Main changes made to the revised manuscript:

- New title: “The enigma of relict large sorted stone stripes in the tropical Ethiopian Highlands”
- Four figures regarding the ground temperature measurements were removed and one was shifted to the appendix
- All tables were shifted to the appendix
- As requested by the reviewers, the manuscript was shortened (from 37 to 32 pages); without the appendix and references, the revised manuscript consists now of 23 pages
- The structure of the manuscript was revised and new subheadings were included in the discussion
- A new figure was included to illustrate the potential genesis of the stone stripes
- The entire text was revised

~~Implications~~ The enigma of ~~present ground temperatures and~~ relict large sorted stone stripes in the tropical Ethiopian Highlands~~for the palaeoclimate of the tropics~~

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Abstract. Large sorted patterned grounds are one of the most prominent features of periglacial and permafrost environments of the ~~mid and high latitudes, but have not yet been verified~~ mid-latitudes and polar regions, but were unknwon for the tropics. Here, we report on relict large sorted ~~polygons (up to 8 m in diameter) and large sorted~~ stone stripes (up to 1000 m long, 15 m wide, and 2 m deep) on the ~~~~~ca. 4000 m high ~~Sanetti Plateau~~ central Sanetti Plateau of the tropical Bale Mountains in the ~~Bale Mountains,~~ southern Ethiopian Highlands. These geomorphic features are enigmatic since patterned grounds exceeding several metres are commonly associated with distinct seasonal ground temperatures, oscillating around 0 °C. For a systematic investigation of ~~past and present frost-related processes and~~ present frost phenomena and relict periglacial landforms in the Bale Mountains, we conducted ~~geomorphological mapping both in the field and on satellite images~~extensive geomorphological mapping. The sorted stone stripes were studied in more detail by applying aerial photogrammetry, ground-penetrating radar measurements, and ^{36}Cl surface exposure dating. In addition, we installed ~~29~~ ground temperature data ~~loggers between 3493~~ logger between 3877 and 4377 m to analyse present frost occurrence and seasonal ~~temperature variations from 2017 to 2020. Finally, we ran a simple experiment and combined recent ground temperature measurements with meteorological data in a statistical model to assess the air temperature depression needed for the past formation of deep seasonal frost and cyclic freezing and thawing on the plateau. Our results show that relict and modern periglacial landforms are common in the Bale Mountains. Nocturnal superficial ground frost on the plateau occurs~~ ground temperature variations. Superficial nocturnal ground frost was measured at 35-90 days per year, but the ground beneath the upper few centimetres remains unfrozen the entire year. Seasonal frost occurrence would require a mean annual ground temperature ~~(~~~~depression of about 11 °C~~) is far off from seasonal or permanent frost conditions. The modelling experiment suggests a minimum air temperature depression on the plateau of 7.6 ± 1.3~~ , corresponding to an air temperature decrease of about 6-8 °C ~~for the emergence of several decimetre deep seasonal frost. The stone stripes probably formed under periglacial conditions~~ (relative to today) as inferred from a simple statistical ground temperature model experiment. Our results suggest a formation of the large sorted stone stripes under past periglacial conditions related to lateral and vertical frost sorting in the course of cyclic freezing and thawing of the ground. It is likely that the stone stripes formed either in proximity of a ~~palaeo~~ former ice cap on ~~Tullu Dimtu during the coldest period(s) of~~ the

Sanetti Plateau due to seasonal frost heave and sorting over the last glacial cycle. We hypothesise that the slightly inclined and unglaciated areas of the plateau, the coexistence of regolith and large blocks, the occurrence of deep seasonal frost, as well as relatively dry conditions beyond the ice cap provided ideal conditions for frost heave and sorting and the formation of large patterned grounds. The period or they developed over multiple cold phases during the Pleistocene. Although certain aspects of the genesis of the large sorted stone stripes remain unresolved, the presence of these landforms and the associated air temperature depression provide further evidence for an amplified cooling of high tropical mountains during the last glacial period that is yet not well captured in global climate modelsgeomorphic features provides independent evidence besides glacial landforms for unprecedented palaeoclimatic and palaeoenvironmental changes in the tropical Bale Mountains during the (Late) Pleistocene.

1 Introduction

The Earth experienced a pronounced global-mean cooling of 5-7 °C during the global Last Glacial Maximum (LGM; 22 ± 4 ka after Shakur compared to the pre-industrial climate, but the magnitude of cooling and expansion of ice sheets and glaciers varied considerably across the globe. While global climate models point towards a maximum cooling over the northern hemisphere ice sheets, they suggest only a moderate cooling for the tropics (Schneider von Deimling et al., 2006).A synthesis of sea surface temperatures testifies to a moderate mean zonal LGM cooling of Sorted patterned grounds in the form of stone polygons, circles or stripes are one of the tropical oceans of ~2 most striking features of periglacial and permafrost environments. They are known from the Arctic (e.g. Nicholson, 1976; Hallet, 2013), Antarctic (e.g. Hallet et al., 2011), mid-latitudes (e.g. Richmond, 1949; Miller et al., 1954; Bal , and high mountains (e.g. Francou et al., 2001; Matsuoka, 2005; Bertran et al., 2010), and were even detected on other celestial bodies like Mars (e.g. Mangold, 2005; Balme et al., 2009). Sorted stone polygons are found in flat areas while stripes typically occur on slightly inclined slopes. Both forms are the product of a self-organising process related to the cyclic freezing and thawing of the ground (Kessler and Werner, 2003). Small-scale patterned grounds in the order of centimetres to decimetres are common on many mid-latitude and high tropical mountains as superficial nocturnal frost is sufficient for their formation (e.g. Francou et al., 2001; Matsuoka, 2005). On the contrary, large sorted forms (with several metres in diameter) occur almost exclusively in permafrost areas where the mean annual air temperature is far below 0 °C (MARGO Project Members, 2009)C (Goldthwait, 1976). Active large sorted stone circles, polygons, and stripes are well-documented for the High Arctic (e.g. Washburn, 1980; I and in relict form also for some mid-latitude mountains (e.g. Ball and Goodier, 1968; Vopata et al., 2006; André et al., 2008; Křížek et al., 2 , but they have not yet been reported for any site in the tropics.

The absence of large sorted patterned grounds in the tropics could generally be explained by the warm tropical climate, the intense solar radiation, and minor seasonal temperature fluctuations. However, terrestrial temperature reconstructions based on calculated snow line depressions on tropical mountains indicate a much stronger and more heterogeneous cooling of 2-14 °C (Mark et al., 2005). Other terrestrial palaeoclimate data from the low-latitudes confirm the pronounced cooling over land and highlight an amplified cooling with increasing elevation (Farrera et al., 1999; Loomis et al., 2017). Disentangling the causes for the mismatch between the reconstructed cooling the missing observation of such landforms could also be partly due to the remoteness of many mountains and the resulting lack of geomorphological investigations. An enigmatic relict landform similar to the large sorted stone stripes known from the mid-latitudes and polar regions has been reported from the ca. 4000 m high central Sanetti Plateau of the tropical oceans and land areas, especially at high elevation, is crucial for understanding and simulating global climate changes during the last glacial period because the energy excess in the the tropics and transport towards higher latitudes drives the large-scale atmospheric and oceanic circulation (Kageyama et al., 2005). Model uncertainties and limitations as well as erroneous marine and terrestrial temperature reconstructions have been discussed as potential causes for the discrepancy. Climate model experiments and latest temperature reconstructions along an elevational gradient in Eastern Africa provide an alternative explanation: they support the interpretation that the amplified cooling at high elevations in the tropics during the global LGM was the result of a drier atmosphere and steeper lapse rate (Kageyama et al., 2005; Tripati et Bale Mountains in the southern Ethiopian Highlands (Miehe and Miehe, 1994). The stone stripes on the southern part of the Sanetti Plateau are several metres wide and tens of metres long. They are located on the slope of an eroded volcanic plug and have therefore originally been termed "trenched boulder slopes" (Miehe and Miehe, 1994; Osmaston et al., 2005) . Grab (2002) pointed out that the large – and for the tropics unique – dimension of the stone stripes may be an indicator for past sporadic permafrost on the plateau. However, climate proxy data from the high tropical mountains are still sparse although they are essential for quantifying global LGM temperature changes in the middle troposphere (Farrera et al., 1999). A promising region for high-elevation palaeoclimatic and geoecological reconstructions in the tropics are the Bale Mountains in a systematic investigation of the relict as well as present geomorphological processes and landforms on the Sanetti Plateau has not yet been performed. When and how the stone stripes formed and what their occurrence implies for the palaeoclimate and palaeoenvironment of the southern Ethiopian Highlands as they comprise Africa's largest alpine environment and provide manifold evidence for past glacial and periglacial processes (Grab, 2002; Osmaston et al., 2005; Hendrickx et al., 2014; Groos et al., in rev . During the Late Pleistocene, an ice cap with several outlet glaciers covered the central Sanetti Plateau and northern valleys is still unexplored.

Information regarding the age and genesis of the large sorted stone stripes are essential for the reconstruction of the palaeoenvironment of the Bale Mountains. The local maximum glacier expansion in the region was reached between 50-30 ka, well before the global LGM, and coincided with a temperature depression of 4-6 °C (Groos et al., in revision). In view of the gradual global cooling until 22 Recent glacial geomorphological and chronological investigations revealed that the Bale Mountains were extensively glaciated during the Late Pleistocene and experienced a pronounced cooling of at least 5.2 ±4 ka, an even stronger temperature depression (>6 0.8 °C) in the Ethiopian Highlands seems likely after 50-30 ka . A conspicuous geomorphological feature beyond the glacial remains of the former during the local Last Glacial Maximum between 28-42 ka (Groos et al., in revision). Since the stone stripes are located near the former margin of the ice cap on the Sanetti Plateauare large sorted stone stripes (several meters wide and hundred meters long) between 3850 and 4150 m. They are associated with past sporadic permafrost and might indicate a severe cooling in the Bale Mountains during the Pleistocene (Miehe and Miehe, 1994; Grab, 2002). Sorted patterned grounds of similar size are typical for periglacial and permafrost environments of the mid and high latitudes (Goldthwait, 1976; André et al., 2008). Diurnal freeze-thaw cycles in tropical mountains are sufficient for the development of small-scale patterned grounds (Francou et al., 2001), but the large dimension , it can be hypothesised that the stone stripes evolved under periglacial conditions during the last glacial period. If cyclic freezing and thawing of the ground was indeed one of the preconditions for the formation of the stone stripes on the Sanetti Plateau is unique for the low latitudes as their formation presumably requires deep ground frost and seasonal freezing and thawing (e.g. Kessler and Werner, 2003). A systematic investigation of the relict periglacial landforms and present frost patterns in the Bale Mountains is lacking. When, how, and under which environmental conditions the relict patterned grounds formed and what their occurrence implies for the palaeoclimate of the tropics is therefore still unexploredplateau, they could serve as potential climate proxy. The deviation of the present mean annual ground temperature (MAGT) from the freezing point (0 °C) would then provide a minimum estimate for the ground temperature depression (relative to today) during the period when the stone stripes formed.

The aim of this study is the a first systematic investigation of past and present frost-related processes and landforms in the Bale Mountains to elaborate the potential of geomorphological features like the the relict large sorted stone stripes for paleoclimatic reconstructions at high-elevations in the tropics. For gaining insights into the spatial and elevational and contemporary frost dynamics and phenomena on the Sanetti Plateau. To analyse the distribution of relict and active periglacial landforms, we conducted geomorphological mapping both extensive geomorphological mapping in the field and on supported by the analysis of high-resolution satellite images. The geometry and internal structure of the sorted stone stripes on the Sanetti Plateau were was studied in more detail by applying aerial photogrammetry, based on Unmanned Aerial Vehicle (UAV) and ground-penetrating radar (GPR) measurements, and surveys. Top surfaces of six rocks from two different stone stripes were sampled for ^{36}Cl surface exposure dating. The ^{36}Cl ages were originally data were published by Groos et al. (in revision) in a palaeoglaciological context, but we present them here again as they are also of because of their relevance for the interpretation of the relict stone stripesgenesis of the stone stripes, we present them here again. Since knowledge on present frost occurrence and ground temperature variations in the Bale Mountains is indispensable for discussing how and under which climatic and environmental conditions the relict structures may have formed, we installed a ground temperature network covering thirteen ground temperature data loggers at six different locations on the Sanetti Plateau and northeastern declivity(Fig. 1). In a final step, we combined the ground temperature measurements with meteorological data from nearby weather stations and applied a simple statistical model to assess experiment to infer the minimum air temperature depression needed for the formation of deep frost and patterned grounds in the tropical Ethiopian Highlandstheoretically needed for seasonal ground frost on the plateau (MAGT ~ 0 °C).

2 Study area

The Bale Mountains (6.6–7.1 °N, 39.5–40.0 °E) are located southeast of the Main Ethiopian Rift and belong to the Bale-Arsi massif, which constitutes the western part of the southern Ethiopian Highlands (Fig. 1). Precambrian rocks and overlying

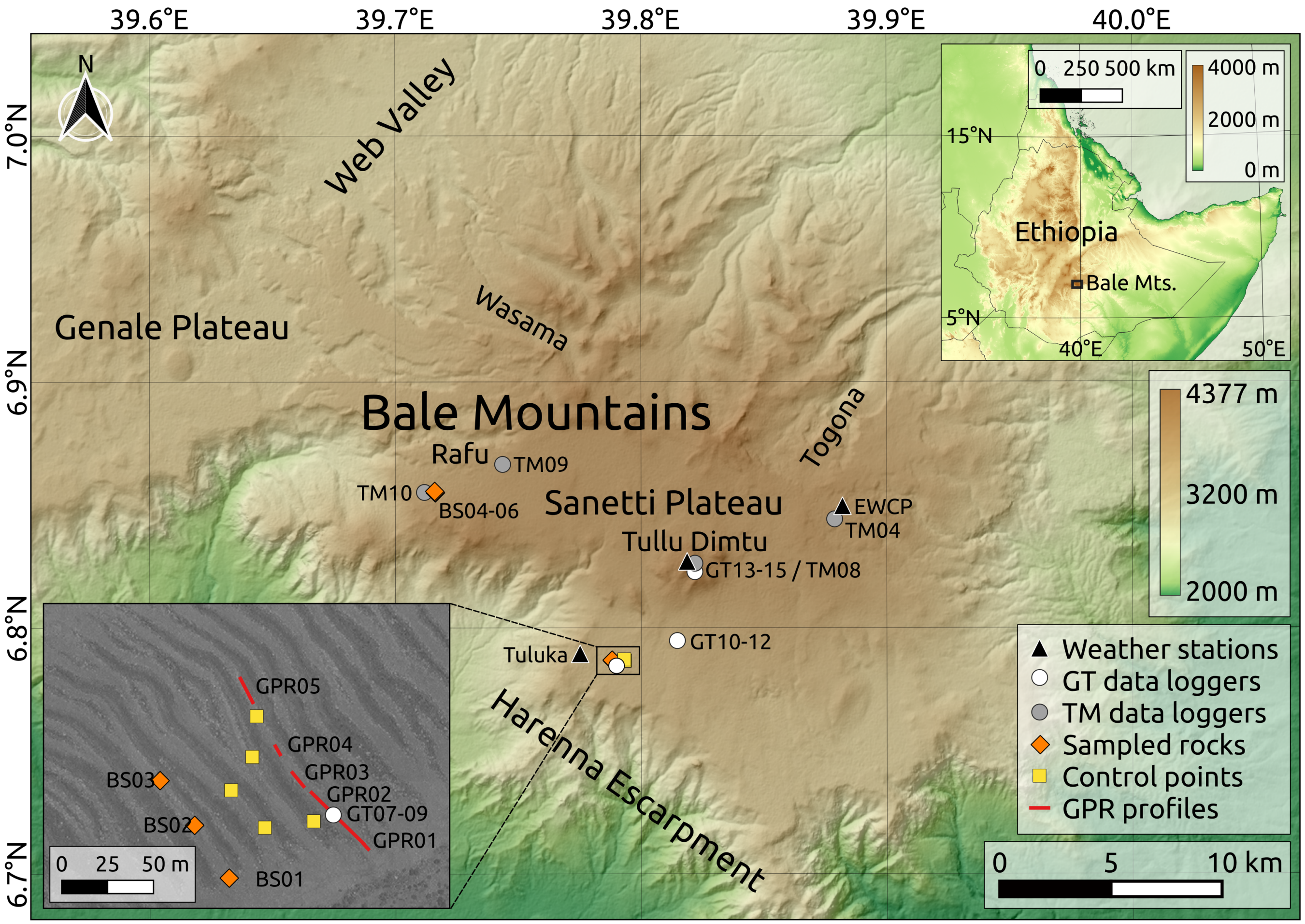

Figure 1. Overview map of the experimental setup and observation observational network in the Bale Mountains , (southern EthiopiaEthiopian Highlands), located in the Horn of Africa. The lowest automatic weather stations Magnete as well as the high-quality (1599 mGT) and Delo Mena low-cost (1315 m) are located 25 and 40 km south of Rira. GT: high-quality temperature data loggers. TM: low-cost) ground temperature data loggers on the Sanetti Plateau were installed in January and February 2017. Unmanned Aerial Vehicle and Ground-Penetrating Radar surveys were performed to obtain information on the morphology and internal structure of the stone stripes (see GPR profiles in the lower left map inset). Rock samples: blocks Six rocks from two different stone stripes were sampled for surface exposure dating. Control points: natural objects used for the georeferencing of the high-resolution orthophoto and digital surface model. GPR: ground-penetrating radar. Data basis: SRTM 1 Arc-Second Global (United States Geological Survey) for the main map and upper right inlet, high-resolution WorldView-1 satellite image (DigitalGlobe Foundation) for the lower left inlet. Ground control points (i.e. natural objects; yellow squares in the inlet) visible in both the georectified WorldView-1 image and the UAV images served for the georeferencing of the UAV data.

Mesozoic marine sediments form the base of the massif and are covered by Cenozoic trachytic and basaltic lava flows (Miehe and Miehe, 1994; Osmaston et al., 2005; Hendrickx et al., 2014). Due to the lack of geological maps, lithological information, geochemical studies, and radiometric dating, especially in the southern Ethiopian Highlands, the exact timing of volcanic eruptions in the region is unknown and the successive formation of the Bale-Arsi massif still poorly understood (Mohr, 1983; Osmaston et al., 2005). Characteristic for the Bale Mountains is the central Sanetti Plateau with a mean elevation of ~~~~~about 4000 m. It is bounded to the west by ~~hardly weathered~~ extensive lava flows, to the north and east by broad U-shaped valleys, and to the south by the Harenna Escarpment. Several volcanic plugs and cinder cones like the highest peak Tullu Dimtu (4377 m) rise above the plateau (Osmaston et al., 2005). With an area of almost 2000 km² above 3000 m, the Bale Mountains comprise Africa's most extensive tropical alpine environment (Groos et al., in revision)~~and~~. Hedberg (1951) defined the afro-alpine belt in tropical Africa as the area above ~3500 m. Others set the lower elevation of the tropical afro-alpine belt to 3200 m (e.g. de Deus Vidal Junior and Clark). The Bale Mountains are an important fresh water source for the surrounding lowlands. The main tributaries of the only two perennial rivers in the Somali lowlands, Shebelle and Jubba, originate from the Bale Mountains.

