



Quaternary glaciations in Southern Africa? A “moraine” in the Lesotho highland revisited

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Abstract: Climate records for the Last Glacial Maximum (LGM) in Southern Africa are scarce, and the glaciation of the highest summits has been controversially discussed. Geomorphological features on south-facing slopes at six sites in the high Drakensberg Escarpment of Eastern Lesotho were postulated as moraines indicating marginally short-lived and site-specific glaciation during the LGM. However, previous discussions on precipitation amounts limiting or inhibiting glaciers are challenged by more recent studies suggesting increased humidity and water availability during the LGM. One postulated moraine site at the Tsatsa-La-Mangaung mountain range near Sani Pass was revisited to address the contradictory results. Drone-based remote sensing and field surveys suggest a different formation process of the moraine-like slightly bent landform considering lithological variance and dike system occurrence, which is connected not to glacial but to gravitational and erosional processes. The formation of landforms interpreted as moraines in the high-altitude regions of Lesotho and their paleoclimatic implications for the LGM require reevaluation.

1 Introduction

Quaternary glacial cycles are an extensively investigated research topic for a deeper understanding of potential future global climate changes. The Last Glacial Maximum (LGM) is a well-defined period (cf. Tierney et al., 2020: 23–19 ka; Clark et al., 2009: 26–19 ka; Hughes and Gibbard, 2015, provide a wider review) and serves as a valuable benchmark for evaluating Earth’s climate sensitivity, as it reflects a quasi-equilibrium climate state with significant changes in forcing and response (Tierney et al., 2020; Zhu and Poulsen, 2021). Because of its global significance, the LGM has received particular attention from climate researchers (e.g., Clark et

al., 2009). The general picture of a globally cold and dry LGM (e.g., Dubey, 2023) was derived from temperatures on the continents ca. 6 °C lower compared to the modern global mean (Schneider von Deimling et al., 2006; Seltzer et al., 2021); growing continental ice sheets, which resulted in a falling sea level; and colder air masses, which absorbed less moisture. It has become evident, however, that the climate during the LGM differed not only between the hemispheres but also in the same hemisphere (Chabangborn et al., 2013; Du et al., 2024; Ludwig and Hochman, 2022). Based on the example of the southern Kalahari, a global climate model suggests a drier-than-contemporary climate (Kim et al., 2007). Proxy data, however, show that more

moisture was available during the LGM. Rivers were perennial, but nowadays they are ephemeral or completely dry. Lakes, some of them large-scale (e.g., Makgadikgadi Basin with ca. 37 000 km²), were at highstands, while nowadays they represent pans which may seasonally partly be filled to shallow depths (Riedel et al., 2014; Geppert et al., 2021). The LGM temperature in the northwestern Kalahari was similar to modern temperatures (Wiese et al., 2020). The need for more proxy-based climate models is evident (Braconnot et al., 2012; Yan et al., 2016).

One of the main issues in climate research leads to the question of potable water availability. The highland of Lesotho represents the water tower of Southern Africa (Wunderle et al., 2016), and its long-term behavior is thus of major interest. On the other hand, the mountains in the Drakensberg range are the highest in Southern Africa (in this case defined as the area south of the Tropic of Capricorn), and evidence and the extent of late Quaternary glacial landforms, i.e., of LGM age, have been discussed controversially (Boelhouwers and Meiklejohn, 2002; Butzer, 1984; Hall, 2004, 2010; Knight, 2012; Lewis and Illgner, 2001; Mark and Osmaston, 2008; Marker, 1991; Mills and Grab, 2005; Mills et al., 2009a, b, 2012). As there are no lake sediments, peat bogs, or speleothems in the highland of Lesotho, which could be used for LGM climate reconstruction (Fitchett et al., 2017; personal observations by the authors), employing glacial landforms for climate reconstruction offers the opportunity to gain insights into the LGM climate of the highlands. The formation of glaciers, on the one hand, requires sufficiently low annual temperatures and, on the other hand, adequate precipitation, which should predominantly fall in winter. We consider it essential to give background information on the contemporary Southern African climate as well as the proxy-based reconstruction of the LGM climate to properly discuss the question of whether glaciers could have formed in the Lesotho highlands.

The Southern African climate is influenced by tropical and midlatitude circulation systems and both Southeastern Atlantic and Southwestern Indian Ocean, leading to diverse climatic settings (Fig. 1) (Chase and Meadows, 2007; Kylander et al., 2021). In general, Southern Africa comprises five main rainfall zones according to Geppert et al. (2022), based on their spatial and temporal rainfall distribution and moisture sources. Major contemporary climate features were discussed in detail by Gasse et al. (2008) and Geppert et al. (2022). The annual precipitation and temperature patterns in Southern Africa are furthermore significantly controlled by topographic factors.

In respect to late Quaternary glacials, shifts of oceanic and atmospheric components with different effects on the changes in temperature and precipitation intensity and patterns over Southern Africa are hypothesized (e.g., Chase and Meadows, 2007; Fitchett et al., 2017; Kohfeld et al., 2013; Rojas, 2013; Sime et al., 2013). However, only a few LGM

climate records are available to validate these assumptions (see Table 1; Fig. 1).

Although Southern African climate zones are quite diverse, LGM temperatures are generally considered to have been lower than temperatures today. Studies generally indicate a mean annual temperature drop of approximately 6 °C compared to present conditions (e.g., Engelbrecht et al., 2019; Heaton et al., 1986; Holmgren et al., 2003; Scott, 1982). However, the estimated mean annual temperature drop ranges from exceeding 10 °C in the high-altitude regions of the Drakensberg Escarpment (Boelhouwers and Meiklejohn, 2002; Lewis and Illgner, 2001; Partridge et al., 1997) to being around 2 °C in other areas (Holmgren et al., 1995; Stute and Talma, 1997; Lee-Thorp and Talma, 2000; Truc et al., 2013), whereas Scott et al. (2012) suggested a slight warming between 20–19 ka at Pakhuis Pass (Table 1), bringing temperatures closer to present-day levels. Furthermore, precipitation or moisture availability varies across sites, being either lower than, higher than, or similar to present-day levels (Table 1, Fig. 1). This wide value range for temperature and moisture availability reconstruction does not turn out satisfactorily. But the major bias in calculating mean annual temperature and moisture availability may be explained by the different archive types, site locations, and analytical methods as highlighted in Table 1.

