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

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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 280Myr 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 river drainage network of some transects of the main rivers of southern Africa.

Glacial landforms have survived over hundreds of million years. This preservation and modern exposure were achieved through burial under piles of Karoo sediments and lavas over ca. 120 to 170 million years and a subsequent exhumation since the middle Mesozoic owing 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 allowed 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 whose offset likely operated before the LPIA, and on which glacial processes are marked under the form of striae. Also, some hill or mountain ranges already existed by LPIA times, likely an expression of Pan-African orogenic belts, whose relief was either reactivated or persisted since then, and was ultimately modelled by glacial erosion. We finally propose that a network of alluvial valleys existed before the LPIA, as southern Africa experienced a long period of exhumation and erosion, and that later served as funneling ice flows from highlands to lowlands.

These 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

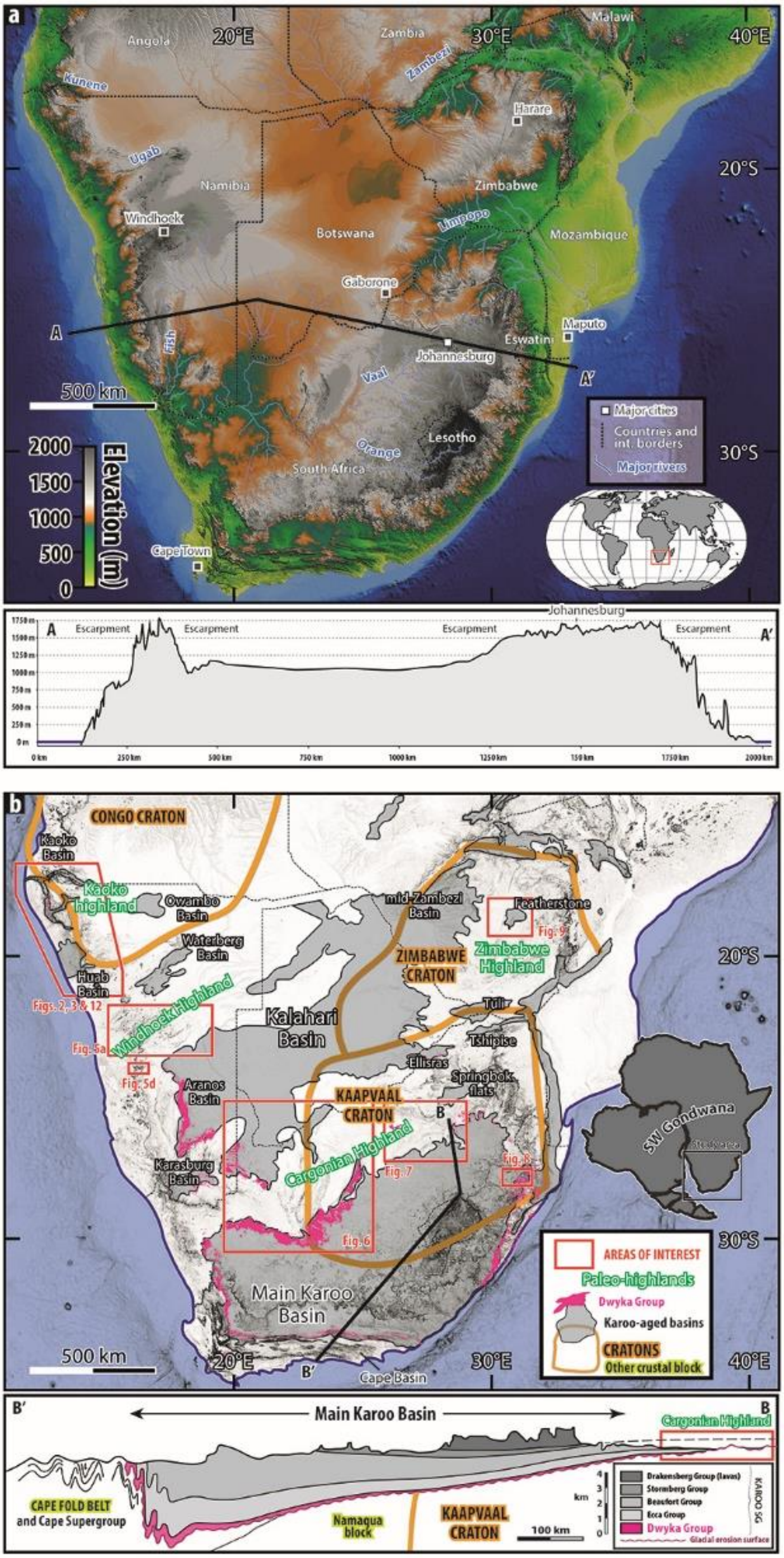

Fig. 1: (a) Modern relief of Southern Africa shown by Digital Elevation Model (DEM) from Shuttle Radar Topographic Mission (https://www2.jpl.nasa.gov/srtm/) along with major river networks, international borders and main cities. The transect highlights the high-standing plateaus. (b) Southern Africa 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
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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.

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

Southern Africa is rooted by three Archean to Paleoproterozoic cratons -the Kaapvaal, Zimbabwe and Congo cratons (Fig. 1b)- that amalgamated via younger terranes during orogenic events throughout the Proterozoic (Tankard et al., 2009; Begg et al., 2015; Torsvik and Cocks, 2016). The assembly of Gondwana, which Southern Africa was part of, occurred through the Pan-African orogeny, at the end of the Proterozoic and early Paleozoic. In southern Africa, this orogeny involved the Congo and Kalahari cratons, the later comprising the already-coalesced Kaapvaal and Zimbabwe cratons, to form the Damara branch of the Panafrican orogeny. The collision between the Rio de la Plate and Congo cratons formed the Kaoko branch, whilst the Gariep and Saldania Belts reflect the Kalahari and Rio de la Plata closure, between ca. 580 and 510 Ma (Begg et al., 2009; Lehmann et al., 2016; Goscombe et al., 2017). This period of acute tectonic activity and its aftermath is reflected by a continuous exhumation since at least 600 Ma over orogenic terrains (Krob et al., 2019) and since 1 Ga over the cratons (Baughmann & Flowers, 2019) until ca. 300 Ma, as expressed by thermochronology cooling. Localised subsidence marked the Cape region from the Cambrian to the lower Carboniferous with deposition of the Cape Supergroup, ca. 3.000 m-thick, deposited likely due to rifting and lithospheric deflection due to subduction-driven mantle flow (Fig. 1b, Theron, 1972; Streel and Theron, 1999; Shone and Booth, 2005; Thamm and Johnson, 2006; Tankard et al., 2009; Fourie et al., 2011, Penn-Clarke et al., 2020). The Cape Basin has then been deformed and inverted during the Cape orogeny and today crops out over ca. 90.000 km² in the Cape Fold Belt at the southern tip of South Africa. This orogen, the only orogenic event that affected the rest of Southern Africa throughout the Phanerozoic, initiated during the Permian-Triassic and was induced by the subduction of the Panthalassic Ocean (Hansma et al., 2016).

From the Late Paleozoic (Carboniferous) to early Mesozoic, large regions of Southern Africa over which erosion previously prevailed, were then subsiding, which promoted the deposition of thick sediment piles in large sedimentary basins named 'Karoo basins'. These basins lie over the basement and the Cape Basin and occupy vast areas, 10^3-10^6 km², and are named after the Main Karoo Basin (MKB) of South Africa, the thickest (5-6 km), largest (ca. 700.000 km²), and most studied of these basins, investigated since at least the mid-XIXth (see Linol and de Wit, 2016). Together, the Karoo basins of southern Africa cover an area of ca. 1.600.000 km², among which ca. 800.000 km² are subcrop, mostly covered by younger sediments of the Kalahari Desert (Fig. 1b, Catuneanu et al., 2005; Haddon, 2005). The volcano-sedimentary pile that forms these Karoo basins -the Karoo Supergroup- can be up to 5 km thick and ranges in age from Carboniferous to Jurassic (in South Africa and Zimbabwe) or Cretaceous (in northern Namibia) (Stratten, 1977; Smith, 1990; Smith et al., 1993a; Johnson et al., 1996; Catuneanu et al., 2005; Milani and De Wit, 2008; Franchi et al., 2021). Depositional environments within the Karoo Supergroup range, from base to top, from glacial (the Dwyka Group), marine (Ecca & Beaufort groups), continental and aeolian (Stormberg Group) and finally subaerial lava outpouring (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 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 Groupis 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 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 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, 1933, 1937;

Martin and Schalk, 1959; Martin, 1961, 1973b, 1973a; see also Haughton, 1949; Milani and De Wit, 2008; Miller, 2011; Linol and de Wit, 2016; Pfaffl and Dullo, 2023)