The seasonal movement of the Intertropical Convergence Zone (ITCZ) and zonal shift of the Congo Air Boundary ~~, which defines the confluence~~ as divide of air masses from the Indian Ocean and Atlantic ~~, determines~~ determine the climate and rainfall patterns of the Ethiopian Highlands (Levin et al., 2009; Tierney et al., 2011; Costa et al., 2014). Due to the complex topography, the mean annual precipitation varies considerably across the region and is strongly ~~linked to~~ controlled by elevation (Gebrechorkos et al., 2019). Three seasons characterise the current climate: The dry season ~~(traditionally called "Bega")~~ lasts from November to February and is followed by two rainy seasons~~("Belg" and "Kiremt"). While "Belg"~~. While the first rainy season (March to June) is more pronounced in the southern Ethiopian Highlands, ~~"Kiremt"~~ the second one (July to October) ~~plays a major role~~ is more important in the northern highlands including the upper catchment area of the Blue Nile (Conway, 2000; Seleshi and Zanke, 2004). ~~During~~ Relatively dry northeasterly trade winds from the Arabian Peninsula and Sea prevail in the Bale Mountains during the dry season ~~, when the ITCZ in Eastern Africa is located~~ as a result of the large-scale atmospheric circulation (i.e. location of the ITCZ south of the equator and persistence of high pressure cells ~~have established~~ over Western Asia and the Sahara~~, northeasterly trade winds from the Arabian Peninsula and Sea prevail in the Bale Mountains and cause only little precipitation~~). Along with the northward movement of the ITCZ from March to June, the main wind direction changes from northeast to southeast and brings moist air from the southern Indian Ocean to the Bale Mountains (Lemma et al., 2020). Although the Gulf of Guinea and Congo Basin are important moisture sources for the northern Ethiopian Highlands (Levin et al., 2009; Viste and Sorteberg, 2013; Costa et al., 2014), they seem of minor relevance for the Bale-Arsi massif (Lemma et al., 2020). The Sanetti Plateau and highest peaks of the massif experience occasional snowfall during the rainy seasons, but the thin snowpack usually melts within hours or days (Miehe and Miehe, 1994). ~~Like most of the other tropical mountains in Eastern Africa, the Bale Mountains are currently unglaciated. The present mean 0 °C isotherm (a rough proxy for the modern snow line in the tropics) is located at least 300 m above the highest peak Tullu Dimtu. However, latest glacial geomorphological and chronological studies provide clear evidence that the snow line was much lower during the Late~~

Pleistocene and favoured the formation of an extensive plateau glaciation with outlet glaciers extending down into the northern valleys. Between 50-30 ka during the local Last Glacial Maximum in the southern Ethiopian Highlands, ice covered about 265 km² of the Bale and additional 83 km² of the adjacent Arsi Mountains. Two later glacial stages were dated to ~18 and ~15 ka. At ~18 ka, the ice extent was slightly smaller than during the local LGM, but ice still covered the central part of the plateau and northern valleys. Deglaciation in the region set in after ~18-15 ka. The highlands remained probably ice-free over the entire Holocene (Ossendorf et al., 2019; Groos et al., in revision). Besides glacial landforms like moraines and roche moutonnées, also relict periglacial features have been reported from the Bale Mountains (Grab, 2002; Hendrickx et al., 2014) . Among those, large sorted stone circles (several meters in diameter) and stone stripes (several meters wide and hundred meter long) on the Sanetti Plateau are the most prominent ones. The formation of such large features is associated with freeze-thaw processes and indicates decimetre to meter deep seasonal frost or sporadic permafrost with a thick active layer (see Sections 3.7, 4, and 5). Field observations and short-term ground temperature measurements between December 1989 and March 1990 verify that nocturnal frost near the soil-atmosphere interface still occurs. The most apparent results of the modern freeze-thaw cycles are the formation of needle ice along saturated stream banks and the presence of sorted stone nets in flat and poorly drained areas on the Sanetti Plateau (Miehe and Miehe, 1994; Grab, 2002).Afroalpine herbs, grasses, *Helichrysum* dwarf shrubs, extrazonal patches of *Erica*, and giant lobelias cover the ice-free and barren Sanetti Plateau today (Miehe and Miehe, 1994). The plateau is home to many endemic plant species like the giant lobelia (*Lobelia rhynchopetalum*) (Chala et al., 2016) and mammal species like the Ethiopian wolf (*Canis simensis*) (e.g. Gottelli et al., 1994), giant mole-rat (*Tachyoryctes macrocephalus*) (e.g. Vlasatá et al., 2017), and mountain nyala (*Tragelaphus buxtoni*) that are restricted to the Ethiopian Highlands (Miehe and Miehe, 1994). Since these endemic species mainly populate the upper valleys and Sanetti Plateau today, palaeoclimatic and -environmental changes like a severe cooling, expansion of the ice cover and periglacial area as well as depression of altitudinal vegetation belts must have directly affected their habitat and are therefore also of relevance in a geoecological context.

3 Data and methods

3.1 Mapping of periglacial landforms

Comprehensive and thorough geomorphological mapping of glacial and periglacial landforms provides crucial data for establishing glacial chronologies and reconstructing the palaeoclimate and palaeoenvironment reconstructing the palaeoenvironment and palaeoclimate of polar and alpine regions (Chandler et al., 2018). We evaluated studied maps, photographs, and field notes from previous studies dealing with periglacial processes and landforms in the Bale Mountains (e.g. Messerli and Winiger, 1992; Miehe and Miehe, 1994; Grab, 2002; Umer et al., 2004; Osmaston et al., 2005) to compile evidence of relict and modern frost occurrence. Since periglacial landforms have yet not not yet been described systematically, we performed extensive geomorphological mapping on the Sanetti Plateau, along the upper Harenna Escarpment, and in the western, northern, and eastern valleys during multiple field excursions trips between 2016 and 2020 (Fig. 2a). In addition, we evaluated analysed high-resolution WorldView-1 satellite images (pixel size = 0.5 m) provided by the DigitalGlobe Foundation to identify geomorphic features in remote ~~and difficult-to-access~~ areas of the mountain range. All periglacial ~~features discovered~~ landforms and other geomorphological features mapped in the field or on satellite images were ~~geotagged and~~ compiled in a catalogue (see ~~Appendix A).~~ Table A1).

3.2 UAV-based aerial surveys

For a detailed analysis of the ~~geomorphology, geometry , and size of the sorted~~ geometry and clast size distribution of the stone stripes on the Sanetti Plateau, we conducted a manual aerial survey (~50 m above ground level) with a small quadcopter (DJI Mavic Pro) on the 30th January 2020 at 2 pm local time. ~~A totalof~~ In total, 75 aerial images were acquired during the survey and were processed with the photogrammetric software OpenDroneMap ~~(following the approach described in Groos et al., 2019)~~ (following the general approach described in Groos et al., 2019) to obtain a high-resolution orthophoto (5 cm) and digital surface model (DSM, 10 cm) of the stone stripes. Five natural objects (rocks and dwarf shrubs) visible ~~on~~ both in the orthorectified WorldView-1 image and at least ~~on~~ in three aerial images were used as ground control points (Fig. 1) ~~for a rough georeferencing of the orthophoto and DSM (Groos et al., 2019)~~to process and georeference the UAV data (see Groos et al., 2019). The necessary elevation information were extracted from the SRTM 1 Arc-Second Global dataset. It was not possible to measure the ground control points directly in the field as a differential Global Positioning System was not available. In principle, a small number of ground control points is sufficient to generate an accurate DSM without any larger deformation if the surveyed area is very small (i.e. 60 x 80 m) (e.g. James and Robson, 2014; Gindraux et al., 2017). The horizontal (XY) accuracy of the final orthophoto is ~0.3 m (relative to the orthorectified WorldView-1 image) and the vertical (Z) accuracy of the DSM is ~0.8 m (relative to the SRTM-1 DEM). The absolute positional accuracy of the orthophoto and DSM might be larger, but this can be neglected as the UAV data are not compared with other datasets. The internal accuracy of the orthophoto and DSM is in the order of just a few centimetres to decimetres.

3.3 Ground-penetrating radar measurements

~~Investigating~~ Information on the internal structure of the coarse stone and fine regolith stripes (i.e. sorting depth, presence/absence of cryoturbation features, etc.) are essential to study the genesis of this landform. However, investigating the internal structure of the sorted stone stripes by excavating a transect was ~~not possible due to regulations. Instead,~~ conflicting with the park rules. As an alterantive we performed a ground-penetrating radar (GPR) survey between two stripes on the southern Sanetti Plateau on the 10th February 2020 (Fig. ~~1~~2b). We made use of ~~the~~ a Pulse EKKO PRO GPR with a 1000 MHz antenna (7.5 cm sensor width) manufactured by Sensors & Software Inc. ~~, which was originally purchased by another subproject of the Ethio-European DFG Research Unit 2358 "The Mountain Exile Hypothesis" for geoecological investigations~~ (for system settings see ~~Appendix B~~Table B1). The GPR was mounted on a compatible pushcart~~(Fig. 2)~~. As survey setting, an exploration depth of 1 m and pulse length of 16 nanoseconds (ns) was applied for the first line and modified to 1.5 m depth and 24 ns pulse length for the following lines. The starting point of the GPR measurement was located 10 m above the position of the data loggers GT07-09~~since the~~ . The uppermost part of the volcanic plug was not accessible with the pushcart. Due to uneven terrain and several natural obstacles like smaller stones and ~~*Helichrysum*~~ dwarf shrubs, the GPR profile between the two stone stripes was split into five

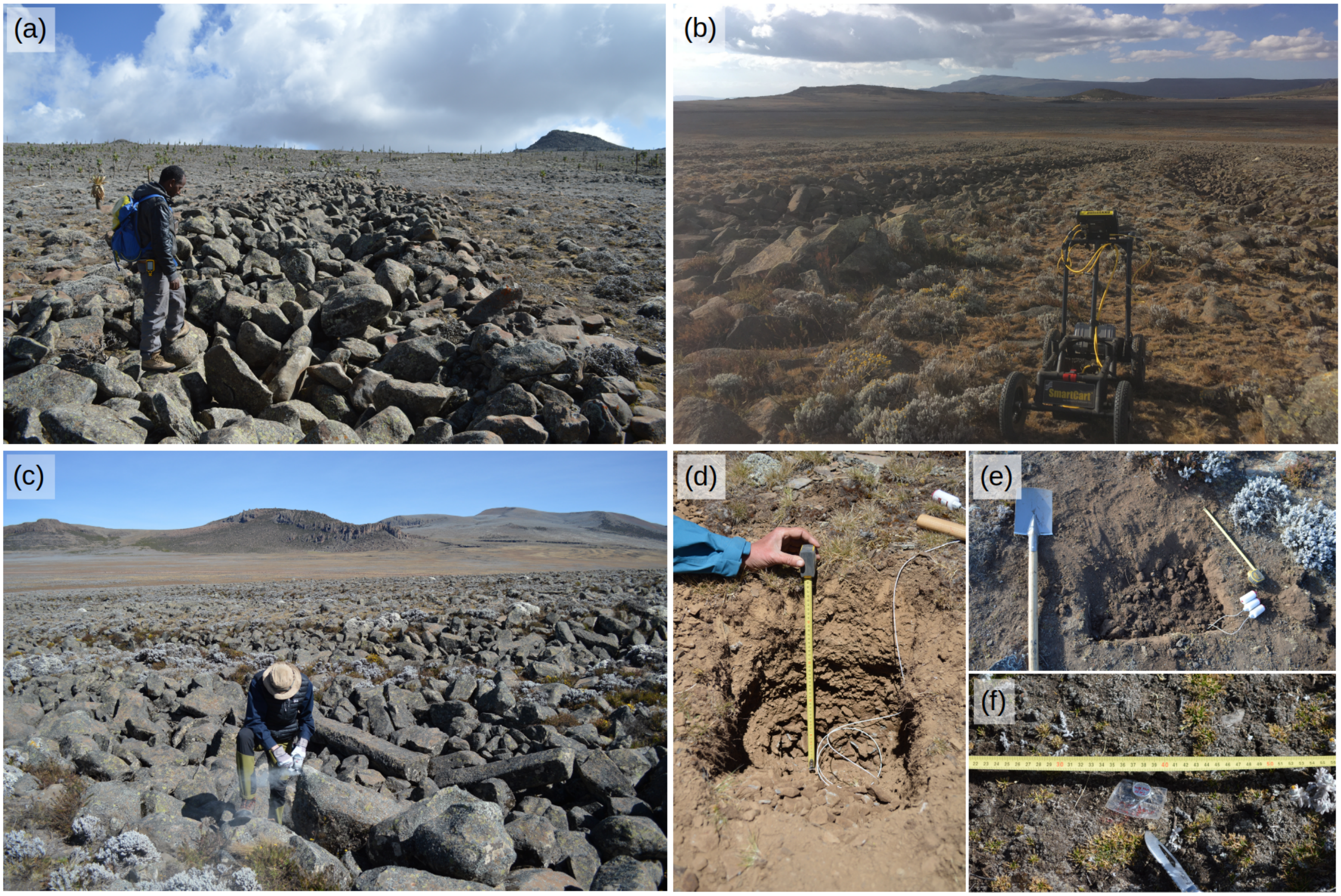

Figure 2. Field work in the Bale Mountains: (a) reconnaissance and mapping of periglacial landforms, (b) ground-penetrating radar survey, (c) sampling of stone stripes for surface exposure dating, (~~c-e~~d-f) installation of ground temperature loggers~~, and (f) ground-penetrating radar survey~~.

separate lines varying between 3.8 and 38.5 m in length. The chaotic structure of the stones stripes prevented a GPR survey inside the troughs and coarse material. ~~For analysis and visualisation of the GPR data, we~~ We used the software EKKO Project (version 5.0) for the analysis and visualisation of the GPR data.

3.4 ^{36}Cl surface exposure dating

Previous studies have ~~demonstrated~~ shown that the stabilisation age of ~~relict periglacial features~~ periglacial landforms like rock glaciers and block fields can be successfully dated with cosmogenic nuclides ~~(e.g. Barrows et al., 2004; Ivy-Ochs et al., 2009; ?) . In analogy, we~~ (e.g. Barrows et al., 2004; Ivy-Ochs et al., 2009; Steinemann et al., 2020). We sampled two sorted stone stripes on the Sanetti Plateau ~~, one about 5 km south and another one about 10 km west of Tullu Dimtu~~ (Fig. 1) ~~, to determine the stabilisation age~~ to exposure date the stabilisation phase of these features. ~~The results were originally published by~~

~~Groos et al. (in revision) in a palaeoglaciological context. We present them here briefly again as they are also of relevance for the discussion of the origin of the sorted stone stripes.~~ From both stone stripes, we selected three ~~columnar rocks~~ boulders for ^{36}Cl surface exposure dating (Table C1). To avoid ~~distorting effects on exposure dating due to strong shielding in the trough-shaped stripes~~ any uncertainties related to the shielding or toppling of rocks after the stabilisation phase, we ~~only chose rocks~~ chose only boulders that were sticking out ~~a bit~~ and were wedged between other ~~rocks~~boulders (Fig. 2c). The upper few centimetres of each ~~target rock~~ boulder were sampled with hammer, chisel, and angle grinder for the subsequent laboratory analysis~~(Fig. 2)~~. An inclinometer was used in the field for measuring the topographic shielding. For extraction of the isotope ^{36}Cl, the six samples were crushed, sieved and chemically treated in the Surface Exposure Dating Laboratory of the University of Bern. Total ~~Cl- and ^{36}Cl-concentrations (see Appendix C~~Cl and ^{36}Cl concentrations (Table C2) were measured from one target at the 6 MV ~~AMS-facility of~~ Accelerator Mass Spectrometre (AMS) fascility at the ETH Zurich using the isotope dilution technique (Ivy-Ochs et al., 2004) and a gas-filled magnet to separate ^{36}S (Vockenhuber et al., 2019). Surface exposure ages were calculated from the measured Cl and ^{36}Cl concentrations with the latest version (2.1) of the CRONUS Earth Web Calculator (http://cronus.cosmogenicnuclides.rocks/2.1/html/cl/) using the physics-based and time-dependent Lifton-Sato-Dunai scaling framework (Lifton et al., 2014; Marrero et al., 2016). For a detailed description of the sample preparation, Cl and ^{36}Cl measurements, and surface exposure age calculation see Groos et al. (in revision).

~~Description of periglacial features on the Sanetti Plateau sampled for ^{36}Cl surface exposure dating.~~

~~Rock Lithology Latitude Longitude Elevation Boulder Boulder Boulder Sample Shielding sample (°N) (°E) (m a.s.l.) length (m) width (m) height (m) thickness (cm) factor BS01 Basalt 6.78634 39.79297 3874 2.1 0.6 1.0 2.5 0.9961 BS02 Basalt 6.78660 39.79280 3869 1.5 0.5 1.4 4.5 0.9961 BS03 Basalt 6.78682 39.79263 3865 0.6 0.4 1.0 3.0 0.9997 BS04 Basalt 6.85491 39.72078 4050 0.8 0.6 1.1 5.0 0.9990 BS05 Trachyandesite 6.85513 39.72074 4049 0.5 0.5 1.0 4.5 0.9990 BS06 Trachyandesite 6.85550 39.72049 4045 1.5 0.5 0.6 3.5 0.9994~~

3.5 Ground temperature measurements

~~Overview of the installed ground temperature data loggers (excluding six lost items).~~

~~Data Latitude Longitude Elevation Depth Slope Aspect Start of Readout logger (°N) (°E) (m a.s.l.) (cm) (°) (°) measurement dates GT16 6.92725 39.77275 4153 2 ± 1 22 140 31.12.17 14.06.18, 23.01.20 GT02 6.92725 39.77275 4153 10 ± 2 22 140 06.01.17 17.12.17, 31.12.17, 14.06.18, 23.01.20 GT03 6.92725 39.77275 4153 50 ± 5 22 140 06.01.17 17.12.17, 31.12.17, 14.06.18, 23.01.20 GT17 6.93000 39.77188 4181 2 ± 1 19 35 31.12.17 14.06.18, 23.01.20 GT05 6.93000 39.77188 4181 10 ± 2 19 35 06.01.17 17.12.17, 31.12.17, 14.06.18, 23.01.20 GT06 6.93000 39.77188 4181 50 ± 5 19 35 06.01.17 17.12.17, 31.12.17, 14.06.18, 23.01.20 GT07 6.78665 39.79342 3877 2 ± 1 8 320 21.01.17 10.12.17, 06.01.18, 25.01.20 GT08 6.78665 39.79342 3877 10 ± 2 8 320 21.01.17 10.12.17, 06.01.18, 25.01.20 GT09 6.78665 39.79342 3877 50 ± 5 8 320 21.01.17 10.12.17, 06.01.18, 25.01.20 GT10 6.79474 39.81469 3932 2 ± 1 10 130 21.01.17 11.12.17, 06.01.18, 26.01.20 GT11 6.79474 39.81469 3932 10 ± 2 10 130 21.01.17 11.12.17, 06.01.18, 26.01.20 GT12 6.79474 39.81469 3932 50 ± 5 10 130 21.01.17 11.12.17, 06.01.18, 26.01.20 GT13 6.82617 39.81897 4377 2 ± 1 0 - 21.01.17 19.12.17, 20.01.20, 26.01.20 GT14 6.82617 39.81897 4377 10 ± 2 0 - 21.01.17 19.12.17, 20.01.20 GT15 6.82617 39.81897 4377 50 ± 5 0 - 21.01.17 19.12.17, 26.01.20~~

~~TM04 6.84411 39.87876 4129 2 ± 1 0 - 18.01.17 09.12.17, 05.01.18, 10.06.18 TM05 6.77522 39.80307 3858 2 ± 1 0 - 18.01.17 09.12.17, 06.01.18, 29.12.18, 25.01.20 TM06 6.77535 39.80311 3857 2 ± 1 0 - 18.01.17 09.12.17, 06.01.18, 29.12.18 TM07 6.77521 39.80318 3856 2 ± 1 0 - 18.01.17 09.12.17, 06.01.18, 29.12.18, 25.01.20 TM08 6.82617 39.81897 4377 2 ± 1 0 - 21.01.17 19.12.17 TM09 6.86644 39.74365 4084 2 ± 1 0 - 23.01.17 12.12.17, 15.06.18, 24.01.20 TM10 6.85509 39.71345 4022 2 ± 1 0 - 23.01.17 13.12.17, 15.06.18, 24.01.20 TM11 7.01307 39.72272 3493 2 ± 1 0 - 29.12.17 14.06.18 TM12 6.95493 39.73463 3769 2 ± 1 0 - 30.12.17 14.06.18, 22.01.20 TM13 6.91937 39.76898 3930 2 ± 1 0 - 31.12.17 14.06.18, 22.01.20 TM14 6.82605 39.80496 4124 10 ± 2 0 - 06.01.18 30.12.18, 26.01.20 TM15 6.81928 39.81152 4185 10 ± 2 0 - 06.01.18 30.12.18, 16.02.20 TM16 6.81327 39.81968 4103 10 ± 2 0 - 06.01.18 30.12.18, 26.01.20 TM17 6.79197 39.81005 3880 10 ± 2 0 - 06.01.18 31.12.18, 26.01.20~~

~~Measurement period(s) of each ground temperature data logger between January 2017 and January 2020. For the statistical gap-filling method applied to obtain complete time series see Section 3.6.~~

For measuring hourly ground temperatures ~~of the Bale Mountains~~on the Sanetti Plateau, we installed high-quality UTL-3 Scientific Dataloggers (hereafter GT data loggers) in 2, 10, and 50 cm depth at ~~five different locations with little vegetation~~ two different stone stripe locations and on Tullu Dimtu, covering an elevation between 3877 and 4377 m (Fig. 1 and Table D1). The GT data loggers ~~are~~ were developed by GEOTEST Ltd. in collaboration with the Swiss Institute for Snow and Avalanche Research. ~~They consist of a waterproof housing, a YSI 44005 thermistor for measuring temperature, a memory for up to 65.000 readings (>7 years by hourly interval), a replaceable 3.6 V lithium battery for power supply, and a USB interface for data transfer. According to the manufacturer, the~~ The measurement accuracy is <0.1 °C at 0 °C~~and the thermometric drift per 100 months is <0.01 °C at 0 °C~~. At each of the ~~five~~ three measurement sites, the upper 50 cm of the ground were removed to install the GT data loggers (Fig. 2d,e). We used data loggers with an external cable and thermistor for the measurements in 10 and 50 cm depth. A standard logger without external cable was placed just below the surface in 2 cm depth. After the installation, each hole was filled in the same order as during the excavation to ensure as little disturbance of the profile as possible. Additional low-cost tempmate.~~-B2~~ -B temperature data loggers (hereafter TM data loggers) in the size of a button cell (Fig. 2f) were distributed ~~across the Bale Mountains between 3493~~ on the plateau between 4022 and 4377 m to increase the spatial coverage of near-surface (2 cm) hourly ground temperature measurements (Fig. 1 and Table D1). The ~~single-use TM data loggers consist of a splashproof housing (we wrapped the loggers in thin tape for better protection), an unspecified thermistor, a memory for up to 8192 readings (341 days by hourly interval), and an irreplaceable 3.0 V battery. A logger-pan-to-USB cable is needed for connecting the TM loggers to a computer and retrieving the data. The~~ measurement accuracy is ± 0.5 °C ~~at -10 to~~ in the range of -10 to 65~~°C according to the manufacturer. Due to the much lower accuracy of the TM data loggers compared to the GT data loggers, we performed a comparative measurement indoor over several hours with logger GT04 as reference. Since the root-mean-square deviation of each TM data logger from the reference measurement was smaller than the stated accuracy of ± 0.5~~ °C~~, a calibration was unnecessary. For a direct cross-comparison in the field, data logger TM08 was installed next to GT13 in 2 cm depth on top of Tullu Dimtu. Two TM data logger (16 and 17) were buried below *Erica* in 10 cm depth for comparison with sites (TM14 and TM15) with only little vegetation~~.