Archeological studies of two rock shelters in the lowland of Lesotho (1790 and 1860 m a.s.l.) have demonstrated human occupation during the LGM and that fish was part of livelihoods (Pargeter et al., 2017; Pazan, 2022).

In a phylogeographic study, Sands et al. (2022) demonstrated that some of Lesotho's river systems were active during the LGM. Engelbrecht et al. (2019) scaled global LGM simulations down to Southern Africa and suggested that the temperatures were 4–6 °C lower along the eastern escarpment and that Lesotho received precipitation all year round.

Against this background, the high summits of Lesotho in proximity to the eastern escarpment received particular attention, and six sites with glacial landforms were suggested for this area (Mills and Grab, 2005; Mills et al., 2009a, b, 2012; Fig. 2). Given its extensive discussion in prior studies (Mills and Grab, 2005; Hall, 2010; Hall and Meiklejohn, 2011), we directed our attention towards the Tsatsa-La-Mangaung site among the proposed locations. We considered the moraine interpretation by Mills and Grab (2005) for the ridges at the Tsatsa-La-Mangaung mountain range near Sani Top (Fig. 2a) disputable for the following reasons: (1) the contour lines of Mills and Grab (2005, their Fig. 2) show no indications or morphological correspondence to either a glacier or nivation. (2) Both remote sensing data and Fig. 2 by Mills and Grab (2005) reveal a fault line at the site (see also the *Geological Map of Lesotho* (Lesotho Government, 1982)). Yet, this aspect was not considered in the process of genesis of the landscape feature. (3) The association between moraine material and the pre-Holocene-dated soil organic

Table 1. Selection of Southern African paleoclimate records (see Fig. 1) and their generalized interpretation of LGM versus modern climate. T = temperature; M = moisture; + and – = higher and lower; ? = differing climate reconstructions and/or fluctuating conditions at the site.

No.	Archive type	Archive type	LGM climate	Key reference(s)
Winter Rainfall Zone				
1	Spitzkloof Rockshelter	Archeological deposit	M+	Dewar et al. (2023)
2	Elands Bay Cave	Archeological deposit, tufa deposit	M+/-?	Cartwright and Parkington (1997); Cowling et al. (1999); Khumalo (2021); Meadows and Baxter (1999)
3	Pakhuis Pass	Hyrax middens	T–, M+/-?	Scott and Vogel (2000); Scott and Woodborne (2007a, b); Scott et al. (2012)
4	Western Cape Mountains	Geomorphological features	T–	Boelhouwers and Meiklejohn (2002)
Year-Round Rainfall Zone				
5	Pella site	Hyrax middens	M+/-?	Lim et al. (2016)
6	Cango Caves	Speleothems combined with groundwater (see no. 9)	T–	Talma and Vogel (1992)
7	Boomplaas Cave	Archeological deposit	T–, M+/-?	Faith et al. (2019); Khumalo (2021); Pargeter et al. (2018); Sealy et al. (2016); Thackeray (1987); Thackeray and Fitchett (2016)
8	Nelson Bay Cave	Archeological deposit	T–, M–	Avery (1982); Faith et al. (2019)
9	Uitenhage	Groundwater	T–	Heaton et al. (1986); Talma et al. (1984)
Summer Rainfall Zone West				
10	Brandberg	Hyrax middens	T–, M+	Scott et al. (2004)
11	Homeb silts	Sediment deposits	M+/-?	Heine and Heine (2002); Vogel (1989)
12	Zizou	Hyrax middens	M+	Chase et al. (2023)
13	Stampriet	Groundwater	T–	Lee-Thorp and Talma (2000); Stute and Talma (1997)
14	Witpan	Pan deposit	M+	Genderjahn et al. (2017); Telfer et al. (2009)
Summer Rainfall Zone Middle				
15	Southwest Kalahari	Dunes	M+	Chase and Brewer (2009); Hürkamp et al. (2011); Lancaster (1979); Stone and Thomas (2008); Telfer and Thomas (2007)
16	Wonderwerk Cave	Stalagmites, dung deposit	T–, M+	Brook et al. (2010)
17	Ghaap Escarpment	Tufa deposit	M+	Brook et al. (2010); Butzer (1984)
18	Alexandersfontein	Lake sediments	M+	Butzer (1984)
19	Lobatse Cave	Speleothems	T–, M+/-?	Holmgren et al. (1995)
Summer Rainfall Zone East				
20	Mount Enterprise	Geomorphological features	T–	Boelhouwers and Meiklejohn (2002); Lewis and Illgner (2001); Mills et al. (2017)
21	Sehonghong Rock Shelter	Archeological deposit	T–	Loftus et al. (2015); Pargeter et al. (2017)
22	Lesotho highlands	Geomorphological features	T–, M+/-?	Mills and Grab (2005); Mills et al. (2009a, b); Mills et al. (2012); Hall (2004)
23	Elim	Swamp deposit	T–, M+/-?	Scott (1989b); Scott et al. (2012)
24	Pretoria Saltpan	Lake sediments	M–	Partridge et al. (1997)
25	Wonderkrater	Spring deposit, peat deposit	T–, M+/-?	Scott (1982, 1989a); Scott et al. (2012); Truc et al. (2013)
26	Cold Air Cave	Groundwater, stalagmite	T–, M–	Holmgren et al. (2003)
27	Voordrag	Sediment deposit, paleosoils	T–, M+/-?	Botha et al. (1992); Clarke et al. (2003)
28	Mfabeni peatlands	Peat deposit	T–, M+/-?	Baker et al. (2014, 2017); Finch and Hill (2008); Miller et al. (2019)