The Karoo basins are separated by cratonic regions over which no or very thin Dwyka and Karoo deposits lie. Wedging out and onlap of Karoo strata against these regions, depositional environments of the Dwyka Group pointing toward a continental ice sheet and the presence of high glacial relief together indicate that these areas correspond to highlands that already existed during the deposition of the Dwyka Group, and hereafter referred to as *paleohighlands* (Fig. 1b, Visser, 1985, 1987a, 1987b, 1997; Smith et al., 1993a; Catuneanu et al., 1998, 2005; Isbell and Cole, 2008). Four paleohighlands exist over Southern Africa: the Kaoko, Windhoek, Cargonian and Zimbabwe, underlain by resistant Archean to Paleoproterozoic basement rocks that form craton and/or shield areas (Fig. 1b). It is over these paleohighlands or on their rims marked by escarpments that most of the glacial landforms and erosion surfaces are observed. These morphological features encompass a range of landform types and shapes ranging from small ($10^{-2\text{-}0}$ m: striae and grooves) to intermediate ($10^{0\text{-}3}$ m: *roches moutonnées*, cirques, whalebacks, and crag-and-tails), and large scale ($10^{4\text{-}6}$ m: fjords, troughs, overdeepenings and area scouring) glacial forms and landsurfaces (Benn and Evans, 2010; Dietrich et al., 2019, 2021). These glacial erosion surfaces have been named ‘ancestral glacial pre-Karoo peneplain’ (Wellington, 1937), ‘pre-Dwyka topography’ (Du Toit, 1954; von Gottberg, 1970b) or ‘Pre-Karoo Surface’ (Lister, 1987). It is indeed generally assumed that they were carved during the LPIA, immediately before the deposition of the Karoo Supergroup that started with the glaciogenic Dwyka Group, although their potential pre-LPIA origin has been recognised previously and is discussed below (section 4.1). These glacial erosion forms are the main focus of the present contribution for which a review and new constraints are provided below (section 3 and figures 2 to 8).

As no major orogenic event affected the region after the deposition of the Karoo Supergroup (Torsvik and Cocks, 2016), except for the localized Permian-Triassic Cape orogeny, glacial paleorelief have preserved their original shape and orientation and Dwyka strata lie mostly horizontally. Though there is slight and local tilt of the Karoo strata in regions which are attributed to vertical motions of the lithosphere induced by the activity of the African superplume or isostatic processes linked to the Atlantic passive margin.

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

Following the break-up of Gondwana which is defined by the opening of the Indian and Atlantic oceans in the early Jurassic and early Cretaceous (Frizon De Lamotte et al., 2015; Thompson et al., 2019; Roche et al., 2021; Roche and Ringenbach, 2022), lithospheric movements were mostly vertical in response to the African mantle ‘superplume’. Pulses in the activity of this plume led to episodes of swelling and 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 (assessment of sediment routing, characterization of kimberlite pipes etc.) 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

thermochronological data show that Cenozoic erosion focused along the present-day river valleys rather than being broadly distributed as during the Middle Cretaceous (Stanley and Flowers, 2023).

Although each pulse of uplift and therefore erosion is thought to be recorded as a planation surface, it has been suggested that very ancient, possibly Jurassic or older, landsurfaces are preserved across southern Africa, older than the initiation of uplift of southern Africa and predating the dislocation of Gondwana, and called the ‘Gondwana surface’ (Du Toit, 1933; King, 1949a, 1949b, 1982; Doucouré and de Wit, 2003).

1. Glacial paleorelief of Southern Africa

In the following section, we describe and review the geomorphology and sedimentary infill of glacial landforms preserved across the paleohighlands of Namibia (the Kaoko and Windhoek highlands, section 3.1 and 3.2), South Africa and Botswana (the Cargonian Highland, section 3.3) and Zimbabwe (the Zimbabwe Highland, section 3.4) (Fig. 1). This is done by combining novel field and aerial/satellite observations, digital elevation model (DEM) from Shuttle Radar Topographic Mission (SRTM, https://www2.jpl.nasa.gov/srtm/) and geological maps analysis as well as an assessment of existing literature. We provide morphostratigraphic transects evidencing the presence of glacially-carved relief and the presence of glaciogenic Dwyka sediments based on geological maps and digital elevation models (fig. 3 to 9).

Based on these data, we provide description and interpretation of the glacial paleorelief and the glaciogenic sedimentary rocks hosted within glacial relief wherever present. Possible pre-glacial origin (surficial expression of tectonic structures enhanced by glacial erosion or older non-glacial erosional forms later re-exploited by glacial erosion) is discussed in section 4.1. For each study site, we present evidence for glacial processes (plain pink line on transects on fig. 2 to 9) or, for suspected glacial landscapes, we provide supporting data and discuss their potential glacial origin (dotted pink line on transects on fig. 2 to 9). For these latter cases, additional field-based examinations targeting striated pavements or other evidence for glacial activity would be required to confirm their glaciogenic nature. Erosion and resulting landforms of mountain glaciers that existed locally during the Quaternary will not be considered in this study (Hall and Meiklejohn, 2011; Knight and Grab, 2015).

The Kaoko Highland

The Kaoko region of NW Namibia is formed by a plateau that stands at ~1000 m.a.s.l. and is located at the boundary between the Congo Craton and the Kaoko branch of the Panafrican orogenic belt (Figs. 1 and 2). This plateau is bordered to the west by a succession of stair-like escarpments (that may correspond to surficial expression of crustal-scale faults, see below) leading to the Atlantic Ocean through a gently inclined, ~50 km-wide coastal plain. Eastward, the plateau leads toward the low relief of the Kalahari plains. On the northern half of the Kaoko region, a network of E-W-oriented valleys, in which modern rivers flow toward the Atlantic, deeply dissect both the plateau and the escarpments. Tongue-shaped troughs, N-S-oriented, are also incised within the highland or at the feet of the escarpments. These troughs either connect with the river network or are endorheic. The southern half of the Kaoko region is characterized by a plateau separated on its western side from the coastal plain by a single escarpment.

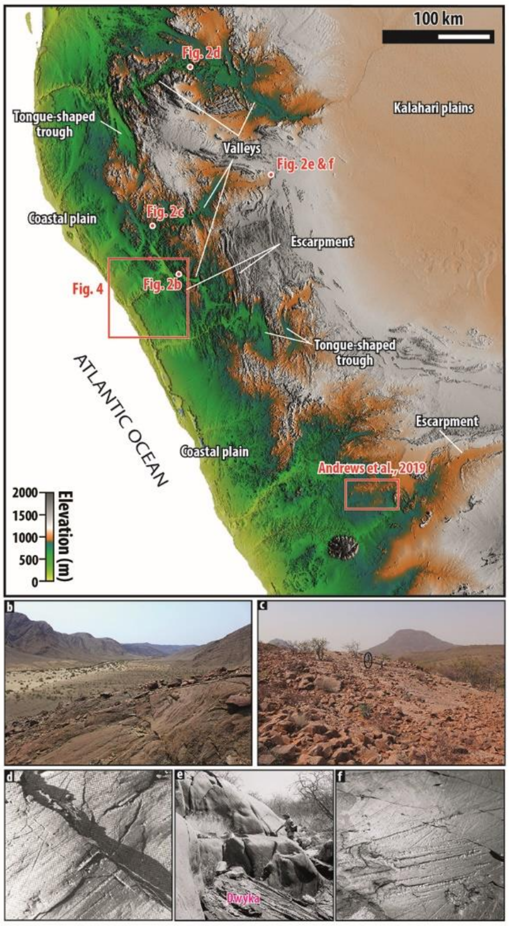


Fig. 2: (a) DEM of the Kaoko region of Northern Namibia, corresponding to the Kaoko paleohighland. The escarpments, valleys and tongue-shaped troughs discussed in the text are arrowed. Location of the pictures are also indicated. Figure 1b for location. (b) the Gomatum valley corresponds to a fjord carved 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).