Several issues occurred during the measurement period from January 2017 to January 2020 and caused considerable data gaps(Fig. ??). The data logger positions were orginially marked with four small plastic poles in 2 m distance. They were apparently too conspicuous and led to the loss of several items (GT01, GT04, GT18, TM01-03, TM08, and TM11). Therefore, we removed all poles and switched to natural markers (dwarf shrubs, stones, etc.). Data loggers GT01 and GT04 were replaced by GT16 and GT17longer data gaps. On Tullu Dimtu, data loggers GT13-15 were taken away removed in May 2017, but could be recovered and reinstalled in January 2018. Furthermore, we also noticed a relatively short battery life of just two years for some of the GT and TM data loggers leading to a substantial data loss. Two years are much shorter than the battery life stated by both manufacturers for the respective sampling interval (GT ~ 3-5 years, TM ~ 5 years). After consultation, the manufacturer of the GT data loggers adjusted the internal handling of the lithium batteries to ensure the stated battery life. The two data loggers TM05 and TM06 temporarily recorded unrealistic low values (down to -40 °C). Individual outliers and longer periods with implausible measurements were removed deleted from the time series. After the first reading of data Data logger GT07 , we realised that it was accidentally placed in 6 cm depth and not in 2 cm as intended. The relocation towards the surface after the first readout in December 2017 led to an abrupt increase in the temperature amplitude. Therefore, we calculated hourly ground temperature gradients between 6 and 10 cm depth from GT07 and GT08 data by applying a simple linear regression to extrapolate the GT07 measurements from 6 to 2 cm in the period 21st January to 10th December 2017. A compilation of all ground temperature time series from the Bale Mountains is provided in Table S1. Data gaps Data gaps in individual time series of the data loggers were filled using a simple linear regression and available data from other GT or TM data loggers to generate a complete data set for the period 1st of February 2017 to 20th January 2020 (see Section ??). All data modifications made for each logger are listed in Table S2 (see data availability statement for supplementary Tables S1-4)2020. We analysed the interpolated hourly ground temperature data statistically to quantify frost occurrence and spatio-temporal ground temperature variations on the Sanetti Plateau.

3.6 Meteorological measurements

Overview of the installed automatic weather stations in the Bale Mountains.

Weather Location Latitude Longitude Elevation First Last Data station (°N) (°E) (m a.s.l.) measurement measurement completeness (%)* BALE001 Tullu Dimtu 6.82693 39.81871 4377 04.02.17 31.01.20 73 BALE002 Tuluka 6.78945 39.77511 3848 02.02.17 30.01.20 100 BALE003 Angesso Station 6.89642 39.90854 3949 31.01.17 30.01.20 68 BALE004 Magnete 6.51622 39.74515 1599 06.02.17 01.02.20 100 BALE005 Meskel Darkina 7.05860 39.62336 3724 09.02.17 05.10.19 97 BALE006 Rira Substation 6.75912 39.72161 2803 06.02.17 19.02.20 86 BALE007 Dinsho Head Quarter 7.09378 39.78966 3208 28.01.17 20.02.20 100 BALE008 Sodota** 6.99249 39.70171 3529 29.01.17 21.04.18 100 BALE009 EWCP Station 6.84945 39.88197 4124 01.02.17 30.01.20 100 BALE010 Delo Mena 6.41199 39.83328 1315 11.02.17 01.02.20 100

Within the framework of the DFG Research Unit 2358ten , automatic weather stations (AWS) were installed in the Bale Mountains national park between 1315 inter alia on the Sanetti Plateau between 3848 and 4377 m beginning of 2017 (Table D2). The AWS are manufactured by Campbell Scientific and consist of a three metre galvanised tubing tripod, a grounding kit, a weather-resistant enclosure, a measurement and control system (CR800), a solar module (SDT200), a 168 Wh battery, a charging regulator, a temperature and relative humidity probe (CS215) with radiation shield, a pyranometer (LI-200R), a two-dimensional ultrasonic anemometer from Gill Instruments, and a rain gauge from Texas Electronics (TR-525USW 8"). For protection, the AWS are wire-fenced by a 3 x 3 m compound. Air temperature, relative humidity, and global radiation are measured in at 2 m height, wind speed and wind direction in at 2.6 m height, and precipitation in at 1 m height. The measurement interval is 15 minutes. All measured variables are finally aggregated to hourly averages.

3.7 Statistical data interpolation and analysis

To obtain a complete and consistent data set of hourly ground temperatures for the Bale Mountains from 1st February 2017 until 20th January 2020 (Table S3), we applied a statistical gap-filling approach. Most of the ground temperature measurements from different locations or depths overlap for a certain period in time (see Fig. ??) and allow to establish a statistical relationship. We applied a simple linear regression model to interpolate missing data points in the time series of a logger using data from a nearby logger for which measurements were available. If multiple logger with a similar equidistance came into question for the interpolation, we chose the one that yielded the best fit (evaluated by the coefficient of determination R^2) and lowest root-mean-square error (RMSE). The overlapping measurement period between the predicting logger and dependent logger was split into a calibration and validation part . For the interpolation of incomplete time series in 10 or 50 cm depth, we drew on available data from 2 cm depth of the same location. We used a moving average of the data from 2 cm depth to account for the time-lag response to atmospheric changes in greater depths. The number of preceding hours considered for the calculation of the moving average that yielded the best prediction (high R^2, low RMSE) of the ground temperatures in 10 or 50 cm depth was chosen. Details on the data gap-filling of each incomplete time series are provided in Table S4. The validation of the simple linear models applied for interpolation revealed an average R^2 The AWS installed in the southern and northern part of 0.86 ± 0.07 and RMSE of 1.9 ± 1.4 °C. The the Sanetti Plateau measured quasi continously, but the time series of the data loggers TM05-06, TM08, and TM14-17 were not interpolated because the data served only for comparative experiments (low-cost vs. high-quality loggers, vegetated vs. unvegetated locations, etc.) and were dispensable for the temporal and elevational analysis.Most of the AWS installed in the Bale Mountains measured continuously, but some of the time series are AWS on the central peak Tullu Dimtu was interrupted due to issues with the power supply (Table D2). The hourly meteorological data from the different AWS are stored in an online database and gaps in the time series of all variables except wind speed and direction are interpolated statistically following a workflow developed by ?. Single missing values are interpolated linearly using the average of the adjacent data points. Longer gaps in a time series are filled using available data from several nearby AWS. A multiple linear regression model fitted with data from the overlapping measurement periods is applied to predict the missing values from data of those AWS that reveal a strong correlation and low RMSE. Predictor variables (AWS) with a high R^2 and low error are given a higher weight in the interpolation.We evaluated the interpolated hourly meteorological and ground temperature data statistically to quantify frost occurrence and spatio-temporal ground temperature variations in the Bale Mountains. Twelve data loggers from 2 cm depth (excluding TM05-06, TM08, and TM14-17) and five loggers from 10 and 50 cm depth were considered for calculating mean annual ground temperatures, daily ground temperature cycles, thermal gradients, number of frost days, frost penetration depth, elevational gradients, etc. To study seasonal ground temperature variations related to changes in insolation, cloudiness and humidity, we conducted the calculations separately for the entire study period, the dry season (Bega: November – February), and the two rainy seasons (Belg: March – June, Kiremt: July – October). Furthermore, comparative measurements were performed to investigate the differences in ground temperature between north- and south-facing slopes (GT16 and GT02-03 vs. GT17 and GT05-06), vegetated and unvegetated areas (TM16-17 vs. TM14-15), and the performance of low-cost vs. high-quality data loggers (TM08 vs. GT13)as described by Wöllauer et al. (2020).

3.7 Ground temperature modelling and palaeoclimate reconstructionexperiment

The potential of periglacial landforms for paleoclimatic and environmental reconstructions has already been pointed out in pioneering studies from more than half a century ago (e.g. Galloway, 1965). Periglacial landforms are often more abundant than glacial deposits, especially in dry regions, and can be a more reliable climate proxy than palaeo glacier extents as their formation is less sensitive to changes in precipitation. Here, we explore a novel and experimental approach to infer palaeoclimatic information from relict periglacial landforms and established ground temperature modelling (e.g. MacLean and Ayres, 1985) using on-site meteorological data and present ground temperature measurements.We make the following main assumptions for our model experiment: First, the large sorted For polar and alpine regions, where stone circles and other patterned grounds form, ground temperatures oscillate typically around 0 °C (e.g. Hallet, 2013). If cyclic freezing and thawing of the ground was one of the drivers for the formation of the stone stripes on the Sanetti Plateauare of periglacial origin and their formation required deep seasonal frost or sporadic permafrost with a thick active layer (see Sections 4 and 5 for arguments supporting this interpretation). Second, deep seasonal frost (or permafrost) forms when the long-term , this landform may serve as a potential climate proxy. The deviation of the present mean annual ground temperature is < -1 (MAGT) from the freezing point (0 °C. Third, the impact of the geothermal heat flux on ground temperatures near the surface is negligible in the Bale Mountain. The principal idea of the introduced method is to establish a statistical relationship between the measured ground temperatures) would provide a minimum estimate for the ground temperature depression (relative to today) during the period when the stone stripes formed. Here, we apply a simple statistical modelling experiment to infer which climatic conditions would theoretically promote a MAGT of ca. 0 °C on the Sanetti Plateau. We first established a statistical correlation between ground temperature and a set of meteorological variablesfor simulating under which climatic conditions (e.g. decrease in air temperature and insolation) the mean ground temperature would approximate frost conditions. For the development of separate multiple linear regression models, we considered three locations on the Sanetti Plateau where ground temperatures and meteorological variables were measured simultaneously (Tullu Dimtu, EWCP Station, Tuluka). We chose only air temperature and global radiation as explanatory variables. The wind speed time series contains data gaps, precipitation is limited to individual rain events, and relative humidity does not show a direct linear relationship with ground temperature (see Section ??Fig. E1). The multiple linear regression model at each site was calibrated for the period 1st February 2017 – 31st January 2019 and validated for the period 1st February 2019 – 20th January 2020. Based on the established statistical relationship, present-day Present-day hourly ground temperatures in 2cm (cm (T_{2cm}) can then be modelled using measured air temperature and incoming shortwave radiation:

$$T_{\text{2cm,i}} = \beta_0 + (\beta_1 \times T_{\text{air,i}}) + (\beta_2 \times Q_{\text{S,i}}), \tag{1}$$

where $T_{air,i}$ ($i = 1,\ldots,n$) is the hourly measured air temperature in °C, $Q_{S,i}$ is the hourly measured incoming shortwave radiation in W m^{-2}, β_0 is the intercept, β_1 is the coefficient for T_{air}, and β_2 is the coefficient for Q_S. The coefficients and goodness of fit for each of the three linear models are provided in Table E1. For simulating ~~past ground temperatures~~a decrease in ground temperature, two additional parameters, ΔT_{air} and ΔQ_S, were introduced:

$$T_{\text{2cm,i}} = \beta_0 + (\beta_1 \times (T_{\text{air,i}} - \Delta T_{\text{air}})) + (\beta_2 \times (Q_{\text{S,i}} - \Delta Q_{\text{S}})), \tag{2}$$

where ΔT_{air} is the ~~difference between the mean present-day and past air temperature~~ air temperature depression of interest (in °C) and ΔQ_S is the difference between the mean present-day and past incoming shortwave radiation in W m^{-2}. For simplicity, we set ΔQ_S to 30 W m^{-2} ~~(the rough lowering of incoming shortwave radiation during the LGM at 15 °N, see Groos et al., in revision)~~ (the rough lowering of incoming shortwave radiation during MIS 2 at 15 °N, see Groos et al., in revision). To infer the air temperature depression ~~at the formation time of the periglacial landforms~~ of interest using *Eq.* 2, we increased ΔT_{air} (starting with: ΔT_{air} = 0 °C) with every iteration until the MAGT (~~T~~$\overline{T}_{2cm}$~~became < -1~~) became smaller 0°C. We tested all three developed multiple linear regression models (Tullu Dimtu, EWCP Station, and Tuluka) to quantify the uncertainty of the approach originating from differences in the model coefficients β (Table E1). Since the lowest-situated stone stripes on the Sanetti Plateau are located at an elevation of 3870-3890 m, we used meteorological data (T_{air} and Q_S) from the Tuluka AWS at 3848 m to run the three models. Alternatively, the meteorological data from the higher-situated AWS (Tullu Dimtu and ECWP Station) can be adjusted to the elevation of the stone stripes using a lapse rate of 0.7 °C per 100 m~~(see Section ??)~~. Running each model with the locally adjusted meteorological data led to the same calculated temperature depression as using the Tuluka AWS data. We rescaled the simulated ground temperatures in 2 cm depth (aggregated to daily values) to the maximum seasonal ground temperature variations in 10 and 50 cm depth observed today ~~(see Section ??)~~ to model temperature variations in these depths:

$$T_{\text{50cm,i}} = (\overline{T}_{\text{2cm}} - a) + \frac{(T_{\text{2cm,i}} - min(T_{\text{2cm}})) \times (b - a)}{(max(T_{\text{2cm}}) - min(T_{\text{2cm}}))}, \tag{3}$$

where ($T_{50cm,i}$) are the simulated daily ground temperatures in 50 cm depth in °C ($i = 1,\ldots,n$), ($T_{2cm,i}$) are the aggregated daily ground temperatures in 2 cm depth in °C ($i = 1,\ldots,n$), $\overline{T}_{2cm}$ is the mean air temperature in 2 cm depth in °C, a (= - 1.25 °C) is the predefined seasonal minimum, and b (= 1.25 °C) the predefined maximum of $T_{50cm,i}$. For 10 cm depth (T_{10cm}), a equals to -3 °C and b to 3 °C. ~~The main drawback of the presented approach is the non-consideration of ground moisture and thermal conductivity due to the lack of respective measurements. To further improve the method in the future, profile sensors measuring moisture, electrical conductivity, and temperature in 5 cm intervals between 0 and 50 cm depth have been installed at three AWS on the Sanetti Plateau in January 2020. The data are not yet available.~~

~~Coefficients and goodness of fit of the three established multiple linear regression models (MLRM) with ground temperature as dependent and air temperature and global radiation as explanatory variables. Distance means the distance between AWS and data logger, β_0 is the intercept, β_1 the air temperature coefficiet, and β_2 the incoming shortwave radiation coefficient.~~

~~Linear regression model Elevation (m) Distance (m) β_0 β_1 β_2 R² cal RMSE cal (°C) R² val RMSE val (°C) MLRM Tullu Dimtu 4377 90 3.7 1.7 0.004 0.73 3.0 0.72 3.0 MLRM EWCP Station 4124 690 1.2 1.6 0.010 0.79 3.6 0.76 3.6 MLRM Tuluka 3848 2050 -0.5 1.9 0.004 0.63 4.9 0.78 4.0~~

4 Results

4.1 ~~Distribution~~ Contemporary ground frost dynamics and ~~characteristics of periglacial landforms~~phenomena

The Bale Mountains comprise a wide range of periglacial landforms and other characteristic ~~geomorphological features~~ phenomena related to present and relict frost ~~occurrence (Fig. 3 and Appendix A). Current frost-induced~~ dynamics (Table A1). Contemporary frost phenomena like frozen waterfalls ~~, needle ice , patterned grounds ,~~ and needle ice as well as active periglacial landforms like patterned grounds and solifluction lobes are limited to the upper part of the valleys (>3900 m), to the Sanetti Plateau, and ~~highest peaks, even though ground temperatures below freezing can sporadically extend to much lower elevations (down to 2700-3000 m)~~to the highest peaks. We observed needle ice (3-5 cm long) mainly along water-saturated stream banks at ~~places~~ sites with cold air ponding. Needle ice is a typical ~~small-scale example for diurnal freeze-thaw cycles~~ superficial frost phenomenon in the Bale Mountains ~~as it~~ related to diurnal freeze-thaw cycles. It forms at clear nights throughout the dry season. Interestingly, we also found evidence for ~~seasonal frost phenomena.~~ a recurring seasonal frost phenomenon: Up to 10 m high ~~frozen water falls evolve~~ water falls at shaded north-exposed cliffs in the Wasama Valley ~~during~~ freeze every year at the beginning of the dry season ~~and last~~ (i.e. October/November) and persist until the onset of the following ~~wet season~~ rainy season (i.e. February/March). They do not evolve at any other location in the Bale Mountains according to the local guides. Active small-scale polygonal stone nets occur in flat and poorly drained areas on the Sanetti Plateau and unvegetated solifluction lobes can be found above 4100 m ~~at~~ on the southern slopes of Mount Wasama ~~.~~ (Fig. 3).

The observed present-day ground temperatures in the Bale Mountains show characteristic daily and seasonal variations, but are way off from seasonal or permanent frost conditions (Fig. 4). At the location of the stone stripes on the southern Sanetti Plateau, the mean multiannual ground temperature between the surface and 50 cm depth is 11 °C. On the highest peak Tullu Dimtu, the mean annual ground temperature is 7.5 °C. The mean air temperature at the same location is 2 °C and therefore about 5.5 °C lower than the mean ground temperature. While the daily ground temperature range is largest near the surface and decreases with depth, the seasonal variations at all depths follow a similar cycle (Fig. 4). On the plateau, the ground cools during the dry season and heats up during the wet seasons. The difference between the seasonal minimum and maximum of daily mean ground temperatures over a year is about 10 °C near the surface, 6 °C in 10 cm, and 2.5 °C in 50 cm depth. This shows that seasonal ground temperature variations are also characteristic for tropical mountains with a pronounced diurnal climate.

Near the surface, the diurnal ground temperature amplitude varies on average between 10-20 °C during the rainy and between 20-30 °C during the dry season. Extreme temperatures of up to 45-50 °C during cloudless days and down to -10 °C during

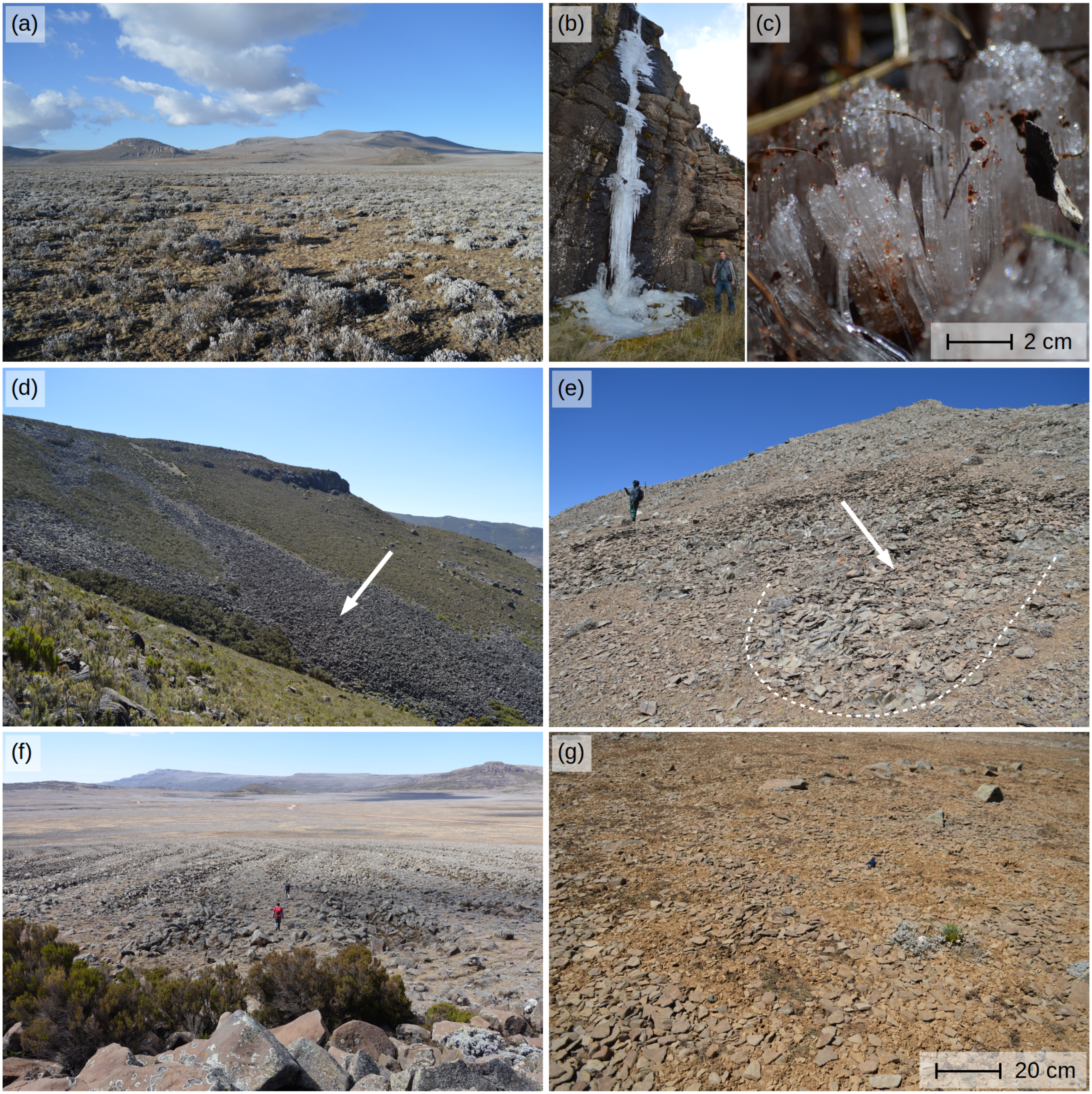

Figure 3. ~~Periglacial environment of~~ Contemporary frost phenomena and relict periglacial landforms in the Bale Mountains: (a) view from the southern Sanetti Plateau towards Tullu Dimtu, (b) seasonally frozen waterfall and (c) diurnal needle ice in the Wasama Valley, (d) relict blockfields along the southern Harenna Escarpment, (e) active solifluction lobes ~~at~~ on Mt. Wasama, (f) relict sorted stone stripes, and (g) active sorted polygons on the Sanetti Plateau.