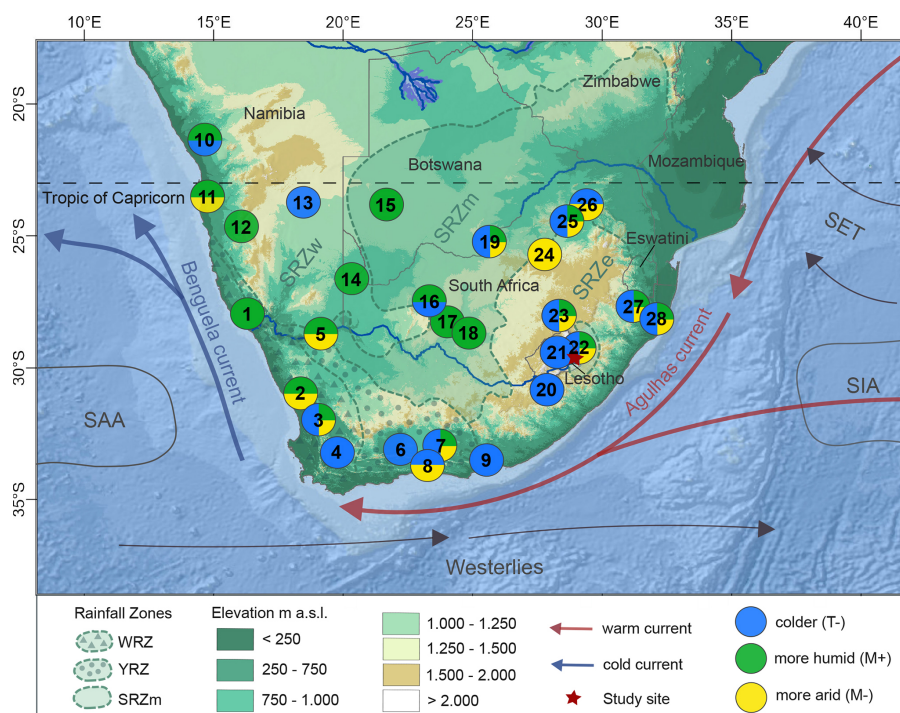


Figure 1. Modern climate setting with selected Southern African sites of LGM climate records (1–28 in Table 1). SRZw = Summer Rainfall Zone West; SRZm = Summer Rainfall Zone Middle; SRZe = Summer Rainfall Zone East; WRZ = Winter Rainfall Zone; YRZ = Year-Round Rainfall Zone; SET = Southeast Trades; SAA = South Atlantic Anticyclone; SIA = South Indian Anticyclone; the positions of the climate systems vary seasonally (rainfall zones after Geppert et al., 2022; SRTM elevation data from U.S. Geological Survey, 2014; oceanic layer from ESRI et al., 2014).

matter described in the trenches presents an unclear relationship, marked by petrographic variability.

We revisited this site to evaluate the moraine interpretation by Mills and Grab (2005). The “moraines” in the Tsatsa-La-Mangaung mountain range have been employed for glacier-based climate reconstruction (Mills et al., 2012). Every glacier-based climate reconstruction should be grounded on securely identified moraines. This is the only landform which has been studied by others in some detail, and the location is in a nowadays hydro-climatologically favorable area, which we assume was the case too during the LGM and thus was favorable for a potential glaciation. Furthermore, due to unfavorable weather and hydrological conditions during our expedition, we could not reach any of the other sites suggested to be moraine-like deposits, which are located far from any roads or passable tracks. Each location requires its own expedition.

2 Regional setting

The study site is located in Eastern Lesotho (Fig. 2a), within the Upper Triassic to Lower Jurassic Drakensberg plagioclase-rich flood basalt (Haskins and Bell, 1995; Schmitz and Rooyani, 1987). Dolerite dikes are common (Haskins and Bell, 1995). The site lies in proximity to the

Sani Top mountain range, outlining the elevated terrain at the head of Sani Pass above the Great Escarpment (Fig. 2b). In this area, elevation ranges from ca. 2800 to 3482 m a.s.l., which is the summit of Thabana-Ntlenyana, the highest mountain of Southern Africa. Valleys are asymmetrically shaped, with south-facing slopes being steeper and shorter than the north-facing slopes (Boelhouwers, 2003; personal observations by the authors).

The moraine-like landform under investigation is located at 29°33′29.37″ S, 29°17′43.50″ E, on a south-facing slope of the Tsatsa-La-Mangaung mountain range, ca. 3 km north of the Sani Pass border and 2 km west of the Great Escarpment.

The study site lies within the Summer Rainfall Zone East (SRZe in Geppert et al., 2022). While northern winds are common all year round, the prevailing summer wind comes from the east, transporting moisture from the Indian Ocean (Geppert et al., 2022). In winter, the wind blows predominantly from the west (Sene et al., 1998). Rainfall is mainly due to large-scale line thunderstorms and orographically induced storms (Tyson et al., 1976).

The WorldClim data set estimates mean annual precipitation values of ~ 1015 mm around Sani Top (Fick and Hijmans, 2017), with 75 % falling from November to March and less than 10 % falling in winter, from May to August, mainly as snow (Nel and Sumner, 2008; Sene et al., 1998). Inter-

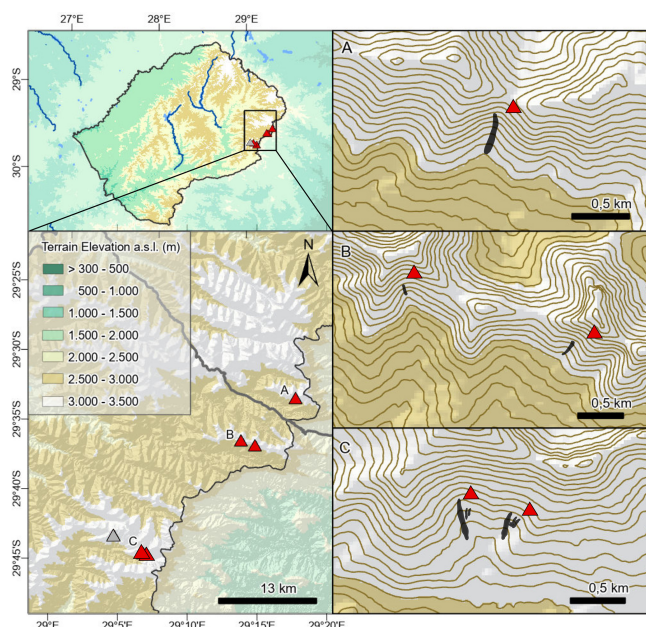


Figure 2. Geographic setting (elevation data from U.S. Geological Survey, 2014). (Top left) Location of focal area in Eastern Lesotho. (Bottom left) Triangles show locations with landforms related to glacial processes by Mills and Grab (2005), Mills et al. (2009a, b), and Mills et al. (2012). The grey triangle indicates a site in Mills et al. (2012) based on remote sensing only. (A) Tsatsa-La-Mangaung (revisited by us and representing our study site). (B) Sekhokong Range. (C) Leqooa Valley; equidistance = 20 m; positive, ridge-like landforms in black; SRTM elevation data from U.S. Geological Survey (2014).

annual variability in snowfall is high (Wunderle et al., 2016). South-facing slopes above 3250 m a.s.l. receive a maximum amount of snow, which can last several weeks to months (Hanvey and Marker, 1992; Mulder and Grab, 2009; NASA, 2023).