In the northern region of the Kaoko Highland, a network of E-W oriented valleys between the Kunene River to the North and the Hoanib River to the South has been interpreted by Dietrich et al. (2021) as an exhumed glacial landscape (Figure 3). These valleys are U-shaped and their floors and subvertical flanks commonly display abundant small-scale hard-bed glacial erosion features such as striae, grooves, whalebacks and *roches moutonnées* (Fig. 2, see also Fedorchuk et al., 2023). Paleovalleys in Angola that cut through the escarpment may also correspond to glacial valleys (Moragas et al., 2023). In places, these glacial erosion features are covered with remnants of glaciogenic sediments of the Dwyka Group (Fig. 3), including frontal and lateral moraines and glaciomarine sediments such as ice-rafted debris scattered in shales (Fig. 2; see also Martin and Schalk, 1959; Dietrich et al., 2021; Menozzo da Rosa et al., 2023), and fig. 16.1 in Miller (2011)). These glaciogenic sediments are typically found abutting against the valley walls (Fig. 3; Le Heron et al., 2024). Based on the relict glaciogenic forms and associated sedimentary rocks, these modern valleys were interpreted as exhumed paleofjords whose modern U-shaped profiles reflects their original glacial morphologies (Dietrich et al., 2021, see also Martin, 1953, 1961, 1968, 1973b, 1981; Martin and Schalk, 1959). As the bottoms of the valleys are frequently covered in recent alluvium, however, it is difficult to observe potential overdeepenings. Moreover, Dietrich et al. (2021) demonstrated that the Purros escarpment separating the high standing plateau to the coastal plain already existed by the LPIA as indicated by glacial striae found on the escarpments (Fig. 2). In this same region, at the downstream end of some of the aforementioned U-shaped valleys are deep and encased bedrock canyons, such as the Purros and Khowarib canyons. Geological maps indicate scattered glaciogenic sedimentary rocks within these canyons (Fig. 4). We therefore suggest that these canyons forming the downstream continuation of exhumed glacial valleys may correspond to gorges similar to those characterizing the base of Quaternary glacial valleys found in almost all terrains that experienced repeated Quaternary glaciations (e.g., Lajeunesse, 2014; Livingstone et al., 2017). Such an interpretation, however, awaits confirmation by further sedimentological and geomorphological characterization. Moreover, the N-S-oriented tongue-shaped troughs, such as the Omarumba-Omutirapo, the Sesfontein and Warmquelle at the head of the glacially-carved Hoanib valley, and the Otjinjange (Fig. 2 & 3) were interpreted as glacial cirques by Martin (1953, 1961, 1968, see also Hoffman et al., 2021 pages 105-106). These troughs are endorheic or connect to the river systems through narrow ravines encased within mountain reliefs, which might suggest glacial overdeepening and subglacial gorge (Dürst Stucki et al., 2012). Here though, no glaciogenic sediments or morphological features have so far been described or reported, hindering a definitive interpretation.

To summarize, the presence of glacial erosion features within the valleys and on the escarpments indicate this relief already existed by LPIA times and was occupied, and then at least partly carved, by glacial ice, although their older origin is discussed below. It remains unclear however whether the interfluves between the glacial valleys are glacial in origin as no trace of glacial erosion has been reported so far, as they might have been lowered down by erosion in post-LPIA times. In both cases however, this network of U-shaped glacial valleys encased within low-relief, high-elevation plateaus would point toward a selective linear erosion *sensu* Benn & Evans (2010). As discussed below, the selective linear erosion may have followed an already existing non-glacial erosional landforms such as alluvial valleys or pediments or weaknesses in the underlying basement geology.

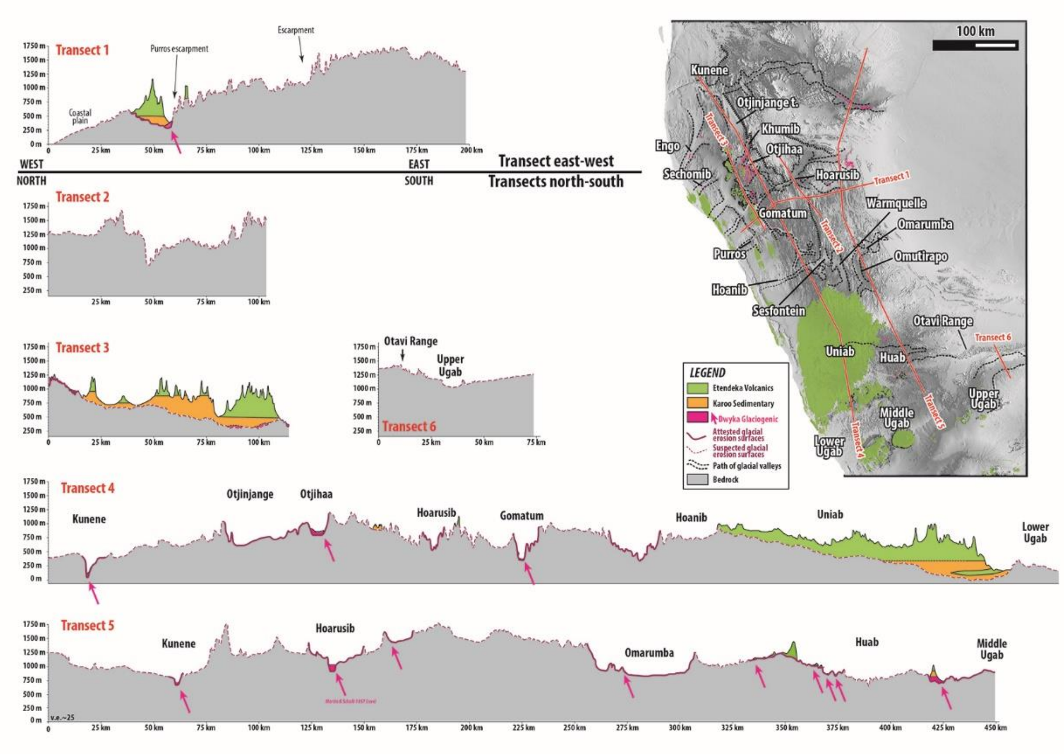


Fig. 3: Geological map indicating the Karoo Supergroup and morphostratigraphic transects across the Kaoko highland, highlighting the morphology of the Kunene, Kaoko, Huab-Ugab regions and the associated glacial valleys and troughs. Etendeka lavas are represented in green, non-glaciogenic Karoo sediments in yellow and glaciogenic Dwyka Group in pink, or indicated by pink arrows. Black dashed lines on the map represent outlines of exhumed glacial reliefs and valleys; 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 consistently used throughout the manuscript. Fig. 1b for location.

Further south, in the Huab-Uniab regions (Figs. 2 and 3), outliers of Karoo sediments and Cretaceous Etendeka lavas topping the Karoo succession form the western part of the plateau, and rest on highly uneven basement rocks dipping southward (transects 4 and 5 on figure 3). This volcano-sedimentary pile, reaching 1000 m in maximum thickness to the south, thins toward the north: the basal sedimentary units are present only in the deepest part of these basins, formed by the Huab and Lower Ugab to the south. The pile of sedimentary rocks wedges out northward to the Unihab Basin where Etendeka lava rests directly on the bedrock. Glaciogenic sedimentary rocks are observed resting directly on the bedrock in the Huab Basin (transect 5 on Fig. 3), whereas none is mapped at the interface between the lavas and the bedrock further north (at the border between the Uniab and Hoanib basins, transect 5 on fig. 3). Andrews et al. (2019) argued that profiled, elongated hills of the middle Ugab basin are glacial megalineations and megawhalebacks indicative of paleo ice streams (Fig. 2; see alsdiscussions in Le

Heron et al., 2022, 2024). Based on these observations, we suggest that this uneven bedrock topography covered by glaciogenic sediments corresponds to an exhumed glaciogenic relief. Given its dimension, i.e. at least 150 km wide and 1000 m deep and the presence of geomorphic evidences for ice streams, we interpreted this glacial topographic depression that form the Huab and Lower Ugab basins (Figs. 2 and 3), as a cross-shelf trough, as its dimensions match those of Quaternary ones, as reviewed by Batchelor & Dowdeswell (2014). The deepest parts of this large glacially-carved depression were filled by sediments of the lower Karoo Supergroup (Holzförster et al., 2000), which probably promoted preservation of the glaciogenic sediments and landforms. Shallower parts to the north remained protruding until the outpouring of the Etendeka lavas some 165 Myr after the glaciation, which likely eroded and erased all evidence for glacial activity.

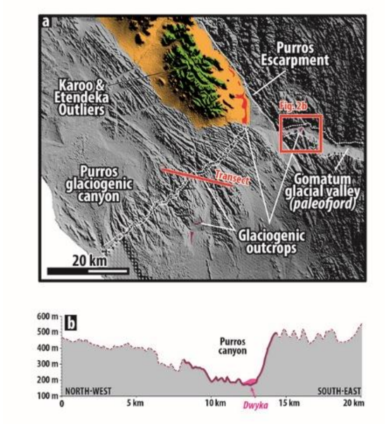


Fig. 4: (a) DEM of the western coastal Kaoko region and (b) morphostratigraphic transect. In the Purros canyon are remnants of glaciogenic sediments, and therefore the canyon is tentatively interpreted here as a relict glacial landform. See Fig. 2 for location.