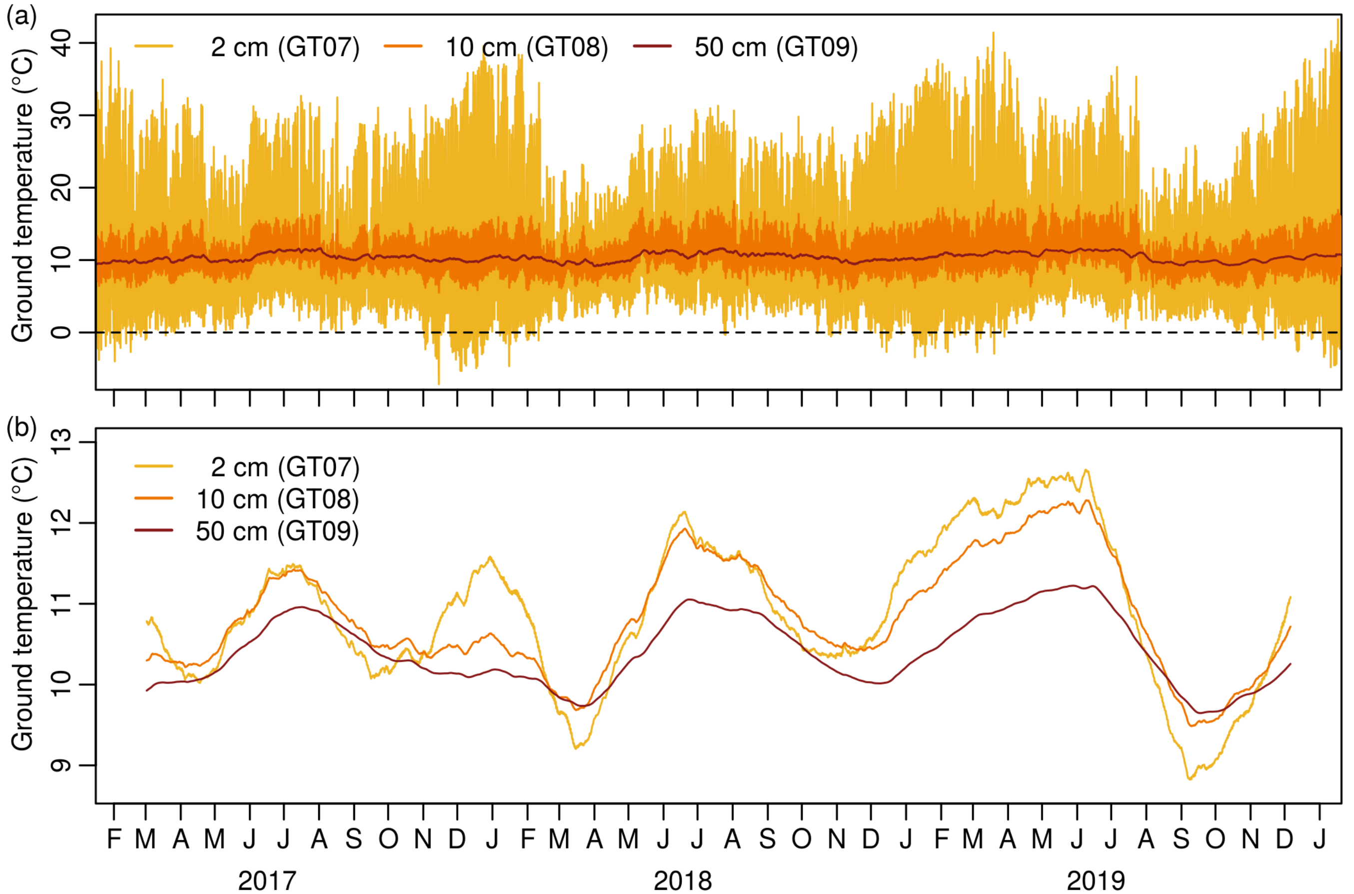

Figure 4. (a) ~~Overview map of periglacial landforms~~ Hourly ground temperatures and ~~other characteristic geomorphological features in the Bale Mountains. (b-c) Sorted stone stripes in the western~~ (b) seasonal ground temperature variations in 2, 10, and ~~southern part (c) of~~ 50 cm depth on the southern Sanetti Plateau ~~as seen on WorldView-1 satellite images~~ (~~DigitalGlobe Foundation~~3877 m) from January 2017 to January 2020. A simple moving average with a window size of 91 days was applied to derive seasonal ground temperature variations from hourly measurements. ~~(d) High-resolution orthophoto and DSM cross-section profile~~ Note that the increase of the ~~stone stripes derived from~~ seasonal ground temperature amplitude over the ~~aerial images~~measurement period is also confirmed for the other sites on the plateau and is not caused by a shift of the thermistors.

clear nights have been observed on the Sanetti Plateau. Nocturnal ground frost on the plateau occurs at 35-90 days per year. However, the frost penetrates only the uppermost centimetres. The diurnal amplitude decreases considerably with increasing depth. At 10 cm depth, temperatures below freezing have not been measured at any of the logger locations during the entire study period. The annual ground temperature profile in the upper 50 cm is relatively constant. The daily temperature difference between the surface and 50 cm depth is rarely larger than ± 2 °C.

4.2 Characteristics of the relict periglacial landforms

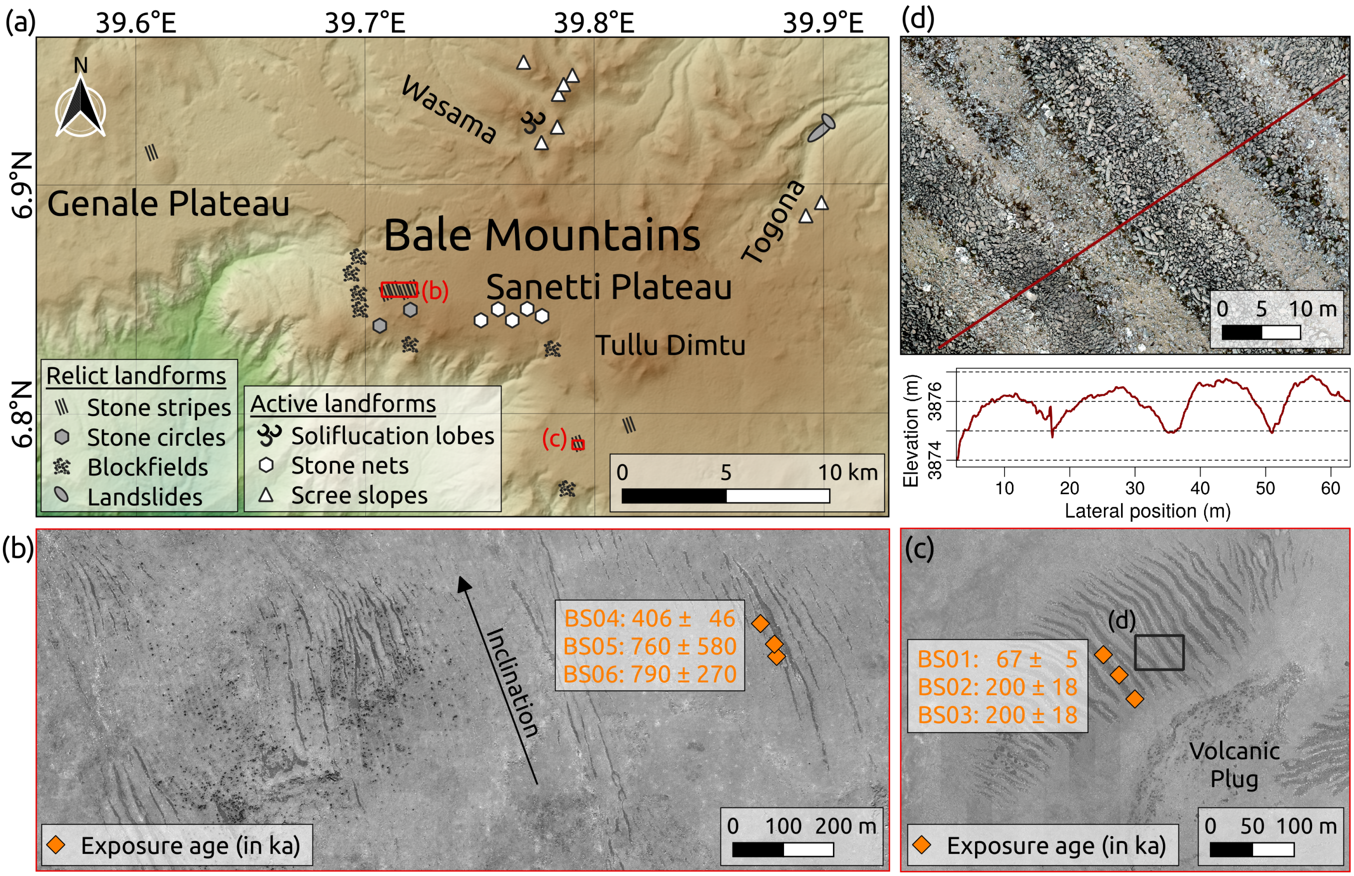

Figure 5. (a) Overview map of relict and active periglacial landforms as well as other characteristic geomorphological features in the Bale Mountains mapped in the field or on high-resolution satellite images. (b) Sorted stone stripes in the western and (c) southern part of the Sanetti Plateau as seen on WorldView-1 satellite images provided by the DigitalGlobe Foundation. The six ^{36}Cl exposure ages were calculated using the Lifton-Sato-Dunai scaling scheme (Lifton et al., 2014; Marrero et al., 2016), are non-erosion corrected, and given in kiloannum (ka) with total uncertainties (1σ). (d) Orthophoto and DSM cross-section profile of the stone stripes derived from the high-resolution UAV data.

Compared to the modern periglacial processes and landforms, ~~relict geomorphological features are larger and much more pronounced~~ the relict geomorphic features in the Bale Mountains ~~.~~are much larger. Most of the relict periglacial ~~features~~ landforms can be found along the Harenna Escarpment, on the Sanetti and Genale Plateau, and ~~at~~ on the slopes of the highest peaks (Fig. 5a). Characteristic for the highest peaks of the northern declivity are bare and gentle slopes and the accumulation of coarse scree below heavily eroded basaltic and trachytic cliffs. This type of deposits ~~is associated inter alia with frost weathering and differs~~ are likely result of frost wedging in combination with other weathering mechanisms such as thermal stress. The scree slopes differ from the chaotic spread of individual boulders below elongated cliffs at lower elevations. ~~Another~~

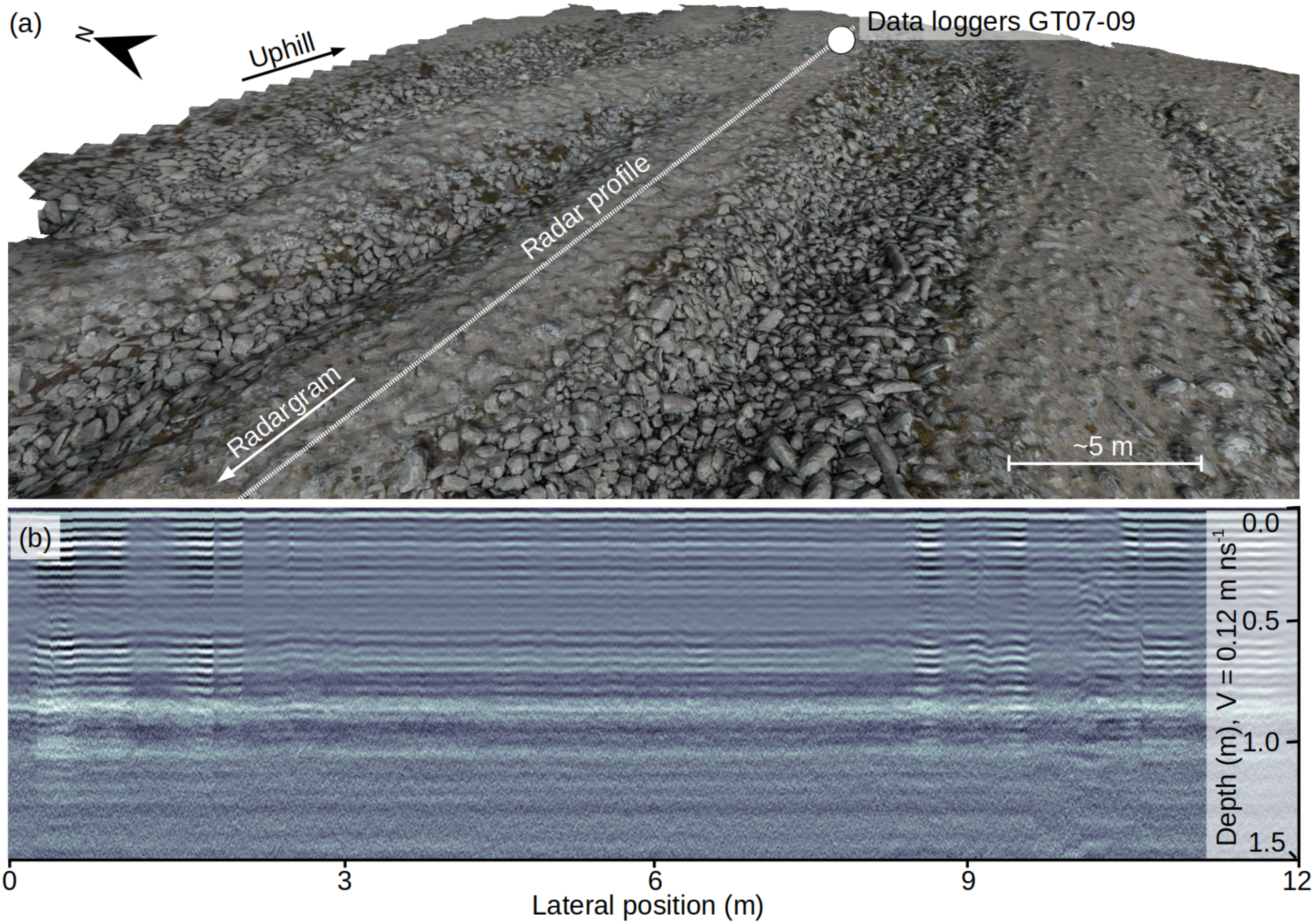

Figure 6. (a) Textured 3D model of the sorted stones stripes on the southern Sanetti Plateau derived from high-resolution UAV data. b) Radargram of a regolith stripe between two coarse stone stripes. For the location of the displayed radargram section (GPR05) see Fig. 1.

~~conspicuous landform associated with periglacial activity~~ Weathering may still contribute to the development of some of these landforms, but the return of Erica shrubs between the stones as well as the lack of parent material (i.e. cliffs) at some locations indicates that they mainly formed in the past. Another landform associated inter alia with the process of frost weathering are large blockfields located between 3500 and 4000 m ~~at~~ on the southern and western ~~slopes~~ declivity of the Sanetti Plateau. The blockfields consist of hardly weathered angular boulders and are no longer active as the presence of lichens and partly reoccupation by ~~*Erica*~~ Erica shrubs prove. Circular patterns across the Sanetti and Genale Plateau as well as elevated areas of the northern declivity are not further considered here since they are, at least in some areas, of biogenic origin related to the activity of the endemic giant mole-rat (Miehe and Miehe, 1994). ~~The most striking~~

The most exceptional geomorphological features on the Sanetti Plateau are large sorted patterned grounds comprising stone ~~stripes and less developed stone circles .The large~~ circles and stripes. In addition to the known sorted stone stripes ~~occur exclusively~~ on the southern ~~and~~ Sanetti Plateau, we also discovered stone stripes on the western Sanetti Plateau and at one site on the lower Genale Plateau (~~Fig. 5~~Figs. 5a-c). On the southern Sanetti Plateau and on the Genale Plateau, the stone stripes formed ~~at~~ on gentle slopes (inclination: 2 – 9°) of three different volcanic plugs between 3700 and 3950 m. The stone stripes consist of hardly weathered angular or columnar basalt boulders (~~Fig. 2and 6~~Figs. 2c and 6a), are partly covered by lichens, and are up to 200 m long, 15 m wide, and 2 m deep ~~(Fig. 5e~~as the satellite images and UAV data show (Figs. 5b-d). While the stone stripes are trough-shaped, the areas with finer material inbetween are ~~more~~ rampart-like (Fig. 5d). The distance between the stone stripes equals in most cases to the width of the stripes. Typical for some of the stone stripes is that ~~they split up into two~~ individual narrower branches in the upper part ~~and merge~~ merge downslope to a single wider ~~branch in the lower part~~stripe. As the GPR survey suggests, the regolith layer between the stone stripes contains no larger rocks (exceeding several decimetres) and is more than 1.5 m deep (Fig. 6b). The surface of the underlying solid rock was not detected. All larger rocks (up to 0.5 m wide and ~~2~~ 3 m long) are located mainly in the troughs or on top of the regolith layer as the UAV data underline. On the slightly inclined (2 - 9°) western Sanetti Plateau between 3950 and 4150 m, the stone stripes are 300 – 1000 m long and mainly 5 – 10 m wide (Fig. 5b). Most of the stripes are connected to ~~heavily~~ eroded cliffs. In the upper part, some of the stripes split up into multiple branches~~and where~~ . Where the plateau flattens, a transition from sorted stone stripes to less developed stone circles is visible in the field, but hardly recognisable on satellite images.

The six dated rock samples from two different locations on the Sanetti Plateau originate from basaltic (BS01-04) and trachytic (BS05-06) ~~lava flows~~ lavaflows as it is indicated by the varying alkali and silica contents (Table C3). We obtained very high ^{36}Cl concentrations, especially for the two trachytic samples (>120 × 10^6 At g^{-1}) from the western part of the plateau (Table C2). ~~In these two samples (BS05 and BS05), ^{36}Cl has reached saturation. This means that the production and decay of ^{36}Cl average out. Since the resulting exposure ages (>1000 ka) are at the limit of the method, they are not explicitly stated in the figures and tables. Based on the remaining samples, we calculated~~ The high ^{36}Cl concentrations translate into non-erosion-corrected ~~^{36}Cl~~ surface exposure ages of ~~84~~ 67 ± ~~4, 281~~ 5, 200 ± ~~12, and 281~~ 18, and 200 ± ~~13~~ 18 ka for the southern and of ~~620~~ 406 ± ~~13~~ 46, 760 ± 580, and 790 ± 270 ka for the western stone stripes (Table C2). However, due to the high ^{36}Cl concentrations, an erosion rate of >1 mm ka^{-1} ~~would lead to considerable older exposure ages for all samples except BS01~~or different choice of scaling would alter the exposure ages considerably. The "old" ages conflict with a relatively young formation age (e.g. global LGM or postglacial) as suggested by the morphology and hardly weathered surface of the investigated angular and columnar boulders. Long-term exposure of the sampled rocks to ^{36}Cl-producing cosmic rays prior to or during the formation of the stone stripes could explain this mismatch. Despite the high ^{36}Cl concentrations, a temporary ice cover overlying the stone stripes for several thousand years during the last glacial cycle cannot be entirely ruled out from the exposure dating alone. A meter-thick ice cover would reduce the production rate, but a period of several thousand years would not be sufficient to affect the ^{36}Cl concentrations noticeably or zero the inheritance. However, a temporary ice cover overlying the stripes seems unlikely in light of the ~~absent field evidence for such a scenario.~~

(a) 3D aerial view and (b) radargram of the sorted stones stripes on the southern Sanetti Plateau. For the location of the displayed radargram section (GPR05) see Fig. 1.

