley echoes the similar, although still covered by Karoo sediment, Virginia valley inferred further east (Visser and Kingsley, 1982; Visser, 1987a, 1987b). The Hotazel valley (Fig. 6) and the valleys flowing northwestward from the Cargonian Highland toward the Kalahari basin are also interpreted as relict glacial valleys (Visser, 1987a, 1987b, 1997). The uneven relief east of the Kaap valley onto which glacial pavements developed and glaciogenic sediments occur is

520    interpreted as a relic trough and uneven glacial erosion surface, possibly a landscape of areal scouring.

521    On the contrary, in the absence of glaciogenic sediments on the Ghaap plateau, it remains unclear

522    whether this surface corresponds to a pristine glacial erosion surface or if it has been reworked since

523    (see discussion in De Wit, 2016). Further south, the Prieska embayment is a topographic depression

524    formed between promontories of the Ghaap plateau delineated by steeply dipping (slope angles up to

525    23%), 300-m high escarpments against which the 5-120 m-thick glaciogenic Dwyka Group onlaps and

526    pinches out. The Prieska embayment is interpreted as a relict embayment or glacial overdeepening (see

527    Visser, 1987b) which formed a depocenter for accumulation of the Dwyka glaciogenic sediments

528    (Visser, 1982, 1985). The Orange River itself, downstream the town of Prieska, flows in a valley that

529    existed already in LPIA times and was occupied by ice: while remnants of glaciogenic sediments occur

530    in the valley thalweg, the surrounding bedrock peaks of the Doringsberg and Asbestos ranges tower

531    some 400 m above (transect 1 on fig. 6). This indicates that this segment of the modern Orange River

532    follows an ancient trough occupied, and perhaps amplified (widening and deepening), by ice during the

533    LPIA, later re-exposed by the removal of soft Karoo sedimentary rocks. The Doringsberg and Asbestos

534    range also already existed per se by LPIA times, and had *at least* the height they have today. Further

535    west, Visser (1985) indicates that the northwesternmost edge of the MKB consists of a succession of

536    glacially carved basins, valleys and embayments, such as the Sout River Valley and the Namaqua Basin,

537    as well as promontories, ridges and spurs, like the Kaiing hills, the Poffader Ridge and the Langberg

538    mountains (Fig. 6). Finally, at the westernmost end of South Africa, south of the Orange River, in the

539    Richtersveld region, characterized by a high relief whose pattern seems mostly controlled by basement

540    structure, Reid (2015) postulated that a single valley, N-S-oriented might correspond to a exhumed

541    glacial valley (Fig. 1, Reid, 2015).

542        The area surrounding Johannesburg and Pretoria, including Archean basement of the

543    Johannesburg Dome, Archean-Paleoproterozoic strata of the Witwatersrand and Transvaal supergroups

544    forming the Witwatersrand and Magaliesberg mountain ranges, Southern part of the Paleoproterozoic

545    Bushveld igneous province and the Mesoproterozoic Pilanesberg alkaline ring complex (Fig. 6), is

546    thought to correspond to an exhumed glacial landscape (Wellington, 1937). In this region, direct

547    evidence for glacial processes occur on the interfluve between the Harts and Mooi River valleys. This

548    even surface is characterized by numerous striated glacial pavements interpreted as a surface of glacial

549    erosion, covered in places by sinuous, diamond-bearing sediment ribbons interpreted as eskers (De Wit,

550    2016; Fig. 7). The Harts and Mooi river valleys, incised within gently-, southward-sloping Transvaal

551    Supergroup dolomite, have U-shaped cross-profiles and the Harts River corresponds to the northward

552    extension of the aforementioned Virginia glacial valley (selective linear erosion). East of the city of

553    Johannesburg, the Witbank coal field also constitutes a pre-Karoo glacial irregular topography. In this

554    region, coal seams of the postglacial Vryheid Formation (Ecca Group) either rest conformably on

555    glaciogenic deposits of the Dwyka Group and fill local hollows and depressions, 10-60 m deep, of the

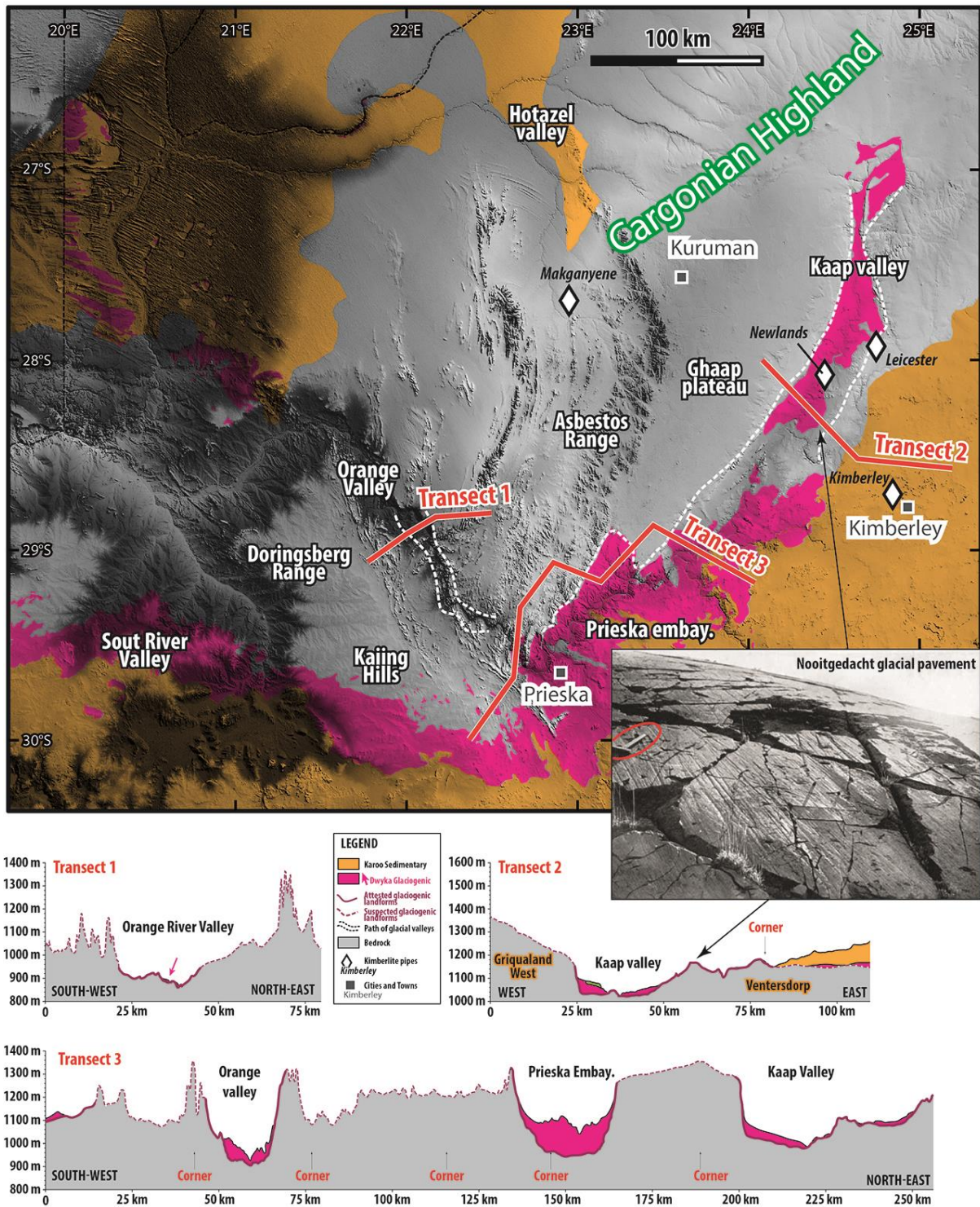



Fig. 6: DEM of the SW Cargonian Highland (central South Africa and Southern Botswana; Fig. 1b for location) and associated geological transects. Widespread Dwyka outcrops in the Kaap valley visible in the landscape interpreted here as an exhumed glacial valley. Diamonds represent kimberlite pipes used for reconstruction in fig. 11. Inset photo: close-up view of the Nooitgedacht glacial pavement (whaleback) in Slater (1932). Circled hammer on the left for scale.

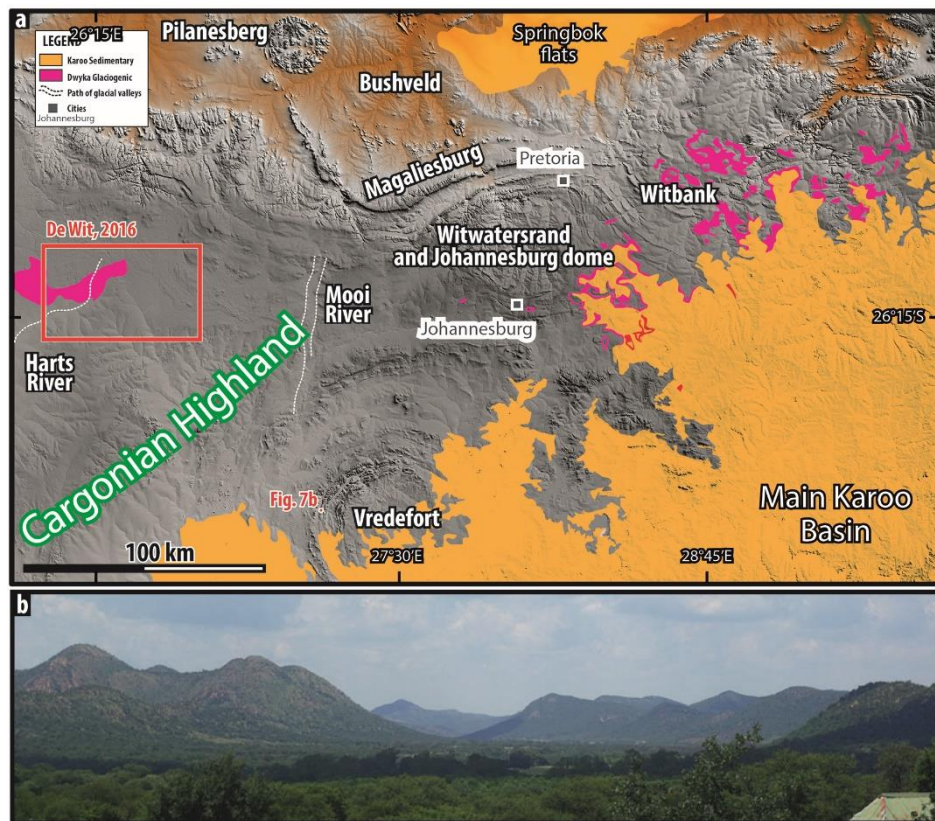



Fig. 7: (a) DEM of the central Cargonian Highland (Johannesburg-Pretoria-Witwatersrand area on the Kaapvaal craton, central South Africa). Fig. 1b for location. The Mooi and Harts river valleys, highlighted by white dashed lines, and the surrounding areas, are interpreted by De Wit (2016) as an exhumed glacial surface. Similarly, the Witbank region to the east, and the Vredefort dome to the south are also interpreted as exhumed glacial surfaces (see text for detail). In between, the Witwatersrand region, the Magaliesburg range, the Pilanesberg dome and the cities of Johannesburg and Pretoria also probably sit on a glacial surface, although further work needs to be done to confirm such a hypothesis. (b) View of the Vredefort dome area where the Vaal river valley shows a U-shaped profile reminiscent of glacial erosion. A small portion of the Vaal River floodplain is seen at centre-right (Fig. 4.5 in Gibson & Reimold, 2015)

559
560

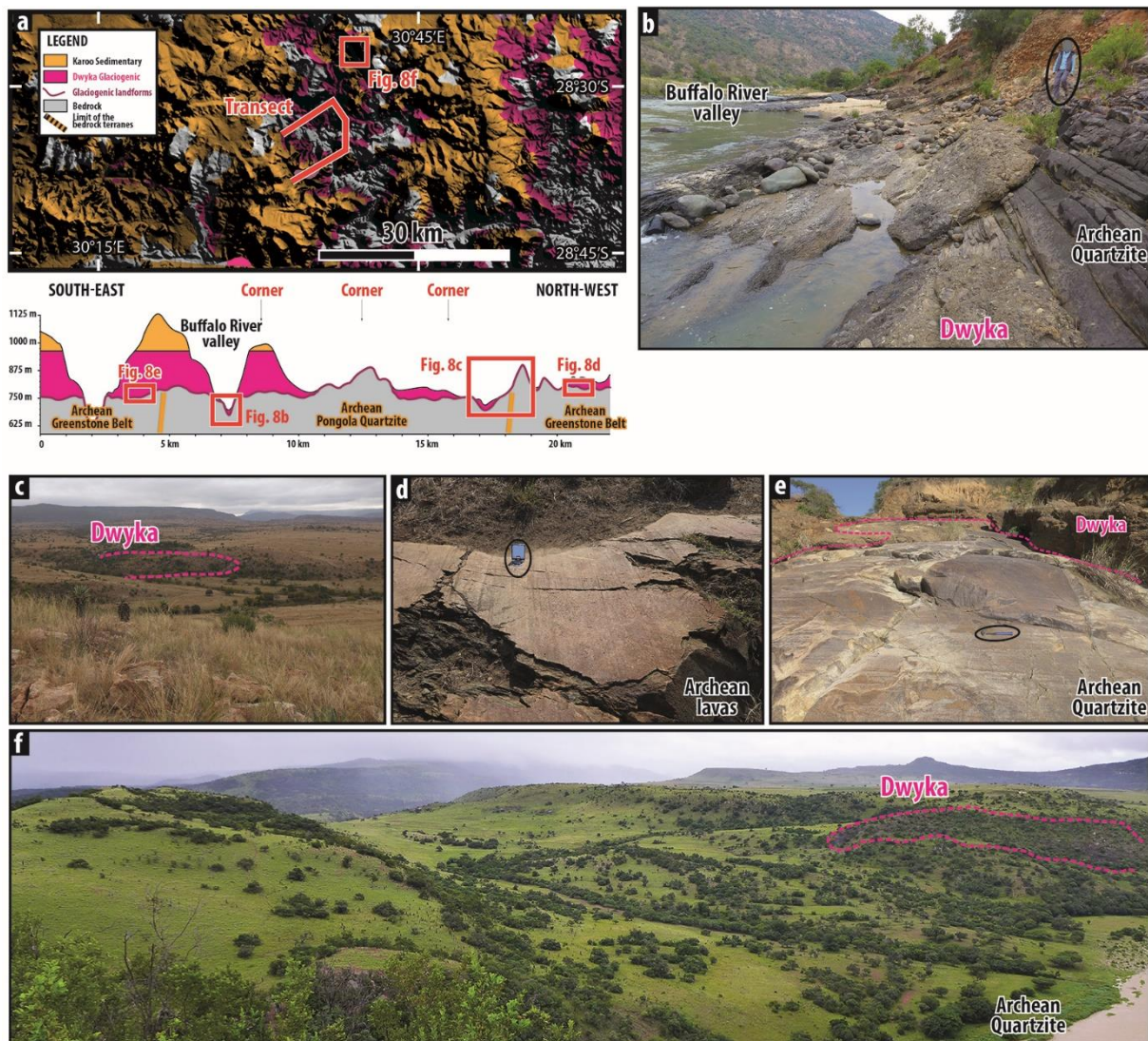



Fig. 8: (a) DEM of the eastern Cargonian Highland (edge of the Main Karoo Basin; Kaapvaal craton, eastern South Africa) and morphostratigraphic transect highlighting the Tugela valley as an exhumed glacial landscape. Fig. 1b for location. See Details in Dietrich & Hofmann (2019). (b) Bank of the Buffalo River exhuming a glacial valley. Stratified, steeply-dipping rock on the right corresponds to Archean Pongola Supergroup quartzite into which steep-flanked relief were carved and upon which coarse-grained deposits corresponding to glaciogenics of the Dwyka Group are plastered. Although the Dwyka sediments are steeply-dipping on the flank of the (paleo)valley, they become horizontal in the river thalweg. Circled geologist for scale; (c) Landscapes of rolling hills corresponding to an exhumed glacial landscape. The relief is carved into Archean Pongola quartzite seen in the foreground: topographic lows preserve remnants of glaciogenic sediments whose bulk has been eroded away by recent erosion, resurrecting the glacial landscape. Striated pavements, such as the ones showcase on fig. 7d and 7e, characterize basement floors. (d) Striated floors carved onto volcanic rocks of Archean greenstone belt, plucking of the joint at the foreground indicate an SSW ice movement. (e) Striated and polished glacial floor exposed in a stream, and showcasing a small-scale roche moutonnée behind the circled hammer, evidencing an ice movement to the SSW. The glacial floor is still covered in place by remnants of glaciogenic sediments. (f) A U-shaped trough, 800 m wide and 100 m deep carved by glacial erosion into Archean Pongola quartzites. Remnants of glaciogenic sediments are still present. Picture from Dietrich & Hofmann (2019).

paleotopography inherited from glacial erosion, or directly lies on the bedrock on paleohighs (Le Blanc Smith and Eriksson, 1979; Le Blanc Smith, 1980; Cairncross and Cadle, 1988; Holland et al., 1989; Götz et al., 2018). The mining of coal seams exhumed the pre-Karoo topography. Further work may reveal that this assemblage of paleo topographic highs and lows may correspond to large-scale *roches moutonnées*, crag-and-tails and lee-side cavity fills, whose co-occurrence would point toward a landscape of areal scouring. Geological maps indicate that small patches of Dwyka deposits also occur in the Johannesburg region. Less direct morphological pieces of evidence suggest that encased ravines and canyons that dissect the cuestas formed by the Magaliesberg mountain range correspond to subglacial canyons carved during LPIA times, as suggested by Wellington (1937). Similarly, Cawthorn et al. (2015) suggested that the Pilanesberg complex forming a 100-500 m high, near-perfect circle of concentric rings of hills surrounding flat terrains of the Bushveld complex has gained its surficial morphology and drainage pattern by the scouring of glacial ice during the LPIA. Here, however, no direct evidence for glacial action (striated pavements, glaciogenic sediments) was found.

Further south, the Vredefort dome, a 2.1 Ga-old meteorite impact structure, displays numerous remnants of glacial erosion processes such as striae, grooves and profiled hills, and patches of glaciogenic sediments as well as far-travelled boulders. The upper Vaal River which crosscuts parts of the impact structure has a U-shaped profile which can be interpreted as the remnant of a glacial valley (Fig. 7b). Together, this indicates that the modern landscape of the Vredefort dome corresponds to a fossil, pre-Karoo glacial landscape (King, 1951; von Gottberg, 1970a; Gibson and Reimold, 2015).