3.2 The Windhoek Highland

The Windhoek highland lies at the center of Namibia and almost reaches 2000 m above sea level, and is composed of neoproterozoic age rocks which formed during the Damara Orogeny (Fig. 5; Begg et al., 2009). Numerous valleys dissect and radiate outward from the Windhoek highland. Most of these valleys have been interpreted or inferred as exhumed glacial valleys by Martin (1975, 1981, see also Miller, 2011). However, the only firm evidence for a glacial origin is the N-S-oriented Black Nossob River valley which has a U-shaped cross-profile, 7-km wide and 30-m deep, at the bottom of which are remnants of glaciogenic sediments preserved, as indicated by geological maps (transect 2 on Fig. 5). The other river valleys dissecting the Windhoek highland, the upper and lower Swakop and its tributary, the Okahandja-Windhoek and the Kurikaub, as well as southward-flowing Skaap, Usip and Nausgamab and the westward-flowing Kuiseb have also been interpreted as glacial in origin by Martin (1975, 1981). Although these valleys have conspicuous U-shaped cross-profile (Fig. 5c), no glaciogenic sediments or morphologies have been mapped or described in the literature or observed during our own fieldwork within the thalweg of these valleys. A Dwyka outcrop has been described in the vicinity of the

Nausgamab valley (Fig. 5, Faupel, 1974), which would witness at least local glacial processes; we however did not locate these deposits during our own field campaign. The Okahandja-Usip is sometimes interpreted as a graben tied to Mesozoic-Cenozoic extensive processes (the Windhoek graben, Schneider, 2004; Waren et al., 2023) whereas the other valleys seem to follow grain of the underlying basement: N-S-oriented valleys follow a network of faults whilst NE-SW oriented valleys follow lithological boundaries. Further field studies are therefore required to confirm a glacial origin of the network of valleys dissecting the Windhoek Highland.

Further south, Korn and Martin (1959) and Martin (1959, 1961) indicate that the encased U-shaped, E-W-oriented Tsondab valley that crosscuts the Naukluft Mountains is a glacial valley, as remnants of Dwyka sediments occur within the valley thalweg (Fig. 5d, e & f). Geological map also indicates glaciogenic sediments on the interfluve of the valley whose form would therefore indicate selective linear glacial erosion (Fig. 5d). Therefore, in this case, the valley and its interfluves where glacial sediments are preserved correspond to a glacial relief. The very name ‘Naukluft’ means ‘narrow gorge’ in Namibian German which unintentionally reflects the presence of the glacial valley.

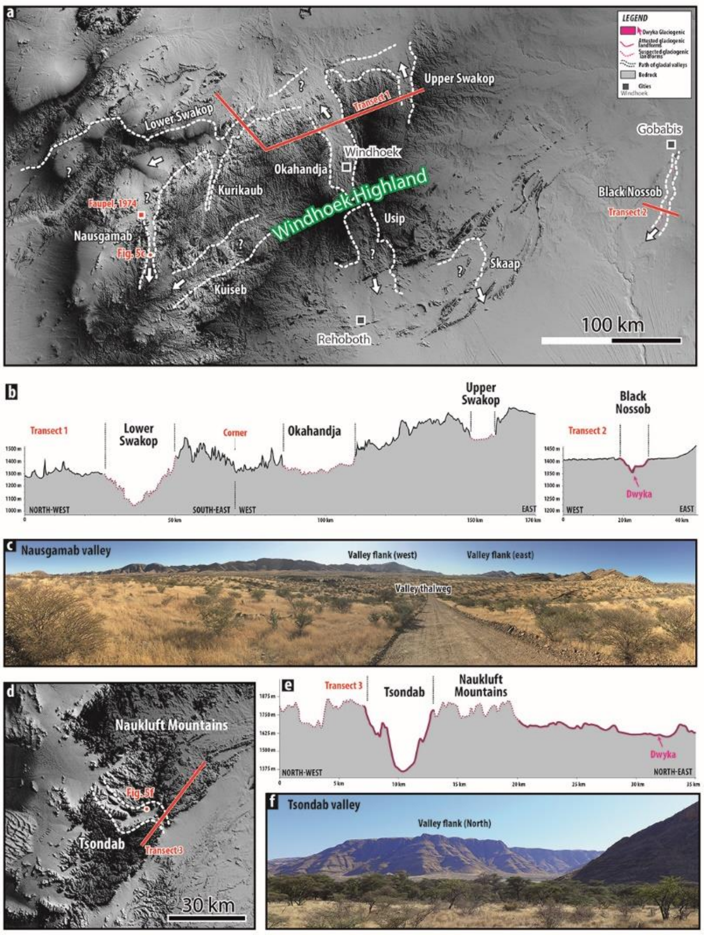


Fig. 5: (a) DEM of the Windhoek highland (central Namibia), (b) their morphostratigraphic transects. And (c) mosaic picture of the U-shaped Nausgamab valley interpreted by Martin (1961) as a potential glacial valley (see also Miller, 2011). Faupel (1974) reported glaciogenic sediments in the vicinity 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.

2.3. 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 & 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 & 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 & 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 (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 interpreted as a relic trough and uneven glacial erosion surface, possibly a landscape of areal scouring. On the contrary, in the absence of glaciogenic sediments on the Ghaap plateau, it remains unclear whether this surface corresponds to a pristine glacial erosion surface or if it has been reworked since (see discussion in De Wit, 2016). Further south, the Prieska embayment is a topographic depression formed between promontories of the Ghaap plateau delineated by steeply dipping (slope angles up to 23%), 300-m high escarpments against which the 5-120 m-thick glaciogenic Dwyka Group onlaps and pinches out. The Prieska embayment is interpreted as a relict embayment or glacial overdeepening (see Visser, 1987b) which formed a depocenter for accumulation of the Dwyka glaciogenic sediments (Visser, 1982, 1985). The Orange River itself, downstream the town of Prieska, flows in a valley that existed already in LPIA times and was occupied by ice: while remnants of glaciogenic sediments occur in the valley thalweg, the surrounding bedrock peaks of the Doringsberg and Asbestos ranges tower some 400 m above (transect 1 on fig. 6). This indicates that this segment of the modern Orange River follows an ancient trough occupied, and perhaps amplified (widening and deepening), by ice during the LPIA, later re-exposed by the removal of soft Karoo sedimentary rocks. The Doringsberg and Asbestos range also already existed per se by LPIA times, and had *at least* the height they have today. Further west, Visser (1985) indicates that the northwesternmost edge of the MKB consists of a succession of glacially carved basins, valleys and embayments, such as the Sout River Valley and the Namaqua Basin, as well as promontories, ridges and spurs, like the Kaiing hills, the Poffader Ridge and the Langberg mountains (Fig. 6). Finally, at the westernmost end of South Africa, south of the Orange River, in the Richtersveld region, characterized by a high relief whose pattern seems mostly controlled by basement structure, Reid (2015) postulated that a single valley, N-S-oriented might correspond to a exhumed glacial valley (Fig. 1, Reid, 2015).

The area surrounding Johannesburg and Pretoria, including Archean basement of the Johannesburg Dome, Archean-Paleoproterozoic strata of the Witwatersrand and Transvaal supergroups forming the Witwatersrand and Magaliesberg mountain ranges, southern part of the Paleoproterozoic Bushveld igneous province and the Mesoproterozoic Pilanesberg alkaline ring complex (Fig. 6), is thought to correspond to an exhumed glacial landscape (Wellington, 1937). In this region, direct evidence for glacial processes occur on the interfluve between the Harts and Mooi River valleys. This even surface is characterized by numerous striated glacial pavements interpreted as a surface of glacial erosion, covered in places by sinuous, diamond-bearing sediment ribbons interpreted as eskers (De Wit, 2016; Fig. 7). The Harts and Mooi river valleys, incised within gently-, southward-sloping Transvaal Supergroup dolomite, have U-shaped cross-profiles and the Harts River corresponds to the northward extension of the aforementioned Virginia glacial valley (selective linear erosion). East of the city of Johannesburg, the Witbank coal field also constitutes a pre-Karoo glacial irregular topography. In this region, coal seams of the postglacial Vryheid Formation (Ecca Group) either rest conformably on glaciogenic deposits of the Dwyka Group and fill local hollows and depressions, 10-60 m deep, of the