4.3 Present frost occurrence and ground temperature variations

(a) Hourly ground temperatures and (b) seasonal ground temperature variations in 2, 10, and 50 cm depth on the southern Sanetti Plateau (3877 m) from January 2017 to January 2020. A local regression with a smoothing span of 0.32 was applied to derive seasonal ground temperature variations from hourly measurements. Daily mean ground temperature variations in 50 cm are provided additionally (thin dark red line).

The observed present-day ground temperatures in the Bale Mountains show characteristic daily and seasonal variations, but are in general way off from permafrost conditions (Fig. 4). At the location of the stone stripes on the southern Sanetti Plateau, the mean multiannual ground temperature between the surface and 50 cm depth is 11 °C. On top of the highest peak Tullu Dimtu, the mean annual ground temperature is 7.5 °C. The mean air temperature at the same location is 2 °C and therefore about 5.5 K lower than the mean ground temperature. While the daily ground temperature range is largest near the surface and decreases with depth, the seasonal variations in all depths follow a similar cycle (Fig. 4). On the plateau, the ground cools down during the dry season (Bega) and warms up during the wet seasons (Belg and Kiremt). The difference between the seasonal minimum and maximum of daily mean temperatures over a year is about 10 K near the surface, 6 K in 10 cm, and 2.5 K in 50 cm depth (in Fig. 4, daily mean ground temperatures are only presented for 50 cm depth). This shows that seasonal temperature variations can also be of relevance for tropical mountains with a pronounced diurnal climate. The time series is far too short for deriving any long-term trends, but the interannual ground temperature variability observed during the three-year period (2017 – 2020) was rather low (<0.5 °C).

(a) Mean multiannual and multiseasonal diurnal ground temperature cycle in 2, 10, and 50 cm depth considering all data (as defined in Section 3.6) between February 2017 and January 2020 from the respective depths. The shaded areas display the mean diurnal ground temperature variability (as standard deviation) resulting from the different logger locations. First column: multiannual mean, second column: multiannual dry season mean (Bega: Nov/Dec/Jan/Feb), third column: multiannual wet season mean (Belg: Mar/Apr/May/Jun), fourth column: multiannual wet season mean (Kiremt: Jul/Aug/Sep/Oct). (b) Multiannual (black) and multiseasonal (Bega: green, Belg: blue, Kiremt: purple) daily ground temperature profiles in 2-50 cm depth between February 2017 and January 2020. Each line represents a mean daily ground temperature profile averaged over the five locations where data loggers where installed in 2, 10, and 50 cm depth. (c) Mean multiannual (black) and multiseasonal (Bega: green, Belg: blue, Kiremt: purple) ground temperature gradients in 2 cm depth between 3493 and 4377 m considering all data (excluding the warm-biased GT16 logger from a southern slope and the cold-biased GT17 logger from a northern slope) from February 2017 to January 2020.

Near the surface, the diurnal ground temperature amplitude is well pronounced and varies on average between 10-20 °C during the wet and 20-30 °C during the dry season (Fig. **??**a). Extreme temperatures of up to 45-50 °C during cloudless days and down to -10 °C during clear night have been observed on the Sanetti Plateau. Nocturnal ground frost on the plateau occurs at 35-90 days per year. However, the frost penetrates only the uppermost centimetres. The diurnal amplitude decreases considerably with increasing depth. At 10 cm depth, temperatures below freezing have not been measured at any of the logger locations during the entire study period. The annual ground temperature profile in the upper 50 cm is homogeneous. The daily temperature difference between the surface and 50 cm depth is rarely larger than ± 2 °C (Fig. **??**b). Annual ground temperatures increase from Tullu Dimtu down to the lowest logger location in the Web Valley by 0.71 °C per 100 m (Fig. **??**c), but noctural frost occurs in the valleys still at 5-25 days per year. The ground temperature gradient of 0.71 °C per 100 m is similar to the annual lapse rate obtained for the plateau (0.70 °C per 100 m) and northern declivity from measured air temperatures (Fig. **??**). Interestingly, the lapse rate obtained for the Harenna Escparment is less steep (0.62 °C per 100 m) and might represent wetter conditions and pronounced cloud formation at the southern declivity between ~1500-3800 m compared to the drier plateau and northern declivity. However, the number of AWS below the afro-alpine belt is not sufficient to determine unequivocally elevations where the mean annual lapse rate changes from a more or less dry adiabatic to a moist adiabatic and vice versa. Distinct elevational changes in the lapse rate could indicate the mean annual condensation level as well as the upper atmospheric storey where dry north-easterly trade winds dominate.The comparative experiment on Mount Wasama shows clear differences between the thermal regime of the southern and northern slope (Fig. **??**a). The southern slope is on average more than 2 °C warmer and reveals a more pronounced seasonality and larger diurnal amplitude which favours freezing and thawing and might explain the presence of solifluction lobes. While the mean daily temperature at the southern slope peaks towards the end of the dry season (January to February) when the sun is in its zenith, it reaches its maximum at the northern slope a few month later when the sun approaches its northernmost position. The ground temperature differences between vegetated and unvegetated areas on the Sanetti Plateau are less obvious (Fig. **??**b). Small *Erica* trees and bushes buffer the diurnal temperature amplitudes of the shaded ground, but have only little impact on the seasonality. Like at Mount Wasama, both south exposed locations at Tullu Dimtu (vegetated and unvegetated) have their temperature maxima at the end of the dry season, whereas the vegetated and unvegetated locations in the plain heat up during June/July. The cross-comparison between low-cost and high-quality data loggers on top of Tullu Dimtu revealed a promising relationship (R^2 = 0.98) and proved that the tested low-cost loggers, which have not been developed explicitly for scientific applications, are suitable for short-term (< 1 year) ground temperature measurements and experiments at high elevations. Both loggers measured nearly the same mean ground temperature (8.46 vs. 8.48 °C). Only the standard deviation of the low-cost logger was a bit larger (9.1 vs. 7.3 °C) since it was installed minimal closer to the surfaceabsence of any erratic boulders or other glacial landforms near the stripes.

Mean multiannual and multiseasonal (Bega: Nov/Dec/Jan/Feb, Belg: Mar/Apr/May/Jun, Kiremt: Jul/Aug/Sep/Oct) lapse rate of air temperature (a) in the Bale Mountains, (b) along the Harenna Escarpment, (c) along the northern declivity, and (d) on the Sanetti Plateau between February 2017 and January 2020. The lapse rate for the northern declivity and Sanetti Plateau is given in °C per 100 m because of the relatively small elevation range (1200 and 500 m).

(a) Comparison of the seasonal ground temperature variations in 2, 10, and 50 cm depth between the northern and southern slope of Mount Wasama. Data from the southern slope at 4153 m are from the loggers GT16/GT02/GT03, and data from the northern slope at 4181 m are from the loggers GT17/GT05/GT06. (b) Comparison of seasonal ground temperature variations in 2, 10, and 50 cm depth between locations with and without Erica at the slopes of Tullu Dimtu. A local regression with a smoothing span of 0.32 was applied to derive seasonal ground temperature variations from hourly measurements.

4.3 Modelled ground temperatures and inferred air temperature depression

4.4 Modelled palaeo ground temperatures

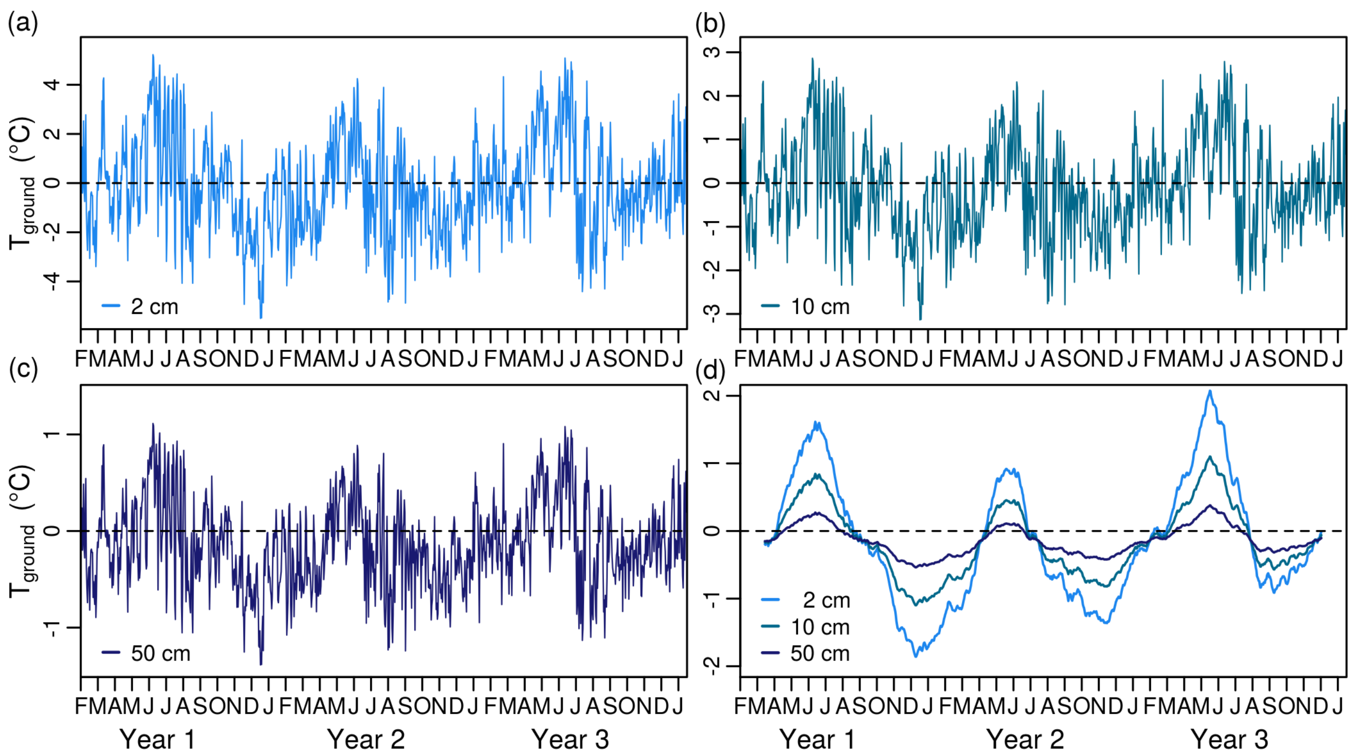

Figure 7. Simulated daily mean ground temperatures in (a) 2 cm, (b) 10 cm, and (c) 50 cm depth on the southern Sanetti Plateau (3877 m) corresponding to a decrease in air temperature of 7.1 ± 1.3 °C and a decrease in global radiation of 30 W/m² relative to the present-day conditions. (d) A simple moving average with a window size of 91 days was applied to derive seasonal ground temperature variations from daily means.

At the three locations on the Sanetti Plateau (Tullu Dimtu, EWCP Station, and Tuluka), where ground temperatures and a set of meteorological variables were measured concurrently, the simultaneously, ground temperature is mainly controlled by air temperature and global radiation (Fig. E1). The two variables can explain together about 75 ± 3 % of the ground temperature variance (Table E1). Ground temperature and the other meteorological variables do not show any significant linear relationshipwhat is not surprising in view of . This can be explained by the non-consideration of ground moisture. Precipitation, relative humidity, and wind speed affect ground moisture as well as evaporationand therefore . Ground moisture and evaporation in turn alter the energy balance at the surface and as well as the energy transfer into the ground. Measuring and considering ground moisture (directly at the AWS) would likely help to reduce the uncertainties of the applied multiple linear regression models (RMSE of 3-4 °C). Nevertheless, the established relationship However, the correlation between ground temperature and air temperature/global radiation explanatory variables is strong enough to use the models for a first palaeoclimatic reconstruction experiment. To obtain mean annual ground temperatures associated with deep seasonal ground frost or sporadic permafrost (T_{ground} < -1 simulate the air temperature depression that corresponds to a MAGT of ca. 0 °C) at the elevation of the lowermost stone stripes on the southern Sanetti Plateau during their time of formation, the three tested linear models require a mean ground temperature depression of ~12 . The diference between the current MAGT at the location of the southern stone stripes and the freezing point is ca. 11 °C. The difference between the seasonal minimum ground temperature and the freezing point is around 9 °C. This would translate into According to the statistical model, such a MAGT depression would result in a mean air temperature depression of 7.6 7.1 ± 1.3 °C (the error is the standard deviation of the three model outputs)which would imply , equivalent to a mean annual air temperature on the southern plateau of -1.9 -1.6 ± 1.3 1.4 °C. The deduced stronger decrease of the ground temperature over the air temperature is due to the observed modern statistical relationship. A cooling/warming of the air of 1 °C relates to a decrease/increase of the ground of 1.6-1.9 °C and vice versa (see Table E1 and Fig. E1). The geophysical reasons for this statistical relationship can be manifold. They are associated with the Ground temperature is mainly controlled by radiative forcing and energy exchange between the atmosphere and ground, which in turn is affected by many factors ranging from insolation, air pressure , relative humidity the temperature, pressure and humidity of the air to the thermal conductivity, specific heat capacity, density, humidity, albedo, etc. of the ground.

Over a year, the seasonal mean daily Provided that the stone stripes and circles on the Sanetti Plateau formed under periglacial conditions (ground temperatures fluctuating around 0 °C), the occurrence of these features may indicate a past air temperature depression at this elevation in the order of 7.1 ± 1.3 °C. However, it should be noted that changes in ground properties (e.g. modified albedo and thermal conductivity due to snow coverage and frost) would certainly affect the nature of the multiple linear regression models and therefore also the simulation results. The experiment shows that seasonal ground temperature fluctuations between the surfaceand near the surface, in 10 cm, and in 50 cm depth were are theoretically large enough to freeze and thaw the upper half metre decimetres of the ground if the MAGT is lowered by 9-11 °C (Fig. 7). However, seasonal freezing and thawing below Due to the small seasonal ground temperature variations in 50 cm depthseems unlikely in the past if the ground properties and seasonal temperature fluctuations were similar like today. A mean annual ground temperature in the order of -1 °C seems critical for the formation of deep seasonal frost , it seems unlikely that much more than the upper half metre of the ground on the Sanetti Plateau since much warmer temperatures would prevent would experience seasonal freezing and lower temperatures seasonal thawing thawing under cooler climatic conditions unless seasonal variations are stronger than today.

Relationship between hourly ground temperatures in 2 cm depth and different meteorological variables at three different locations: (a) Tullu Dimtu (GT13 vs. BALE001), (b) EWCP Station (TM04 vs. BALE009), (c) Tuluka (GT07 vs. BALE002).

Simulated daily mean ground temperatures in (a) 2 cm, (b) 10 cm, and (c) 50 cm depth on the southern Sanetti Plateau (3877 m) assuming a decrease in temperature of 7.6 ± 1.3 °C and decrease in global radiation of 30 W/m² relative to present-day conditions. (d) A local regression with a smoothing span of 0.32 was applied to derive seasonal ground temperature variations from daily mean values.

5 Discussion

~~Comprehensive geomorphological investigations in combination with different field measurements, ^{36}Cl surface exposure dating, and statistical ground temperature modelling presented here provide novel insights in the distribution , characteristics, and palaeoclimatic implications of modern and relict periglacial landforms in~~ This study provides a first systematic investigation of the distribution and characteristics of the enigmatic large sorted stone stripes on the central Sanetti Plateau of the tropical Bale Mountains in the southern Ethiopian Highlands. ~~Modern diurnal and seasonal frost phenomena like small-scale patterned grounds, solifluction lobes, frozen waterfalls, and needle ice are limited to the Sanetti Plateau, the highest peaks, and the upper part of the northern valleys above 3900 m. Relict periglacial landforms are more abundant and much more pronounced in the Bale Mountains. Besides extensive blockfields along the southern and western Harenna Escarpment, large sorted stone~~ The extensive geomorphological mapping in the field and on satellite images led to the documentation of previously undescribed large sorted stripes on the ~~southern and~~ western Sanetti Plateau ~~between 3850 to 4150 m are the most prominent geomorphological features. These features are associated with seasonal freezing and thawing of the upper half metre of the ground . Ground temperature measurements at sixteen locations between 3493 to 4377 m over a three-year period (2017-2020) verify seasonal temperature variations and frequent nocturnal frost on the plateau and in the valleys. However, the frost penetrates only the uppermost centimetres of the ground. The mean annual present-day ground temperature between the southern stone stripes (~11 °C) is way off from permafrost conditions. Experimental modelling suggests that a distinct ground temperature depression of ~12 °C and air temperature depression of 7.6 ± 1.3 °C would be necessary for the formation of deep seasonal frost at the elevation of the stone stripes. The main aim of~~ and the lower-elevated Genale Plateau. High-resolution UAV data, GPR radargrams, and ^{36}Cl surface exposure ages in combination with ground temperature measurements provide basic information on the geometry, internal structure, and age of the stone stripes as well as on the contemporary frost dynamics on the Sanetti Plateau. In the following discussion ~~is to elaborate when and how the large structures may have formed and what their presence implies for the palaeoclimate and palaeogeoecology of the tropical~~ i) we compare the stone stripes from the Bale Mountains with similar landforms in other regions, ii) elaborate a conceptual model for their genesis considering the available data and results, and iii) assess the implications of their occurrence for the reconstruction of the palaeoclimate and palaeoenvironment of the Ethiopian Highlands. ~~Patterned grounds comprising~~

5.1 Comparison of the sorted stone stripes with similar landforms in other regions

The large sorted stone stripes ~~, circles, and polygons are a common feature of periglacial environments and are known from the Arctic (e.g. Nicholson, 1976; Hallet, 2013), Antarctic (e.g. Hallet et al., 2011), mid latitudes (e.g. Richmond, 1949; Miller et al., 1954; Bal , and high mountains worldwide (e.g. Francou et al., 2001; Matsuoka, 2005; Bertran et al., 2010). They have also been detected on other celestial bodies like Mars (e.g. Mangold, 2005; Balme et al., 2009). Small-scale sorted stone stripes in the order of centimetres to decimetres, which are associated with superficial diurnal freeze-thaw cycles, are typical~~ on the Sanetti Plateau are an exceptional geomorphic feature as they represent the only known example of large sorted patterned grounds on a tropical mountain. Most examples of sorted stone polygons, nets, and circles with a diameter exceeding several metres originate from the High Arctic (i.e. Alaska, Greenland, Svalbard) (see review of Washburn, 1980). Well-developed relict patterned grounds consisting of clasts with a diameter of at least several decimetres are also documented for several mid-latitude and also high tropical mountains (e.g. Francou et al., 2001; Matsuoka, 2005)mountains like the Culebra Range (>4000 m; 37 °N) in southern Colorado (Vopata et al., 2006) or the High Sudetes (>1300 m; 50 °N) in Central Europe (Křížek et al., 2019). However, large sorted stone stripes comparable to those on the Sanetti Plateau (10-15 m wide and 100-1000 m long) have a global compilation and comparison of large sorted patterned grounds and their climatic and environmental setting is lacking in the scientific literature. Sorted stone stripes with a width of up to 15 m and length of up to 1000 m as on the western Sanetti Plateau have even not been reported from any other tropical mountain and seem to be a rare phenomenon in general. In contrast to small-scale features which do not necessarily require mean annual air temperatures below freezing, large sorted patterned grounds like stone circles and polygons that are well-documented for the High Arctic (e.g. Kessler and Werner, 2003; Hallet, 2013) occur commonly in permafrost areas with mean annual air temperatures of -4 to -6 °C (Goldthwait, 1976)the polar regions. The only other location worldwide where stone stripes in the same order of magnitude as on the Sanetti Plateau and even and larger have been described are the non-volcanic Falkland Islands in the South Atlantic (André et al., 2008).

The vernacular term for extensive blockstreams and stone stripes in the Falkland Islands is “stone runs”. Stone runs cover large parts of the eastern and western island and are linked connected to quartzite outcrops in the elevated areas (50-700 m). The stone stripes in the Falkland Island show some interesting similarities and differences with the features on the Sanetti Plateau. They occur in clusters at on gentle slopes (inclination: 1-10°), are several hundred meters long, several meters wide, consist of large angular blocks (up to 2 m wide and 5 m long), and originate in some cases from eroded ridges and summit areas. As on the Sanetti Plateau, the coarse stone stripes in the Falkland Islands run parallel downslope and alternate with stripes of fine-grained material of similar width (André et al., 2008). However, the partial emergence of stone stripes from blockfields and downslope transition into vast blockstreams as it is typical for the Falkdland Islands is uncommon for the Bale Mountains where the stripes are restricted to the plateau and the blockfields to the southern and western escarpment. Also the geological (volcanic vs. sedimentary and metamorphic rocks), climatic (continental vs. oceanic), and geographical setting (tropical mountain vs. mid-latitude island) between the Bale Mountains and Falkland Islands differs considerably. A link between Typical for both locations is the coexistence of coarse and fine-grained material (large angular blocks and regolith) and the evidence for glaciations and colder cooler conditions during the Pleistocene (Clapperton, 1971; Clapperton and Sudgen, 1976; Groos et al., in revision).