At the easternmost edge of the Main Karoo Basin (Fig. 1 and 8), the removal of less-resistant Karoo strata exhumed LPIA glacial landscapes sculpted into resistant Archean granites, greenstones and quartzites (Dietrich and Hofmann, 2019). The Buffalo River valley follows an inherited 100-140 m deep glacial trough carved into Pongola Supergroup quartzites, abrupt valley flanks (30-60°) made of quartzites are draped by glaciogenic clast-rich diamictites that become horizontal in the valley thalweg (Fig. 8b). In the intervening interfluves, the landscape of rolling hills made of Archean quartzites and greenstone belt volcanics constitute an exhumed landscape of areal scouring as indicated by pockets of glaciogenic sediments in paleotopographic depressions whereas paleohighs are made of basement rocks (Fig. 8c), which often display hard-bed striated pavements (Fig. 8d and 8e). These hills and hollows may therefore represent crag-and-tails and a field of large *roches moutonnées*. An exhumed U-shaped glacial trough, 800 m wide, 100 m deep and 2-km in which remnants of glaciogenic sediments occur has also been observed (Fig. 8f, Dietrich and Hofmann, 2019).

The northern margin of the MKB over the Cargonian Highland hosts glaciogenic Dwyka Group rocks which reflects a threefold segmentation with regard to the paleotopography, as emphasised by numerous authors (Visser, 1987a, 1987c; Brunn et al., 1994; Von Brunn, 1996; Haldorsen et al., 2001a; Johnson et al., 2006; Isbell et al., 2008; Tankard et al., 2009; Dietrich and Hofmann, 2019; Griffis et al., 2019a, 2021): (1) The *basement-high* facies association, deposited on the Cargonian highland, seldom

597 exceeding a few meters in thickness, is represented by massive to poorly stratified diamictites
598 representing subglacial till or esker deposited on land (De Wit, 2016), (2) *The valley-fill facies*
599 *association* (sometimes referred to as the Mbizane Formation), up to 300 m in thickness but
600 characterized by rapid thickness changes, consists of an alternation between massive and stratified
601 diamictites, sandstones and conglomerates, whose deposition was largely controlled by the underlying
602 relief and corrugated topography such as escarpments and valley walls carved into the escarpment
603 delineating the highland. (3) *The platform-basin facies association* (Elandsvlei Formation) is recognized
604 at the centre of the Main Karoo Basin, commonly reaching 800 m in thickness, consisting of alternation
605 between diamictite and mudstones (marine to glaciomarine) units deposited in deep glaciomarine
606 environments represent ancient lowlands.

## 3.4. The Zimbabwe Highland

608 The Zimbabwe highland corresponds to the central region of Zimbabwe and the Zimbabwe Craton (Fig.
609 1 and 9). This highland is floored by Archean greenstone belts, granites and other resistant lithologies
610 that were intruded during the late Archean by the layered complexe of the Great Dyke (Mukasa et al.,
611 1998). Over the basement lies the Karoo Supergroup represented by isolated, ca. 100 m thick
612 sedimentary successions at the base of which glaciogenic sediments are sometimes present (Bond, 1970)
613 and capped by 50-100 m thick Jurassic lavas of the Drakensberg Group (Rhodesia Geol. Map
614 1971:https://zimgeoportal.org.zw). Lister (1987) comprehensively detailed the polyphased, polygenic
615 nature of the 'Pre-karoo Surface', emphasizing the role of glacial and non-glacial erosion processes,
616 pediplanation, folding and structuration that happened before (or during, over basement outliers) the
617 deposition of the Karoo sediments. This pre-Karoo surface, characterizing vast region of Zimbabwe, has
618 then been covered and re-exhumed, and as a result, largely due to erodibility contrast between the
619 basement rocks and the sedimentary cover, '*in many respects the Pre-Karoo landscape of Zimbabwe*
620 *was remarkably similar to that existing at the present day*' (Lister, 1987).
621 The Great Dyke now forms a prominent morphological ridge that stands well above the
622 surrounding basement-floored rocks of central Zimbabwe (Fig. 9). In the Featherstone region, east of
623 the Great Dyke, the Archean Mwanesi Greenstone Belt also forms a prominent ridge against which the
624 Karoo sediments onlap (Fig. 9). Although no glaciogenic sedimentary series have formally been
625 identified on geological maps ('undifferentiated Karoo') and no field study has reported glaciogenic
626 sediments, to our knowledge, the surrounding sedimentary basins encompass evidence for glacial
627 processes (mid-Zambezi: Bond and Stocklmayer, 1967; Bond, 1970; Cabora Bassa: Oesterlen and
628 Millsteed, 1994; Fernandes et al., 2023; Somabula: Moore and Moore, 2006; Tuli: Bordy and
629 Catuneanu, 2003). We therefore posit that the Mwanesi Greenstone Belt and the Great Dyke, formed
630 prominent reliefs during LPIA times as proposed by Lister (1987). This relief, sealed by Karoo rocks,

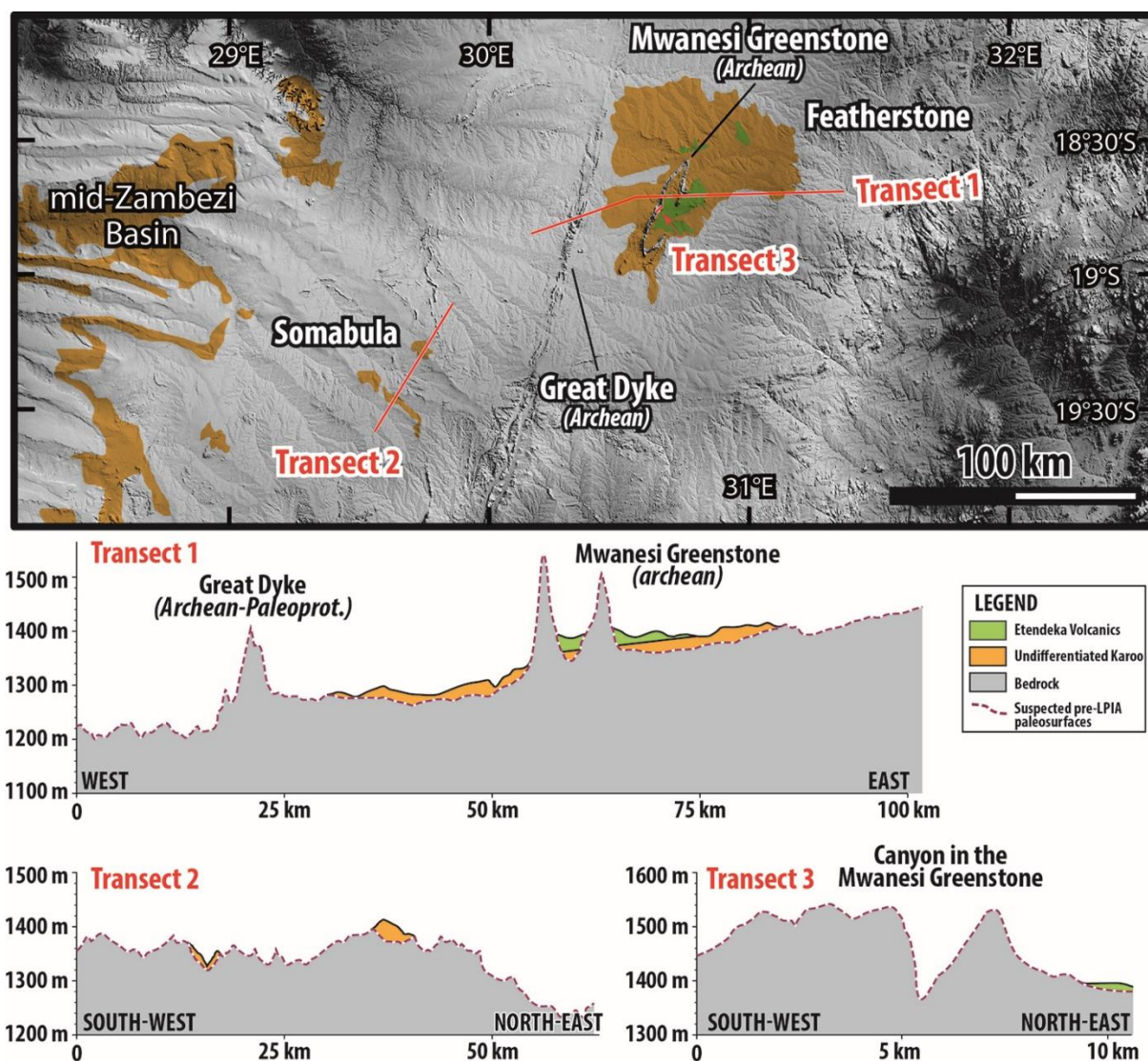
631   is now being exposed by the erosion of the sedimentary rocks and basalts. Furthermore, Moore et al.
632   (2009) suggested that U-shaped valleys, canyons, defiles and ravines (locally named 'poort', meaning
633   gateway in Afrikaan) incised trough this greenstone belt as well as through the Great Dyke within which
634   modern streams flow do not match any structural pattern and cannot have been cut by these streams.
635   Rather, the incision corresponds to exhumed glacial valleys that are now used by streams to cross the
636   topographic barriers (Moore et al., 2009).

637

Fig. 9: DEM of the Zimbabwe Highland (central Zimbabwe) and morphostratigraphic transects across the Great Dyke, the Mwanesi Greenstone Belt and the Somabula region. The reader is redirected to Moore & Moore (2006), Moore et al. (2009) and Lister (1986) for further details. Fig. 1b for location.

638

Further SW, in the Somabula region (Fig. 9), patches of diamond-bearing sediments attributed to Dwyka-filled hollows and topographic depressions are carved into Archean granite (Moore and Moore, 2006). The uneven topography onto which the Dwyka lies could correspond to a glacial topography, possibly partly reworked later during deposition of the Upper Karoo Supergroup. This pre-Karoo glacial landscape should be more degraded where removal of the Karoo cover occurred earlier but at proximity of Karoo outliers, the glacial landscape must be pristine (Lister, 1987). Future field campaigns may reveal glacial features that may provide valuable clues on glacial processes and associated paleolandscapes.

# 4. Synthesis and implications: the glacial paleo landscapes of Southern Africa and their preservation

## 4.1. The glacial paleolandscapes of Southern Africa

We have compiled the landscapes that existed during the LPIA and distinguished the attested ones from the suspected ones at the scale of Southern Africa, as presented under the form of a map on figure 10a. On this map, only valleys with geomorphic-sedimentological evidence for glacial processes are mapped as attested glacial landscapes while their interfluves are mapped as suspected. The main and foremost finding deduced from our analysis is that, over Southern Africa, an area of ca. 71.000 km² consists in attested exhumed glacial landscapes and 360.000 km² correspond to suspected glacial landscapes, which together correspond to ca. 10% of the total area of the region (Fig. 10a). Compared to area floored by a substrate older than the Karoo Supergroup, i.e. older than ca. 300 Myr (ca. 1.700.000 km²), this proportion rises to ca. 25%, as the glacial paleolandscapes are mostly found on the paleohighlands formed by Archean and Paleoproterozoic terrains.

From that map, it appears that some aspects of the modern geomorphology of Southern Africa in fact correspond to ancient, re-exhumed paleolandscapes, the pre-Karoo topography that, as discussed below, may originate from glacial and older, non-glacial erosion processes and surficial expression of basement structures. Notably, some modern escarpments are exhumed paleoescarpments delineating the paleohighlands from the basins, such as in the Kaoko region of Namibia or along the Kaap Valley in South Africa. In other instances, the escarpment is still buried under Karoo sediments, such as in central South Africa and Lesotho and Southern Botswana, deduced from abrupt increase in thickness in Dwyka glaciogenic sediments toward the south, as observed from drilling (Fig. 10a; see Visser, 1987a, 1987b). Moreover, the modern river drainage follows the pattern of inherited glacial relief: the Vaal River in the Kaap Valley and the Orange River in the Orange Valley (South Africa), the Kunene and other NW Namibian rivers in the fossil fjords as well the Ugab, Swakop and Black Nossob rivers and the Zambezi River funneled by the Zambezi escarpment (Zimbabwe). In addition, narrow ravines cut into prominent topographic barriers, such as the Great Dyke and Mwanesi in Zimbabwe, the Magaliesberg and

673 Doringsberg-Asbestos mountains in South Africa and the Naukluft in Namibia, seem to correspond to
674 exhumed glacial gorges.

## 4.2. Paleogeography

676    The map of attested and suspected exhumed glacial paleolandscapes (Fig. 10a), the compilation of
677 sedimentary facies as well as on previous local paleogeographic reconstructions (e.g., Smith, 1984;
678 Lister, 1987; Visser, 1983b, 1985, 1987a, 1987b, 1989, 1992, 1993, 1997; Daly et al., 1989; von Brunn,
679 1991, 1993; Veevers et al., 1994; Smith et al., 1993; Johnson et al., 1996, 1997; Haldorsen et al., 2001;
680 Isbell et al., 2008; Dietrich et al., 2019a, 2021), is used to construct the paleogeographic configuration
681 of Southern Africa at the end of the LPIA (Fig 10b). The threefold morphological pattern is highlighted,
682 with (1) highlands; (2) escarpments into which glacial valleys and fjords are incised, and that lead
683 downstream to (3) sedimentary basins (the Karoo basins) that correspond to the lowland counterparts of
684 the highlands.

685    We propose that the original extent of the Karoo basins was greater than their modern outcrops, as
686 offshore data indicate the presence of Karoo sediments on the modern continental margin. As the
687 offshore Walvis and Lüderitz Basins hosts Karoo sediments (Clemson et al., 1997, 1999; Aizawa et al.,
688 2000; Baby et al., 2018b; 2020), we have extended the Aranos and Kaoko basins further west and
689 connected them to their offshore counterparts. Martin (1973b) states that, as no glacial erratics sourced
690 from the Kaoko have been found in the Parana Basin, the Brazilian Karoo equivalent, a topographic
691 depression or a basin, perhaps oceanic, should have existed between Namibia and Brazil during the
692 LPIA, likely corresponding to the northern realm of the Walvis Basin. And he concludes that
693 '*paleogeographic evidence does not easily fit into the concept of a direct join of the African and the*
694 *South American continental plates*'. Griffis et al. (2021) moreover indicate that only Gondwanan-scale
695 deglacial events permitted the delivery of African-sourced sediments into the Paraná Basin while glacial
696 flows between Africa and South America were hindered, suggesting the presence of substantial
697 topographic barriers such as a basin that would have deflected/hindered ice flows. For the connection
698 between the Aranos and Lüderitz basins and their extent further west, the absence of sediments between
699 these offshore-onshore realms would be explained by their removal through the post Gondwana-breakup
700 functioning of the escarpment passive margin (see section 2.4; Braun et al., 2014; Braun, 2018a), which
701 nowadays delineates the western border of the Aranos Basin. This escarpment therefore postdates the
702 LPIA. In line with this, Visser (1987b) states that '*Towards the west, [the Kalahari] basin probably*
703 *opened into a sea*. Martin (1973b) *favoured the extension of the Kalahari basin into South America as*
704 *goniatites of the same subgenus were found in Uruguay and Namibia in very similar stratigraphic*
705 *positions. Those deposits, however, formed during an interglacial period when large parts of SW*
706 *Gondwana were inundated as a result of sea-level rise*'. About the offshore continuation of the Main
707 Karoo Basin, Karoo sediments have also been found both in the offshore Orange Basin to the west (the

Fig. 10: (a) Synthesis of glacial paleolandscapes at the scale of Southern Africa. Dark pink indicates attested glacial surface and light pink indicates suspected glacial surfaces whose compilation is based on the presence of glacial morphological features (see text for details). Dark grey regions are Karoo basins. Exhumed paleo-escarpments are represented by black bold lines and escarpments still buried under sediments are after Visser, 1987a, 1987b. Light orange region corresponds to surficial sediments of the Kalahari Desert, after Haddon (2005). (b) Proposed paleogeographic reconstruction of Southern Africa at the end of the LPIA. Blue-grey areas represent highlands whose names are written in green, sedimentary basins are represented in dark yellow where attested or light yellow where suspected. Escarpments delineating the highlands from the basins and glacial valleys carved into it are represented as bold solid lines where attested or as dashed lines where suspected (see Visser, 1987a, 1987b). Hills or mountainous regions are also indicated. Region where no data is available mostly corresponds to the Kalahari Desert – see fig. 10a above. Names of glacial valleys and escarpments refer to those discussed in the text to which the reader is redirected for further details.

South Atlantic Sea Arm of Visser, 1987b, sea also Baby et al., 2018b) and in the Durban Basin (Baby et al., 2020) and on the Falklands-Malvinas Islands (the Dwyka-equivalent Fitzroy tillite), whose restored position is off the modern SE coast of South Africa (Hyam and Marshall, 1997; Meadows, 1999; Stone, 2016). Finally, the Karoo sediments may have extended up to the modern coast of Mozambique, as Karoo sediments crop out at the South Africa-Mozambique border, dipping west (Viljoen, 2015) and Karoo sediments and volcanics are observed on seismic imagery at the base of the Limpopo and Zambezi coastal basins (Salman and Abdula, 1995; Ponte et al., 2019; Senkans et al., 2019; Roche et al., 2021; Roche and Ringenbach, 2022).