The study area features one of the highest precipitation levels in Southern Africa and the lowest annual temperatures (Fick and Hijmans, 2017; Meque et al., 2022). Temperatures range from a monthly mean of -0.6°C in July to 8.7°C in January (Fick and Hijmans, 2017). Temperatures drop below zero regularly, and up to 200 d of ground frost per year is assumed in the study region (Sene et al., 1998). Considering the intense insolation under the mostly cloudless winter sky, diurnal melt–freeze cycles result (Hanvey and Marker, 1992). Rock surface temperatures during winter show a mean of 7.2°C at a north-facing slope and of -5°C at a south-facing slope near Sani Top, at 3060 m a.s.l. (Grab, 2007a). Air temperatures on south-facing slopes may decline to -13.5°C in July (Grab, 2007a). Grab (2007a, b) emphasized a considerable “frost cracking window”. In this context, Boelhouwers and Sumner (2003) reported high block concentrations on south-facing slopes above 3000 m a.s.l. Periglacial pro-

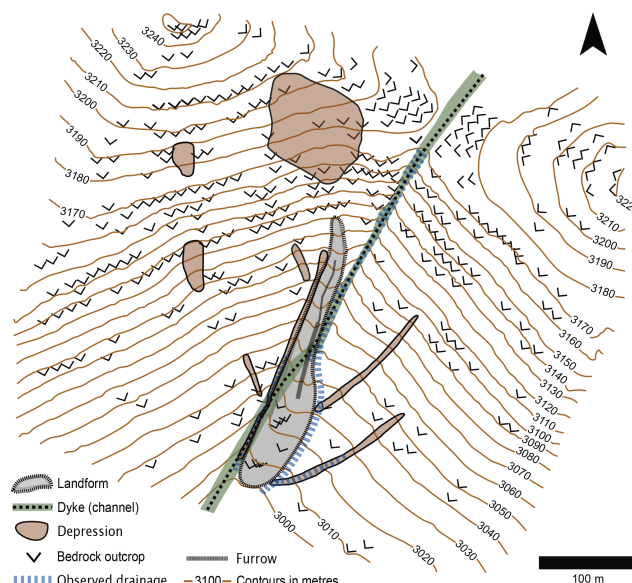


Figure 3. Geomorphological map of moraine-like landform at Tsatsa-La-Mangaung.

cesses appear to be limited to the few summit areas above 3400 m a.s.l. (Grab et al., 2021).

The regional regolith cover is generally thin, and soils are poorly developed on slopes. However, alpine vegetation of grass and heath communities is fairly well developed (Mills and Grab, 2005; Grab, 2010; Fig. 3).

3 Material and methods

Our field survey at the Tsatsa-La-Mangaung was conducted during March 2022. The field campaign included topographical surveying, geomorphological mapping, and sedimentological prospection. Photo documentation of the study site, accompanied by georeferenced markers, was used to record features and phenomena relevant to substrate and process determination. Furthermore, a DJI Mavic 2 Pro Quadcopter carrying a Hasselblad L1D-20c camera was employed to obtain high-resolution aerial imagery of the landform and surrounding slopes. Therefore, several different viewing angles were captured. Additionally, geological maps and remote sensing data were examined to assess the presence of dikes. Drone-derived data were processed using the software Agisoft Metashape Professional (2023). The workflow included the alignment of 37 georeferenced drone photos and placing and verifying markers with nearly 20 000 tie points. A high-resolution dense-cloud and depth map with mild filtering was built. This dense cloud served as the fundamental input data for the construction of a 3D mesh, a crucial component for texture reference. Following this, the digital elevation model (DEM) was computed from the high-resolution dense cloud, and the texture was integrated. Additionally, contours and high-resolution cross sections were derived from the DEM,

further enhancing the analysis and visualization capabilities. Google Earth Pro (2022) was employed for verification purposes and for searching further co-occurrences of moraine-like landforms and dikes.

The temporary snow line in the highland of Lesotho was documented by snow cover maps of MODIS on NASA's Terra satellite (NASA, 2018, 2023) and, specifically for the study site, on the ground by photo camera in late July 2022.

4 Results

The ridge stretches from NNE to SSW, perpendicular to the contour lines, following the gradient (Fig. 3). This feature formed at the junction of two slopes with a mean angle of $\sim 20\text{--}22^\circ$ ($\sim 36\text{--}40\%$) facing SSE and SW, respectively (Figs. 4a, 6). Both slopes feature basaltic bedrock outcrops, which, mainly in the upper part, follow a bank-like structure (Figs. 3, 4b–c, 6). These outcrops can also be observed in satellite data above the other postulated moraine sites at the Sekhokong Range (Fig. 2d) and Leqooa Valley (Fig. 2e) (Google Earth Pro, 2022). At Tsatsa-La-Mangaung, block-like weathering has primarily occurred in the upper parts of the slopes (Fig. 5g). Outcrops are more massive, whereas the blocks have mainly diameters ranging from around 0.15 to approximately 2 m, covering both slopes. Weathering of these blocks has added ample numbers of coarse granular clasts to the regolith. A thin soil layer has allowed the growth of grass and heath communities (Fig. 4c).

The studied landform is about 330 m long, descending from ca. 3120 to 3000 m a.s.l. (Fig. 3). The upper section (3090–3120 m a.s.l.) is bent and positioned on the SE-facing slope (Fig. 4a–d). Further down in the middle part (3000–3090 m a.s.l.), the landform becomes rather straight (Fig. 4a, c). At lower elevations (3050–3000 m a.s.l.), it is situated on the SW-facing slope (Figs. 3, 4a, 6). The width of the landform ranges from 12 to 47 m, with a general increase from the upper to the lower section (Figs. 4a, 6). Towards the slope base, the shape of the landform is noticeably more expanded (Figs. 3, 4a, 6, e). A small-scale furrow was identified in the upper and middle parts, widening downslope and delineating a seam within the landform (Fig. 3). The upper portion of the landform has a slope angle of ca. 23° (42 %, 3050–3120 m a.s.l.), while the lower part of the ridge features a slope angle of ca. 17° (30 %, 3000–3050 m a.s.l.) (Fig. 6f).