The origin and genesis of the stone runs in the Falkland Islands has been discussed controversially over the last one hundred years and numerous theories have been proposed to explain their formation as a result of different interconnected periglacial processes (frost shattering, frost heave, frost sorting, etc.). Based on a literature review and micromorphological analyses, André et al. (2008) come to a more nuanced conclusion and consider the stone runs as complex polygenetic landform. The authors hypothesise that the parent material (blocks and regolith) formed under subtropical or temperate conditions during the Neogene/Palaeogeneand . They interpret the stone runs as the product of subsequent frost-sorting during the cold stages of the

Pleistocene. Nevertheless, , but the understanding of the physical processes underlying the frost-related sorting of such large blocks clasts is still fragmentary (Aldiss and Edwards, 1999). The limited process understanding, the

5.2 Genesis of the sorted stone stripes

The small number of analogies worldwide , and the lack of a cross-section profile complicate the interpretation of the stone stripes on the Sanetti Plateauin . Since the Bale Mountains , but the following observations and findings suggest that deep seasonal frost and periglacial processes played a major role are of volcanic origin, the stone stripes could be interpreted as remains of former lava flows. However, the regular alternation of coarse and fine-grained stripes as well as the loose and random configuration of blocks in the coarse stripes argue against this hypothesis. The coarse stone stripes consist of igneous rocks, but volcanic processes were certainly not involved in the formation of this landform. As aforementionend, the Bale Mountains were covered by an extensive ice cap and experienced a pronounced cooling of 4-6 °C between 50-30 ka (Ossendorf et al., 2019; Groos et al., in revision). It is important to note that the stone stripes on the western and southern Sanetti Plateau are located beyond the glacial remains and the assumed maximum extent of Although some of the former ice cap. The obtained ^{36}Cl surface exposure ages of >600 ka (^{36}Cl has reached saturation in two samples) for the western and of 84 ± 4, 281 ± 12, and 281 ± 13 ka for the southern stone stripes predate the local last glacial maximum. However, the exposure ages probably do not represent the timing of formation or stagnation of the features. Since the sampled trachytic blocks and columnar basalt originate from eroded cliffs and volcanic plugs, it is likely that they were exposed to cosmic radiation during and prior to wider stripes resemble river beds, surface runoff can also not explain the stone stripe pattern (e.g. the alternation of coarse and fine stripes as well as the interruption of many stripes on the western plateau, see Fig. 5b). Furthermore, the total area (ca. 100 x 100 m) above the stone stripe slopes on the volcanic plugs (Fig. 5c) seems too small to generate sufficient surface runoff for the formation of up to 15 m wide river beds. Our data and findings suggest that periglacial processes were the main driver of the formation of the stone stripes . as we will outline below.

To deduce the underlying mechanisms of the stone stripe genesis, it is important to shortly summarise the characteristics of this landform again. Typical for the stone stripe pattern is the alternation of coarse and fine stripes on gentle slopes. Both coarse and fine stripes are ~5-15 m wide and run parallel to the maximum slope gradient. The well-preserved morphology, the absence of erratic boulders in the surrounding area, and the high ^{36}Cl concentrations indicate that the stone stripes have not been eroded and deformed by a dynamic and warm-based glacier. However, we cannot compeletely rule out that stagnant, cold-based, and relatively shallow ice covered the stripes for several thousand years. Such an ice cover would not have been sufficient to zero the inheritence (high ^{36}Cl concentrations). We interpret the hardly weathered surface of the angular blocks andlittle reoccupation by vegetation as an indication for a younger formation stage high-resolution UAV orthophotos show that the width of the stripes is about 10-20 times larger than the average size of the clasts. Furthermore, the UAV-based DSM reveals that the coarse stripes are trough-shaped and up to 2 m deep (Fig. 6). Boelhouwers et al. (2003) revealed for sorted stone stripes along an altitudinal gradient in the maritime Subantarctic that the up-doming of the fine material between the coarse stripes increases with elevation due to deeper frost penetration. The deeper frost penetration at higher elevations results in a deeper depths of vertical sorting and, thus, also a greater degree of lateral sorting (Boelhouwers et al., 2003). Another relevant detail of the stone stripes ~~coinciding probably with the coldest and driest phase in Africa (30-15 ka)during the last glacial period (e.g. Tierney et al., 2008). The ice extent in the Bale Mountains at ~18 ka was slightly smaller compared to the local LGM despite the general cooling trend in Eastern Africa. The lack of any evidence for a major glacier advance between the local LGM and the ~18 ka stage might be indicative of a cold and dry climate which provides ideal conditions for periglacial processes~~is the downslope convergence of individual branches and smaller stripes to wider single stone stripes (see Fig. 5c). All these observations correspond surprisingly well to the development of frost patterns on slightly inclined slopes after several hundred freeze-thaw cycles as simulated by numerical computer models (see Fig. 8 and Werner and Hallet, 1993; Mulheran, 1994; Kessler et al., 20 . Such numerical models can reproduce the self-organization of different sorted grounds by varying just a few parameters (mainly stone concentration, hillslope gradient, and degree of lateral confinement) and need about 500 to 1000 freeze-thaw cycles to form similar stripe patterns as found on the southern Sanetti Plateau (Fig. 5c). Less cycles would lead to a more random configuration and more cycles would eliminate the smaller branches and lead to a “perfect” sorting of the stripes (Fig. 8). Assuming downslope displacement rates of 10-50 cm per year (or cycle) for clasts as it is observed for small-scale periglacial features in the tropics (Francou and Bertran, 1997) would require a similar number of cycles (about 400 to 2000) to form the 200 m long stone stripes on the southern plateau.

A precondition for the formation of patterned grounds is cyclic freezing and thawing ~~of a decimetre- to meter-thick layer~~ and the coexistence of ~~fine-grained material and larger stones or blocks~~ larger stones and a frost susceptible ground (Kessler et al., 2001; Kessler and Werner, 2003). Both large blocks and ~~fine-grained material~~ a frost susceptible ground are present on the Sanetti Plateau. A ~~decimetre-thick regolith layer rich in silt and loam~~ more than 1.5 metre thick regolith layer covers the underlying bedrock of the plateau ~~(Lemma et al., 2019)~~as indicated by the GPR measurements. Whether the regolith ~~has developed during~~ developed over the Pleistocene or during warmer periods before, as suggested for the Falkland Islands (André et al., 2008), remains unclear. The ~~accumulation of trachytic blocks and columnar basalt at some places on the plateau is probably related to intensive frost wedging at cliffs and volcanic plugs during the last glacial cycle. As our ground temperature modelling suggests, a half-meter-thick frozen layer could have formed seasonally on the plateau outside the glaciated area as the result of a pronounced air temperature cooling of 7.6 ± 1.3 °C during the coldest period of the last glacial cycle. Deep~~ regolith layer is rich in silt and loam (Lemma et al., 2019) and, thus, sufficiently porous to allow capillary action and the formation of ice lenses. The absensce of any larger stones (exceeding several decimetres) in the fine stripes as confirmed by the GPR surveys is indicative of vertical as well as lateral frost sorting. Another indicator for past frost sorting on the Sanetti Plateau is the up-doming of the regolith between the coarse stone stripes (Boelhouwers et al., 2003) as well as the presence of large stone polygons in the highest and even areas of the western plateau (Miehe and Miehe, 1994). How the sorted stone stripes could have evolved from a random configuration of blocks below eroded cliffs in the course of cyclic freezing and thawing of the ground is illustred in Fig. 8.

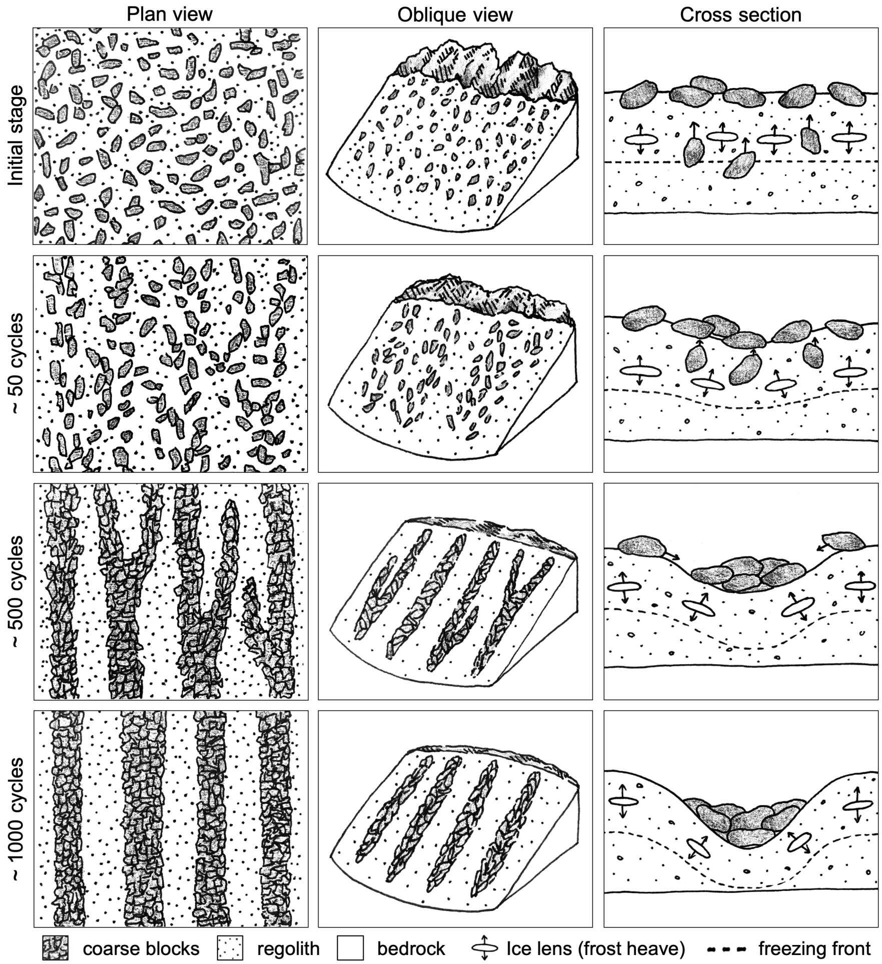

Figure 8. Conceptual model of the genesis of sorted stone stripes on a slightly inclined slope under periglacial conditions. Plan view (downslope orientation towards the bottom of the figure): Stages during the evolution of stone stripes from a random configuration after ~50, ~500, and ~1000 freeze-thaw cycles as simulated by a numerical model that considers lateral frost sorting and the movement of stones along the axis of elongated stone domains (for a detailed model description and the original model outputs see Werner and Hallet, 1993). Note that in the numerical model narrower stripes merge into wider stripes over time. Oblique view: hypothetical stone stripe formation on the Sanetti Plateau below an eroding cliff of a volcanic plug due to cyclic freezing and thawing of the ground. The current status of the self-organisation of stone stripes on the Sanetti Plateau is similar to the configuration in the model after several hundred freeze-thaw cycles. Cross section: principles of the stone stripe formation (although many aspects remain elsuive). In the initial stage the rocks are distributed randomly on the surface and in the fine regolith layer. With the downward penetration of the freezing front (0 °C isotherm) from the surface, ice lenses form and cause vertical frost heave. The recurring formation of ice lenses over time leads to the upfreezing of interior stones and the random movement of blocks on the surface. Randomly formed clusters of blocks are less prone to perturbations than indivual stones or the fine-grained material. The freezing front descends faster in dry and well-drained stone domains than in the wetter fine-grained regolith (which must freeze and be cooled). Since frost expands perpendicular to the freezing front, the stone domain is squezed and blocks are trapped. Blocks in the stone domaine move along the slope gradient and form sorted stripes over time. Drawn by Francesca Andermatt.

A central question related to the genesis of the stone stripes is the MAGT and minimum frost penetration depth needed to sort the largest clasts, which are up to 3 m long and certainly weigh between one and two tonnes. Seasonally frozen grounds and sporadic permafrost still exist at some of the highest tropical and subtropical mountains in Africa (Kaser et al., 2004; Vieira et al., 2017). Potential evidence for past sporadic permafrost in the Bale Mountains exists in the northeastern Togona Valley, which was covered by a 8 km long valley glacier during the Late Pleistocene (Groos et al., in revision). During or after deglaciation of the lower part of the valley, two large landslides (0.5 and 1.5 km long; see Fig. 5a) occurred between the ~18 ka and ~15 ka moraine stages and might have been triggered by slope destabilisation due to thawing permafrost. ~~The strongest arguments for the stone stripes being the "final" product of frost heave and sorting is their configuration as well as the presence of less-pronounced relict large sorted stone polygons in the highest flat parts of the western plateau.~~The ~~width of the alternating fine-grained and coarse stone stripes (about 10-20 times larger than the average block size) , the absence of larger blocks in the fine-grained stripes,~~ contemporary ground temperature measurements show that the formation of seasonal or permanent frost to a depth of several decimetres on the Sanetti Plateau would require a decrease of the MAGT in the order of 9-11 °C. According to the simple statistical model experiment, such a decrease would correspond to an air temperature depression of 7.1 ± 1.3 °C (relative to today).

The coldest and driest period in Africa (ca. 15-45 ka) during the last glacial period (e.g. Tierney et al., 2008) seems the most likely climatic period for a cooling of that magnitude. Between 28-42 ka, an extensive ice cap extending down into the northern valleys covered the Sanetti Plateau. The large stone stripes are located beyond the glacial remains and the assumed maximum extent of the former ice cap (Ossendorf et al., 2019; Groos et al., in revision). One plausible scenario would be the development of the stone stripes in close proximity to the ice cap over several hundred to thousand years due to seasonal freezing and thawing of the ground. Such a scenario would also be plausible for the Falkland Islands, where the stone stripes are located outside the former glacial remains (Clapperton, 1971; Clapperton and Sudgen, 1976). Cool katabatic winds originating from the extensive ice cap on the Sanetti Plateau might have promoted an amplified cooling in the area of the ~~axis orientation of the stripes parallel to the greatest slope, and the convergence of individual narrower branches to wider single stripes is remarkably similar to patterned grounds at gentle slopes predicted by numerical models after several hundred freeze-thaw cycles (Werner and Hallet, 1993; Mulheran, 1994; Kessler et al., 2001; Kessler and Werner, 2003). Such numerical models can reproduce the self-organization of different sorted grounds by varying just a few parameters (mainly stone concentration, hillslope, and degree of lateral confinement) and need about 500 to 5000 freeze-thaw cycles to form similar stripe patterns as found on the southern Sanetti Plateau (Fig. 5). Less cycles would lead to a more random configuration and more cycles would eliminate the smaller branches and lead to a "perfect" sorting of the~~ stone stripes~~(see Fig. 2 in Werner and Hallet, 1993) . Assuming downslope displacement rates of 10-50 cm per year (or cycle) for clasts as it is observed for small-scale periglacial features in the tropics (Francou and Bertran, 1997) would require a similar number of cycles (about 400 to 2000) to form the 200 m long stone stripeson the southern plateau. In view of the length of the coldest phase~~ . The hardly weathered surface of the stone stripe boulders on the Sanetti Plateau supports a formation during the coldest period of the last glacial ~~period, the formation of the stone stripes on the plateau in proximity to the ice cap over several hundred to thousand cycles/years is~~

a plausible scenario.Instead of seasonal variations, longer freeze-thaw cycles could theoretically also explain cycle, but most of the obtained ^{36}Cl surface exposure ages predate this period. However, it is possible that the exposure ages do not represent the formation or stabilisation age of these features. Since the sampled igneous rocks originate from eroded cliffs and volcanic plugs, they were likely exposed to cosmic radiation prior to (and during) the formation of the stone stripeson the Sanetti Plateau. A formation . Another scenario is the evolution of the stone stripes over several cold stages during the Pleistocene as proposed for the stone runs in the Falkland Islands (Wilson et al., 2008)is conceivable. This would imply the formation of sporadic permafrost during the colder periods and the complete thawing of the ground during the warmer periods of the Pleistocene. The "old" exposure ages In this case, the stone stripes would have rather formed over several thousand to ten thousand than over a few hundred or thousand years. The exposure ages and high ^{36}Cl would generally support such a scenario, although the mismatch between the high ^{36}Cl concentrations of the western stone stripe compared to the lower concentrations of the southern stone stripe would remain an open question. However, due to the well-preserved morphology of the stone stripes, the verified seasonal ground temperature variations on the Sanetti Plateau, and the absence of further evidence for the formation over several cold stages, we propose seasonal freezing and thawing during the last glacial cycle as the main mechanism for the formation of the stripes.The presence of .

5.3 The sorted stone stripes as potential climate proxy

The previous analysis provides first evidence that the large sorted stone stripes and other relict frost-related landforms above 3800-4100 m on the Sanetti Plateau and along the Harenna Escarpment provide further evidence that the Bale Mountains underwent severe climatic and environmental changes most likely evolved under periglacial conditions during the Pleistocene. Both glacial and periglacial processes played a major role in shaping the afroalpine landscape. The inferred cooling of 7.6 ± 1.3 Ground temperatures fluctuating around 0 °C and mean annual air temperatures below 0 °C are common for areas where large patterned grounds occur (Goldthwait, 1976; Hallet, 2013). Thus, it is reasonable to assume that a MAGT in the order of 0 °C needed for the formation of large patterned grounds and a mean annual air temperature smaller 0 °C was a precondition for the genesis of the stone stripes on the Sanetti Plateauis much larger than the temperature decrease in the Bale Mountains of 5.1 ± 0.7 . Since the present climatic conditions (the mean annual air tempeature is 5.7 °C derived from the estimated snow line depression during the local last glacial maximum 50-30 ka (Groos et al., in revision). This discrepancy mighty indicate a further cooling in the southern Ethiopian Highlands from the time of the local maximum glacier expansion to the global LGM (22 ± 4 ka) as seen in other climate records from Eastern Africa and worldwide (e.g. Jouzel et al., 2007; Tierney et al., 2008). Moreover, the reconstructed temperature decrease from at the Tuluka AWS, see Fig. 1) do not support the formation of seasonal or permanent ground frost on the plateau, the existence of these features is an indicator for severe climatic and environmental changes in the Ethiopian Highlands in comparison with the reconstructions from the lower-situated Congo Basin and Lake Tanganyika during the Pleistocene. The difference between the present MAGT and freezing point in the order of 4 to 4.5 11 °C (Weijers et al., 2007; Tierney et al., 2008) reveals an amplified tropical cooling at high elevations in Eastern Africa during the global LGM. Strong evidence for such a cooling is also provided by sea surface and air temperature reconstructions from different lakes along an elevational transect in Eastern Africa. Loomis et al. (2017) explain the observed elevational trend with a steeper tropical lapse rate (Γ_{LGM} = 6.7 ± 0.3 °C km^{-1} vs. Γ_{modern} = 5.8 provides a rough estimate for the ground temperature depression during the formation of the stone stripes. Moreover, the statistical model experiment shows that such a decrease of the MAGT would theoretically correspond to an air temperature depression of 7.1 ± 0.1 1.3 °C km^{-1}) related to a drier atmosphere during the global LGM. The present-day mean annual lapse rate and ground temperature gradient on the Sanetti Plateau of 0.7 and an absolute mean annual air temperature on the southern plateau of -1.6 ± 1.4 °Cper 100 m (Fig. ?? and ??) is larger than the palaeo (Γ_{LGM}) and modern (Γ_{modern}) East African lapse rate between 474 and 3081 m. This emphasises that attention should be drawn to temporal . Since the exposure ages generally support a formation of the stone stripes during MIS 2 and 3 as well as vertical changes in the lapse rate when reconstructing or simulating the palaeoclimate of the tropics. Despite improvements, global climate models still tend to underestimate the cooling at high elevations in the tropics during the last glacial cycle (Loomis et al., 2017).The palaeoclimatic and environmental findings presented here have direct implications for the settlement history and ecology of the Bale Mountains . Latest archaeological excavations at 3469 m in the northwestern part of the Bale Mountains along with biogeochemical, zoogeographical, and glacial chronological investigations reveal that Middle Stone Age foragers resided in the highlands already between 47 to 31 ka and made use of the available alpine resources (Ossendorf et al., 2019). Why the residential site was abandoned after 31 ka is unclear, but might be related to a gradual cooling and dessication of the highlands until the global LGM as suggested by the large-scale periglacial landforms and lack of major glacier advances between 50-30 and ~18 ka (Groos et al., in revision). Moreover, the temperature depression, ice cover, and periglacial conditions must have also affected the habitat of endemic mammal species like the Ethiopian wolf, giant mole-rat, and mountain nyala that currently populate the Sanetti Plateau and upper valleys (Miehe and Miehe, 1994). Due to the absence of any evidence for glacial extinction events in the region, we conclude that endemic plants and mammals as well as Middle Stone Age foragers coped with the harsh climatic and environmental conditions in the Ethiopian Highlands during the Pleistocene.Many questions regarding the relict periglacial processes and landforms over a longer period during the Pleistocene, it is currently not possible to link the inferred high-elevation cooling in the Bale Mountains to a specific climatic period in tropical Eastern Africa. To corroborate a past regional cooling of that magnitude, further evidence of large patterned grounds or other high-elevation climate proxies from the Ethiopian Highlands would be necessary.