## 4.3. Preservation of the glacial paleolandscapes

The preservation through geological times of the fossil glacial landscape and their modern exposure (Fig. 10a) is achieved through an early burial -the deposition of the Karoo Supergroup- in order to preserve landforms from post-glacial erosion and a geologically recent re-exposure achieved by stripping off this sedimentary cover. We provide on figure 11 a synthesis of the burial-exhumation trends of these fossil glacial landscapes on the basis of data available in the literature such as sedimentological, stratigraphic, magmatic, geomorphologic and thermochronometrical data as well as other available information for constraining uplift and erosion, such as the location, ages and exhumation history of kimberlite pipes and erosion-deposition budgets (see section 2.4). The burial-exhumation history is given for the Kaoko paleohighland (Fig. 11a), the Southern margin of the Cargonian paleohighland (Fig. 11b) and the Zimbabwe paleohighland (Fig. 11c). To reconstruct the burial-exhumation history using thermochronometric data -such as apatite and zircon fission tracks as well as U-Th-Sm)/He analyses on apatite- geothermal gradients of 25°C.km$^{-1}$ are assumed for the Kaoko, and Zimbabwe and Cargonian highlands (Mackintosh et al., 2019; Macgregor et al., 2020). As an example, a warming/cooling of 100°C would indicate a burial/exhumation of 4 km. The history proposed here spans the whole period between the LPIA (ca. 300 Ma) and today. Given the discrepancies in data availability between these three regions, the level of details is significantly different and the stages/ages highlighted may not be equivalent. Also, significant discrepancies may exist between different thermochronometrical-kimberlites pipes-sediment budgets datasets for a single region, leading to profound differences in inferred rate, timing and amplitude of burial-exhumation processes (see also discussion in Chardon, 2023). For example, over the Kaoko highland (Fig. 11A), thermochronometric data from Margirier et al. (2019) and Raab et al. (2005) indicate different times when these rocks passed through the temperature range of 120-60°C. The former suggests significant cooling of approximately 200°C between 130 and 100 Ma while the later indicates cooling of about 120°C between 100 and 65 Ma. Over the Cargonian Highland of South Africa (Fig. 11b), Wildman et al. (2016) postulate a sustained and continuous cooling of 50°C since the LPIA until today while Baughman and Flowers (2019) and Flowers and Schoene (2010) indicate an early warming (50-80°C between 300 and 250 Ma) later followed by a 80-100°C cooling around 100 Ma. Altogether however, the combination of the

different datasets points toward a twofold burial-exhumation history broadly common to the three highlands, characterized by an early burial (the deposition of the Karoo sediments in the immediate aftermath of the LPIA and later volcanics until 183 Ma, date of the outpouring of the Drakensberg LIP) and a late exhumation tied to the polyphase activity of the African Superplume (Fig. 11).

In the following, we list the parameters that are necessary for this relict pre-Karoo topography, and the glacial landforms, to be preserved and cropping out:

(i)  The glacial erosion surfaces were covered by (Karoo) sediments not long after their carving which protected them from erosion and further obliteration.

(ii)  The sedimentary piles that covered these surfaces were then eroded away by post-LPIA erosion, in order to expose the relict surfaces (Fig. 1b). Over paleo-highlands and/or area characterized by weak subsidence, limited sedimentary accumulation and re-exposed glacial surface contrast with the center of the Karoo basins where the sedimentary piles are too thick to have been eroded away in recent times. At the other end of the spectrum, areas that experienced early exhumation, because having been covered by only thin sediments, not covered at all, or experienced early tectonic uplift, have been eroded away and overprinted by more recent erosion processes. Lister (1987) summarized this concept as '*Older landsurfaces [...] are thereby buried or fossilized until such time as the overlying sediments or lavas are removed, thus permitting the older landsurfaces to become subaerial once again. Modern erosion quickly destroys the resurrected landsurfaces so that their original form is most accurately seen in proximity to their contact with the cover*'. In fact, the preservation of delicate striae and other micro- to meso-scale erosional forms requires an almost immediate burial and a very recent exhumation which led to their re-exposure.

(iii)  The erodibility contrast between the weathering-resistant Archean to Proterozic basement (metamorphic and magmatic-granitic rocks) into which the glacial reliefs developed, and the weaker, prone to erosion sedimentary (prone to mechanic erosion) and volcanic (prone to weathering) cover likely played a significant role in rejuvenating these surfaces (see also Braun et al., 2014). Accordingly, post-LPIA erosion was likely significantly slowed down when reaching the basement that therefore acted as a structurally-controlled erosion surface.

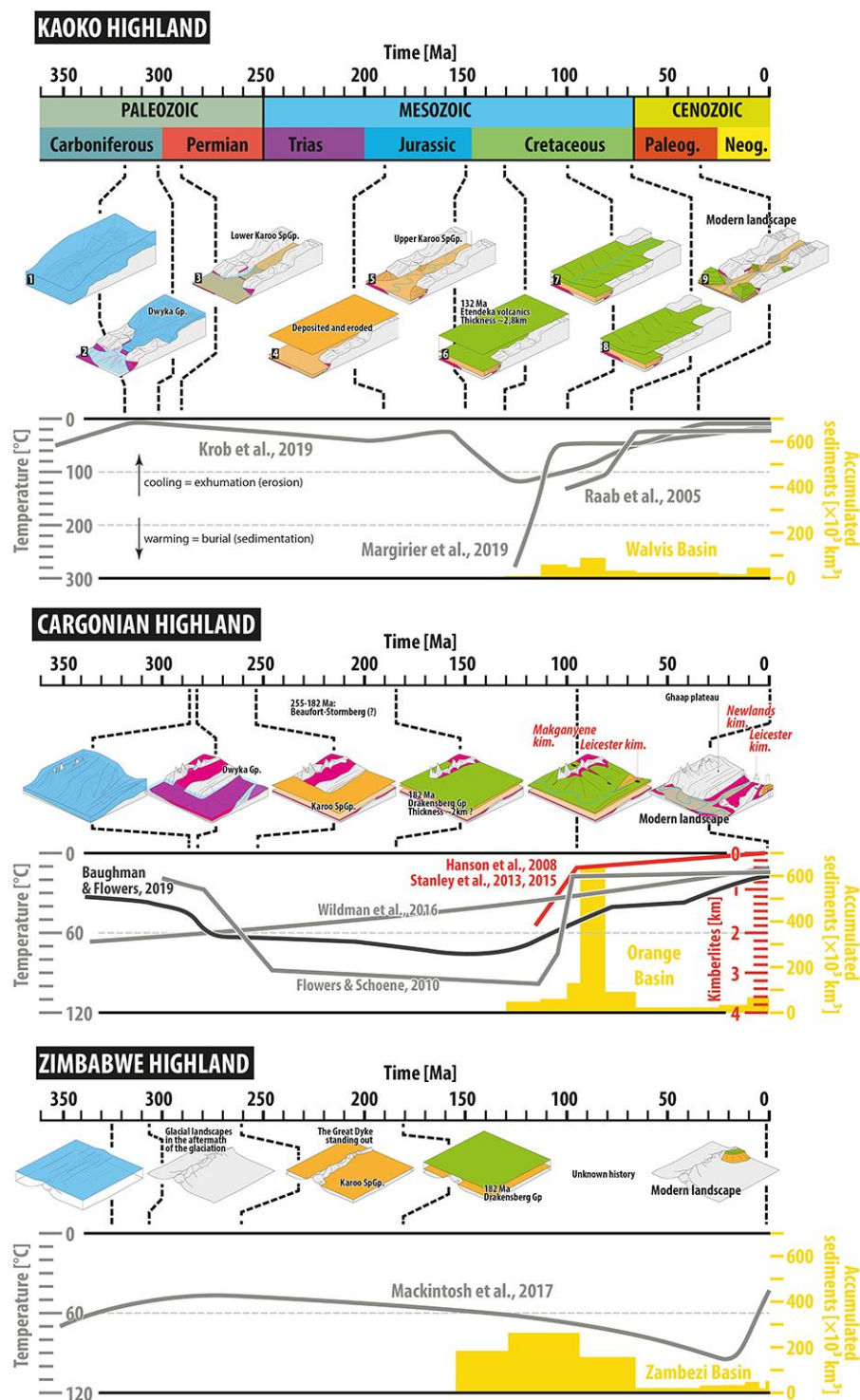



Fig. 11: Burial-exhumation history models the Kaoko (Fig. 2), Cargonian (Fig. 6) and Zimbabwe (Fig. 9) highlands. Thermochronological inferences are provided in the graphs, exhumation evidenced from kimberlites for the Cargonian Highlands are displayed in red and sediment volume accumulated on the continental margins are showcased in yellow. Raab et al. (2005), Krob et al. (2019) and Margirier et al. (2019) for the Kaoko; Stanley et al. (2015, 2019, 2021) and Wildman et al., 2015 for central south Africa and Mackintosh et al. (2017) for central Zimbabwe.

## 4.4. Implication for quantifying finite uplift of Southern Africa

The preservation of relief inherited from the LPIA may provide valuable clues about their paleoaltitudes and local finite uplift of the lithosphere since the late Paleozoic. Indeed, the paleofjords of Namibia bear sedimentological evidence for coastal, and sometimes even intertidal, environments (Dietrich et al., 2021), providing the paleo zero altitude. The presence of such coastal-intertidal sediments in the Hoarusib valley (Dietrich et al., 2021), today observed at 300-400 meters above modern sea level at ca. 50 km away from the modern shoreline, indicate that the finite uplift of this region since the Late Paleozoic was of a similar value. Within this same Hoarusib valley, but 120 km upvalley, near the town of Opuwo, glaciomarine i.e. submarine sediments lie today at 1200 m.a.sl., indicating there an uplift of at least 1200 m since the LPIA, and therefore also a differential uplift of ca. 7 m.km-1 between these two localities. This would apply to any region where sediments indicating the altitude zero would be found. Secondly, the presence of coastal sediments within paleovalleys indicate that their interfluve immediately after the LPIA stood at an altitude corresponding to *at least* the elevation difference between them and the valley thalwegs, considering that the interfluves may have been eroded and levelled down since then.

# 5. Discussion

## 5.1. Pre-LPIA evolution: existing reliefs amplified by glacial erosion?

We have shown that Southern Africa is characterized by exhumed paleolandscapes displaying geomorphic evidence for glacial erosion processes. These landscapes therefore date *at least* back to the LPIA, ca. 300 Ma. Accordingly, this surface has been termed 'ancestral glacial pre-Karoo peneplain' (Wellington, 1937), 'sub-Karoo surface' (King, 1948) or more specifically 'pre-Dwyka topography' (du Toit, 1954; von Gottberg, 1970). However, an array of sedimentological, thermochronometrical, structural and morphological data suggest that glacial erosion processes may have in fact reshaped and/or amplified an even older landsurface that existed before LPIA times, formed by alluvial erosion processes, pediplanation, and by surficial expression of basement and tectonic structures such as faults and folds. The pre-Karoo landscape, in its multiple expression, would therefore be polygenic and polyphased, the glacial erosion processes being the last episode of a long history of surficial processes (e.g., Lister, 1987, de Wit, 2016). Just as it is the case for Quaternary glacial landscapes (Jess et al., 2019), the pre-Karoo landscape probably resulted from a combination of ice sheet dynamics, pre-glacial landscape evolution and underlying geology. The preservation of preglacial forms, at least locally or regionally, would finally suggest that glacial erosion was minimal enough to prevent their complete obliteration, which could ultimately lead to a quantification of glacial erosion during the LPIA.

5.1.1. *Highlands and escarpments: surficial expression of basement structure and tectonic activity?*

809     The threefold morphological pattern (highlands, escarpments and sedimentary basins) that greatly
810 controlled mode of glaciogenic sedimentation, seems to correspond to surficial expression of basement
811 structures (Fig. 12). Indeed, the highlands correspond to Archean and Paleoproterozoic cratons while
812 the escarpments edging the highlands match crustal-scale faults, either delineating the cratons and their
813 surroundings accreted terranes or intra-cratons faults (Figs. 1 and 12; Daly et al., 1989; Tankard et al.,
814 2009a; Begg et al., 2015). The escarpments may therefore correspond to fault offsets, with glacial
815 valleys carved into it. And, in order for the glacial valleys to be carved into it, these fault escarpments
816 must have formed before or during the development of the ice masses of the LPIA, implying relative
817 uplift of the cratonic areas and subsidence of the surrounding terranes. Below are speculations of the
818 possible timing and processes involved in pre-LPIA vertical movements that led to the partitioning
819 between highlands and lowlands separated by escarpments.

820     The Kaoko region of NW Namibia corresponds tectonically to the Kaoko Branch of the Pan-
821 African orogen that developed between the Congo Craton and other terranes 580-480 Myr ago
822 (Goscombe and Gray, 2008). There, the escarpments edging the Kaoko highland into which paleofjords
823 are carved correspond to faults delineating the Congo Craton to the east and the Kaoko belt to the west
824 (Fig. 12a; Goscombe and Gray, 2008). Therefore, considering the crustal structure of the region prior
825 and during the LPIA, two hypotheses for the genesis of the escarpment -a fault offset- and the existence
826 of the high ground are suggested, as summarized in figure 12a:

827    **(1) Hypothesis 1, peneplanation and rejuvenation:** In this hypothesis, relief generated during
828        the Pan-African orogeny that terminated around 480 Myr would have been flattened,
829        possibly through peneplanation for 180 Ma, until the LPIA. Immediately before or during
830        the LPIA, tectonic processes such as subsidence of the Kaoko belt and/or uplift of the Congo
831        craton, reactivated basement structures and faults inherited from the Pan-African orogeny
832        and rejuvenated their surficial expression (Daly et al., 1989; Pysklywec and Mitrovica, 1999;
833        Pysklywec and Quintas, 1999; Tankard et al., 2009). Tectonism and fault reactivation may
834        relate to the extension as Karoo rift systems have been proposed for Northern Namibia (Daly
835        et al., 1989; Clemson et al., 1997, 1999; Aizawa et al., 2000). Such a Late Paleozoic rift
836        system would be signified by the thermochronometric data that indicate a period of enhanced
837        exhumation during the Devonian-Carboniferous after a quiescent period that lasted between
838        the Cambrian and the Devonian, itself following a period of exhumation (curves 1, 2 and 3
839        in figure 11 of Krob et al., 2020), that we suggest may represent a peneplanation period.

840    **(2) Hypothesis 2, inherited high topography:** The alternative hypothesis is that the
841        topographic escarpment formed during the Pan-African orogeny, marking the topographic
842        boundary between different tectonic provinces, the Coastal Terrane and the Congo Craton,
843        and persisted since then owing to incomplete peneplanation. This would indicate that the
844        modern relief of the Kaoko is very old, dating to the early Phanerozoic, as it has also been

845    suggested for the Scandinavian Margin by Pedersen et al. (2016) or the Canadian Shield by
846    Ambrose (1964).

847    The Southern flank of the Cargonian Highland in South Africa is also marked by an escarpment
848    into which large glacial valleys are carved (the Kaap and Virginia valleys, fig. 12b). These valleys
849    funnelled ice flows and controlled mode of glaciogenic sedimentation. Here, the escarpment
850    corresponds to crustal structures (Fig. 12b). Tankard et al. (2009) indicate that subsidence of the MKB
851    started during the LPIA and was initially characterized by vertical motion of rigid crustal blocks that
852    correspond to terranes accreted to the Kaapvaal craton, accommodated by crustal-scale faults between
853    these terranes in an epeirogenic context. On the one hand, in the central MKB, the Virginia glacial valley
854    is fault-controlled as well as the promontory between the Virginia and Kaap valleys (Fig. 13b). The
855    Kaap valley does not seem however to be associated with a fault and may therefore correspond to the
856    headvalley retreat that originated from the escarpment formed by the offset of the Doringsberg fault
857    (Fig. 12b, second cartoon). On the other hand, in the eastern Karoo, the Natal escarpment into which
858    smaller glacial valleys are carved corresponds to a basement step formed by the Tugela thrust front,
859    delineating the Kaapvaal craton to the north and Natal Province to the South (see figure 13 in Tankard
860    et al., 2009).

861    It must finally be mentioned that the incision of fjords through the escarpment during the LPIA
862    may have amplified an already existing topography through isostatic uplift (Fig. 12; Medvedev et al.,
863    2018; Pedersen et al., 2019). Depending on the flexural rigidity of the lithosphere, the isostatic uplift
864    would have been in the order of a third of the thickness of eroded material. Quantifying the depth of
865    glacial erosion (valleys only vs. valleys and their interfluve) would therefore appear crucial for
866    constraining the amount of postglacial isostatic uplift (see the notion of geophysical relief in Pedersen
867    et al., 2019).

868    *5.1.2. Valleys and plateaus: marks of pre-LPIA alluvial erosion processes?*

869    Along with the crustal structure of Southern Africa, which may have largely contributed in
870    creating the reliefs that existed at the onset of the LPIA, preglacial alluvial erosion processes might have
871    contributed to shape relief later exploited by glacial ice during the LPIA, as indicated by sparse and
872    sometimes indirect evidences, as listed below.