The base of the landform is a basaltic bedrock rib built up from several bedrock outcrops (Figs. 3, 4b, 5j). In a larger context, it is part of the bank-like-structured outcrops running mainly along the contour lines of the slopes (Figs. 3, 4a, 6). In relation to the landform, the bedrock rib is obvious because of bedrock outcrops in the middle and lower parts (Figs. 3, 4b, 5j, h). In the lower section, for example, a massive rock wall of ca. 2 m height and 15 m length is exposed (Figs. 4b, 5j), stretching between 3020 and 3030 m a.s.l. and facing from northeast (NE) to southwest (SW) and there-

fore nearly parallel to the contour lines (Figs. 3, 4b, 6). Furthermore, the positive landform consists of blocks and clasts, with sizes similar to the surrounding slopes but in a greater number (Figs. 4c–e, 5h). It encompasses both in situ-weathered material from the bedrock rib and material accumulation from the adjacent slopes, featuring a portion that has also experienced in situ weathering at the location of deposition. The skeletal structure, formed by these larger rocks and blocks, is partially filled in the cavities with loose sediment material containing smaller clasts as well as aggregations of regolith and soil cover (Fig. 4d). There is no noticeable difference in soil properties and vegetation cover at the adjacent slopes. Only the vegetation occurring in the deeper parts of the furrow in the middle part of the landform (Fig. 3) is akin to the denser vegetation found in the depressions along the slopes and within the dike. Whereas the bend in the upper part of the landform primarily represents an accumulation of slope material, blocks on and along the rib in the middle and lower part are the product of in situ-weathered outcrops (Fig. 5h, k).

The adjacent slopes are mainly straight to slightly convex, with some small local depressions (Fig. 6). The uppermost part (ca. 3150–3205 m a.s.l.; mean slope 20.5° (36 %)) of the SW-facing slope exhibits the most significant depression (ca. 0.01 km^2) in the study area. It points towards the bent upper section of the moraine-like landform along the steepest gradient (Figs. 4a, 6). Using the high-resolution DEM, mostly shallow, partly channel-like depressions can be identified on both slopes, not above but beside the landform (Figs. 3, 6). In addition, a narrow, channel-like depression runs parallel to the landform's western side (Figs. 3, 4a, 6), becoming more pronounced with declining elevation (Fig. 5c–d). These linear, narrow, channel-like depressions act as drainage pathways after rainfall (observed in March 2022; see Fig. 3). A depression corresponding to a glacier or nival niche could not be identified on either of the slopes, given the presence of massive outcrops (Figs. 3, 4a–c, 5g, 6) and given that it would further be evident in the high-resolution DEM (Fig. 6) as a noticeable depression.

A linear dike from and to neighboring mountain ranges, visible in low-angle field observation and satellite data, features specific vegetation and a channeled erosional structure (Figs. 4a, 5i). On the surrounding mountain ranges to the NNE, it is visible as a channeled depression (Fig. 5a). In the SSW direction, the dike is detectable by the vegetation differing (Fig. 5i). The geology in this area is marked in general by basalt and dike intrusions of different spatial extents, spanning local to regional structures with varying orientations. The dike can also be found at the postulated moraine site Sekhokong (Fig. 2d). At the Tsatsa-La-Mangaung site, the dike trends from NNE to SSW, running perpendicular to the contour lines and along the depth line at the junction of the slopes (Figs. 3, 4a, 6). It joins the moraine-like landform at the landform's transition from bent to straight (ca. 3090 m a.s.l.) (Figs. 3, 4a, c, d, 6). The dike runs parallel