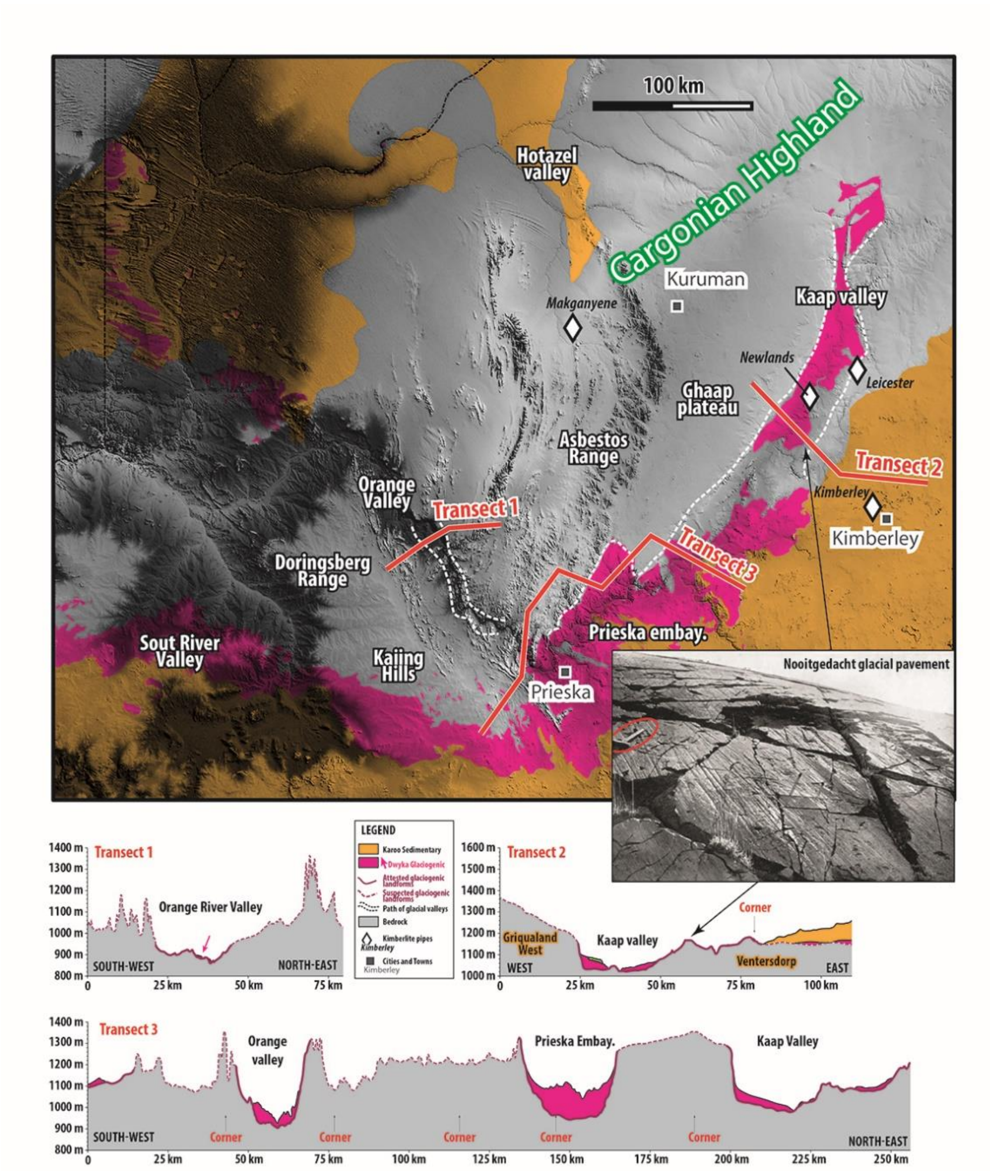


Fig. 6: DEM of the SW Cargonian Highland (central South Africa and southern Botswana; Fig. 1b for location) and associated geological transects. Widespread Dwyka outcrops in the Kaap valley visible in the landscape interpreted here as an exhumed glacial valley. Diamonds represent kimberlite pipes used 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.

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 & 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 & 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).

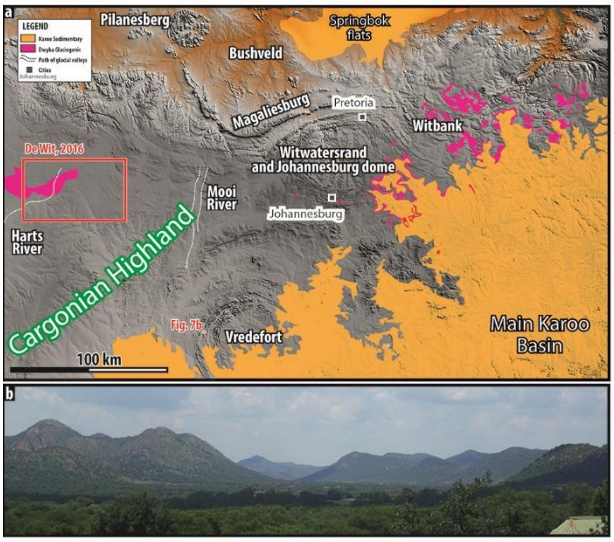


Fig. 7: (a) DEM of the central Cargonian Highland (Johannesburg-Pretoria-Witwatersrand area on the Kaapvaal craton, central South Africa). Fig. 1b for location. The Mooi and Harts river valleys, highlighted by white dashed lines, and the surrounding areas, are interpreted by De Wit (2016) as an exhumed 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)

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

2.4. The Zimbabwe Highland

The Zimbabwe highland corresponds to the central region of Zimbabwe and the Zimbabwe Craton (Fig. 1 & 9). This highland is floored by Archean greenstone belts, granites and other resistant lithologies that were intruded during the late Archean by the layered complexe of the Great Dyke (Mukasa et al., 1998). Over the basement lies the Karoo Supergroup represented by isolated, ca. 100 m thick sedimentary successions among at the base of which glaciogenic sediments are sometimes present (Bond, 1970)

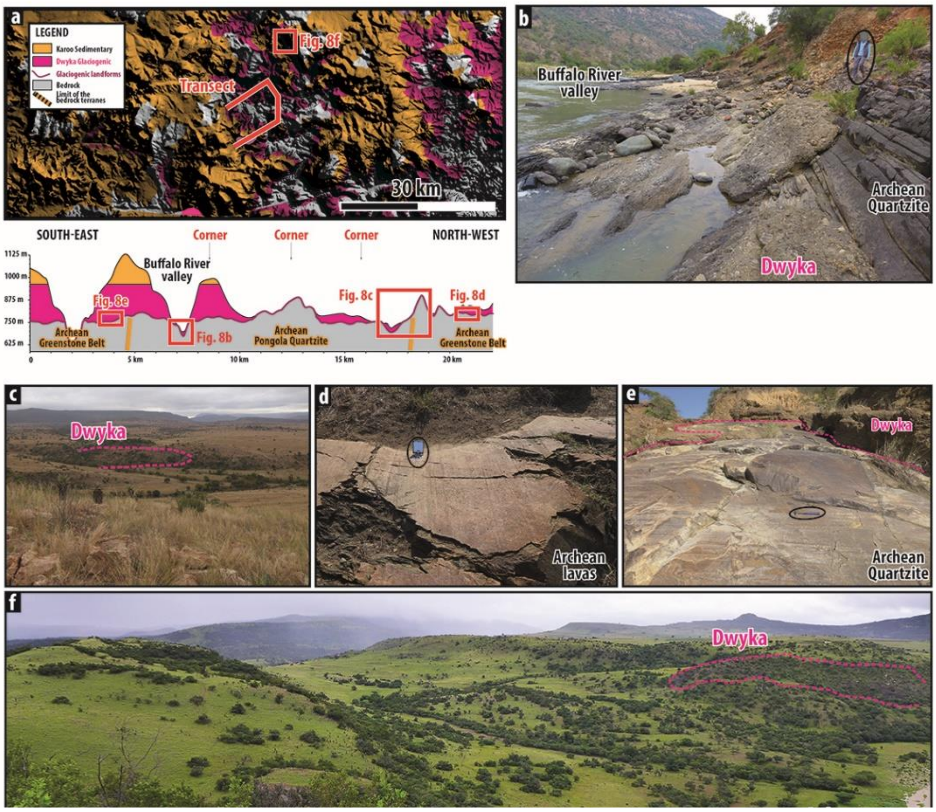


Fig. 8: (a) DEM of the eastern Cargonian Highland (edge of the Main Karoo Basin; Kaapvaal craton, eastern South Africa) and morphostratigraphic transect highlighting the Tugela valley as an exhumed glacial landscape. Fig. 1b for location. See Details in Dietrich & Hofmann (2019). (b) Bank of the Buffalo 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).

capped by 50-100 m thick Jurassic lavas of the Drakensberg Group (Rhodesia Geol. Map 1971:https://zimgeoportal.org.zw). Lister (1987) comprehensively detailed the polyphased, polygenic nature of the 'Pre-karoo Surface', emphasizing the role of glacial and non-glacial erosion processes, pediplanation, folding and structuration that happened before (or during, over basement outliers) the deposition of the Karoo sediments. This pre-Karoo surface, characterizing vast region of Zimbabwe, has then been covered and re-exhumed, and as a result, largely due to erodibility contrast between the basement rocks and the sedimentary cover, '*in many respects the Pre-Karoo landscape of Zimbabwe was remarkably similar to that existing at the present day*' (Lister, 1987).