873    Over the Cargonian, Kaoko and Zimbabwe highland, thermochronometrical data indicate that
874    cooling, which reflects exhumation, continuously prevailed since at least 500 Ma ago until the LPIA,
875    suggesting that the LPIA was the ultimate episode of a >200 Ma-long history of erosion. Over the
876    Cargonian Highland, cooling occurred between 600-500 Ma and 400 Ma, leaving ca. 100 Ma of erosion
877    (Wildman et al., 2017; Baughman and Flowers, 2020). Moreover, no Lower Paleozoic sedimentary
878    basin exists over Southern Africa, with the notable exception of the Cape Basin, hosting the Cape
879    Supergroup, spanning from the Cambrian to the late Devonian. Provenance studies and paleocurrents

880  indicate that sediments that fed the Cape Basin were sourced in the north, over the Namaqua-Natal

881  suture belt, and funneled to the Cape basin through a network of southward-flowing valleys (e.g.,

882  Theron, 1972, Fourie et al., 2011). The Kaap valley may therefore correspond to such an alluvial valley

883  later reused by the ice. Over the Kaoko Highland, cooling occurred between 550 Ma and the onset of

884  the LPIA (Krob et al., 2019), leaving about 250 Ma for erosion. In Zimbabwe, Lister (1987) indicates

885  the presence of a pre-LPIA pediplain and 'older [than LPIA] fluvial valley', being part of the so-called

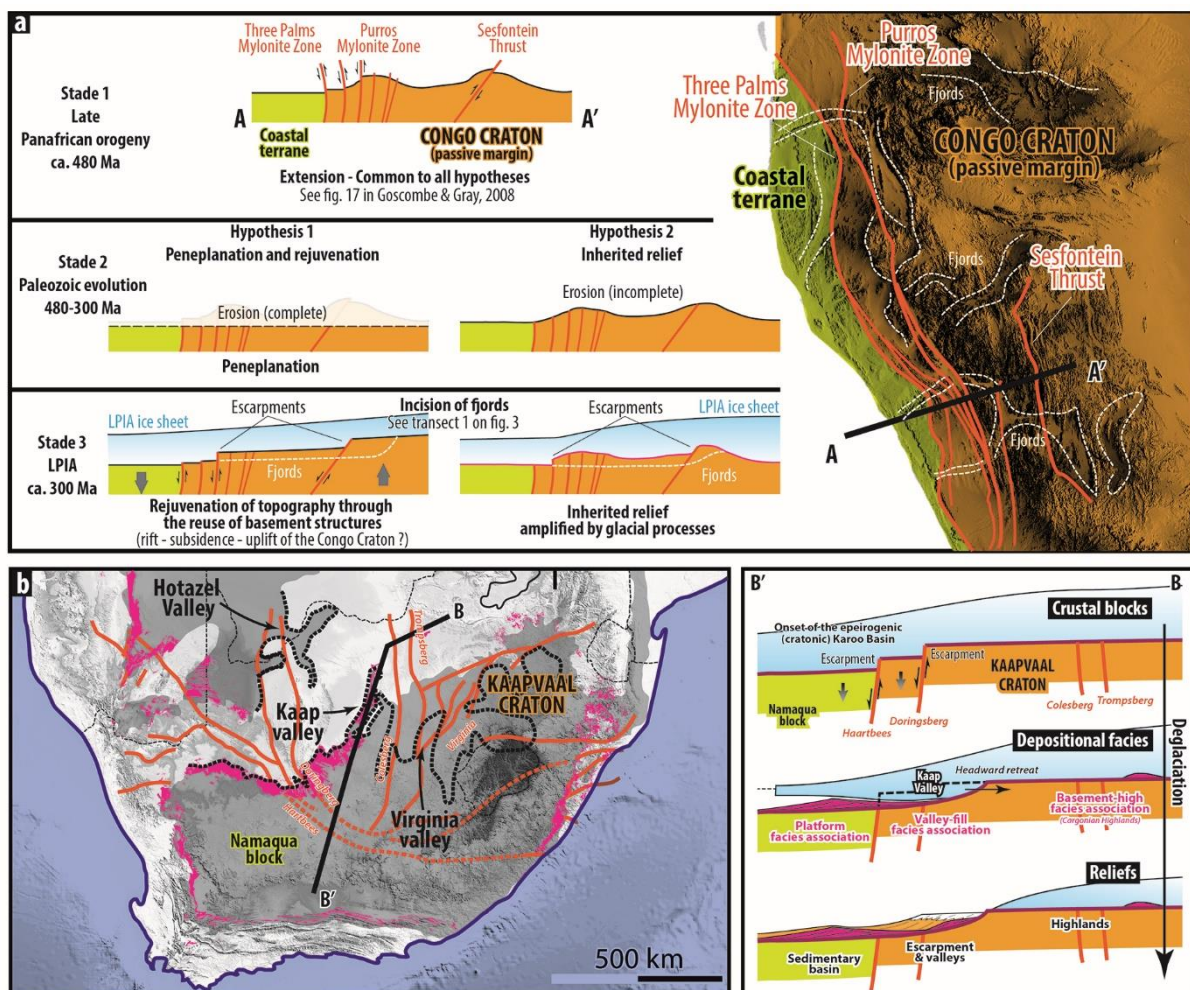
886  "pre-Karoo fossil surface", which would indicate alluvial processes. Therefore, we suggest that before

887  the LPIA, most of Southern Africa, with exception of the Cape Supergroup, was an erosional landscape

888  dominated by alluvial forms: valleys and possibly pediments and pediplains. At the onset of the LPIA,

889  these networks of alluvial valleys may have controlled the path of local ice flows and its funnelling into

890  what later became the fjords punctured through the escarpment (see also Lister, 1987).

891

892  Fig. 12: (a) Structural map of the Kaoko Highland (Figs 2 and 3), faults are after Goscombe & Gray (2008) and two alternative models for the evolution of the escarpments and the associated valleys before the LPIA, as follows: Hypothesis 1 implies that the relief created at the end of the Pan-African orogeny around 480 Myr was entirely levelled down before the LPIA and rejuvenated owing to vertical crustal movements during or immediately prior the LPIA whose ice flow carved valleys into it. Hypothesis 2 implies that the relief created by the Pan-African orogeny was only partly eroded during the time interval between the Pan-African orogeny and the LPIA and was amplified by glacial processes. The first stage representing the end of the Pan-African orogeny – extension tied to post-orogenic collapse – is common to both hypothesis and derived from Goscombe & Gray (2008). (b) Structural map of the Main Karoo Basin and the Cargonian Highlands; faults are after Tankard et al. (2009); and proposed model for the carving of the Kaap valley (Fig. 6) that corresponds to a headward retreat of the valley due to glacial erosion from the offsetting Doringsberg fault. See text for details

## 5.2. Can the pre-Dwyka relief be mistaken for post-LPIA planation surfaces or rifts?

LPIA glacial valleys, like the Kaap valley in South Africa or the paleofjords of NW Namibia, are U-shaped valleys prominent in the modern desert landscape. These valleys occur at different elevations, are incised within escarpments, and are separated by flat surfaces. Although glacial erosion processes were major in shaping these landforms, their origin likely also involves pre-glacial structural and/or alluvial processes. In this regard, these LPIA-related landforms resemble "planation surfaces" (pediments, pediplains, and pedivalleys) of the African Surfaces described by Guillocheau et al. (2018), which are interpreted as successive steps of staircases carved on the slopes of growing reliefs since ca. 30 Ma (e.g., Burke and Gunnell, 2008; Guillocheau et al., 2018). This interpretation has recently been challenged by Chardon (2023) who argues that most of the tropical African highlands are inherited reliefs dating back at least to the Cretaceous. He further suggests that the apparent staircase-like arrangement of African planation surfaces is primarily controlled by long-term climatic processes rather than resulting from episodic epeirogenic uplift. In a complementary way, our study emphasises the need of considering the morphological heritage, particularly related to the LPIA glacial erosion, when assessing the evolution and modern aspect of the landscapes of Southern Africa.

Alternatively, the glacial U-shaped valleys of Southern Africa can also be mistaken for post-LPIA, Mesozoic or Cenozoic rift or tectonic structures. The Kunene River valley, defining the border between Namibia and Angola, is a conspicuous glacial valley, with coarse-grained glaciogenic sediments and boulder-sized erratic plastered along its walls. Yet, this valley has been interpreted as 'structurally controlled' by Brunotte and Spoenemann (2003). Many other valleys exhibit large-scale morphological features consistent with a glacial origin -U-shaped cross profiles, endorheic troughs suggesting glacial overdeepening, and valley directions radiating out of the Windhoek highlands- yet lack definitive evidence of glacial processes and have been classified as rifts by various authors. For instance, the Upper Ugab and Waterberg valleys of Northern Namibia, as well as the Karasburg Basin of Southern Namibia - interpreted by Martin (1973b) and Visser (1987b) as resulting of a glacial overdeepening - have been considered rift-related structures, alongside the Tshipise, Tuli, Ellisras, and Springbok Flats basins in South Africa and Zimbabwe (Daly et al., 1989; Smith and Swart, 2002; Frizon De Lamotte et al., 2015; Guillocheau, 2018). However, the relatively thin accumulation of the Karoo Supergroup (100-200 m) within these basins (Holzförster et al., 2000; Smith and Swart, 2002; Bordy and Catuneanu, 2003; Johnson et al., 2006; Bordy, 2018), indicating very low accommodation and subsidence, largely incompatible with rift-related processes, as well as the absence of bounding faults in some cases, question such a tectonic interpretation.

# 4. Conclusions and perspectives

Linley A. Lister (née King, 1936-2016) wrote in 1987 in her treatise on 'The Erosion surfaces of Zimbabwe' that *In many respects the Pre-Karoo landscape of Zimbabwe was remarkably similar to that existing at the present day'.* In the present contribution, we show that the same applies to many cratonic areas floored by Archean to Proterozoic rocks over Southern Africa. Attested geomorphic legacy of the LPIA in Southern Africa is present under the form of U-shaped valleys in Namibia and South Africa in which glaciogenic sediments are found, and as fields of *roches moutonnées* and crag-and-tails in South Africa. Other forms are suspected to be glacial in origin, although no firm evidence has been found: valleys radiating out the Windhoek Highlands, ravines encased within mountain ranges and small 'sedimentary' basins. Many other landforms have existed at least since the LPIA but bear evidence for structural and/or alluvial processes, and may have therefore be only reshaped and/or reused by glacial processes. These glacially-modified forms are mountain ranges in Zimbabwe and South Africa and escarpments in which glacial valleys are incised, in Namibia and South Africa. We therefore underscore the probable existence of a relict non-glacial landscape that prevailed before the LPIA and the extension of ice masses during the Late Paleozoic may have only reshaped slightly such forms. As it is the case for the Quaternary, the modern landscapes of Southern Africa may therefore represent a combination of glacial and alluvial erosion and tectonic-structural processes. We have also highlighted the importance of immediate deposition after the LPIA of volcanic and sedimentary cover in preserving the ancient landforms that must be restored to understand the evolution of the Southern African relief. Nowadays, after a 300 Ma-long history of burial and exhumation, preserving them from weathering and erosion, these glacial landscapes have been resurrected and characterize the modern landscape of Southern Africa. Finally, these observations partly call into question the geomorphological studies carried out in Southern Africa, which have interpreted the shelving of the subcontinent as reflecting successive phases of uplift since the break-up of Gondwana (e.g., Partridge and Maud, 1997, 2000; van der Beek et al., 2002; Burke and Gunnell, 2008, Guillocheau et al., 2018).

Whilst our findings apply for Southern Africa, similar inferences most likely hold for other cratonic areas that experienced the late Paleozoic Ice Age, as demonstrated by widespread striated surfaces and glacial morphological features or suggested by ancient (Carboniferous-Permian) thermochronometric ages:

- In South America, where paleofjords characterize the edge of Karoo-aged basins (Kneller et al., 2004; Rosa et al., 2016; Tedesco et al., 2016; Mottin et al., 2018; Assine et al., 2018).
- Vast regions of Central Africa host relict glacial morphological features and glaciogenic sediments (Studt, 1913; Dixey, 1937; Boutakoff, 1948; Wopfner and Kreuser, 1986; Ring, 1995; Wopfner and Diekmann, 1996; Catuneanu et al., 2005b) and Carboniferous-Permian thermochronometric ages have been inferred for widespread erosion surfaces such as in Malawi (McMillan et al., 2022, see also Mathian et al., in press)

- Likely in Madagascar, where glacial strata are found at the very base of the Karoo-aged Majunga and Morondava sedimentary basins (Rakotosolofo et al., 1999)
- In India, where Dwyka-equivalent strata lie on the cratonic bedrock (Casshyap and Srivastava, 1987; Dasgupta, 2020)
- In Australia, where vast sedimentary basins bear Dwyka-equivalent strata over cratonic areas (Fielding et al., 2023)
- And in Antarctica where Rolland et al. (2019) postulate the presence of vast glacial landscapes inherited from the LPIA. It may even be conceivable that Cenozoic glacial erosion reused and superimposed glacial reliefs carved during the LPIA (e.g., Carter et al., 2023, this volume).

# Competing interests

The contact author has declared that none of the authors has any competing interests

# Acknowledgements

P. Dietrich and D. Le Heron acknowledge funding from the South Africa–Austria joint project of the National Research Foundation (NRF) of South Africa and the *Österreichischer Austauschdienst* of Austria (OEAD project ZA 08/2019). Ana C. Fonseca and Adrian M. Hall are warmly thanked for their thorough and detailed reviews and relevant suggestions that greatly led to the improvement of the manuscript. We dedicate this paper to Alexander du Toit (1878-1948), Henno Martin (1910-1998), Lester King (1907-1989), Linley Lister (1936-2016), Maarten de Wit (1947-2020), and Johann Visser whose work laid the groundwork of the 'ancestral landscapes' of Southern Africa.

# Reference cited

**Aizawa, M., Bluck, B.J., Cartwright, J., Milner, S., Swart, R., and Ward, J.D.**, 2000, Constraints on the geomorphological evolution of Namibia from the offshore stratigraphic record: Communications Geological Survey Namibia, v. 12, p. 38–393.

**Ambrose, J, W.**, 1964, Exhumed paleoplains of the Precambrian Shield of North America: American Journal of Science, v. 262, p. 817–857.

**Anderson, C.**, 1978, The geology of the East Charter area.

**Andrews, G.D., McGrady, A.T., Brown, S.R., and Maynard, S.M.**, 2019, First description of subglacial megalineations from the late Paleozoic ice age in Southern Africa: PLoS ONE, v. 14, p. 1–10.

**Assine, M.L., de Santa Ana, H., Veroslavsky, G., and Vesely, F.F.**, 2018, Exhumed subglacial

993      landscape in Uruguay: Erosional landforms, depositional environments, and paleo-ice flow in the

994      context of the late Paleozoic Gondwanan glaciation: Sedimentary Geology, v. 369, p. 1–12.

995   **Baby, G.**, 2017, Mouvements verticaux des marges passives d'Afrique australe depuis 130 Ma, étude

996      couplée : stratigraphie de bassin - analyse des formes du relief: Université de Rennes 1, 369 p.

997   **Baby, G., Guillocheau, F., Boulogne, C., Robin, C., and Dall'Asta, M.**, 2018a, Uplift history of a

998      transform continental margin revealed by the stratigraphic record: The case of the Agulhas

999      transform margin along the Southern African Plateau: Tectonophysics, v. 731–732, p. 104–130.

1000  **Baby, G., Guillocheau, F., Morin, J., Ressouche, J., Robin, C., Broucke, O., and Dall'Asta, M.**,

1001     2018b, Post-rift stratigraphic evolution of the Atlantic margin of Namibia and South Africa:

1002     Implications for the vertical movements of the margin and the uplift history of the South African

1003     Plateau: Marine and Petroleum Geology, v. 97, p. 169–191.

1004  **Baby, G., Guillocheau, F., Braun, J., Robin, C., and Dall'Asta, M.**, 2020, Solid sedimentation rates

1005     history of the Southern African continental margins: Implications for the uplift history of the South

1006     African Plateau: Terra Nova, v. 32, p. 53–65.

1007  **Backeberg, N.R., and Rowe, C.D.**, 2009, Mega-scale (~50m) Ordovician load casts at de balie, South

1008     Africa: Possible sediment fluidization by thermal destabilisation: South African Journal of

1009     Geology, v. 112, p. 187–196.

1010  **Bangert, B., Armstrong, R., Stollhofen, H., Lorenz, V., and Armstrong, R.**, 1999, The

1011     geochronology and significance of ash-fall tuffs in the glaciogenic Carboniferous-Permian Dwyka

1012     Group of Namibia and South Africa: Journal of African Earth Sciences, v. 29, p. 33–49.

1013  **Baughman, J.S., and Flowers, R.M.**, 2020, Mesoproterozoic burial of the Kaapvaal craton, Southern

1014     Africa during Rodinia supercontinent assembly from (U-Th)/He thermochronology: Earth and

1015     Planetary Science Letters, v. 531.

1016  **van der Beek, P., Summerfield, M.A., Braun, J., Brown, R.W., and Fleming, A.**, 2002, Modeling

1017     postbreakup landscape development and denudational history across the southeast African

1018     (Drakensberg Escarpment) margin: Journal of Geophysical Research: Solid Earth, v. 107, p. ETG

1019     11-1-ETG 11-18.

1020  **Begg, G.C. et al.**, 2009, The lithospheric architecture of Africa: Seismic tomography, mantle petrology,

1021     and tectonic evolution: Geosphere, v. 5, p. 23–50.

1022  **Belica, M.E., Tohver, E., Poyatos-Moré, M., Flint, S., Parra-Avila, L.A., Lanci, L., Denyszyn, S.,**

1023     **and Pisarevsky, S.A.**, 2017, Refining the chronostratigraphy of the Karoo Basin, South Africa:

1024     Magnetostratigraphic constraints support an early Permian age for the Ecca Group: Geophysical

1025    Journal International, v. 211, p. 1354–1374.

1026    **Benn, D.I., and Evans, D.J.A.**, 2010, Glaciers and glaciation: London, Hodder Edition, 817 p.

1027    **Blignault, H.J., and Theron, J.N.**, 2017, Diapirism and the fold zone controversy of the ordovician
1028        glaciomarine pakhuis formation, South Africa: South African Journal of Geology, v. 120, p. 209–
1029        222.

1030    **Blignault, H.J., and Theron, J.N.**, 2010, Reconstruction of the ordovician pakhuis ice sheet, South
1031        Africa: South African Journal of Geology, v. 113, p. 335–360.

1032    **Bond, G., and Stocklmayer, V.R.C.**, 1967, Possible ice-margin fluctuations in the Dwyka series in
1033        Rhodesia: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 3, p. 433–446.

1034    **Bond, G.,** 1970, The Dwyka Series in Rhodesia. Proc. Geol. Assoc, V. 81, p. 463-172.

1035    **Bordy, E.M.**, 2018, Lithostratigraphy of the Tshidzi Formation (Dwyka Group , Karoo Supergroup),
1036        South Africa: South African Journal of Geology, v. 121, p. 109–118.

1037    **Bordy, E.M., and Catuneanu, O.**, 2003, Sedimentology of the lower Karoo Supergroup fluvial strata
1038        in the Tuli Basin, South Africa: Journal of African Earth Sciences, v. 35, p. 503–521.

1039    **Boutakoff, N.**, 1948, Les Formations glaciaires et postglaciaires fossilifères, d'âge permo-carbonifère
1040        (Karroo Inférieur) de la région de Walikale (Kivu, Congo Belge): Mémoire de l'institut
1041        Géologique de l'Université de Louvain, v. 9, p. 124.

1042    **Braun, J.**, 2018, A review of numerical modeling studies of passive margin escarpments leading to a
1043        new analytical expression for the rate of escarpment migration velocity: Gondwana Research, v.
1044        53, p. 209–224.

1045    **Braun, J.**, 2010, The many surface expressions of mantle dynamics: Nature Geoscience, v. 3, p. 825–
1046        833.

1047    **Braun, J., Guillocheau, F., Robin, C., Baby, G., and Jelsma, H.**, 2014, Rapid erosion of the Southern
1048        African Plateau as it climbs over a mantle superplume: Journal of Geophysical Research: Solid
1049        Earth, v. 119, p. 6093–6112.

1050    **Brown, R.W., Summerfield, M.A., and Gleadow, A.J.W.**, 2002, Denudational history along a transect
1051        across the Drakensberg Escarpment of Southern Africa derived from apatite fission track
1052        thermochronology: Journal of Geophysical Research: Solid Earth, v. 107.

1053    **Burke, K., and Gunnell, Y.**, 2008, The African Erosion Surface: A Continental-Scale Synthesis of
1054        Geomorphology, Tectonics, and Environmental Change over the Past 180 Million Years: Memoir
1055        of the Geological Society of America, v. 201, p. 1–66.

1056 **Cairncross, B.**, 2001, An overview of the Permian (Karoo) coal deposits of Southern Africa: Journal of
1057     African Earth Sciences, v. 33, p. 529–562.