5.4 Future research and outreach

Certain aspects of the genesis and implications of the large sorted stone stripes on the Sanetti Plateau in the Bale Mountains remain open due to the pioneering and experimental character of this study and may hopefully stimulate further research on this topicunresolved. A key challenge for better understanding the landscape evolution on the Sanetti Plateau a better understanding of the palaeoclimate and palaeoenvironment of the Bale Mountains is the development of a robust geochronology. The radiometric age of the volcanic plugs, the formation time phase of the regolith and stone stripes as well as the deglaciation history of the former ice cap on Tullu Dimtu are uncertain. Moreover, termination of the plateau glaciation are relatively uncertain. Additional information on the depth and internal structure (grain size distribution, mineral compositionindicators for cryoturbation, etc.) of the coarse and fine-grained stone stripes would provide additional be very useful to gain further insights into the genesis of the landforms. To reduce the uncertainty of the statistical model applied for ground temperature simulations

~~and air temperature reconstructions, considering the impact of moisture on the thermal conductivity and heat capacity~~ this landform. Simultaneous ground measurements in the coarse and fine stripes would help to figure out whether the structure of the coarse stone stripes promotes a faster cooling of the ground ~~as well as energy fluxes into the ground is necessary.It is possible that ground moisture and stagnant water played a more important role during the Late Pleistocene than today due to (perma)frost-induced waterlogging and perennial melting of snow and ice. Why the relict patterned grounds are restricted to the southern and western Sanetti Plateau can be explained by the assumed preconditions for their formation: a relatively flat and unglaciated terrain, presence of coarse and fine grained material, deep ground frost, and absence of a thick snow layer~~than the adjacent fine stripes (e.g. Harris and Pedersen, 1998; Juliussen and Humlum, 2008; Wicky and Hauck, 2020).

Since the large sorted stone stripes are a rare and unique geomorphic feature, they represent an important geoheritage site in Ethiopia that complements other geological sites of public iterest such as the Blue Nile Gorge or the active basaltic shield volcano Erta Ale (Williams, 2020). The stone stripes are located in the centre of the Bale Mountains National Park. Some of these features are accessible via dirt road. Hence, the sorted stone stripes may be another suitable destination for geotourism in the park.

6 Conclusions

This contribution provides ~~further evidence that the tropical~~ a first systematic investigation of contemperorary small-scale frost phenomena and relict large sorted stone stripes on the more than 4000 m high central Sanetti Plateau of the Bale Mountains in the ~~southern Ethiopian Highlandswere subject to severe climatic and environmental changes during the Late Pleistocene. Both glacial and periglacial processes have shaped the afro-alpine environment. Compared to the modern nocturnal and seasonal frost phenomena, relict periglacial landforms like blockfields along the Harenna Escarpment and sorted~~ tropical Ethiopian Highlands. The coarse stone stripes on the ~~Sanetti Plateau are much larger and more developed. The large sorted stone stripesare exceptional for the tropics and probably formed under periglacial conditions in proximity of the palaeo ice cap on Tullu Dimtu during the coldest period(s) of the last glacial cycle. We hypothesise that the slightly inclined and unglaciated areas of the Sanetti Plateau,~~ slightly inclined Sanetti Plateau, which alternate with fine regolith stripes, are an exceptional geomorphic feature as they consist of very large clasts (up to 3 m long) and are up to 2 m deep, 15 m wide, and 1000 m long. Moreover, these features are enigmatic in a way that patterned grounds exceeding several metres have yet only been reported from the mid-latitudes and polar regions, but not from the tropics. The detailed analysis of the ~~coexistence of regolith and large blocks, the occurrence of deep seasonal frost, as well as relatively dry conditions beyond the ice cap provided ideal conditions for frost heave and sorting and the formation of large patterned grounds. Based on our ground temperature measurements and modelling experiment, we propose a distinct ground temperature depression of ~12 °C and air temperature depression of 7.6 ± 1.3 °C as precondition for the formation of deep ground frost~~ stone stripes' geometry and internal structure based on UAV and GPR surveys reveals an up-doming of the fine regolith stripes, a lack of larger clasts inside the fine regolith stripes, and a downslope convergence of individual narrower stone stripes and branches into single wider stone stripes. All these details suggest lateral and vertical sorting in the course of cyclic freezing and thawing of the ground as main mechanism for the genesis of the stone stripes from an intial random configuration of blocks below eroded cliffs. Superficial nocturnal ground frost occurs frequently on the Sanetti Plateau. The novel idea of using a statistical relationship between measured present-day ground temperatures and meteorological variables to assess past climatic changes through the simulation of palaeo ground temperatures has also potential for other regions where relict frost-related periglacial landforms exist. Comparing the reconstructed air temperature depression from the Bale Mountains with climate records from lower elevations in Eastern Africa emphasises a strongly amplified cooling at high elevations that has already been outlined for many other tropical mountains. Such a cooling in tandem with the extensive glaciation and frost action must have dramatically affected the habitat of endemic mammal species like the Ethiopian wolf, giant mole-rat, and mountain nyala that currently populate , but the ground below the upper few centimetres remains unfrozen the entire year. The measured ground temperatures suggest a mean annual ground temperature depression of about 11 °C for the formation of seasonal or permanent frost, corresponding to an air temperature decrease of about 6-8 °C (relative to today). Two different scenarios are plausible for the genesis of the stone stripes and are in principle supported by the exposure ages. Either they formed in proximity of the former ice cap on the Sanetti Plateau and upper valleys of the Bale Mountains. Attention should therefore be given to the amplified middle troposphere cooling when reconstructing and modelling climatic and geoecological due to seasonal frost heave and sorting during the last glacial cycle or they developed over multiple cold phases of the Pleistocene. Although certain aspects of the genesis of the large sorted stone stripes remain elusive, the presence of these geomorphic features provides independent evidence besides the glacial landforms for unprecedented palaeoclimatic and palaeoenvironmental changes in the tropical mountains of Eastern AfricaBale Mountains during the Pleistocene.

Data availability. Ground temperature data, meteorological data, UAV data, GPR data as well as additional field photos of the stone stripes are available upon request by email to the corresponding author.

Author contributions. ARG, NA, and HV designed the research concept, conducted the geomorphological mapping, sampled the stone stripes for exposure dating, and installed the ground temperature data loggers. ARG and NA processed the rock samples in the laboratory. FH set up the weather stations. LW conducted the GPR measurements and serviced the weather stations. FH, LW, and TN processed and provided the meteorological data. ARG and JN processed the ground temperature data, conducted the statistical analysis, and performed the ground temperature simulations. ARG drafted the manuscript and figures with contributions from all authors.

Competing interests. The authors declare that they have no conflict of interest.

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Appendix A: Catalogue of periglacial ~~features~~landforms

Table A1. Overview of periglacial landforms and other characteristic geomorphological features in the Bale Mountains mapped in the field and on satellite images. A compilation of glacial landforms in the Bale Mountains is provided by Groos et al. (in revision).

ID	Landform / Feature
1	~~Frozen waterfalls active 6.91508 39.76298 3980 – 4000 32 – 37 350 – 10 2 Needle ice active 6.91784 39.76978 3925 – 3935 0 3~~ Sorted stone
~~4~~ 2	Scree slope
~~5~~ 3	Solifluction lobes
~~6~~ 4	Sorted stone stripes
~~7~~ 5	Sorted stone stripes
~~8~~ 6	Sorted stone stripes
~~9~~ 7	Sorted stone stripes
~~10~~ 8	Sorted stone stripes
~~11~~ 9	Sorted stone stripes
~~12~~ 10	Sorted stone stripes
~~13~~ 11	Sorted stone polygons
~~14~~ 12	Sorted stone polygons
~~15~~ 13	Blockfield
~~16~~ 14	Blockfield
~~17~~ 15	Blockfield
~~18~~ 16	Blockfield
~~19~~ 17	Blockfield
~~20~~ 18	Blockfield
~~21~~ 19	Blockfield
~~22~~ 20	Scree slope
~~23~~ 21	Scree slope
~~24~~ 22	Scree slope
~~25~~ 23	Scree slope
~~26~~ 24	Scree slope
~~27~~ 25	Scree slope
~~28~~ 26	Scree slope
~~29~~ 27	Landslide
~~30~~ 28	Landslide

Appendix B: GPR system settings

Table B1. System settings of the used Pulse EKKO PRO GPR.

Setting type	Setting	Setting type	Setting	Setting type	Setting
Frequency:	1000 MHz	Survey type:	Reflection	Start offset:	0 m
Time window:	30 ns (1.6 m)	Step size:	0.010 m	GPR trigger:	Odometer
Sampling Interval:	Normal (100 ps)	Calibration:	1080.0	Antenna separation:	0.15 m
Stacks:	4	Transmitter:	pE Pro Auto	Antenna polarization:	broadside
Velocity:	0.12 m ns^{-1}	Receiver:	pulseEKKO Pro	Antenna orientation:	Perpendicular

Appendix C: Cosmogenic ^{36}Cl data

Table C1. Description of periglacial features on the Sanetti Plateau sampled for ^{36}Cl surface exposure dating.

Rock sample	Lithology	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l.)	Boulder length (m)	Boulder width (m)	Boulder height (m)	Sample thickness (cm)	Shielding factor
BS01	Basalt	6.78634	39.79297	3874	2.1	0.6	1.0	2.5	0.9961
BS02	Basalt	6.78660	39.79280	3869	1.5	0.5	1.4	4.5	0.9961
BS03	Basalt	6.78682	39.79263	3865	0.6	0.4	1.0	3.0	0.9997
BS04	Basalt	6.85491	39.72078	4050	0.8	0.6	1.1	5.0	0.9990
BS05	Trachyandesite	6.85513	39.72074	4049	0.5	0.5	1.0	4.5	0.9990
BS06	Trachyandesite	6.85550	39.72049	4045	1.5	0.5	0.6	3.5	0.9994

Data from Groos et al. (in revision).

Table C2. Cosmogenic ^{36}Cl data and surface exposure ages of the rock samples from the Sanetti Plateau.

Rock sample	Rock dissolved (g)	^{35}Cl Spike (mg)	Cl (ppm)	^{36}Cl (10^5 At g^{-1})	Exposure age (ka)*	Exposure age (ka)**	Exposure age (ka)***
BS01	30.0307	2.5682	20.7 ± 0.08	30.44 ± 0.82	66.5 ± 4.5	68.2 ± 5.2	70.8 ± 5.9
BS02	30.0068	2.5584	31.5 ± 0.07	85.93 ± 1.63	200.0 ± 18.0	221.0 ± 25.0	282.0 ± 46.0
BS03	29.9887	2.5584	29.1 ± 0.04	85.66 ± 2.45	200.0 ± 18.0	221.0 ± 26.0	283.0 ± 46.0
BS04	29.9982	2.5652	40.9 ± 0.22	153.56 ± 2.58	406.0 ± 46.0	580.0 ± 180.0	–
BS05	30.0349	2.5719	1027.6 ± 11.19	1268.53 ± 25.03	760.0 ± 580.0	510.0 ± 270.0	–
BS06	30.0705	2.5682	1228.0 ± 13.43	1394.82 ± 46.40	790.0 ± 270.0	500.0 ± 300.0	–

Data from Groos et al. (in revision). *Erosion rate = 0 mm ka^{-1}. **Erosion rate = 1 mm ka^{-1}. ***Erosion rate = 2 mm ka^{-1}

Table C3. Major and trace element data of the six rock samples from the Sanetti Plateau.

Rock sample	O *	C *	Na *	Mg *	Al *	Si *	P *	K *	Ca *	Ti *	Mn *	Fe *	B **	Sm **	Gd **	U **	Th **
BS01	57.88	5.13	1.74	5.61	7.40	21.97	0.09	0.62	7.86	1.44	0.15	9.10	3	3.3	3.6	0.3	1.1
BS02	56.64	5.09	1.70	5.50	7.23	21.13	0.14	0.61	7.90	1.41	0.15	9.13	11	3.8	4.1	0.3	1.3
BS03	56.17	4.98	1.68	5.23	7.52	20.90	0.15	0.60	8.00	1.44	0.14	8.97	12	3.8	4.1	0.3	1.2
BS04	54.79	3.85	2.50	3.56	8.30	22.86	0.14	0.81	6.96	1.42	0.15	8.81	6	4.3	4.4	0.4	1.7
BS05	47.82	0.68	5.01	0.21	9.09	28.42	0.05	3.59	1.92	0.24	0.19	4.39	1	6.4	4.8	2.9	14.8
BS06	46.47	0.66	5.16	0.18	9.42	26.99	0.05	3.64	1.90	0.24	0.19	4.41	15	6.7	4.9	1.9	15.5

Data from Groos et al. (in revision). *Unit = % w/w. **Unit = ppm.

Appendix D: Weather stations and ground temperature data loggers

Table D1. ~~Cosmogenic ^{36}Cl data and surface exposure ages~~ Overview of the ~~rock samples from~~ ground temperature data loggers installed on the Sanetti Plateau.

~~Rock~~ Data ~~sample~~ logger	~~Rock~~ Latitude ~~dissolved (g~~(°N)	~~^{35}Cl Spike~~ Longitude (~~mg~~°E)	~~Cl~~ Elevation (~~ppm~~m a.s.l.)	~~^{36}Cl~~ Depth (~~10^5 At g^{-1}~~cm)	~~Exposure~~ Slope ~~age (ka) *~~ (°)	~~Exposure~~ Aspect ~~age (ka) **~~ (°)	~~age~~
~~BS01~~ GT07	~~30.0307~~ 6.78665	~~2.5682~~ 39.79342	~~20.7 ± 0.08~~ 3877	~~30.44~~ 2 ± ~~0.82~~ 1	~~84.2 ± 3.7~~ 8	~~86.7 ± 3.9~~ 320	~~9~~
~~BS02~~ GT08	~~30.0068~~ 6.78665	~~2.5584~~ 39.79342	~~31.5 ± 0.07~~ 3877	~~85.93~~ 10 ± ~~1.63~~ 2	~~280.8 ± 11.8~~ 8	~~332.0 ± 16.5~~ 320	~~78~~
~~BS03~~ GT09	~~29.9887~~ 6.78665	~~2.5584~~ 39.79342	~~29.1 ± 0.04~~ 3877	~~85.66~~ 50 ± ~~2.45~~ 5	~~280.8 ± 13.0~~ 8	~~334.5 ± 17.6~~ 320	~~85~~
~~BS04~~ GT10	~~29.9982~~ 6.79474	~~2.5652~~ 39.81469	~~40.9 ± 0.22~~ 3932	~~153.56~~ 2 ± ~~2.58~~ 1	~~620.1~~ 10	130	
GT11	6.79474	39.81469	3932	10 ± ~~28.0~~ 2	10	130	
~~BS05~~ GT12	~~30.0349~~ 6.79474	~~2.5719~~ 39.81469	~~1027.6~~ 3932	50 ± ~~11.19~~ 5	~~1268.53~~ 10	130	
GT13	6.82617	39.81897	4377	2 ± ~~25.03~~ 1	0	-	
GT14	6.82617	39.81897	4377	10 ± 2	0	-	
GT15	6.82617	39.81897	4377	50 ± 5	0	-	
~~BS06~~ TM04	~~30.0705~~ 6.84411	~~2.5682~~ 39.87876	~~1228.0~~ 4129	2 ± ~~13.43~~ 1	~~1394.82~~ 0	-	
TM08	6.82617	39.81897	4377	2 ± ~~46.40~~ 1	0	-	
TM09	6.86644	39.74365	4084	2 ± 1	0	-	
TM10	6.85509	39.71345	4022	2 ± 1	0	-	

Table D2. Overview of the automatic weather stations installed on the Sanetti Plateau.

Weather station	Location	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l.)	First measurement	Last measurement	Data completeness (%)*
BALE001	Tullu Dimtu	6.82693	39.81871	4377	04.02.17	31.01.20	73
BALE002	Tuluka	6.78945	39.77511	3848	02.02.17	30.01.20	100
BALE009	EWCP Station	6.84945	39.88197	4124	01.02.17	30.01.20	100

*Ratio of actual to maximum possible measurements during the respective measurement period.

Appendix E: Ground temperature model

Table E1. Coefficients and goodness of fit of the three established multiple linear regression models (MLRM) with ground temperature as dependent and air temperature and global radiation as explanatory variables. Distance means the distance between AWS and ground temperature data logger, β_0 is the intercept, β_1 the air temperature coefficiet, and β_2 the incoming shortwave radiation coefficient.

Linear regression model	Elevation (m)	Distance (m)	β_0	β_1	β_2	R^2 cal	RMSE cal (°C)	R^2 val	RMSE val (°C)
MLRM Tullu Dimtu	4377	90	3.7	1.7	0.004	0.73	3.0	0.72	3.0
MLRM EWCP Station	4124	690	1.2	1.6	0.010	0.79	3.6	0.76	3.6
MLRM Tuluka	3848	2050	-0.5	1.9	0.004	0.63	4.9	0.78	4.0

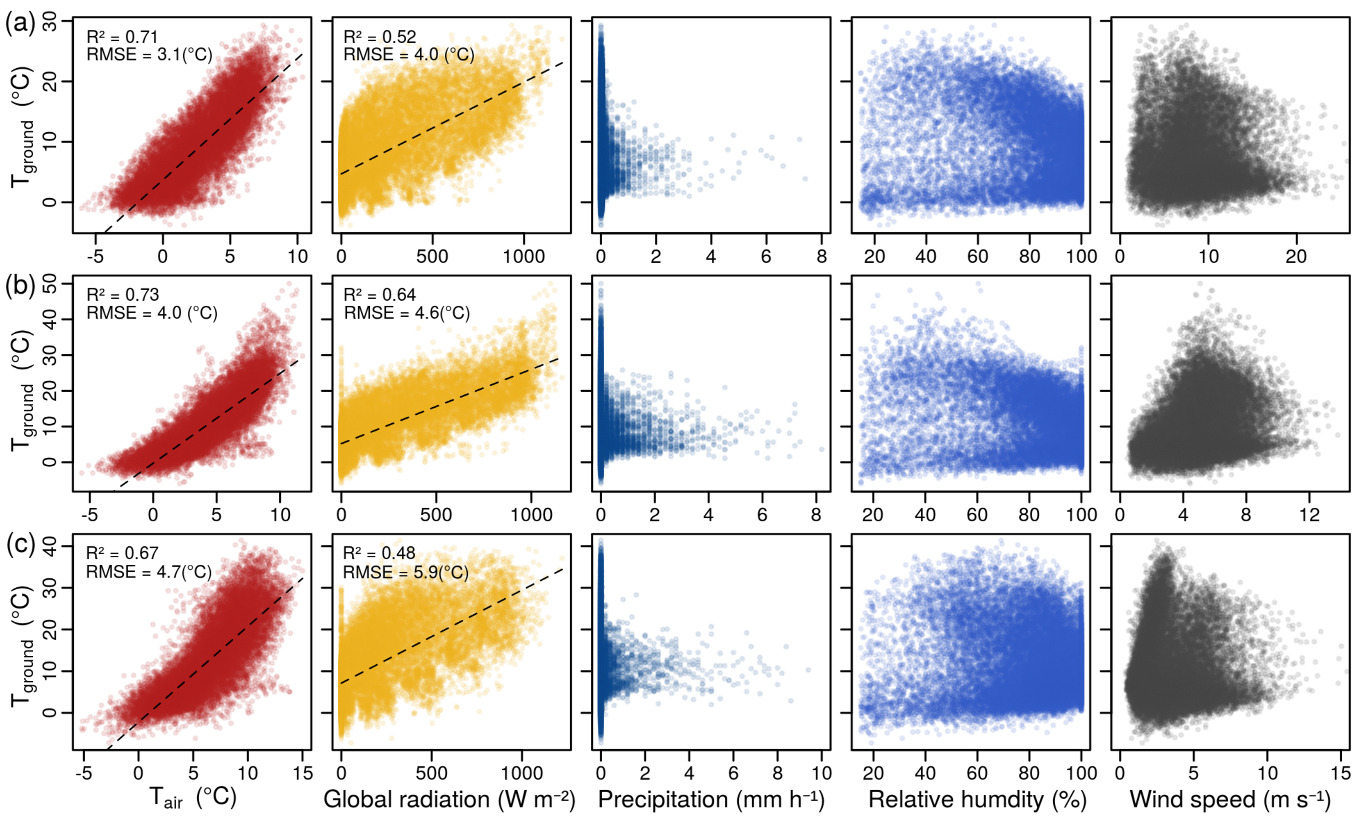

Figure E1. Correlation between hourly ground temperatures in 2 cm depth and different meteorological variables at three different locations: (a) Tullu Dimtu (GT13 vs. BALE001), (b) EWCP Station (TM04 vs. BALE009), (c) Tuluka (GT07 vs. BALE002).