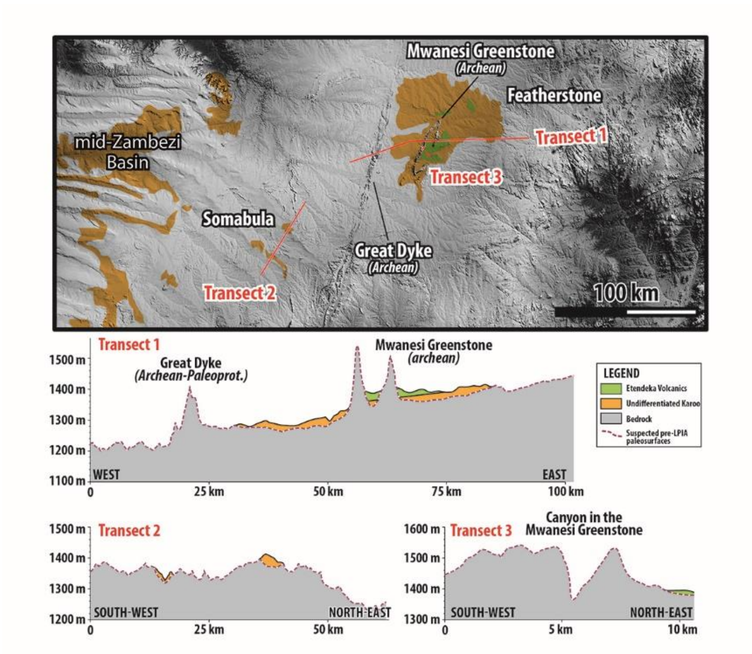


Fig. 9: DEM of the Zimbabwe Highland (central Zimbabwe) and morphostratigraphic transects across the Great Dyke, the Mwanesi Greenstone Belt and the Somabula region. The reader is redirected to Moore & Moore (2006), Moore et al. (2009) and Lister (1986) for further details. Fig. 1b for location.

The Great Dyke now forms a prominent morphological ridge that stands well above the surrounding basement-floored rocks of central Zimbabwe (Fig. 9). In the Featherstone region, east of the Great Dyke, the Archean Mwanesi Greenstone Belt also forms a prominent ridge against which the Karoo sediments onlap (Fig. 9). Although no glaciogenic sedimentary series have formally been identified on geological maps ('undifferentiated Karoo') and no field study has reported glaciogenic sediments, to our knowledge, the surrounding sedimentary basins encompass evidence for glacial processes (mid-Zambezi: Bond and Stocklmayer, 1967; Bond, 1970; Cabora Bassa: Oesterlen and Millsteed, 1994; Fernandes et al., 2023; Somabula: Moore and Moore, 2006; Tuli: Bordy and Catuneanu, 2003). We therefore posit that the Mwanesi Greenstone Belt and the Great Dyke, formed prominent reliefs during LPIA times as proposed by Lister (1987). This relief, sealed by Karoo rocks, is now being exposed by the erosion of the sedimentary rocks and basalts. Furthermore, Moore et al. (2009) suggested that U-shaped valleys, canyons, defiles and ravines (locally named 'poort', meaning gateway in Afrikaan) incised trough this greenstone belt as well as through the Great Dyke within which modern streams flow do not match any structural pattern and cannot have been cut by these streams. Rather, the incision corresponds to exhumed glacial valleys that are now used by streams to cross the topographic barriers (Moore et al., 2009).

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 IMPLICATION: THE GLACIAL PALEOLANDSCAPES 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 in fact 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

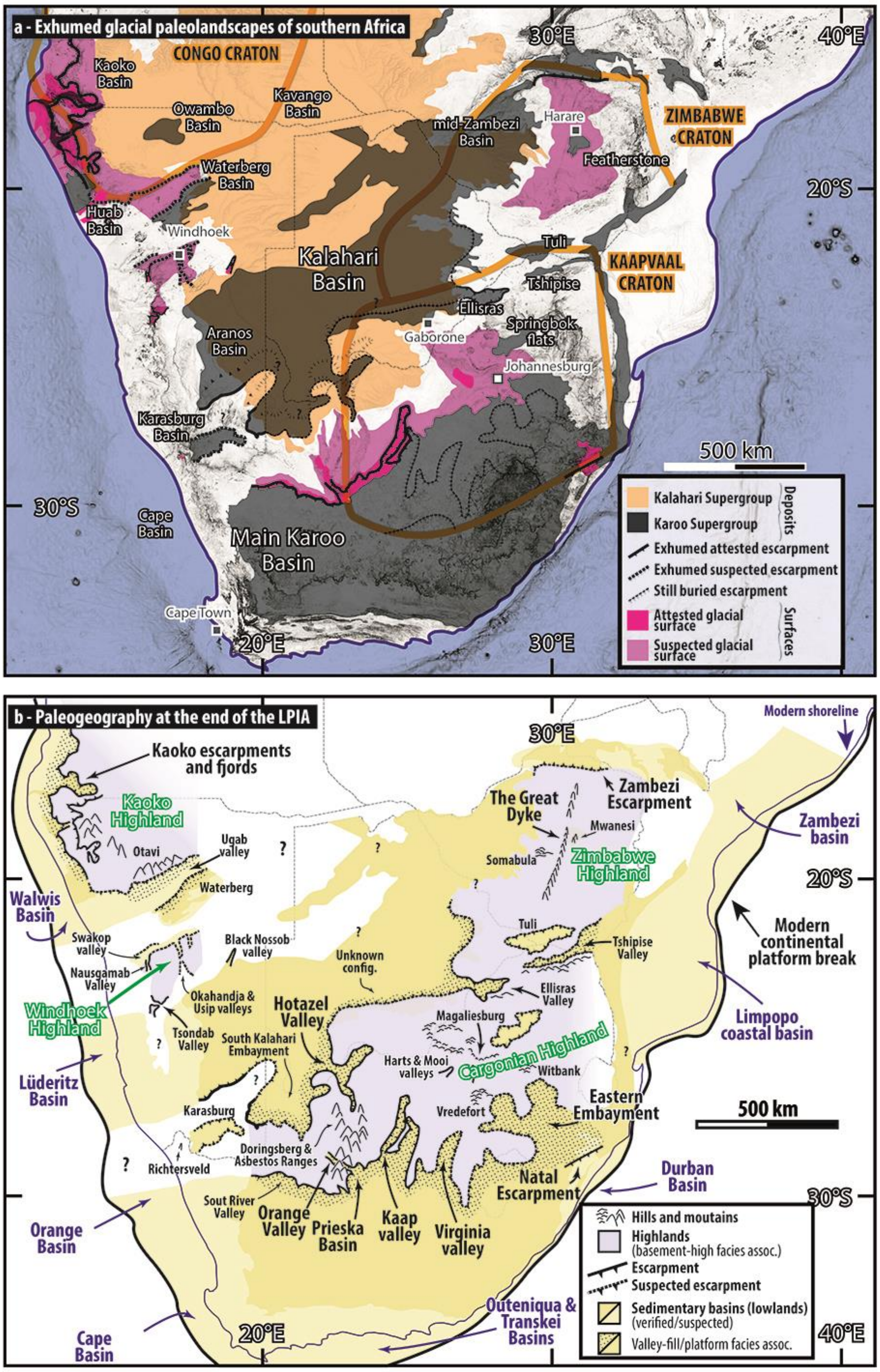


Fig. 10: (a) Synthesis of glacial paleolandscapes at the scale of Southern Africa. Dark pink indicates attested glacial surface and light pink indicates suspected glacial surfaces whose compilation is based on the presence of glacial morphological features (see text for details). Dark grey regions are 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.