1058 **Cairncross, B., and Cadle, A.B.**, 1988, Palaeoenvironmental control on coal formation , distribution
1059     and quality in the Permian Vryheid Formation , East Witbank Coalfield , South Africa: v. 9, p.
1060     343–370.

1061 **Carter, C. M., Bentley, M. J., Jamieson, S. S. R., Paxman, G. J. G., Jordan, T. A., Bodart, J. A.,**
1062     **Ross, N., & Napoleoni, F.** [preprint], Extensive palaeo-surfaces beneath the Evans-Rutford region
1063     of the West Antarctic Ice Sheet control modern and past ice flow, EGUsphere,
1064     https://doi.org/10.5194/egusphere-2023-2433, 2023

1065 **Casshyap, S.M., and Srivastava, V.K., 1987**, Glacial and proglacial Talchir sedimentation in Son-
1066     Mahanadi Gondwana Basin: Paleogeographic reconstruction: Gondwana Six: Stratigraphy,
1067     Sedimentology, and Paleontology, Volume 41,.

1068 **Catuneanu, O.**, 2004, Basement control on flexural profiles and the distribution of foreland facies: The
1069     Dwyka Group of the Karoo Basin, South Africa: Geology, v. 32, p. 517–520.

1070 **Catuneanu, O., Hancox, P.J., and Rubidge, B.S.**, 1998, Reciprocal flexural behaviour and contrasting
1071     stratigraphies: A new basin development model for the Karoo retroarc foreland system, South
1072     Africa: Basin Research, v. 10, p. 417–439.

1073 **Catuneanu, O., Wopfner, H., Eriksson, P.G., Cairncross, B., Rubidge, B.S., Smith, R.M.H.H., and**
1074     **Hancox, P.J.**, 2005, The Karoo basins of south-central Africa: Journal of African Earth Sciences,
1075     v. 43, p. 211–253.

1076 **Cawthorn, R.G., Knight, J., and McCarthy, T.S.**, 2015, Geomorphological Evolution of the
1077     Pilanesberg, *in* World Geomorphological Landscapes, Springer, Cham, p. 39–46.

1078 **Chardon, D.,** 2023 Landform-regolith patterns of Northwestern Africa: Deciphering Cenozoic surface
1079     dynamics of the tropical cratonic geosystem: Earth-Science Reviews, 242, 104452.

1080 **Clemson, J., Cartwright, J., and Booth, J.**, 1997, Structural segmentation and the influence of
1081     basement structure on the Namibian passive margin: Journal of the Geological Society, v. 154, p.
1082     477–482.

1083 **Clemson, J., Cartwright, J., and Swart, R.**, 1999, The Namib Rift: a rift system of possible Karoo
1084     age, offshore Namibia: Geological Society Special Publication, v. 153, p. 381–402.

1085 **Cloos, H.**, 1915, Die unterkarbonischen Glazialbildungen des Kaplandes: Geologische Rundschau, v.
1086     6, p. 337–351.

1087 **Couette, P.O., Lajeunesse, P., Ghienne, J.F., Dorschel, B., Gebhardt, C., Hebbeln, D., and**
1088      **Brouard, E.**, 2022, Evidence for an extensive ice shelf in northern Baffin Bay during the Last
1089      Glacial Maximum: Communications Earth and Environment, v. 3.

1090 **Crowell, J.C., and Frakes, L.A.**, 1972, Late paleozoic glaciation: Part V, Karroo Basin, South Africa:
1091      Bulletin of the Geological Society of America, v. 83, p. 2887–2919.

1092 **Cui, X. et al.**, 2022, Global fjords as transitory reservoirs of labile organic carbon modulated by organo-
1093      mineral interactions: Science Advances, v. 8.

1094 **Cui, X., Bianchi, T.S., Savage, C., and Smith, R.W.**, 2016, Organic carbon burial in fjords: Terrestrial
1095      versus marine inputs: Earth and Planetary Science Letters, v. 451, p. 41–50.

1096 **Daly, M.C., Chorowicz, J., and Fairhead, J.D.**, 1989, Rift basin evolution in Africa: The influence of
1097      reactivated steep basement shear zones: Geological Society Special Publication, v. 44, p. 309–334.

1098 **Dasgupta, P.**, 2020, Formation of intracratonic Gondwana basins: Prelude of Gondwana fragmentation?
1099      Journal of Mineralogical and Petrological Sciences, v. 115, p. 192–201.

1100 **Dauteuil, O., Deschamps, F., Bourgeois, O., Mocquet, A., and Guillocheau, F.**, 2013, Post-breakup
1101      evolution and palaeotopography of the North Namibian Margin during the Meso-Cenozoic:
1102      Tectonophysics, v. 589, p. 103–115.

1103 **Davies, N.S., Shillito, A.P., and Penn-clarke, C.R.**, 2020, Cold Feet : trackways and burrows in ice-
1104      marginal strata of the end-Ordovician glaciation ( Table Mountain Group , South Africa ):

1105 **Deynoux, M., and Ghienne, J.F.**, 2004, Late Ordovician glacial pavements revisited: A reappraisal of
1106      the origin of striated surfaces: Terra Nova, v. 16, p. 95–101.

1107 **Diester-Haass, L., Meyers, P.A., and Rothe, P.**, 1990, Miocene history of the Benguela Current and
1108      Antarctic ice volumes: Evidence from rhythmic sedimentation and current growth across the
1109      Walvis Ridge (Deep Sea Drilling Project Sites 362 and 532): Paleoceanography, v. 5, p. 685–707.

1110 **Dietrich, P., Franchi, F., Setlhabi, L., Prevec, R., and Bamford, M.**, 2019, The nonglacial diamictite
1111      of Toutswemogala Hill (Lower Karoo Supergroup, Central Botswana): Implications on the extent
1112      of the Late Paleozoic ice age in the Kalahari–Karoo basin: Journal of Sedimentary Research, v.
1113      89, p. 875–889.

1114 **Dietrich, P., Ghienne, J.-F., Lajeunesse, P., Normandeau, A., Deschamps, R., and Razin, P.**, 2018,
1115      Deglacial sequences and glacio-isostatic adjustment: Quaternary compared with Ordovician
1116      glaciations: Geological Society, London, Special Publications, v. 475, p. SP475.9.

1117 **Dietrich, P., Ghienne, J.F., Schuster, M., Lajeunesse, P., Nutz, A., Deschamps, R., Roquin, C., and**

**Duringer, P.**, 2017, From outwash to coastal systems in the Portneuf–Forestville deltaic complex (Québec North Shore): Anatomy of a forced regressive deglacial sequence (C. Fielding, Ed.): Sedimentology, v. 64, p. 1044–1078.

**Dietrich, P., Griffis, N.P., Le Heron, D.P., Montañez, I.P., Kettler, C., Robin, C., and Guillocheau, F.**, 2021, Fjord network in Namibia: A snapshot into the dynamics of the late Paleozoic glaciation: Geology, v. 49, p. 1521–1526.

**Dietrich, P., and Hofmann, A.**, 2019, Ice-margin fluctuation sequences and grounding zone wedges: The record of the Late Palaeozoic Ice Age in the eastern Karoo Basin (Dwyka Group, South Africa ): The Depositional Record, v. 5, p. 247–271.

**Ding, X., Salles, T., Flament, N., Mallard, C., and Rey, P.F.**, 2019, Drainage and Sedimentary Responses to Dynamic Topography: Geophysical Research Letters, v. 46, p. 14385–14394.

**Dixey, F.**, 1937, The pre-Karroo landscape of the Lake Nyasa Region, and a comparison of the karroo structural directions with those of the Rift Valley: Quarterly Journal of the Geological Society of London, v. 93, p. 77–93.

**Dodd, S.C., Mac Niocaill, C., and Muxworthy, A.R.**, 2015, Long duration (>4 Ma) and steady-state volcanic activity in the early Cretaceous Paraná-Etendeka Large Igneous Province: New palaeomagnetic data from Namibia: Earth and Planetary Science Letters, v. 414, p. 16–29.

**Doucouré, C.M., and de Wit, M.J.**, 2003, Old inherited origin for the present near-bimodal topography of Africa: Journal of African Earth Sciences, v. 36, p. 371–388.

**Dowdeswell, J.A., Canals, M., Jakobsson, M., Todd, B.J., Dowdeswell, E.K., and Hogan, K.A.**, 2016, Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient: Geological Society, London, Memoirs, v. 46, p. NP.1-NP.

**Dunn, J.E.**, 1898, Northward extension of Derrinal Conglomerate (Glacial): Proceedings Royal Society Victoria, v. 10, p. 204.

**Dunn, J.E.**, 1886, Report on a supposed extensive deposit of coal underlying the central district of the Colony (R. and Sons, Ed.): Cape Town.

**Dürst Stucki, M., Schlunegger, F., Christener, F., Otto, J.-C. & Götz, J.,** 2012, Deepening of inner gorges through subglacial meltwater — An example from the UNESCO Entlebuch area, Switzerland, Geomorphology. 139-140, 506-517.

**Eriksson, P.G., Altermann, W., Catuneanu, O., Van der Merwe, R., and Bumby, A.J.**, 2001, Major influences on the evolution of the 2.67-2.1 Ga Transvaal basin, Kaapvaal craton: Sedimentary

1149    Geology, v. 141–142, p. 205–231.

1150    **Erlank, A.J., Marsh, J.S., Duncan, A.R., Miller, R.M., and Hawkesworth, C.J.**, 1984, Geochemistry
1151        and petrogenesis of the Etendeka volcanic rocks from SWA/Namibia. In: Petrogenesis of the
1152        volcanic rocks of the Karoo Province: Geological Society of South Africa (Special Publication),
1153        v. 13, p. 185–247.

1154    **Eyles, N.**, 1993, Earth's glacial record and its tectonic setting: Earth Science Reviews, v. 35, p. 1–248.

1155    **Faupel, J.**, 1974, Geologisch-mineralogishe Untersuchungen am Donkerhoek-Granit(Karibib-District,
1156        Südwest-Afrika): Göttinger Arb. Geol. Paläont., v. 15, p. 95.

1157    **Feakins, S.J., and Demenocal, P.B.**, 2012, Global and African Regional Climate during the Cenozoic,
1158        *in* Cenozoic Mammals of Africa, University of California Press, p. 45–56.

1159    **Fedorchuk, N.D., Isbell, J.L., Rosa, E.L.M., Swart, R., and McNall, N.B.**, 2023, Reappraisal of
1160        exceptionally preserved s-forms, striae, and fractures from late Paleozoic subglacial surfaces in
1161        paleofjords, NW Namibia: Sedimentary Geology, v. 456.

1162    **Fernandes, P., Hancox, P.J., Mendes, M., Pereira, Z., Lopes, G., Marques, J., Jorge, R.C.G.S., and**
1163        **Albardeiro, L.**, 2023, The age and depositional environments of the lower Karoo Moatize
1164        Coalfield of Mozambique: insights into the postglacial history of central Gondwana: Palaeoworld,.

1165    **Fielding, C.R., Frank, T.D., and Birgenheier, L.P.**, 2023, A revised, late Palaeozoic glacial time-
1166        space framework for eastern Australia, and comparisons with other regions and events: Earth-
1167        Science Reviews, v. 236.

1168    **Fielding, C.R., Frank, T.D., and Isbell, J.L.**, 2008, The late Paleozoic ice age; a review of current
1169        understanding and synthesis of global climate patterns: Special Paper - Geological Society of
1170        America, v. 441, p. 343–354.

1171    **Fildani, A., Drinkwater, N.J., Weislogel, A., McHargue, T., Hodgson, D.M., and Flint, S.S.**, 2007,
1172        Age Controls on the Tanqua and Laingsburg Deep-Water Systems: New Insights on the Evolution
1173        and Sedimentary Fill of the Karoo Basin, South Africa: Journal of Sedimentary Research, v. 77, p.
1174        901–908.

1175    **Fildani, A., Weislogel, A., Drinkwater, N.J., McHargue, T., Tankard, A., Wooden, J., Hodgson,**
1176        **D., and Flint, S.**, 2009, U-Pb zircon ages from the southwestern Karoo Basin, South Africa -
1177        Implications for the Permian-Triassic boundary: Geology, v. 37, p. 719–722.

1178    **Flowers, R.M., and Schoene, B.**, 2010, (U-Th)/He thermochronometry constraints on unroofing of the
1179        eastern Kaapvaal craton and significance for uplift of the Southern African plateau: Geology, v.

1180   38, p. 827–830.

1181 **Fourie, P.H. et al.**, 2010, Glacial Ordovician new evidence in the Pakhuis Formation, South Africa:
1182   sedimentological investigation and palaeo-environnemental reconstruction: South African Journal
1183   of Geology, v. 114, p. 2009–10536.

1184 **Franchi, F., Kelepile, T., Di Capua, A., De Wit, M.C.J., Kemiso, O., Lasarwe, R., and Catuneanu,**
1185   **O.**, 2021, Lithostratigraphy, sedimentary petrography and geochemistry of the Upper Karoo
1186   Supergroup in the Central Kalahari Karoo Sub-Basin, Botswana: Journal of African Earth
1187   Sciences, v. 173, p. 104025.

1188 **Frizon De Lamotte, D., Fourdan, B., Leleu, S., Leparmentier, F., and De Clarens, P.**, 2015, Style
1189   of rifting and the stages of Pangea breakup: Tectonics, v. 34, p. 1009–1029.

1190 **Gallagher, K., and Brown, R.**, 1999, The Mesozoic denudation history of the Atlantic margins of
1191   Southern Africa and southeast Brazil and the relationship to offshore sedimentation: Geological
1192   Society Special Publication, v. 153, p. 41–53.

1193 **Ghienne, J., Le Heron., D.P., Moreau, J., Denis, M., and Deynoux, M.**, 2007, The Late Ordovician
1194   glacial sedimentary system of the North Gondwana platform: International Association of
1195   Sedimentologists Special Publications,.

1196 **Gibson, R.L., and Reimold, W.U.**, 2015, Landscape and Landforms of the Vredefort Dome: Exposing
1197   an Old Wound: World Geomorphological Landscapes, p. 31–38.

1198 **Gilchrist, A.R., Kooi, H., and Beaumont, C.**, 1994, Post-Gondwana geomorphic evolution of
1199   southwestern Africa: implications for the controls on landscape development from observations
1200   and numerical experiments: Journal of Geophysical Research, v. 99.

1201 **Goddéris, Y., Donnadieu, Y., Carretier, S., Aretz, M., Dera, G., MacOuin, M., and Regard, V.**,
1202   2017, Onset and ending of the late Palaeozoic ice age triggered by tectonically paced rock
1203   weathering: Nature Geoscience, v. 10, p. 382–386.

1204 **Gomes, A.S., and Vasconcelos, P.M.**, 2021, Geochronology of the Paraná-Etendeka large igneous
1205   province: Earth-Science Reviews, v. 220, p. 103716.

1206 **Goscombe, B.D., and Gray, D.R.**, 2008, Structure and strain variation at mid-crustal levels in a
1207   transpressional orogen : A review of Kaoko Belt structure and the character of West Gondwana
1208   amalgamation and dispersal: v. 13.

1209 **Goscombe, B., David A. Foster, D.A., Gray, D., Wade, B., Marsellos, A., and Titus, J.** 2017,
1210   Deformation correlations, stress field switches and evolution of an orogenic intersection: The Pan-

1211        African Kaoko-Damara orogenic junction, Namibia, Geosciences Frontiers, 8, 1187-1232

1212 **von Gottberg, B.**, 1970, The occurrence of Dwyka Rocks and glacial topography in the South-Western
1213        Transvaal: Transactions of the geological Society of South Africa,.

1214 **Götz, A.E., Ruckwied, K., and Wheeler, A.**, 2018, Marine flooding surfaces recorded in Permian black
1215        shales and coal deposits of the Main Karoo Basin (South Africa): Implications for basin dynamics
1216        and cross-basin correlation: International Journal of Coal Geology, v. 190, p. 178–190.

1217 **Goudie, A., and Viles, H.**, 2015, Landscapes and Landforms of Namibia:

1218 **Green, P.F., Duddy, I.R., Japsen, P., Bonow, J.M., and Malan, J.A.**, 2017, Post-breakup burial and
1219        exhumation of the Southern margin of Africa: Basin Research, v. 29, p. 96–127.

1220 **Griffis, N.P., Mundil, R., Montañez, I.P., Isbell, J., Fedorchuk, N., Vesely, F., Iannuzzi, R., and**
1221        **Yin, Q.Z.**, 2018, A new stratigraphic framework built on U-Pb single-zircon TIMS ages and
1222        implications for the timing of the penultimate icehouse (Paraná Basin, Brazil): Bulletin of the
1223        Geological Society of America, v. 130, p. 848–858.

1224 **Griffis, N.P. et al.**, 2019a, Coupled stratigraphic and U-Pb zircon age constraints on the late Paleozoic
1225        icehouse-to-greenhouse turnover in south-central Gondwana: Geology, v. 47, p. 1146–1150.

1226 **Griffis, N.P. et al.**, 2019b, Isotopes to ice: Constraining provenance of glacial deposits and ice centers
1227        in west-central Gondwana: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 531, p.
1228        108745.

1229 **Griffis, N. et al.**, 2021, High-latitude ice and climate control on sediment supply across SW Gondwana
1230        during the late Carboniferous and early Permian: Bulletin of the Geological Society of America,
1231        v. 133, p. 2113–2124.

1232 **Griffis, N., Mundil, R., Montañez, I., Le Heron, D., Dietrich, P., and Iannuzzi, R.**, 2023, A
1233        Carboniferous apex for the late Paleozoic icehouse: Geological Society, London, Special
1234        Publications, v. 535, p. 117–129.

1235 **Grimaud, J.L., Rouby, D., Chardon, D., and Beauvais, A.**, 2018, Cenozoic sediment budget of West
1236        Africa and the Niger delta: Basin Research, v. 30, p. 169–186.

1237 **Guillocheau, F.**, 2018, La diversité de l'architecture des bassins de rift: Géochronique, v. 145, p. 52–
1238        56.

1239 **Guillocheau, F., Rouby, D., Robin, C., Helm, C., Rolland, N., Le Carlier de Veslud, C., and Braun,**
1240        **J.**, 2012, Quantification and causes of the terrigeneous sediment budget at the scale of a continental
1241        margin: A new method applied to the Namibia-South Africa margin: Basin Research, v. 24, p. 3–

1242    30.

1243    **Guillocheau, F., Simon, B., Baby, G., Bessin, P., Robin, C., and Dauteuil, O.**, 2018, Planation
1244        surfaces as a record of mantle dynamics: The case example of Africa: Gondwana Research, v. 53,
1245        p. 82–98.