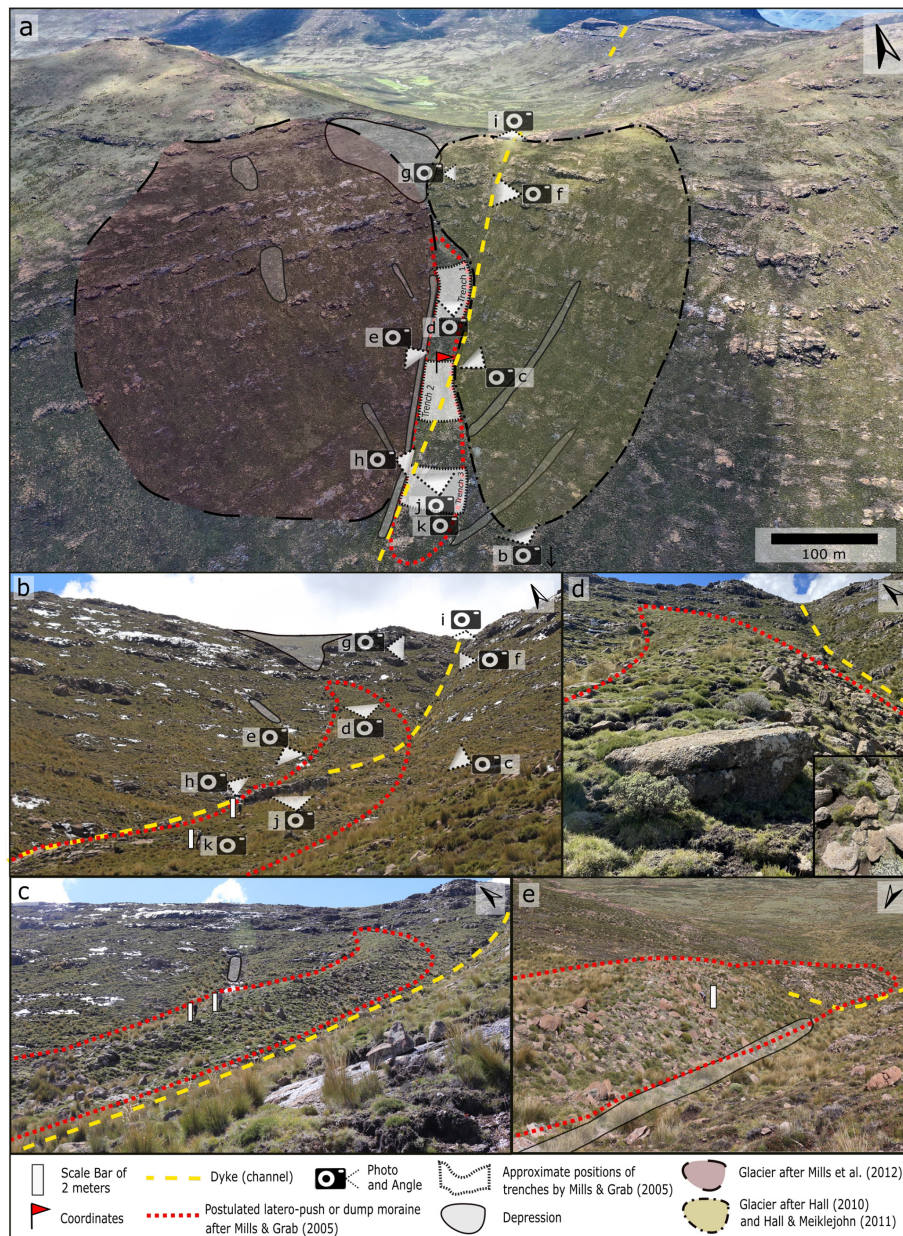


Figure 4. (a) High-resolution drone image showing the moraine-like ridge at Tsatsa-La-Mangaung. (b) Ground photo of ridge. (c) Lateral view of the middle and upper ridge. (d) Upper part of the ridge. (e) Lateral view of the middle and lower part of the ridge. Arrows in the upper-right corner of each panel indicate orientation to the north.

to the landform, accentuating its eastern flank, until it cuts the landform's lower section at ca. 3055 m a.s.l. (Figs. 3, 4a, b, 6). At lower elevations, the dike channel, which reaches its maximum width, is situated on the western flank of the landform (Figs. 3, 4a, e, 6e). The lower section of the landform is located on the SW-facing slope and is more radiating, with a width of up to nearly 50 m (Figs. 3, 4a, 6). The channeled structure of the dike indicates that it consists of rock that is more easily weatherable than the adjacent bedrock. In the uphill position, the dike channels are up to 5 m deep

(Fig. 6b) and capture surface water flow (field observation, March 2022; see Fig. 3), including snowmelt (Fig. 7b). The relative deep incision at a short distance to the watershed suggests either relatively low erosional resistance of the dike or active faulting. Furthermore, the watershed ridge is formed as a smooth saddle (cf. Fig. 4a) without indicating active faulting. Also, the valley head shows a continuous transition from extensive denudation to fluvial erosion. Together with the relatively high number of smaller-sized clasts within the channel (Fig. 5f), we can carefully assume that the incision

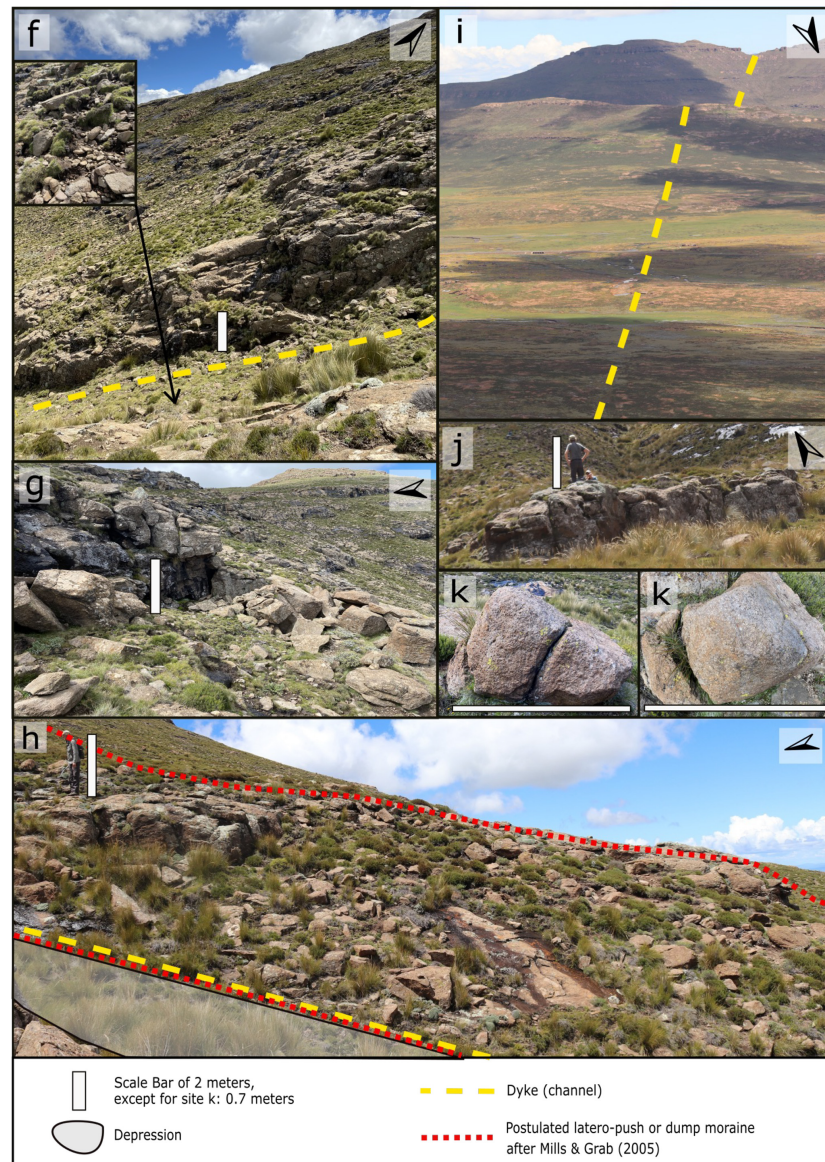


Figure 5. (f) The dike channel is deepest along the upper part of the ridge. (g) Block-like weathering on the upper slope. (h) Western flank of the middle to upper section of the ridge. (i) The dike extending to at least neighboring valleys and mountain ranges. (j) Massive stone wall, which is part of the bedrock rib of the ridge. (k) In situ weathering of large blocks within the ridge (see legend for symbols and scales).

is more likely related to more easily weatherable rock types of the dike than the hypothesis of active tectonic processes. Furthermore, the soil layer and vegetation display enhanced density. In the high-resolution cross-sections C–E depicted in Fig. 6, it is evident that the landform rises less than 3 m above the surrounding slope level.