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

4.2. Paleogeography

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

We propose that the original extent of the Karoo basins was greater than their modern outcrops, as offshore data indicate the presence of Karoo sediments on the modern continental margin. As the offshore Walvis and Lüderitz Basins hosts Karoo sediments (Clemson et al., 1997, 1999; Aizawa et al., 2000; Baby et al., 2018b; 2020), we have extended the Aranos and Kaoko basins further west and connected them to their offshore counterparts. Martin (1973b) states that, as no glacial erratics sourced from the Kaoko have been found in the Parana Basin, the Brazilian Karoo equivalent, a topographic depression or a basin, perhaps oceanic, should have existed between Namibia and Brazil during the LPIA, likely corresponding to the northern realm of the Walvis Basin. And he concludes that '*paleogeographic evidence does not easily fit into the concept of a direct join of the African and the South American continental plates*'. Griffis et al. (2021) moreover indicate that only Gondwanan-scale deglacial events permitted the delivery of African-sourced sediments into the Parana Basin while glacial flows between Africa and South America were hindered, suggesting the presence of substantial topographic barriers such as a basin that would have deflected/hindered ice flows. For the connection between the Aranos and Lüderitz basins and their extent further west, the absence of sediments between these offshore-onshore realms would be explained by their removal through the post Gondwana-breakup functioning of the escarpment passive margin (see above section 2.4; Braun et al., 2014; Braun, 2018a), which nowadays delineates the western border of the Aranos Basin. This very escarpment therefore postdates the LPIA. In line with this, Visser (1987b) states that '*Towards the west, [the Kalahari] basin probably opened into a sea.* Martin (1973b) *favoured the extension of the Kalahari basin into South America as goniatites of the same subgenus were found in Uruguay and Namibia in very similar stratigraphic positions. Those deposits, however, formed during an interglacial period when large parts of SW Gondwana were inundated as a result of sea-level rise*'. About the offshore continuation of the Main Karoo Basin, Karoo sediments have also been found both in the offshore Orange Basin to the west (the 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). For the need of the reconstruction of the burial-exhumation history from thermochronometrical data (apatite and zircon fission tracks, (U-Th-Sm)/He 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. For example, over the Kaoko highland (Fig. 11a), thermochronometrical data of Margirier et al. (2019) indicate that a significant cooling of ca. 200°C occurred between 130 and 100 Ma while thermochronometrical data of Raab et al. (2005) rather indicate a cooling of 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 & Flowers (2019) and Flowers & 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.

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.

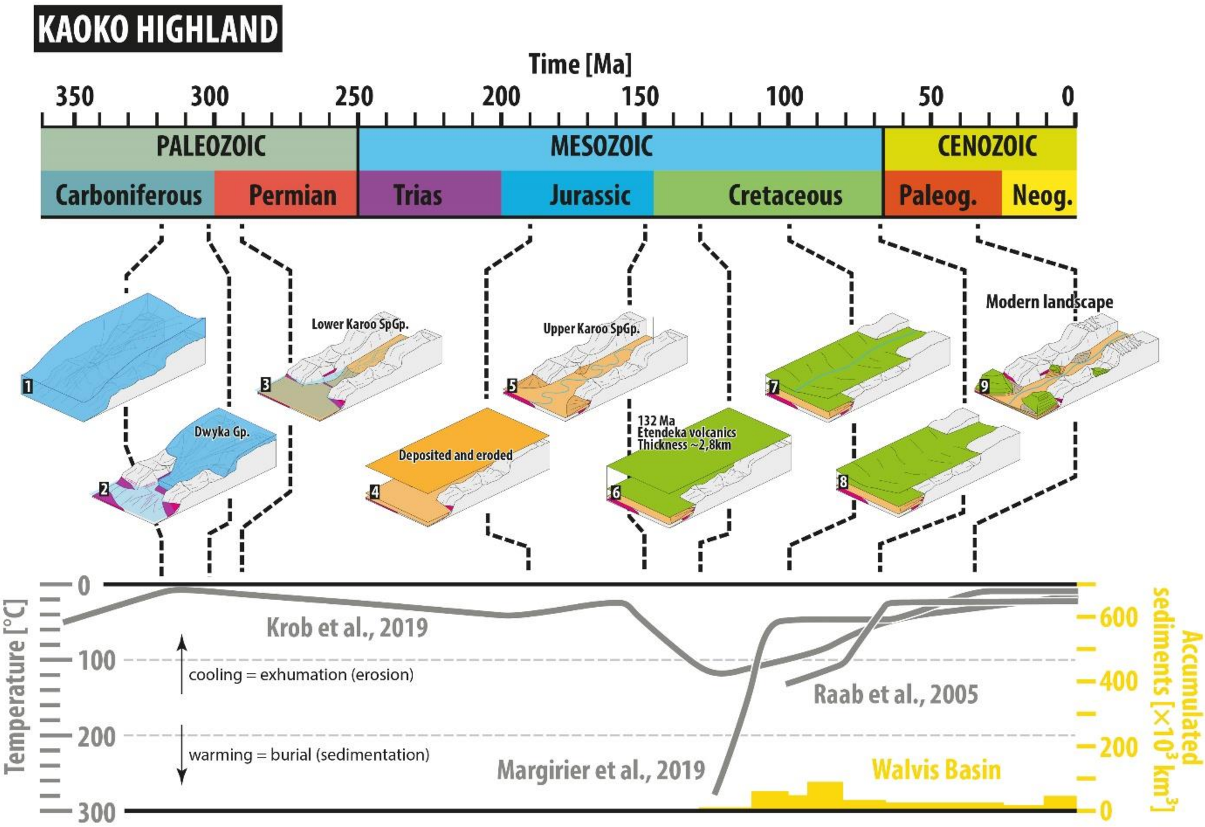
5. Discussion

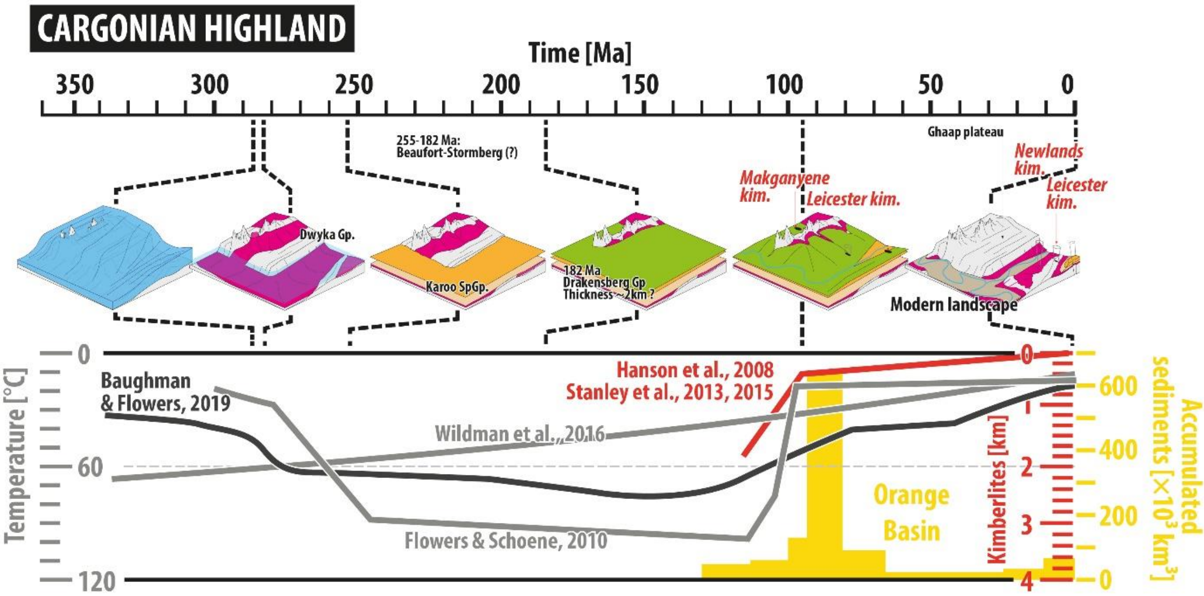
5.1. Pre-LPIA evolution: existing reliefs amplified by glacial erosion?

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-Karroo 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?*

The threefold morphological pattern (highlands, escarpments and sedimentary basins) that greatly controlled mode of glaciogenic sedimentation, seems to correspond to surficial expression of basement structures (Fig. 12). Indeed, the highlands correspond to Archean and Paleoproterozoic cratons while the escarpments edging the highlands match crustal-scale faults, either delineating the cratons and their surroundings accreted terranes or intra-cratons faults (Figs. 1 & 12; Daly et al., 1989; Tankard et al., 2009a; Begg et al., 2015). The escarpments may therefore correspond to fault offsets, with glacial


KAOKO HIGHLAND
Time [Ma]
350 300 250 200 150 100 50 0
PALEOZOIC
MESOZOIC
CENOZOIC
Carboniferous
Permian
Trias
Jurassic
Cretaceous
Paleog.
Neog.
Lower Karoo SpGp.
Upper Karoo SpGp.
Modern landscape
Dwyka Gp.
Deposited and eroded
132 Ma
Etendeka volcanics
Thickness ~2,8km
Temperature [°C]
Krob et al., 2019
cooling = exhumation (erosion)
warming = burial (sedimentation)
Raab et al., 2005
Margirier et al., 2019
Walvis Basin
Accumulated sediments [×10³ km³]


CARGONIAN HIGHLAND
Time [Ma]
350 300 250 200 150 100 50 0
255-182 Ma:
Beaufort-Stormberg (?)
Ghaap plateau
Newlands kim.
Makganyene kim.
Leicester kim.
Leicester kim.
Dwyka Gp.
Karoo SpGp.
182 Ma
Drakensberg Gp
Thickness ~2km ?
Modern landscape
Temperature [°C]
Baughman & Flowers, 2019
Hanson et al., 2008
Stanley et al., 2013, 2015
Wildman et al., 2016
Flowers & Schoene, 2010
Orange Basin
Kimberlites [km]
Accumulated sediments [×10³ km³]