1246    **Haddon, I.G.**, 2005, The Sub-Kalahari Geology and Tectonic Evolution of the Kalahari Basin, Southern
1247        Africa: Thesis, p. 1–360.

1248    **Haddon, I.G., and McCarthy, T.S.**, 2005, The Mesozoic-Cenozoic interior sag basins of Central
1249        Africa: The Late-Cretaceous-Cenozoic Kalahari and Okavango basins: Journal of African Earth
1250        Sciences, v. 43, p. 316–333.

1251    **Haldorsen, S., von Brunn, V., Maud, R., and Truter, E.D.**, 2001, A Weichselian deglaciation model
1252        applied to the Early Permian glaciation in the northeast Karoo Basin , South Africa: v. 16, p. 583–
1253        593.

1254    **Hall, K., and Meiklejohn, I.**, 2011, Glaciation in Southern Africa and in the Sub-Antarctic: Elsevier,
1255        v. 15, 1081–1085 p.

1256    **Hansma, J., Tohver, E., Schrank, C., Jourdan, F., and Adams, D.**, 2016, The timing of the Cape
1257        Orogeny : New 40 Ar / 39 Ar age constraints on deformation and cooling of the Cape Fold Belt ,
1258        South Africa: Gondwana Research, v. 32, p. 122–137.

1259    **Hanson, E.K., Moore, J.M., Bordy, E.M., Marsh, J.S., Howarth, G., and Robey, J.V.A.**, 2009,
1260        Cretaceous erosion in central South Africa: Evidence from upper-crustal xenoliths in kimberlite
1261        diatremes: South African Journal of Geology, v. 112, p. 125–140.

1262    **Haughton, S.H.**, 1949, Obituary - Alexander Logie Du Toit, 1878-1948: Biographical memoirs of the
1263        fellows of the Royal Society, v. 6, p. 384–395.

1264    **Haughton, S.H.**, 1963, Stratigraphic history of Africa South of the Sahara (Oliver & Boyd, Ed.):
1265        London.

1266    **Lehmann, J., Kerstin Saalmann, K., Naydenov, K.V., Milani, L., Belyanin, G.A., Zwingmann, H.,**
1267        **Charlesworth, G. and Kinnaird, J.A.,** 2016, Structural and geochronological constraints on the
1268        Pan-African tectonic evolution of the northern Damara Belt, Namibia. Tectonics, 35, 103-135.

1269

1270    **Le Heron, D.P. Busfield, M.E., Chen, X., Corkeron, M., Davies, B.J., and Dietrich, P.**, 2022, New
1271        Perspectives on Glacial Geomorphology in Earth ' s Deep Time Record: v. 10, p. 1–17.

1272    **Le Heron, D.P., Craig, J., and Etienne, J.L.**, 2009, Ancient glaciations and hydrocarbon

accumulations in North Africa and the Middle East: Earth-Science Reviews, v. 93, p. 47–76.

**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.

**le Heron, D.P., and Dowdeswell, J.A.**, 2009, Calculating ice volumes and ice flux to constrain the dimensions of a 440 Ma North African ice sheet: Journal of the Geological Society, v. 166, p. 277–281.

**Le Heron, D.**P., Kettler, C., Dietrich, P., Griffis, N.P., Montanez, I.P. and Wohlschlägl, R. 2024 Decoding the late Palaeozoic glaciated landscape of Namibia: a photogrammetric journey; Sedimentary Geology, 106592

**Hoffman, P.F. et al.**, 2021, Snowballs in Africa: sectioning a long-lived Neoproterozoic carbonate platform and its bathyal foreslope (NW Namibia): Earth-Science Reviews, v. 219.

**Holland, M.J., Cadle, A.B., Pinheiro, R., and Falcon, R.M.S.**, 1989, Depositional environments and coal petrography of the Permian Karoo Sequence: Witbank Coalfield, South Africa: International Journal of Coal Geology, v. 11, p. 143–169.

**Holtar, E. Forsberg, W.**, 2000, Postrift Development of the Walvis Basin, Namibia: Results from the Exploration Campaign in Quadrant 1911, *in* Mello, M.R. and Katz, B.J. eds., AAPG Memoir 73 - Petroleum systems of South Atlantic margins, p. 429–446.

**Holzförster, F., Stollhofen, H., and Stanistreet, I.**, 2000, Lower Permian deposits of the Huab area, Namibia: a continental to marine transition: Communications of the Geological Survey Namibia, v. 12, p. 247–257.

**Hyam, D.M., and Marshall, J.E.A.**, 1997, Carboniferous diamictite dykes in the Falkland Islands: v. 25, p. 505–517.

**Isbell, J.L. et al.**, 2021, Evaluation of physical and chemical proxies used to interpret past glaciations with a focus on the late Paleozoic Ice Age: Earth-Science Reviews, v. 221, p. 103756.

**Isbell, J.L., Cole, D.I., and Catuneanu, O.**, 2008, Carboniferous-Permian glaciation in the main Karoo Basin, South Africa: Stratigraphy, depositional controls, and glacial dynamics: Special Paper 441: Resolving the Late Paleozoic Ice Age in Time and Space, v. 441, p. 71–82.

**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.

1304  **James, D.E.**, 2003, Imaging crust and upper mantle beneath Southern Africa: The Southern Africa
1305      broadband seismic experiment: The Leading Edge, v. 22, p. 238–249.

1306  **Jelsma, H.A., de Wit, M.J., Thiart, C., Dirks, P.H.G.M., Viola, G., Basson, I.J., and Anckar, E.**,
1307      2004, Preferential distribution along transcontinental corridors of kimberlites and related rocks of
1308      Southern Africa: South African Journal of Geology, v. 107, p. 301–324.

1309  **Jerram, D., Mountney, N., Holzförster, F., and Stollhofen, H.**, 1999, Internal stratigraphic
1310      relationships in the Etendeka group in the Huab Basin, NW Namibia: understanding the onset of
1311      flood volcanism: Journal of Geodynamics, v. 28, p. 393–418.

1312  **Jerram, D.A., Mountney, N., Howell, J., and Stollhofen, H.**, 2000, The Fossilised Desert: recent
1313      developments in our understanding of the Lower Cretaceous deposits in the Huab Basin, NW
1314      Namibia: Communs geol. Surv. Namibia, v. 12, p. 303–313.

1315  **Jess, S., Stephenson, R., Jess, S., Stephenson, R., Roberts, D.H., and Brown, R.**, 2019, Differential
1316      erosion of a Mesozoic rift flank : Establishing the source of topography across Karrat , central
1317      West Greenland Geomorphology Differential erosion of a Mesozoic rift fl ank : Establishing the
1318      source of topography across Karrat , central West : Geomorphology, v. 334.

1319  **Johnson, M., Van Vuuren, C., Hegenberger, W.F., Key, R., and Shoko, U.**, 1996, Stratigraphy of
1320      the Karoo Supergroup in Southern Africa: an overview: Journal of African Earth Sciences, v. 23,
1321      p. 3–15.

1322  **Johnson, M.R., Van Vuuren, C.J., Visser, J.N.J., Cole, D.I., Wickens, H.D. V., Christie, A.D.M.,**
1323      **and Roberts, D.L.**, 1997, Chapter 12 The foreland karoo basin, south africa: Sedimentary Basins
1324      of the World, v. 3, p. 269–317.

1325  **Johnson, M., van Vuuren, C.J., Visser, J.N.J., Cole, D.I., Wickens, H. de V., Christie, A.D.M.,**
1326      **Roberts, D.L., and Brandl, G.**, 2006, Sedimentary rocks of the Karoo Supergroup, *in* Johnson,
1327      M.R., Anhaeusser, C.R., and Thomas, R.J. eds., Geology of South Africa, Johannesburg, Council
1328      for Geoscience, p. 461–500.

1329  **Kamp, U., and Owen, L.A.**, 2013, Polygenetic Landscapes: Treatise on Geomorphology, v. 5, p. 370–
1330      393.

1331  **Kessler, M.A., Anderson, R.S., and Briner, J.P.**, 2008, Fjord insertion into continental margins driven
1332      by topographic steering of ice: Nature Geoscience, v. 1, p. 365–369.

1333  **King, L.C.**, 1948, On The ages of African land-surfaces: Quarterly Journal of the Geological Society of
1334      London, v. 104, p. 439–459.

King, L.C., 1949a, On the ages of African landscapes: Geological Society of London Quaterly Journal, v. 104, p. 439–459.

King, L.C., 1951, South African Scenery: A textbook of geomorphology: London.

King, L.C., 1982, The natal monocline - explaining the origin and scenery of Natal, South Africa: Pietermaritzburg, 144 p.

King, L., 1949b, The Pediment Landform: Some Current Problems: Geological Magazine, v. 86, p. 245–250.

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: Bulletin of the Geological Society of America, v. 116, p. 348–367.

Knight, J., and Grab, S., 2015, The Drakensberg Escarpment: Mountain Processes at the Edge: World Geomorphological Landscapes, p. 47–55.

Korn, H., and Martin, H., 1959, Gravity tectonics in the Naukluft Mountains of South West Africa: Bulletin of the Geological Society of America, v. 70, p. 1047–1078.

Kounov, A., Viola, G., Dewit, M., and Andreoli, M.A.G., 2009, Denudation along the Atlantic passive margin: New insights from apatite fission-track analysis on the western coast of south africa: Geological Society Special Publication, p. 287–306.

Kounov, A., Viola, G., Dunkl, I., and Frimmel, H.E., 2013, Southern African perspectives on the long-term morpho-tectonic evolution of cratonic interiors: Tectonophysics, v. 601, p. 177–191.

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.

Lajeunesse, P., 2014, Buried preglacial fluvial gorges and valleys preserved through Quaternary glaciations beneath the eastern Laurentide Ice Sheet: Bulletin of the Geological Society of America, v. 126, p. 447–458.

Lajeunesse, P., Dietrich, P., and Ghienne, J.-F., 2018, Late Wisconsinan grounding zones of the Laurentide Ice Sheet margin off the Québec North Shore (NW Gulf of St Lawrence): Geological Society, London, Special Publications, v. 475.

Le Blanc Smith, G., 1980, Genetic stratigraphy for the Witbank coalfield: Transactions of the geological Society of South Africa, v. 83, p. 313–326.

Le Blanc Smith, G., and Eriksson, K, A., 1979, A fluvioglacial and glaciolacustrine deltaic

depositional model for Permo-Carboniferous coals of the Northeastern Karoo Basin, South Africa: Palaeogeography Palaeoclimatology Palaeoecology, v. 27, p. 67–84.

**Linol, B., and Wit, M.J. De**, 2016a, Origin and Evolution of the Cape Mountains and Karoo Basin (R. Oberhänsli, M. J. de Wit, & F. M. Roure, Eds.): Springer.

**Lister, L.A.**, 1987a, The Erosion Surfaces of Zimbabwe: Zimbabwe Geological Survey Bulletin No. 90,.

**Lithgow-Bertelloni, C., and Silver, P.G.**, 1998, Dynamic topography, plate driving forces and the African superswell: Nature 1998 395:6699, v. 395, p. 269–272.

**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.

**Lopes, G., Pereira, Z., Fernandes, P., Marques, J., Mendes, M., and Götz, A.E.**, 2021, Permian stratigraphy and palynology of the Lower Karoo Group in Mozambique – a 2020 perspective:

**López-Gamundí, O.R., and Buatois, L.A.**, 2010, Late Paleozoic glacial events and postglacial transgressions in Gondwana:

**Mabbutt, J.A.**, 1951, The evolution of the middle Ugab valley, Damaraland, South West Africa: Transactions of the Royal Society of South Africa, v. 33, 333–365 p.

**MacGregor, A.M.**, 1921, The geology of the diamond-bearing gravels of the Somabula Forest: Zimbabwe Geological Survey, Bulletin, v. 8, p. 38.

**Macgregor, D.S.** 2020, Regional variations in geothermal gradient and heat flow across the African plate: Journal of African Earth Sciences, v. 171, 103950

**Mackintosh, V., Kohn, B., Gleadow, A., and Gallagher, K.**, 2019, Tectonophysics Long-term reactivation and morphotectonic history of the Zambezi Belt , northern Zimbabwe , revealed by multi-method thermochronometry: v. 750, p. 117–136.

**Mackintosh, V., Kohn, B., Gleadow, A., and Tian, Y.**, 2017, Phanerozoic Morphotectonic Evolution of the Zimbabwe Craton: Unexpected Outcomes From a Multiple Low-Temperature Thermochronology Study: Tectonics, 36, p. 2044–2067.

**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.

**Martin, H.**, 1953, Notes on the Dwyka Succession and on some Pre-Dwyka Valleys in South West Africa.pdf: Geological Society of South Africa, v. 56, p. 37–41.

1397  **Martin, V.H.**, 1968, Pal ~ iomorphologische Formelemen ' te in den Landschaften Siidwest-Afrikas:

1398  **Martin, H.**, 1973a, Palaeozoic, Mesozoic and Cenozoic deposits on the coast of South-West Africa, *in*
1399  Sedimentary Basins of the African Coasts, Paris, Union Internationaledes Sciences Géologiques -
1400  Association of African Geological Surveys.

1401  **Martin, H.**, 1973b, The Atlantic margin of Southern Africa between Latitude 17° south and the Cape
1402  of Good Hope, *in* Nairn, A.E.M. and Stehli, F.G. eds., The ocean basins and margins - Volume 1
1403  The South Atlantic,.

1404  **Martin, H.**, 1961, The hypothesis of continental drift in the light of recent advances of geological
1405  knowledges Brazil and South-West Africa, *in* Alex. L. du Toit Memorial Lectures No. 7, v. LXIV.

1406  **Martin, B.H.**, 1981, The late Palaeozoic Gondwana glaciation:

1407  **Martin, H., and Schalk, K.**, 1959, Gletscherschliffe an der Wand eines U-Tales im nördlichen
1408  Kaokofeld, Südwestafrika: Geologische Rundschau, v. 46, p. 571–575.

1409  **Master, S.**, 2012, Hertzian fractures in the sub-dwyka nooitgedacht striated pavement, and implications
1410  forthe former thickness of karoo strata near Kimberley, South Africa: South African Journal of
1411  Geology, v. 115, p. 561–576.

1412  **Mckay, M.P. et al.**, 2015, U-PB zircon tuff geochronology from the Karoo Basin , South Africa :
1413  implications of zircon recycling on stratigraphic age controls: International Geology Review, v.
1414  57, p. 393–410.

1415  **McMillan, M.F., Boone, S.C., Kohn, B.P., Gleadow, A.J., and Chindandali, P.R.**, 2022,
1416  Development of the Nyika Plateau, Malawi: A Long Lived Paleo-Surface or a Contemporary
1417  Feature of the East African Rift?: Geochemistry, Geophysics, Geosystems, v. 23, e2022GC010390

1418  **Meadows, N.S.**, 1999, Basin evolution and sedimentary fill in the Palaeozoic sequences of the Falkland
1419  Islands: Geological Society Special Publication, v. 153, p. 445–464.

1420  **Meadows, M.E., and Compton, J.S.**, 2015, Table Mountain: Wonder of Nature at the Foot of Africa:
1421  World Geomorphological Landscapes, p. 95–102.

1422  **Medvedev, S., Hartz, E.H., and Faleide, J.I.**, 2018, Erosion-driven vertical motions of the circum
1423  Arctic: Comparative analysis of modern topography: Journal of Geodynamics, v. 119, p. 62–81.

1424  **Menozzo da Rosa, E., Isbell, J.L., McNall, N., Fedorchuk, N., and Swart, R.**, 2023, Gravitational
1425  resedimentation as a fundamental process in filling fjords: Lessons from outcrops from a late
1426  Palaeozoic fjord in Namibia: Sedimentology,.

1427  **Milani, E.J., and De Wit, M.J.**, 2008, Correlations between the classic Paraná and Cape–Karoo

1428 sequences of South America and Southern Africa and their basin infills flanking the Gondwanides:
1429 du Toit revisited: Geological Society, London, Special Publications, v. 294, p. 319–342.

1430 **Miller, R.**, 2011, Karoo Supergroup, *in* The Geology of Namibia, Ministry of Mines and Energy -
1431 Geological Survey of Namibia, p. 115.

1432 **Modie, B.N.**, 2002, Glacial records in Botswana: , p. 2002.

1433 **Modie, B.**, 2008, The palaeozoic palynostratigraphy of the Karoo supergroup and palynofacies insight
1434 into palaeoenvironmental interpretations , Kalahari Karoo Basin , Botswana

1435 **Molengraaf, G.A.F.**, 1898, The glacial origin of the Dwyka Conglomerate: Transactions of the
1436 geological Society of South Africa, v. IV, p. 103–115.

1437 **Montañez, I.P.**, 2021, Current synthesis of the penultimate icehouse and its imprint on the Upper
1438 Devonian through Permian stratigraphic record: in Lucas, SG, Schneider, J.W., Wang, X and
1439 Nikoleva, S (eds) The Carboniferous Timescale. Geological Society, London, Special Publication,
1440 v. 512,

1441 **Montañez, I.P., McElwain, J.C., Poulsen, C.J., White, J.D., Dimichele, W.A., Wilson, J.P., Griggs,
1442 G., and Hren, M.T.**, 2016, Climate, pCO2 and terrestrial carbon cycle linkages during late
1443 Palaeozoic glacial-interglacial cycles: Nature Geoscience, v. 9, p. 824–828.

1444 **Montañez, I.P., and Poulsen, C.J.**, 2013, The late Paleozoic ice age: An evolving paradigm: Annual
1445 Review of Earth and Planetary Sciences, v. 41, p. 629–656.

1446 **Moore, A.E., Cotterill, F.P.D., Broderick, T., and Plowes, D.**, 2009, Landscape evolution in
1447 Zimbabwe from the permian to present, with implications for kimberlite prospecting: South
1448 African Journal of Geology, v. 112, p. 65–88.

1449 **Moore, A.E., and Larkin, P.A.**, 2001, Drainage evolution in south-central Africa since the breakup of
1450 Gondwana: South African Journal of Geology, v. 104, p. 47–68.

1451 **Moore, A., and Moore, J.**, 2006, A glacial ancestry for the Somabula diamond-bearing alluvial deposit,
1452 Central Zimbabwe: South African Journal of Geology, v. 109, p. 625–636.

1453 **Moore, A.E., and Verwoerd, W.J.**, 1985, The olivine melilitite - kimberlite Carbonatite suite of
1454 Namaqualand and Bushmanland, South Africa: Transactions of the geological Society of South
1455 Africa, p. 281–294.