5 Discussion and conclusions

We did not find any indication that the moraine-like landform in the Tsatsa-La-Mangaung mountain range was formed by a glacier (see, e.g., Hall, 2010; Hall and Meiklejohn, 2011;

Mills and Grab, 2005; Mills et al., 2012). We interpret the identified bedrock rib as a barrier where material from the upper slope could accumulate. The accumulated blocks and clasts are mainly found in the upper section of the landform, which has created the bent extension of the bedrock rib. We could identify the corresponding supply area of ca. 0.01 km² (Fig. 6), with the steepest gradient trending towards the central accumulation zone. This co-occurrence is in phase due to the lack of evidence of a downslope landform that could represent a terminal moraine. Other supply areas (Figs. 4a, 6) are much smaller and directed towards the lower parts of the landform, explaining why less slope material has been

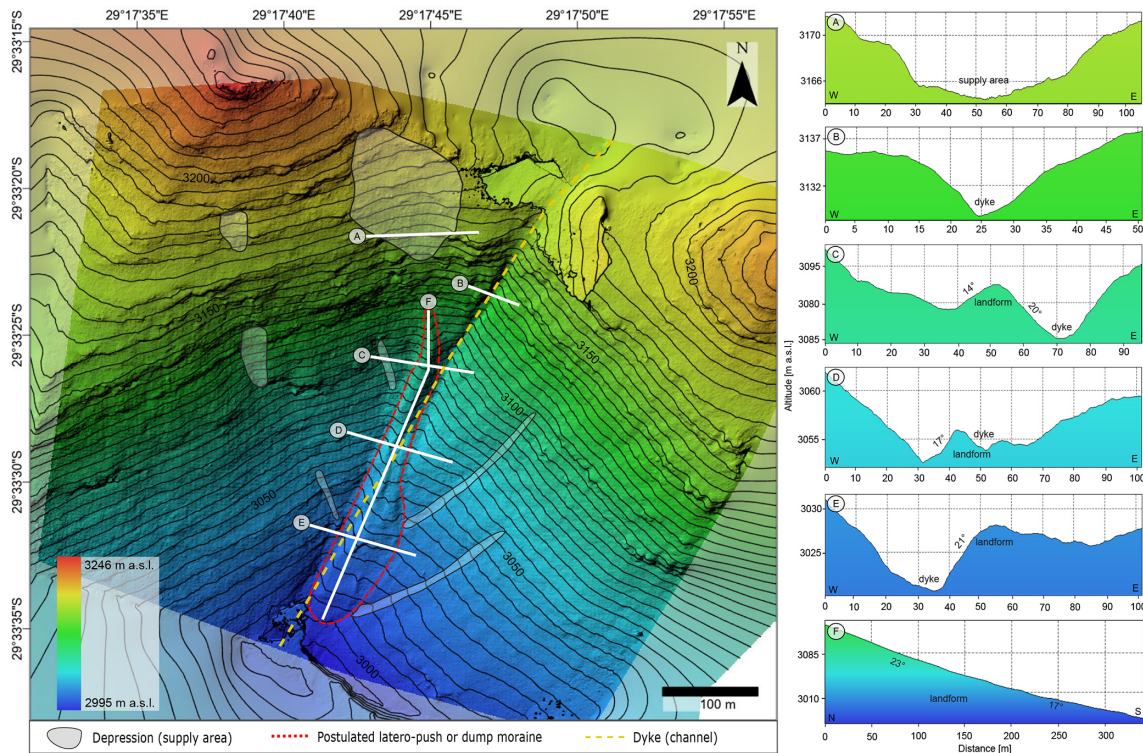


Figure 6. Left: high-resolution digital elevation model (DEM) with texture and contour lines derived by drone imagery, showing the study site. (A) Cross section through the major depression above the landform. (B–E) Cross sections at different positions of the dike and the landform. (F) Longitudinal profile through the landform (see legend for symbols).

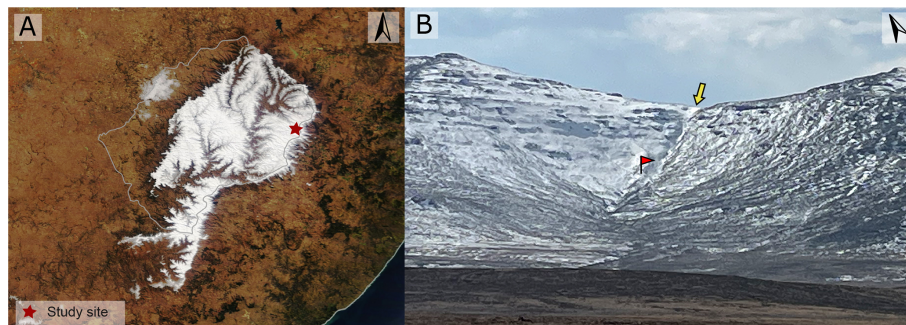


Figure 7. (a) Temporary snow line in the highlands of Lesotho on 6 August 2018 (NASA, 2018). (b) Snow cover on Tsatsa-La-Mangaung (photo from 29 July 2022). The flag indicates the position of the moraine-like landform; the arrow points at the snow-filled dike channel.

deposited there; however, they contribute to the downslope broadening of the landform. Part of the blocks represent in situ weathering of the bedrock rib or deposited rocks and blocks (Fig. 5k). The primary source area of the blocks and clasts which have accumulated at the upper section of the bedrock rib represents the only larger depression on the two adjacent slopes (Fig. 6). Therefore, the glacier locations sketched by Hall (2010) and Hall and Meiklejohn (2011) for the SW-facing slope and by Mills et al. (2012) for the SSE-facing slope show no geomorphological match (Fig. 4a), except for the bent block and clast accumulation at the upper

section of the landform, which is clearly not of glacial origin. Small glaciation and a short lifespan of glaciers were presented by Mills and Grab (2005) as arguments for not causing substantial erosion and depositional remnants, which were already discussed in Hall (2010) and Knight (2012). Nevertheless, a glacier that lays down a moraine would grind at least the area. But there is no evidence of glacial abrasion; in contrast, there is strongly weathered micro-relief, which would not have withstood glacial processes. Furthermore, we found sharp bank-like bedrock outcrops (Figs. 3, 4a–c, 6) and convex forms over the vast extent of both slopes (Fig. 6, also

mentioned in Hall, 2010). These findings are consistent with the uniform contour lines, which show no significant depressions, presented in Fig. 2 by Mills and Grab (2005). In summary, we could not identify signs of glacial erosion or a nival niche deep and large enough in which a glacier could have developed.