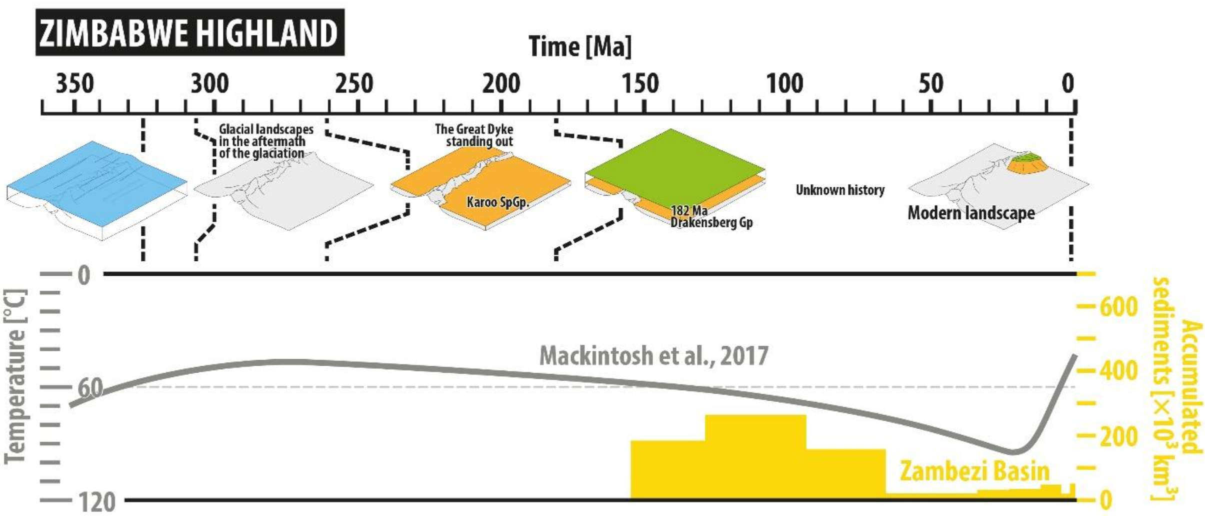

ZIMBABWE HIGHLAND
Time [Ma]
350 300 250 200 150 100 50 0
Glacial landscapes in the aftermath of the glaciation
The Great Dyke standing out
Karoo SpGp.
182 Ma
Drakensberg Gp
Unknown history
Modern landscape
Temperature [°C]
Mackintosh et al., 2017
Zambezi Basin
Accumulated sediments [×10³ km³]

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.

valleys carved into it. And, in order for the glacial valleys to be carved into it, these fault escarpments must have formed before or during the development of the ice masses of the LPIA, implying relative uplift of the cratonic areas and subsidence of the surrounding terranes. Below are speculations of the possible timing and processes involved in pre-LPIA vertical movements that led to the partitioning between highlands and lowlands separated by escarpments.

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

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

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

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

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

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

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

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

Over the Cargonian, Kaoko and Zimbabwe highland, thermochronometrical data indicate that cooling, which reflects exhumation, continuously prevailed since at least 500 Ma ago until the LPIA, suggesting that the LPIA was the ultimate episode of a >200 Ma-long history of erosion. Over the Cargonian Highland, cooling occurred between 600-500 Ma and 400 Ma, leaving ca. 100 Ma of erosion (Wildman et al., 2017; Baughman & Flowers, 2020). Moreover, no Lower Paleozoic sedimentary basin exists over southern Africa, with the notable exception of the Cape Basin, hosting the Cape Supergroup, spanning from the Cambrian to the late Devonian. Provenance studies and paleocurrents indicate that sediments that fed the Cape Basin were sourced in the north, over the Namaqua-Natal suture belt, and funneled to the Cape basin through a network of southward-flowing valleys (e.g., Theron, 1972, Fourie et al., 2011). The Kaap valley may therefore correspond to such an alluvial valley later reused by the ice. Over the Kaoko Highland, cooling occurred between 550 Ma and the onset of the LPIA (Krob et al., 2019), leaving about 250 Ma for erosion. In Zimbabwe, Lister (1987) indicates the presence of a pre-LPIA pediplain and 'older [than LPIA] fluvial valley', being part of the so-called "pre-Karoo fossil surface", which would indicate alluvial processes. Therefore, we suggest that before the LPIA, most of southern Africa, with exception of the Cape Supergroup, was an erosional landscape possibly dominated by alluvial forms: valleys and possibly pediments and pediplains. At the onset of the LPIA, these networks of alluvial valleys may have controlled the path of local ice flows and its funnelling into what later became the fjords punctured through the escarpment (see also Lister, 1987).

5.2. Can the pre-Dwyka relief be mistaken for post-LPIA pediments 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. They occur at different elevations, are incised within escarpments and separated by flat surfaces and although glacial erosion processes were major in shaping these reliefs, they likely encompass pre-glacial structural and/or alluvial origin. In that sense, these LPIA reliefs resemble what Guillocheau et al. (2018) describe as pediments, pediplains and pedivalleys, abundant in central and southern Africa, –flat erosional surfaces bounded by escarpment but eroded in arid or humid condition –and may thus be mistaken for such erosional landforms. As a matter of fact, the topographic escarpments at the edge of the modern highlands are conventionally interpreted as scarps between planation surfaces that initiated during the Atlantic rifting, and the valleys incised within these scarps are sometimes taken for pediments and pedivalleys that originated in the Cenozoic break-up system (Braun et al., 2014; Salomon et al., 2015; Baby et al., 2018, 2019). Our study therefore emphasises the need of considering the morphological legacy of the Late Paleozoic Ice Age 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 on the valley walls. Yet, this valley has been interpreted as 'structurally controlled' by Brunotte & Spoenemann (2003). Many other valleys that bear large-scale morphological features that can match a glacial origin (U-shaped cross profile, endorheic troughs suggesting glacial overdeepening, valley directions radiating out of the Windhoek highlands), but for which no indisputable evidence for glacial processes has not been found, were qualified by various authors as rifts. For instance, the Upper Ugab and Waterberg valleys of Northern Namibia, the

Karasburg Basin of Southern Namibia (that Martin, 1973b and Visser, 1987b qualify a glacial overdeepening) as well as the Tshipise, Tuli, Ellisras and Springbok Flats basins of South Africa and Zimbabwe are interpreted as rift basins (Daly et al., 1989; Smith and Swart, 2002; Frizon De Lamotte et al., 2015; Guillocheau, 2018). The reduced thickness of the entire 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 processes, and in some cases the absence of faults bordering these Karoo strata, question such an tectonic interpretation.

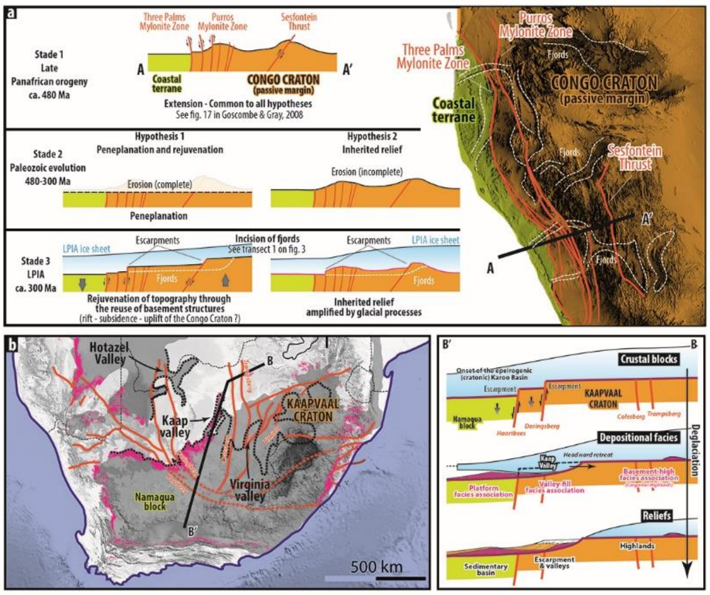


Fig. 12: (a) Structural map of the Kaoko Highland (Figs 2 and 3), faults are after Goscombe & Gray (2008) and two alternative models for the evolution of the escarpments and the associated valleys before the LPIA, as follows: Hypothesis 1 implies that the relief created at the end of the Pan-African 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.

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

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Figure captions

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.

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).

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. Etendeka lavas are represented in green, non-glaciogenic Karoo sediments in yellow and glaciogenic Dwyka Group in pink, or indicated by pink arrows. Black dashed lines on the map represent outlines of exhumed glacial reliefs and valleys; 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 consistently used throughout the manuscript. Fig. 1b for location.

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.

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.

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)

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).

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 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.

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.