1456 **Moragas, M. et al.**, 2023, Paleoenvironmental and diagenetic evolution of the Aptian Pre-Salt
1457 succession in Namibe Basin (Onshore Angola): Marine and Petroleum Geology, v. 150.

1458 **Mottin, T.E., Vesely, F.F., de Lima Rodrigues, M.C.N., Kipper, F., and de Souza, P.A.**, 2018, The

paths and timing of late Paleozoic ice revisited: New stratigraphic and paleo-ice flow interpretations from a glacial succession in the upper Itararé Group (Paraná Basin, Brazil): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 490, p. 488–504.

**Moucha, R., and Forte, A.M.**, 2011, Changes in African topography driven by mantle convection: Nature Geoscience, v. 4, p. 707–712.

**Moulin, M., Aslanian, D., and Unternehr, P.**, 2010, A new starting point for the South and Equatorial Atlantic Ocean: Earth-Science Reviews, v. 98, p. 1–37.

**Mukasa, S.B., Wilson, A.H., and Carlson, R.W.**, 1998, A multielement geochronologic study of the Great Dyke, Zimbabwe: Significance of the robust and reset ages: Earth and Planetary Science Letters, v. 164, p. 353–369.

**Mvondo Owono, F., Ntamak-Nida, M.J., Dauteuil, O., Guillocheau, F., and Njom, B.**, 2016, Morphology and long-term landscape evolution of the South African plateau in South Namibia: Catena, v. 142, p. 47–65.

**Myers, T.S.**, 2016, Palaeoclimate: CO2 and late Palaeozoic glaciation: Nature Geoscience, v. 9, p. 803–804.

**Nyambe, I.A.**, 1999, Tectonic and climatic controls on sedimentation during deposition of the Sinakumbe Group and Karoo Supergroup, in the mid-Zambezi Valley Basin, Southern Zambia: Journal of African Earth Sciences, v. 28, p. 443–463.

**Oesterlen, P.M., and Millsteed, B.D.**, 1994, Lithostratigraphy, palaeontology, and sedimentary environments of the western Cabora Bassa Basin, Lower Zambezi Valley, Zimbabwe: South African Journal of Geology, v. 97, p. 205–224.

**Partridge, T.C.**, 1998, Of diamonds , dinosaurs and diastrophism : 150 million years of landscape evolution in Southern Africa: v. 01, p. 167–184.

**Partridge, T.C., and Maud, R.R.**, 1987, Geomorphic evolution of Southern Africa since the Mesozoic No Title: South African Journal of Geology, v. 90, p. 179–208.

**Partridge, T.C., and Maud, R.R.**, 2000, Macroscale geomorphic evolution of Southern Africa, *in* Partridge, T.C. and Maud, R.R. eds., The Cenozoic of Southern Africa, New York, Oxford University Press, p. 3–18.

**Paton, D.A., van der Spuy, D., di Primio, R., and Horsfield, B.**, 2008, Tectonically induced adjustment of passive-margin accommodation space; influence on the hydrocarbon potential of the Orange Basin, South Africa: American Association of Petroleum Geologists Bulletin, v. 92, p.

589–609.

Paul, J.D., 2021, Controls on eroded rock volume, a proxy for river incision, in Africa: Geology, v. 49, p. 422–427.

Paxman, G.J.G., Jamieson, S.S.R., Ferraccioli, F., Bentley, M.J., Ross, N., Armadillo, E., Gasson, E.G.W., Leitchenkov, G., and DeConto, R.M., 2018, Bedrock Erosion Surfaces Record Former East Antarctic Ice Sheet Extent: Geophysical Research Letters, v. 45, p. 4114–4123.

Pedersen, V.K., Huismans, R.S., and Moucha, R., 2016, Isostatic and dynamic support of high topography on a North Atlantic passive margin: Earth and Planetary Science Letters, v. 446, p. 1–9.

Pedersen, V.K., Larsen, N.K., and Egholm, D.L., 2019, The timing of fjord formation and early glaciations in North and Northeast Greenland: Geology, v. 47, p. 682–686.

Pfaffl, F.A., and Dullo, W.C., 2023, Early investigations of the Permo-Carboniferous glaciation of South Africa: International Journal of Earth Sciences, v. 112, p. 2199–2204.

Pickford, M., and Senut, B., 1997, Cainozoic mammals from coastal Namaqualand, South Africa: Palaeontologia Africana, v. 34, p. 199–217.

Ponte, J., 2018, La marge africaine du canal du Mozambique, le système turbiditique du Zambèze : une approche " source to sink " au Méso-Cénozoïque: Université de Rennes 1.

Ponte, J., Robin, C., Guillocheau, F., Popescu, S., and Suc, J., 2019, The Zambezi delta (Mozambique channel , East Africa): High resolution dating combining bio- orbital and seismic stratigraphies to determine climate (palaeoprecipitation) and tectonic controls on a passive margin: Marine and Petroleum Geology, v. 105, p. 293–312.

Prasicek, G., Larsen, I.J., and Montgomery, D.R., 2015, Tectonic control on the persistence of glacially sculpted topography: Nature Communications, v. 6.

Pysklywec, R.N., and Mitrovica, J.X., 1999, The role of subduction-induced subsidence in the evolution of the Karoo Basin: Journal of Geology, v. 107, p. 155–164.

Pysklywec, R.N., and Quintas, M.C.L., 1999, A mantle flow mechanism for the late Paleozoic subsidence of the Parana Basin: Journal of Geophysical Research, v. 105, p. 16,359-16,370.

Raab, M.J., Brown, R.W., Gallagher, K., Weber, K., and Gleadow, A.J.W., 2005, Denudational and thermal history of the Early Cretaceous Brandberg and Okenyenya igneous complexes on Namibia's Atlantic passive margin: Tectonics, v. 24, p. 1–15.

Rakotosolofo, N.A., Torsvik, T.H., Ashwal, L.D., Eide, E.A., and De Wit, M.J., 1999, The Karoo

Supergroup revisited and Madagascar-Africa fits, *in* Journal of African Earth Sciences, v. 29, p. 135–151.

**Reid, D.L.**, 2015, The Richtersveld: An Ancient Rocky Wilderness, *in* World Geomorphological Landscapes, Springer, Cham, p. 75–83.

**Ring, U.**, 1995, Tectonic and lithological constraints on the evolution of the Karoo graben of northern Malawi (East Africa): Geologische Rundschau, v. 84, p. 607–625.

**Roche, V., Leroy, S., Guillocheau, F., Revillon, S., Ruffet, G., Watremez, L., d'Acremont, E., Nonn, C., Vetel, W., and Despinois, F.**, 2021, The Limpopo Magma-Rich Transform Margin, South Mozambique – 2: Implications for the Gondwana Breakup: Tectonics, v. 40, p. 1–23.

**Roche, V., and Ringenbach, J.C.**, 2022, The Davie Fracture Zone: A recorder of continents drifts and kinematic changes: Tectonophysics, v. 823, p. 229188.

**Rolland, Y., Bernet, M., van der Beek, P., Gautheron, C., Duclaux, G., Bascou, J., Balvay, M., Héraudet, L., Sue, C., and Ménot, R.P.**, 2019, Late Paleozoic Ice Age glaciers shaped East Antarctica landscape: Earth and Planetary Science Letters, v. 506, p. 123–133.

**Rosa, E.L.M. da, Vesely, F.F., and França, A.B.**, 2016, A review on late Paleozoic ice-related erosional landforms in the Paraná Basin: origin and paleogeographical implications: Brazilian Journal of Geology, v. 46, p. 147–166.

**Rouby, D., Bonnet, S., Guillocheau, F., Gallagher, K., Robin, C., Biancotto, F., Dauteuil, O., and Braun, J.**, 2009, Sediment supply to the Orange sedimentary system over the last 150 My: An evaluation from sedimentation/denudation balance: Marine and Petroleum Geology, v. 26, p. 782–794.

**Rowe, C.D., and Backeberg, N.R.**, 2011, Discussion on: Reconstruction of the Ordovician Pakhuis ice sheet, South Africa by H.J. Blignault and J.N. Theron: South African Journal of Geology, v. 114, p. 95–102.

**Said, A., Moder, C., Clark, S., and Ghorbal, B.**, 2015, Cretaceous-Cenozoic sedimentary budgets of the Southern Mozambique Basin: Implications for uplift history of the South African Plateau: Journal of African Earth Sciences, v. 109, p. 1–10.

**Salles, T., Husson, L., Rey, P., Mallard, C., Zahirovic, S., Boggiani, B.H., Coltice, N., and Arnould, M.**, 2023, Hundred million years of landscape dynamics from catchment to global scale: Science, v. 379, p. 918–923.

**Salman, G., and Abdula, I.**, 1995, Development of the Mozambique and Ruvuma sedimentary basins,

1552    offshore Mozambique: Sedimentary Geology, v. 96, p. 7–41.

1553  **Salomon, E., Koehn, D., and Passchier, C.**, 2015, Brittle reactivation of ductile shear zones in NW
1554    Namibia in relation to South Atlantic rifting: Tectonics, v. 34, p. 70–85.

1555  **Schneider, G.**, 2004, The roadside Geology of Namibia: Berlin-Stuttgart, Gebr Borntraeger, 294 p.

1556  **Scholtz, A.**, 1985, The palynology of the Upper lacustrine sediments of the Arnot Pipe, Banke,
1557    Namaqualand: Annals of the South African Museum, v. 95, p. 1–109.

1558  **Schreiber, U.M.**, 2011, Sheet 1812 - Opuwo: Geological Map of Namibia - 1 : 250000,.

1559  **Senkans, A., Leroy, S., d'Acremont, E., Castilla, R., and Despinois, F.**, 2019, Polyphase rifting and
1560    break-up of the central Mozambique margin: Marine and Petroleum Geology, v. 100, p. 412–433.

1561  **Seward, A.C., and Holtum, B.A.**, 1921, On a collection of fossil plants from Southern Rhodesia:
1562    Zimbabwe Geological Survey, Bulletin, v. 8, p. 39–45.

1563  **Shone, R.W., and Booth, P.W.K.**, 2005, The Cape Basin, South Africa: A review: Journal of African
1564    Earth Sciences, v. 43, p. 196–210.

1565  **Siesser, W.G.**, 1980, Late Miocene Origin of the Benguela Upswelling System off Northern Namibia:
1566    Science, v. 208, p. 283–285.

1567  **Simoes, M., Braun, J., and Bonnet, S.**, 2010, Continental-scale erosion and transport laws: A new
1568    approach to quantitatively investigate macroscale landscapes and associated sediment fluxes over
1569    the geological past: Geochemistry, Geophysics, Geosystems, v. 11.

1570  **Slater, G., du Toit, A.L., and Haughton, S.H.**, 1932, The glaciated surfaces of nooitgedacht, near
1571    kimberley, and the upper dwyka boulder shales of the eastern part of griqualand west (cape
1572    province), 1929: Transactions of the Royal Society of South Africa, v. 20, p. 301–325.

1573  **Smith, R.M.H.**, 1990, A review of stratigraphy and sedimentary environments of the Karoo Basin of
1574    South Africa: Journal of African Earth Sciences (and the Middle East), v. 10, p. 117–137.

1575  **Smith, R.A.**, 1994, The lithostratigraphy of the Karoo Supergroup in Botswana (R. O. THE MINISTRY
1576    OF MINERAL RESOURCES AND WATER AFFAIRS & BOTSWANA, Eds.): Director,
1577    Geological Survey Department, Private Bag 14, Lobatse, Botswana, 256 p.

1578  **SMITH, R.M.H.**, 1986, Sedimentation and palaeoenvironments of Late Cretaceous crater-lake deposits
1579    in Bushmanland, South Africa: Sedimentology, v. 33, p. 369–386.

1580  **Smith, R.W., Bianchi, T.S., Allison, M., Savage, C., and Galy, V.**, 2015, High rates of organic carbon
1581    burial in fjord sediments globally: v. 8.

1582  **Smith, R.M.H., Eriksson, P.G.G., Botha, W.J.J., Smrrh, R.M.H., Epaksson, P.G., and Ha, W.J.B.**,
1583     1993, A review of the stratigraphy and sedimentary environments of the Karoo-aged basins of
1584     Southern Africa: Journal of African Earth Sciences, v. 16, p. 143–169.

1585  **Smith, R.M.H., and Swart, R.**, 2002, Changing Fluvial Environments and Vertebrate Taphonomy in
1586     Response to Climatic Dring in a Mid- Triassic Rift Valley Fill : The Omingonde Formnation (
1587     Karoo Supergroup ) of Central Namibia:

1588  **Stanley, J.R., Braun, J., Baby, G., Guillocheau, F., Robin, C., Flowers, R.M., Brown, R., Wildman,**
1589     **M., and Beucher, R.**, 2021, Constraining Plateau Uplift in Southern Africa by Combining
1590     Thermochronology, Sediment Flux, Topography, and Landscape Evolution Modeling: Journal of
1591     Geophysical Research: Solid Earth, v. 126.

1592  **Stanley, J.R., and Flowers, R.M.**, 2023, Localized Cenozoic erosion on the Southern African Plateau:
1593     A signal of topographic uplift? Geology, v. 51, p. 549–553.

1594  **Stanley, J.R., Flowers, R.M., and Bell, D.R.**, 2015, Erosion patterns and mantle sources of topographic
1595     change across the Southern African Plateau derived from the shallow and deep records of
1596     kimberlites: Geochemistry, Geophysics, Geosystems, v. 16, p. 3235–3256.

1597  **Stanley, J.R., Flowers, R.M., and Bell, D.R.**, 2013, Kimberlite (U-Th)/He dating links surface erosion
1598     with lithospheric heating, thinning, and metasomatism in the Southern African Plateau: Geology,
1599     v. 41, p. 1243–1246.

1600  **Steer, P., Huismans, R.S., Valla, P.G., Gac, S., and Herman, F.**, 2012, Bimodal plio-quaternary
1601     glacial erosion of fjords and low-relief surfaces in Scandinavia: Nature Geoscience, v. 5, p. 635–
1602     639.

1603  **Stollhofen, H., Werner, M., Stanistreet, I.G., and Armstrong, R. a**, 2008, Single-zircon U-Pb dating
1604     of Carboniferous-Permian tuffs, Namibia, and the intercontinental deglaciation cycle framework:
1605     Geological Society of America Special Papers, v. 441, p. 83–96.

1606  **Stone, P.**, 2016, Geology reviewed for the Falkland Islands and their offshore sedimentary basins, South
1607     Atlantic Ocean: Earth and Environmental Science Transactions of the Royal Society of Edinburgh,
1608     v. 106, p. 115–143.

1609  **Stratten, T.**, 1977, Conflicting directions of ice flow in the western Cape Province and Southern West
1610     Africa: Transactions of the Geological Society of South Africa, v. 80, p. 79–86.

1611  **Streel, M., and Theron, J.N.**, 1999, The Devonian-Carboniferous boundary in South Africa and the
1612     age of the earliest episode of the Dwyka glaciation: New palynological result: Episodes, v. 22, p.
1613     41–44.

1614     **Studt, F.E.**, 1913, The Geology of Katanga and Northern Rhodesia : An outline of the Geology of South
1615          Central Africa: Transactions of the Geological Society of South Africa, v. 16, p. 44–80.

1616     **Sugden, D., and Denton, G.**, 2004, Cenozoic landscape evolution of the Convoy Range to Mackay
1617          Glacier area, Transantartic Mountains: Onshore to offshore synthesis: Bulletin of the Geological
1618          Society of America, v. 116, p. 840–857.

1619     **Sutherland, P.C.**, 1870, Notes on an ancient boulder-clay of Natal: Geological Society of London,
1620          Quarterly Journal, v. 26.

1621     **Sutherland, P.C.**, 1868, The Geology of Natal (South Africa) (A. and Co, Ed.): Durban.

1622     **Tankard, A., Welsink, H., Aukes, P., Newton, R., and Stettler, E.**, 2009, Tectonic evolution of the
1623          Cape and Karoo basins of South Africa: Marine and Petroleum Geology, v. 26, p. 1379–1412.

1624     **Tedesco, J., Cagliari, J., Coitinho, J. dos R., da Cunha Lopes, R., and Lavina, E.L.C.**, 2016, Late
1625          Paleozoic paleofjord in the Southernmost Parana Basin (Brazil): Geomorphology and sedimentary
1626          fill: Geomorphology, v. 269, p. 203–214.

1627     **Thamm, A.., and Johnson, M.R.**, 2006, The Cape Supergroup, *in* The Geology of South Africa, p.
1628          443–460.

1629     **Thompson, J.O., Moulin, M., Aslanian, D., de Clarens, P., and Guillocheau, F.**, 2019, New starting
1630          point for the Indian Ocean: Second phase of breakup for Gondwana: Earth-Science Reviews, v.
1631          191, p. 26–56.

1632     **Tinker, J., de Wit, M., and Brown, R.**, 2008a, Linking source and sink: Evaluating the balance
1633          between onshore erosion and offshore sediment accumulation since Gondwana break-up, South
1634          Africa: Tectonophysics, v. 455, p. 94–103.

1635     **Tinker, J., de Wit, M., and Brown, R.**, 2008b, Mesozoic exhumation of the Southern Cape, South
1636          Africa, quantified using apatite fission track thermochronology: Tectonophysics, v. 455, p. 77–93.

1637     **Du Toit, A.L.**, 1921, The Carboniferous glaciation of South Africa: South African Journal of Geology,
1638          v. 24, p. 188–227.

1639     **Du Toit, A.L.**, 1927, A geological comparison of South America with South Africa: Carnegie Institution
1640          of Washington, Publication 381, 157 p.

1641     **Du Toit, A.L.**, 1933, Crustal movement as a factor in the geographical evolution of South Africa: The
1642          South African Geographical Journal, v. XVI.

1643     **Du Toit, A.L.**, 1937, Our wandering continents: an hypothesis of continental drifting (Oliver & Boyd,
1644          Eds.): Edinburgh, 366 p.

**Du Toit, A.L.**, 1954, The Geology of South Africa (S. H. Haughton, Ed.): London, Oliver and Boyd, 611 p.

**Torsvik, T.H., and Cocks, L.R.M.**, 2016, Earth History and Palaeogeography:

**Twidale, C.R.**, 1998, Antiquity of landforms: An 'extremely unlikely' concept vindicated: Australian Journal of Earth Sciences, v. 45, p. 657–668.

**Twidale, C.R.**, 2003, "Canons" revisited and reviewed: Lester King's views of landscape evolution considered 50 years later: Bulletin of the Geological Society of America, v. 115, p. 1155–1172.