The three trenches described by Mills and Grab (2005) (Fig. 4a) align with our findings. However, they primarily consist of diamictic material in the form of larger rocks and blocks, which is indicative of rockfall, obviously to be expected by the uphill slope and rock wall stairs. The subsequent infilling with colluvial fine material and weathering processes, along with post-sedimentological accumulation of fine soil particles due to soil development, contribute to the formation of the observed soil profiles. Nevertheless, we cannot contextualize these profiles with evidence of glacial deposits. The original dating of soil organic matter by Mills and Grab (2005) from depths between 1.35 and 1.5 m in the trenches indicates that these local pits developed during the pre-Holocene period, covering a period of nearly 7 ka. This supports the hypothesis of a sequential accumulation of the landform, resulting from several successive events.

Mills and Grab (2005) provided a review and a discussion of potential underlying processes, which made them conclude that a glacial moraine represents the most likely interpretation of the landform. We agree with their sedimentological analysis that particle properties are not exactly typical of debris flows, but we suggest small-scale debris flows likely occurred. This is against the background that we measured a slope angle of 23° above the landform, which is steep enough to initiate debris flow (Iverson et al., 1997), while Mills and Grab (2005) wrote that the angle has to exceed 27°. In this context, it is noteworthy that the highlands of Lesotho are tectonically active (Cherry, 1996). Mills and Grab (2005) admitted that the little-sorted, dominantly angulated clasts found at the landform are characteristic of pronival ramparts (Hall and Meiklejohn, 1997), but following their own conclusion that no debris flow could have occurred, they excluded the possibility that the moraine-like structure was solely formed by erosional gravitational processes. Instead, they interpreted debris-flow-like sediment components as supraglacially derived (Mills and Grab, 2005). We doubt the validity of the idea of supraglacial transport because a potential glacier would have formed just below the culmination (cf. Fig. 4a in Mills et al., 2012, and Fig. 4a in this paper), and thus there would have been only a small source area of clasts. Furthermore, we find the assumption of Mills and Grab (2005) that coarser debris can flow onto a glacier but not along an ice-free slope questionable. Benn and Ballantyne (1994) suggested that differentiation between moraine material and frost-weathered scree by the aggregated class roundness index cannot be evidenced. The latter suggestion is in line with our interpretation.

Frost weathering is considered to be pronounced at the study site, with its terrain above ca. 2900 m a.s.l. termed sub-

periglacial (*sensu* Karte, 1983) by Marker (1992). This classification includes extended seasonal diurnal freeze–thaw cycles. In Fig. 7b the snow line runs almost exactly along the 2900 m contour line. During cold spells the snow cover can be sustained at elevation a few hundred meters lower (Fig. 7a). The accumulation of snow at the study site is enhanced in the depressions including the dike channel (arrow in Fig. 7b). The availability of meltwater is thus higher and the frost cracking more intense.

Furthermore, a linear dike structure is evident at the Tsatsa-La-Mangaung site, extending to both sides and reaching the Sekhokong site in the SSE direction (Fig. 2d; Lesotho Government, 1982). At the Tsatsa-La-Mangaung site, a channel-like depression combined with the dike channel shaped and accentuated the landform by erosion (Figs. 4a, 6). After the landform deposition, the narrow, channel-like depression developed parallel to its western flank, as precipitation and meltwater began to preferentially drain down beside the landform (observed after rainfall in March 2022; see Fig. 3). Alongside the dike channel, which also collects surface water (observed in March 2022; see Fig. 3), the form is accentuated on both sides through enhanced weathering processes and fluvial erosion. This is particularly evident in the cross sections in Fig. 6c–e. The dike channel therefore contributes to the landform's development and shape, deepening the eastern flank in the upper part of the landform by erosion and increasing its slope gradient (Fig. 6c). The resulting asymmetrical slope is therefore no indication for a latero-push or dump moraine as suggested by Mills and Grab (2005). In summary, the sedimentological parameters presented by Mills and Grab (2005) are not mandatory for glacial deposits (cf., e.g., Bennett et al., 1999). They assume appropriate erosional features, but no morphological evidence for glacier erosion could be presented for this site. Finally, the discussed sedimentological properties are not designed to prove glacial accumulation on such small scales (cf., e.g., Benn and Ballantyne, 1994, among others).

Five other sites in Eastern Lesotho have been considered to show glacial landforms (Mills and Grab, 2005; Mills et al., 2009a, b, 2012; Fig. 2). They have, in common with our study site, an altitude above 3000 m, and the four ground-investigated sites show assumed moraines, which are also oriented perpendicular to the contour lines following the gradient of south-facing slopes (Fig. 2d–e). The Sekhokong (Fig. 2d) and Leqooa Valley (Fig. 2e) sites furthermore also show an absence of irregularities in contour lines above the formations, as illustrated in the morphological maps by Mills and Grab (2005) and Mills et al. (2009a) in their Figs. 4 and 3, respectively. Google Earth Pro (2022) imagery further confirms the presence of substantial bedrock outcrops above the landscape features at these additional sites. High-resolution digital elevation models are crucial for accurately analyzing and interpreting the described landforms at the investigated locations. Furthermore, for the Sekhokong site (Fig. 2d), it is essential to incorporate the influence of

dike structures outlined in the *Geological Map of Lesotho* (Lesotho Government, 1982) on the formation of the landscape features. Whether these landforms can be explained by processes other than glacial processes will remain unanswered until these sites are re-investigated. Moreover, the interior of the highland is understudied, and a detailed landscape analysis is needed to discuss whether LGM temperatures were low enough for glaciers to form.

Data availability. The image data and derived DEM can be requested from the corresponding author.

Author contributions. FR, KH, and VB conducted the field survey and data collection. JM was essential in supporting the fieldwork by organizing the flight permit for the drone. VB performed the data analyses. The interpretation of the data presented in this scientific publication was conducted collaboratively by VB, MB, KH, and FR. VB wrote the initial manuscript with support from all other authors. KH conducted the revision process.

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

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