**Veevers, J.J., Cole, D.I., and Cowan, E.J.**, 1994, Southern Africa: Karoo Basin and Cape Fold Belt: Memoir of the Geological Society of America, v. 184, p. 223–279.

**Vérité, J., Ravier, E., Bourgeois, O., Pochat, S., Lelandais, T., Mourgues, R., Clark, C.D., Bessin, P., Peigné, D. & Atkinson, N.,** 2021, Formation of ribbed bedforms below shear margins and lobes of paleo-ice streams: The Cryosphere, v. 15, p. 2889-2916.

**Vérité, J., Ravier, E., Bourgeois, O., Bessin, P. & Pochat, S.,** 2023, New metrics reveal the evolutionary continuum behind the morphological diversity of subglacial bedforms: Geomorphology, v. 427, 108627.

**Vérité, J., Ravier, E., Bourgeois, O.,Pochat, S., & Bessin, P.,** 2024, The kinematic significance of subglacial bedforms and their use in palaeo-glaciological reconstructions: Earth and Planetary Science Letters, v. 626, 118510

**Viljoen, M.**, 2015, The Kruger National Park: Geology and the Geomorphology of the Wilderness, *in* Grab, S., Knight, J. ed., Landscapes and Landforms of South Africa, Springer International Publishing, p. 111–120.

**Visser, J.N.J.**, 1982, Upper Carboniferous glacial sedimentation in the Karoo Basin near Prieska, South Africa: Palaeogeography Palaeoclimatology Palaeoecology, v. 38, p. 63–92.

**Visser, J.N.J.**, 1983, Glacial-Marine Sedimentation in the Late Paleozoic Karoo Basin, Southern Africa, *in* Glacial-Marine Sedimentation, Boston, MA, Springer US, p. 667–701.

**Visser, J.N.J.**, 1985, The Dwyka Formation along the north-western margin of the Karoo Basin in the Cape Province, South Africa: South African Journal of Geology, v. 88, p. 37–48.

**Visser, J.N.J.J.**, 1987a, The influence of topography on the Permo-Carboniferous glaciation in the Karoo Basin and adjoining areas, Southern Africa, *in* Garry D. McKenzie ed., Gondwana Six: Stratigraphy, Sedimentology, and Paleontology, Volume 41, American Geophysical Union, v. 41, p. 123–129.

Visser, J.N.J., 1987b, The palaeogeography of part of southwestern Gondwana during the Permo-Carboniferous glaciation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 61, p. 205–219.

Visser, J.N.J., 1989, The Permo-Carboniferous Dwyka Formation of Southern Africa: deposition by a predominantly subpolar ice sheet: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 70, p. 377–391.

Visser, J., 1990, The age of the late Palaeozoic glacigene deposits in Southern Africa: South African Journal of Geology, v. 93, p. 366–375.

Visser, J.N.J., 1992, Deposition of the early to late Permian Whitehill Formation during a sea-level highstand in a juvenile foreland basin: South African Journal of Geology, v. 95, p. 181–193.

Visser, J.N.J., 1993, Sea-level changes in a back-arc-foreland transition; the Late Carboniferous Permian Karoo Basin of South Africa: Sedimentary Geology, v. 83, p. 115–131.

Visser, J.N.J., 1994, The interpretation of massive rain-out and debris-flow diamictites from the glacial marine environment, *in* Earth's Glacial Record, p. 83–94.

Visser, J.N.J., 1997, Deglaciation sequences in the Permo-Carboniferous Karoo and Kalahari basins of Southern Africa: A tool in the analysis of cyclic glaciomarine basin fills: Sedimentology, v. 44, p. 507–521.

Visser, J.N.J., and Hall, K.J., 1985, Boulder beds in the glaciogenic Permo-Carboniferous Dwyka Formation in South Africa: Sedimentology, v. 32, p. 281–294.

Visser, J.N.J., and Kingsley, C.S., 1982, Upper Carboniferous glacial valley sedimentation in the Karoo Basin, Orange Free State: Transactions of the geological Society of South Africa, v. 85, p. 71–79.

Visser, J.N.J., and Loock, J.C., 1987, Ice margin influence on glaciomarine sedimentation in the Permo—Carboniferous Dwyka Formation from the southwestern Karoo, South Africa: Sedimentology, v. 34, p. 929–941.

Visser, J.N.J., and Loock, J., 1988, Sedimentary facies of the Dwyka Formation associated with the Nooitgedacht glacial pavements, Barkly West District: South African Journal of Geology, v. 91, p. 38–48.

Von Brunn, V. 1994, Glaciogene deposits of the Permo-Carboniferous Dwyka Group in the eastern region of the Karoo Basin, South Africa (M. Deynoux, J. M. G. Miller, E. W. Domack, N. Eyles, I. Fairchild, & G. M. Young, Eds.): Earth's Glacial Record, v. 5, p. 60–69.

Von Brunn, V., 1996, The Dwyka Group in the northern part of Kwazulu/Natal, South Africa:

1707    Sedimentation during late palaeozoic deglaciation: Palaeogeography, Palaeoclimatology,
1708        Palaeoecology, v. 125, p. 141–163.

1709    **Wagner, P.A.**, 1915, The Dwyka series in South-West Africa: Transactions of the geological Society
1710        of South Africa,.

1711    **Walford, H.L., White, N.J., and Sydow, J.C.**, 2005, Solid sediment load history of the Zambezi Delta:
1712        v. 238, p. 49–63.

1713    **Waren, R., Cartwright, J.A., Daly, M.C., and Swart, R.**, 2023, Late Cretaceous to Early Cenozoic
1714        initiation of rifting of the Windhoek Graben, Namibia: South African Journal of Geology, v. 126,
1715        p. 195–216.

1716    **Wellington, J.H.**, 1955, Southern Africa: a Geographical suty, *in* Physical Geography, New York,
1717        Cambridge Univiersity Press, p. 528 pp.

1718    **Wellington, J.H.**, 1937, The Pre-Karroo peneplain in the South-Central Transvaal: South African
1719        Journal, v. XXXIII, p. 281–295.

1720    **Werner, M., and Lorenz, V.**, 2006, The stratigraphy, sedimentology, and age of the Late Palaeozoic
1721        Mesosaurus Inland Sea, SW-Gondwana: Geological Institute, p. 428.

1722    **Wildman, M., Brown, R., Watkins, R., Carter, A., Gleadow, A., and Summerfield, M.**, 2015, Post
1723        break-up tectonic inversion across the southwestern cape of South Africa: New insights from
1724        apatite and zircon fission track thermochronometry: Tectonophysics, v. 654, p. 30–55.

1725    **Wildman, M., Brown, R., Beucher, R., Persano, C., Stuart, F., Gallagher, K., Schwanethal, J., and**
1726        **Carter, A.**, 2016, The chronology and tectonic style of landscape evolution along the elevated
1727        Atlantic continental margin of South Africa resolved by joint apatite fission track and (U-Th-
1728        Sm)/He thermochronology: Tectonics, v. 35, p. 511–545.

1729    **Wildman, M., Brown, R., Persano, C., Beucher, R., Stuart, F.M., Mackintosh, V., Gallagher, K.,**
1730        **Schwanethal, J., and Carter, A.**, 2017, Contrasting Mesozoic evolution across the boundary
1731        between on and off craton regions of the South African plateau inferred from apatite fission track
1732        and (U-Th-Sm)/He thermochronology: Journal of Geophysical Research: Solid Earth, v. 122, p.
1733        1517–1547.

1734    **De Wit, M.C.J.**, 2016, Early permian diamond-bearing proximal eskers in the Lichtenburg/Ventersdorp
1735        area of the North West province, South Africa: South African Journal of Geology, v. 119, p. 585–
1736        606.

1737    **De Wit, M.C.J.**, 1999, Post-Gondwana drainage and the development of diamond placers in western

1738      South Africa: Economic Geology, v. 94, p. 721–740.

1739    **Wopfner, H., and Diekmann, B.**, 1996, The Late Palaeozoic Idusi Formation of southwest Tanzania:
1740      A record of change from glacial to postglacial conditions: Journal of African Earth Sciences, v.
1741      22, p. 575–595.

1742    **Wopfner, H., and Kreuser, T.**, 1986, Evidence for late palaeozoic glaciation in Southern Tanzania:
1743      Palaeogeography, Palaeoclimatology, Palaeoecology, v. 56, p. 259–275.

## Figure captions

1745 Fig. 1: (a) Modern relief of Southern Africa shown by Digital Elevation Model (DEM) from Shuttle
1746 Radar Topographic Mission (https://www2.jpl.nasa.gov/srtm/) along with major river networks,
1747 international borders and main cities. The transect highlights the high-standing plateaus. (b) Southern
1748 Africa with regions of interest discussed in the text shown by red frame. The Archean to
1749 Paleoproterozoic Congo, Kaapvaal and Zimbabwe cratons are evidenced by thick orange lines and
1750 Karoo basins are represented by grey shaded area. The glaciogenic Dwyka group is represented by pink
1751 colour. The four paleohighlands discussed in the text are evidenced in green. Inset map shows western
1752 Gondwana formed by Africa and South America. Transect displays the thickness and sedimentary
1753 succession of Main Karoo Basin (MKB) of South Africa, the glaciogenic Dwyka Group in pink, the
1754 glacial erosion surface (wavy pink line) at the base of the Karoo Supergroup and the underlying
1755 basement structure (cratons vs. accreted terranes). Transect modified after Johnson et al., 1996 and
1756 Karoo basins after Catuneanu et al., 1998.

1757

1758 Fig. 2: (a) DEM of the Kaoko region of Northern Namibia, corresponding to the Kaoko paleohighland.
1759 The escarpments, valleys and tongue-shaped troughs discussed in the text are arrowed. Location of the
1760 pictures are also indicated. Figure 1b for location. (b) the Gomatum valley corresponds to a fjord carved
1761 during the LPIA, later sealed and exhumed in recent times. See Dietrich et al., 2021 for further details.
1762 Valley is ca. 2.5 km wide and 550 m deep. (c) A field of *roches moutonnées* and whalebacks
1763 characterized by glacial striae and grooves and polished floors covered in places by boulder pavement,
1764 evidencing a westward ice movement. Circled geologist for scale, see Le Heron et al. (2024) for details.
1765 (d) Striated floor in the Kunene valley, plucking at the joint shows ice movement from east to west.
1766 Picture from Martin, 1961; (e) Glacially polished walls and (f) floor in NE Kaoko. Pictures taken by
1767 K.E.L. Schalk, geologist Henno Martin for scale, see Miller (2011).

1768

1769 Fig. 3: Geological map indicating the Karoo Supergroup and morphostratigraphic transects across the
1770 Kaoko highland, highlighting the morphology of the Kunene, Kaoko, Huab-Ugab regions and the
1771 associated glacial valleys and troughs. Etendeka lavas are represented in green, non-glaciogenic Karoo

1772 sediments in yellow and glaciogenic Dwyka Group in pink, or indicated by pink arrows. Black dashed

1773 lines on the map represent outlines of exhumed glacial reliefs and valleys; solid purple lines on

1774 morphostratigraphic transects represent glacial surfaces and dashed purple lines represent suspected

1775 glacial surfaces. Bedrock in grey indicates substrate older than the Karoo Supergroup Note that this

1776 colouration is consistently used throughout the manuscript. Fig. 1b for location.

1777

1778 Fig. 4: (a) DEM of the western coastal Kaoko region and (b) morphostratigraphic transect. In the Purros

1779 canyon are remnants of glaciogenic sediments, and therefore the canyon is tentatively interpreted here

1780 as a relict glacial landform. See Fig. 2 for location.

1781

1782 Fig. 5: (a) DEM of the Windhoek highland (central Namibia), (b) their morphostratigraphic transects.

1783 And (c) mosaic picture of the U-shaped Nausgamab valley interpreted by Martin (1961) as a potential

1784 glacial valley (see also Miller, 2011). Faupel (1974) reported glaciogenic sediments in the vicinity of

1785 this valley; (d) DEM of the Naukluft mountain crosscut by the U-shaped Tsondab valley interpreted by

1786 Korn & Martin (1959) and Martin (1961) as a glacial valley. (e) morphostratigraphic transect and (f)

1787 picture of the Tsondab valley. Fig. 1b for location.

1788

1789 Fig. 6: DEM of the SW Cargonian Highland (central South Africa and Southern Botswana; Fig. 1b for

1790 location) and associated geological transects. Widespread Dwyka outcrops in the Kaap valley visible in

1791 the landscape interpreted here as an exhumed glacial valley. Diamonds represent kimberlite pipes used

1792 for reconstruction in fig. 11. Inset photo: close-up view of the Nooitgedacht glacial pavement

1793 (whaleback) in Slater (1932). Circled hammer on the left for scale.

1794

1795 Fig. 7: (a) DEM of the central Cargonian Highland (Johannesburg-Pretoria-Witwatersrand area on the

1796 Kaapvaal craton, central South Africa). Fig. 1b for location. The Mooi and Harts river valleys,

1797 highlighted by white dashed lines, and the surrounding areas, are interpreted by De Wit (2016) as an

1798 exhumed glacial surface. Similarly, the Witbank region to the east, and the Vredefort dome to the south

1799 are also interpreted as exhumed glacial surfaces (see text for detail). In between, the Witwatersrand

1800 region, the Magaliesburg range, the Pilanesberg dome and the cities of Johannesburg and Pretoria also

1801 probably sit on a glacial surface, although further work needs to be done to confirm such a hypothesis.

1802 (b) View of the Vredefort dome area where the Vaal river valley shows a U-shaped profile reminiscent

1803 of glacial erosion. A small portion of the Vaal River floodplain is seen at centre-right (Fig. 4.5 in Gibson

1804 & Reimold, 2015)

1805

1806 Fig. 8: (a) DEM of the eastern Cargonian Highland (edge of the Main Karoo Basin; Kaapvaal craton,

1807 eastern South Africa) and morphostratigraphic transect highlighting the Tugela valley as an exhumed

glacial landscape. Fig. 1b for location. See Details in Dietrich & Hofmann (2019). (b) Bank of the Buffalo River exhuming a glacial valley. Stratified, steeply-dipping rock on the right corresponds to Archean Pongola Supergroup quartzite into which steep-flanked relief were carved and upon which coarse-grained deposits corresponding to glaciogenics of the Dwyka Group are plastered. Although the Dwyka sediments are steeply-dipping on the flank of the (paleo)valley, they become horizontal in the river thalweg. Circled geologist for scale; (c) Landscapes of rolling hills corresponding to an exhumed glacial landscape. The relief is carved into Archean Pongola quartzite seen in the foreground: topographic lows preserve remnants of glaciogenic sediments whose bulk has been eroded away by recent erosion, resurrecting the glacial landscape. Striated pavements, such as the ones showcase on fig. 7d and 7e, characterize basement floors. (d) Striated floors carved onto volcanic rocks of Archean greenstone belt, plucking of the joint at the foreground indicate an SSW ice movement. (e) Striated and polished glacial floor exposed in a stream, and showcasing a small-scale *roche moutonnée* behind the circled hammer, evidencing an ice movement to the SSW. The glacial floor is still covered in place by remnants of glaciogenic sediments. (f) A U-shaped trough, 800 m wide and 100 m deep carved by glacial erosion into Archean Pongola quartzites. Remnants of glaciogenic sediments are still present. Picture from Dietrich & Hofmann (2019).

Fig. 9: DEM of the Zimbabwe Highland (central Zimbabwe) and morphostratigraphic transects across the Great Dyke, the Mwanesi Greenstone Belt and the Somabula region. The reader is redirected to Moore & Moore (2006), Moore et al. (2009) and Lister (1986) for further details. Fig. 1b for location.

Fig. 10: (a) Synthesis of glacial paleolandscapes at the scale of Southern Africa. Dark pink indicates attested glacial surface and light pink indicates suspected glacial surfaces whose compilation is based on the presence of glacial morphological features (see text for details). Dark grey regions are Karoo basins. Exhumed paleo-escarpments are represented by black bold lines and escarpments still buried under sediments are after Visser, 1987a, 1987b. Light orange region corresponds to surficial sediments of the Kalahari Desert, after Haddon (2005). (b) Proposed paleogeographic reconstruction of Southern Africa at the end of the LPIA. Blue-grey areas represent highlands whose names are written in green, sedimentary basins are represented in dark yellow where attested or light yellow where suspected. Escarpments delineating the highlands from the basins and glacial valleys carved into it are represented as bold solid lines where attested or as dashed lines where suspected (see Visser, 1987a, 1987b). Hills or mountainous regions are also indicated. Region where no data is available mostly corresponds to the Kalahari Desert – see fig. 10a above. Names of glacial valleys and escarpments refer to those discussed in the text to which the reader is redirected for further details.

Fig. 11: Burial-exhumation history models the Kaoko (Fig. 2), Cargonian (Fig. 6) and Zimbabwe (Fig. 9) highlands. Thermochronological inferences are provided in the graphs, exhumation evidenced from

1844     kimberlites for the Cargonian Highlands are displayed in red and sediment volume accumulated on the

1845     continental margins are showcased in yellow. Raab et al. (2005), Krob et al. (2019) and Margirier et al.

1846     (2019) for the Kaoko; Stanley et al. (2015, 2019, 2021) and Wildman et al., 2015 for central south Africa

1847     and Mackintosh et al. (2017) for central Zimbabwe.

1848

1849     Fig. 12: (a) Structural map of the Kaoko Highland (Figs 2 and 3), faults are after Goscombe & Gray

1850     (2008) and two alternative models for the evolution of the escarpments and the associated valleys before

1851     the LPIA, as follows: Hypothesis 1 implies that the relief created at the end of the Pan-African orogeny

1852     around 480 Myr was entirely levelled down before the LPIA and rejuvenated owing to vertical crustal

1853     movements during or immediately prior the LPIA whose ice flow carved valleys into it. Hypothesis 2

1854     implies that the relief created by the Pan-African orogeny was only partly eroded during the time interval

1855     between the Pan-African orogeny and the LPIA and was amplified by glacial processes. The first stage

1856     representing the end of the Pan-African orogeny – extension tied to post-orogenic collapse – is common

1857     to both hypothesis and derived from Goscombe & Gray (2008). (b) Structural map of the Main Karoo

1858     Basin and the Cargonian Highlands; faults are after Tankard et al. (2009); and proposed model for the

1859     carving of the Kaap valley (Fig. 6) that corresponds to a headward retreat of the valley due to glacial

1860     erosion from the offsetting Doringsberg fault. See text for details.