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General response

First of all, we would like to thank the associate editor for obtaining two valuable reviews and the two referees, Stefan Grab and one anonymous, for their critical, thorough and constructive comments on our manuscript. We are pleased that both referees show interest in the presented data and findings and generally support the publication of the manuscript if their concerns are properly addressed. Both referees criticised the length of the manuscript and a lack of focus in some places. Hence, we decided to shorten and restructure the entire manuscript, to remove some of the ground temperature data, and change the initial title. We propose the following new title for the revised manuscript: *“The enigma of relict large sorted stone stripes in the tropical Ethiopian Highlands”*. The new title emphasizes the peculiarity of the studied stone stripes with respect to their size and occurrence on a tropical mountain. In the revised manuscript, we will focus on the characteristics of the stone stripes and outline two different scenarios regarding their genesis and age. We will keep some of the ground temperature data as well as the modelling experiment in the manuscript to discuss the recent climatic setting and elaborate on the potential palaeoclimatic and environmental conditions during the formation of the stone stripes. We are convinced that the manuscript will improve due to the reviewers’ remarks, questions and suggestions. On the following pages, we respond to the reviewers’ comments point by point. The reviewers’ comments are highlighted in gray and the responses in white. We hope that the responses qualify us to submit a revised version of the manuscript.

Response to Referee Comment 1 (Stefan Grab)

Referee report on: Implications of present ground temperatures and relict stone stripes in the Ethiopian Highlands for the palaeoclimate of the tropics Authors: Groos et al. General comments I am pleased to see that the Bale Mnts are receiving this geomorphic attention it deserves. I have worked on a variety of periglacial landforms in various African environments over many years now - but to me the large scale sorted stone stripes presented in this paper from the Sanetti Plateau, are the most special and unique periglacial landforms I have yet seen in Africa. They are truly special and must rank amongst the largest and best examples globally, I would think. So work on these is certainly called for and important to publish. I think the big challenge with these amazing landforms is ascertaining when they developed, how long they were actively forming for and when they might have become inactive (relict) periglacial phenomena. The second great challenge is ascertaining how they formed, because any misunderstanding as to their formation has serious implications to any climatic controls we attach to their genesis. I think these challenges are very real for this paper and when I read the work I see that this is where the paper has its struggles. I have several major concerns with this paper, which I will outline next, but at the same time wish to also assist with providing suggestions that might help rework this paper into something that might be publishable.
We thank Stefan Grab for his helpful comments and for his contribution to improve the manuscript. Below, we will respond to his major points of criticism.
Major concerns to address 1. The paper is far too long and tries to tackle too many things with too much detail, such that the connections between the various bits of collected data/information, become somewhat muddled and lost in the discussion/conclusion. The extent of detail to such things as instrumentation and story behind the logger battery issues etc may be valuable to place in a technical report or PhD thesis, but is not suitable for a journal publication. The text requires substantial trimming down and tightening up throughout.
We agree that some of the detailed ground temperature data and results go beyond the scope of the manuscript and may distract from the main discussion about the active periglacial processes and relict patterned grounds in the Bale Mountains. To improve the readability and structure of the manuscript, we decided to shorten and reorganise it. We will trim the entire text and remove some of the ground temperature data as well as figures 8-10 (others will be shifted to the appendix). Furthermore, we propose a new title for the revised version of the manuscript (see general remark). We will also include subheadings in the discussion as suggested by the anonymous referee.
2. Although the written style is relatively uncomplicated and for the most part satisfactory, there is a tendency towards colloquial language style, which is not suitable. The written style thus requires considerable improvement for publication.
We appreciate the general feedback regarding the written style and do not doubt that the language can still be improved, but it would have been helpful if some examples for the stated “tendency towards colloquial language” would have been provided. We will carefully proofread the manuscript again and revise the sentence structure and choice of words where necessary. We will also ask for professional language editing if that is recommended/requested for final publication.
3. a) The Scientific methods are notable and impressive for such a region given the logistical hurdles. However, great or large quantities of data may not always be the most useful or necessary

data for the study objectives. - While it is great having 36Cl results for the landforms, these raise more questions than provide answers. These do not necessarily inform us when the landforms first developed, or how long they were actively forming for, or when they became ‘periglacially inactive’. So, despite all the efforts in obtaining exposure ages, the authors are still left with merely assuming that the landforms are of Late Glacial age. Such an assumption might be reached without the exposure ages and have in fact also been made for other openwork block deposits (e.g. block streams) in the high Drakensberg (southern Africa) – see for e.g. Boelhouwers et al. (2002). Without any real sense of timeframe, it is impossible to use the landforms for any palaeo-climate reconstructions.

We were aware that determining the stabilisation phase of relict periglacial landforms with cosmogenic nuclides like ^{36}Cl is challenging and may be impossible if the sampled rocks have been exposed to cosmic radiation for several ten or hundred thousand years prior to (and/or during) their formation. However, several studies have demonstrated that the stabilisation phase of relict periglacial features like rock glaciers and block fields can be successfully dated with cosmogenic nuclides in some cases (e.g. Barrows et al., 2004; Ivy-Ochs et al., 2009; Steinemann et al., 2020). Since we were already sampling erratic boulders on the Sanetti Plateau for ^{36}Cl surface exposure dating and the reconstruction of the former ice cap, we decided to test whether this method can also help to constrain the period when the stone stripes became inactive. As already discussed in the manuscript, this was apparently not the case. The sampled rocks reveal very high ^{36}Cl concentrations, corresponding to exposure ages between 65 and 700 ka (recalculated with the latest version of the CRONUS Earth Web Calculator and a time-dependent “LSDn” scaling). The high concentrations could be interpreted in terms of a stone stripe formation over several cold stages during the Pleistocene as proposed for the stone runs in the Falkland Islands (Wilson et al., 2008). But they might also be the result of a long-term pre-exposure of the sampled rocks. Due to the well-preserved morphology and hardly weathered surface of the stone stripes as well as the required temperature depression, we argued that the stone stripes most likely formed during the coldest period(s) of the Late Pleistocene (i.e. MIS 2). The referee is right that such an assumption might be reached without the obtained exposure ages, but this is of course impossible to know before applying this method to the unique landform. Now that we have the ^{36}Cl data, it would be odd not to present and discuss them (also from a methodological perspective). Furthermore, we think that the measured concentrations provide additional information that are valuable for the interpretation of the paleoenvironment. The high concentrations for example suggest (not necessarily prove) that the stone stripes were probably never covered by thick ice for thousands of years and might have formed at the margin of the paleo ice cap (all this is discussed in detail in the manuscript…). We will emphasize the added value of including the ^{36}Cl dataset more clearly in the revised version of the manuscript.

3. b) Great effort was also undertaken with the Ground-penetrating radar measurements; something not previously done for periglacial landforms in Africa. However, the results to me do not show much that is of significance - and so does not add enough value to provide for anything noteworthy to add to the discussion or meet the aim/objectives of this paper. I would like to be proven wrong here – so if the authors can indeed use these data in a way that enhances/strengthens the discussion, then that would be good. - The authors provide considerable temperature data (ground and air). In fact I think too much is attempted with these temperature records and in the process of trying too

much with it (also too many graphs), the scientific value and merit is lost. I will elaborate on temperature data separately as this constitutes a major concern.
Information on the internal structure of the coarse stone stripes and fine regolith in between are essential to ascertain the genesis of this landforms and to address some important questions: How thick is the regolith layer above the volcanic bedrock? Is there any evidence of cryoturbation in the regolith layer? Does the regolith contain any larger blocks? Answering these questions would help to assess the former frost depth (or thickness of the active layer) and to evaluate whether frost heave and sorting were the main mechanisms for the formation of the stone stripes. Therefore, we intended to excavate a transect across the regolith (and if possible also across the coarse stone stripes). However, we didn't receive the necessary permission to do such an excavation in the national park. As an alternative, we conducted a first GPR survey. The GPR measurements show a relatively homogeneous regolith layer without any major reflection. The radargram is visually not very "exciting", but it provides a minimum depth for the regolith layer of more than 1.5 m. In addition, the GPR survey suggests that the regolith layer between the stone stripes contains no larger rocks (i.e. exceeding several decimetres). We interpret this observation, the coexistence of alternating regolith and coarse stine stripes, as an indication of frost sorting, which is one important mechanism and precondition for the formation of sorted patterned grounds. We will stress in the revised manuscript that these data are noteworthy for the discussion of the genesis of the stone stripes.
4. Temperature data: While the temperature data recorded at various localities might be used for various scientific purposes, I think the way in which the data have been used in this paper requires very careful reconsideration. - The work is built upon the presumption that the sorted stripes are a product of past seasonal or sporadic permafrost that would have required ground temps of -1 ◦ C . . .or a thermal reduction of around 12 ◦ C from those recorded more recently. And the authors argue on their modelling basis that air temps would thus have been lowered by around 7.6 ◦ C. This is all highly presumptuous and very controversial. In the first instance, ground temperatures were measured in the finer textured soil stripes and not within the openwork block deposits. When these features first formed, they may have formed in a scree of such open-work block deposition because of unique localized air flow (cooling) with depth through such openwork material, thus possibly creating 'pockets' of long lasting frozen ground phenomena (be it extended seasonal freeze or permafrost). So, the soils in which the authors have done their measurements may not have been as extensively frozen as for instance in the adjacent blocky material. Please see some published work which has shown enhanced cooling through blocky periglacial phenomena (e.g. Harris & Pedersen (1998) show much colder ground thermal conditions below blocky materials than finer textured regolith cover). - A further point is that the authors have not considered the likely thermal impacts of snow in a palaeo-environmental context. It is thus impossible to begin modelling likely air temperature reductions unless we know 1) the actual palaeo-ground temperature at exactly the same site as the contemporary measurements were taken (which is assumed to have been below 0 ◦ C – but very much built on assumption as the stripes may have formed when there was deep freeze beneath the blocky material but only limited/shallow/seasonal freeze in the finer textured soil stripes), and 2) the depth, duration etc of snow which would have had an insulating effect – or maybe helped preserve cooling during particular times of the year etc. The distribution and thickness of snow across the landscape would almost certainly have had impacts on the

spatial/temporal characteristics of ground freeze and thaw during past colder periods. In summary re the temperature data – it is ‘stretching the data too far’ to try and start modelling past air temperatures as the scientific context is far too simplistic in the way it has been presented here. In reality, the contexts are much more complicated than the authors make it out to be. At best, I think the authors can use contemporary ground temperature data to reflect on contemporary shallow soil frost phenomena.
We do not share the referees concern regarding the ground temperature modelling experiment and are convinced that it is an appropriate method to assess which paleoclimatic conditions would have theoretically been required for the formation of the stone stripes on the Sanetti Plateau. First of all, we would like to point out that “experimental and numerical modelling of Earth surface processes” is one of the journal’s main subject areas. Hence, we think that such a modelling experiment generally fits the scope of journal. Based on all evidence we have gathered so far, the structure and characteristics of the stone stripes can be best explained by the mechanism of frost heave and sorting. Although it does not seem very likely, we can of course not exclude that a different, yet unknown, geomorphic mechanism might have caused the formation of the stone stripes. But if we assume that sub-freezing air temperatures and ground frost (no matter how deep) were an essential paleoclimatic precondition for their genesis (e.g. Goldthwait, 1976; Washburn, 1980), we can use our recent measurements to provide an order of magnitude for a past ground and air temperature depression in the Bale Mountains. The modern mean annual air temperature at the location of the stone stripes (~3900 m) is ~6 °C and the mean ground temperature (in the regolith) ~11 °C. The seasonal air and ground temperature minima are ~4 °C and 9 °C, respectively. This would translate into an air and ground temperature depression of at least ~4-6 °C and 9-11 °C, respectively. We agree at this point with the referee that the stone stripes might have formed at the beginning in a scree of open-work block deposits that promoted colder ground thermal conditions than the fine textured regolith layer (we pick up on this topic in a response further below...). However, this does not affect our assumption on the potential air temperature depression because sub-freezing air temperatures are probably also a precondition for the formation of frost in such open-work block deposits. During further sorting of the material, also the regolith between the stone stripes must have experienced frost action. Otherwise the absence of any larger blocks in the fine regolith between the coarse stone stripes is hard to explain. Hence, we think that the postulated rough ground temperature depression of at least 9-11 °C is justified. The referee also raised concern that the thermal impacts of snow on ground temperature were neglected. He argues that snow might have “helped preserve cooling during particular times of the year”. The distribution and thickness of snow certainly modulates the energy exchange between the atmosphere and ground. Snow has an isolating effect and may prevent the ground from cooling as well as heating, depending on the timing of snowfall. However, the absence of any glacial landforms or sediments on the southern plateau margin as well as along the southern escarpment suggests that the area of the stone stripes was very dry during the Late Pleistocene. Larger quantities of snow should have promoted the glaciation of the southern and western Sanetti Plateau, but this was apparently not the case (see Ossendorf et al., 2019; Groos et al., under review). Apart from that, a seasonal snow cover by itself would have required (or led to) a ground temperature at the freezing point or below. Without a decrease in ground temperature of more than 9-11 °C, neither seasonal nor annual frost could have formed on the Sanetti Plateau. We did not claim anywhere in the manuscript that we intended to

simulate the energy exchange between the ground and atmosphere on the plateau in a physical manner, where the consideration of the snow pack etc. would have been indispensable. What we wanted to test with the simple statistical model is under which paleoclimatic conditions (i.e. decrease in temperature and insolation) the mean ground temperature would approximate frost conditions. An essential assumption underlying such an approach is that the established statistical relationship between the dependent and independent variables did not change. This is not necessarily the case as the thermal conductivity and heat capacity of the ground might for example change due to variations in soil moisture. We will discuss the limitations of our model experiment in more detail in the revised version of the manuscript. Furthermore, we will interpret the results in a more conservative way.

References:

- Barrows, T., Stone, J. O., and Fifield, L. K.: Exposure Ages for Pleistocene Periglacial Deposits in Australia, Quat. Sci. Rev., 23, 697–708, https://doi.org/10.1016/j.quascirev.2003.10.011, 2004.
- Goldthwait, R. P.: Frost Sorted Patterned Ground: A Review, Quat. Res., 6, 27–35, 1976.
- Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P. W., and Schlüchter, C.: Latest Pleistocene and Holocene Glacier Variations in the European Alps, Quat. Sci. Rev., 28, 2137–2149, https://doi.org/10.1016/j.quascirev.2009.03.009, 2009.
- Steinemann, O., Reitner, J. M., Ivy-Ochs, S., Christl, M., and Synal, H.-A.: Tracking rockglacier evolution in the Eastern Alps from the Lateglacial to the early Holocene, Quat. Sci. Rev., 241, 1–19, https://doi.org/10.1016/j.quascirev.2020.106424, 2020.
- Washburn, A. L.: Permafrost features as evidence for climatic change, Earth-Sci. Rev., 15, 327–402, https://doi.org/10.1016/0012-8252(80)90114-2, 1980.

More detailed technical matters to address: P3, line 23: How do you define ‘alpine environment’ . . .on what basis? Is it based on a Eurocentric view of ‘alpine’, or is it based on what has commonly been defined as the ‘Afro-alpine’ zone? I am not advocating any given view but the authors should define what they understand makes the Bale Mnts the largest African ‘alpine’ environment. . .as opposed to for instance the Atlas Mnts or high Drakensberg-Maloti mnt system in Lesotho, Southern Africa (in both these cases one might argue for extensive ‘alpine and/or Afro-alpine’ regions which are larger than that of the Bale).

We refer to Hedberg (1951), who defined the afro-alpine belt in tropical Africa as the area above ~3500 m. Others set the lower elevation of the tropical afro-alpine belt to ~3200 m (e.g. de Deus Vidal Jr & Clark 2019). However, we are aware that the afro-alpine belt tends to be lower in the subtropical mountains like the High Atlas or Drakensberg. The afro-alpine area on these mountains might therefore be similar or larger than that of the Bale Mountains. To be more specific, we will write “With an area of more than 1000 km^2, the Bale Mountains comprise Africa’s most extensive alpine environment above 3500 m”. Furthermore, we will directly refer in the text to the references below.

References:

- Hedberg O.: Vegetation belts of East African Mountains. Svensk bot Tidskr, 45, 140–202, 1951.

• de Deus Vidal Jr, J. and Clark V. R.: Afro-Alpine Plant Diversity in the Tropical Mountains of Africa.Encyclopedia of the World's Biomes, 373–394, https://doi.org/10.1016/B978-0-12-409548-9.11885-8, 2019.
P5, lines 13-14- the values of glacial extent mentioned here is according to who? Needs a reference.
We refer to our separate manuscript on the glacial chronology of the Bale Mountains that is currently under review (Groos et al., in review). The reference will be included after the statement.
P5, line 20: the authors say here that the large periglacial features are associated with freeze-thaw processes. Unless the authors can verify that they have measured freezing and thawing dynamics here, and that these mechanisms produced these landforms, then this is a scientific assumption. So rather write as '. . ..features are likely associated with. . ..'
As outlined above, we think it is a reasonable scientific assumption that the stone stripes are the product of frost heave and sorting. However, we cannot provide any direct evidence for this assumption as the stone stripes constitute an inactive landform. Hence, we will write "The formation of these features is likely associated with freeze-thaw processes [...]".
P 5, line 30 would read better to say are 'endemic to'
The concerning section will be removed to shorten the manuscript.
P13, line 11: Stone stripes apparently required a thick active layer. Why do you say it had to be thick? What do you understand to be 'thick' rather than 'thin'? What dimensions are we dealing with here? Can it be that the relict sorted stripe sorting depth might say something re to active layer thickness. . .or depth to which [periglacial] geomorphic mechanisms operated?
With "thick" we meant an active layer that was at least several decimetres thick (as mentioned before and afterwards in the manuscript). We used the attribute "thick" to differentiate between decimetre to metre deep freezing and thawing, which we assume initiated the past formation of the large sorted stone stripes (see response to general comments), and superficial ("thin") frost that creates the present small scale patterned grounds on the Sanetti Plateau. We will specify this in the revised version of the manuscript. Whether the depth (~2 m) of the relict sorted stone stripes says something about the active layer thickness (or depth to which the freezing front operated in case of the absence of permafrost) is an interesting and important question. The largest clasts of the stone stripes are up to 2 m long, 0.5 m wide, and weigh probably more than 1000 kg. We assume that an active layer or freezing depth of at least several decimetres was necessary to heave and sort these large clasts. The freezing front usually descends faster in coarse blocks than in fine material (Kessler and Werner, 2003). The faster descend of the freezing front in coarse blocks is mainly explained by three different processes: 1) The better thermal coupling between the ground and air due to enhanced conduction (i.e. heat transfer) through the blocks in the presence of snow (Juliussen and Humlun, 2008) . 2) Pronounced ground cooling through free convection of air in coarse blocks in the absence of snow (Wicky and Hauck, 2020). 3) Coarse blocks retain less water than wetter fine-grained soils that must be cooled before freezing (Kessler and Werner, 2003). Due to these mechanisms, it is likely that the freezing front at the interface between the coarse stone stripes and the fine regolith was inclined (causing lateral frost heave), while it was rather horizontal in the regolith (causing vertical frost heave), coresponding to the concept presented by Kessler and Werner (2003). Since the freezing front was probably deeper below the coarse and trough-shaped stone stripes than in the fine and rampart-like

regolith (mimicking the morphology of the landform), the relative frost depth (distance between ground surface and freezing front) was probably smaller than the sorting depth (~2 m) of the stone stripes, but larger than a few decimetres (as inferred from the size of the clasts). This would provide a potential frost depth (or active layer thickness) in the order of several decimetres up to 2 m during the formation period of the stone stripes. Cryoturbation was probably limited to a depth of maximum 2-3 m as this seems to be the maximum regolith thickness on the plateau.

References:

- Juliussen, H. and Humlun, O.: Thermal regime of openwork block fields on the mountains Elgåhogna and Sølen, central-eastern Norway, Permafrost Periglac. Process., 19, 1–18, http://doi.wiley.com/10.1002/ppp.607, 2008.
- Kessler, M. A. and Werner, B. T.: Self-Organization of Sorted Patterned Ground, Science, 299, 380–383, https://doi.org/10.1126/science.1077309, 2003.
- Wicky, J. and Hauck, C.: Air Convection in the Active Layer of Rock Glaciers, Front. Earth Sci., 8, 1–17, https://www.frontiersin.org/article/10.3389/feart.2020.00335/full, 2020.

P14 – at the bottom of this page the authors list so called ‘frost-induced phenomena’ such as frozen waterfalls, needle ice, patterned ground and solifluction lobes. This is a bit confusing as it mixes geomorphic periglacial landform types (i.e. patterned ground and solifluction lobes) with ice types (massive ice as frozen waterfalls or needle ice developed in soil). Ground ice types might be seen as mechanistic agents, while the landforms might be seen as products of the former.

In the revised version of the manuscript, we will distinguish more carefully between ice types and landforms.

Figure 4: These are impressive photos and all valuable to add here. In photo g, I can see the patterned ground (blocky borders) – in fact they look impressive to me, but the dotted white line that the authors have placed to supposedly outline the borders (shape) do not correspond with the pattern border localities in the photo.

Thanks, we realised that the simplified/idealised shape of the drawn borders does not align with the actual borders of the patterns shown in Fig. 4g. We will remove the anticipated (dotted) borders in the revised figure.

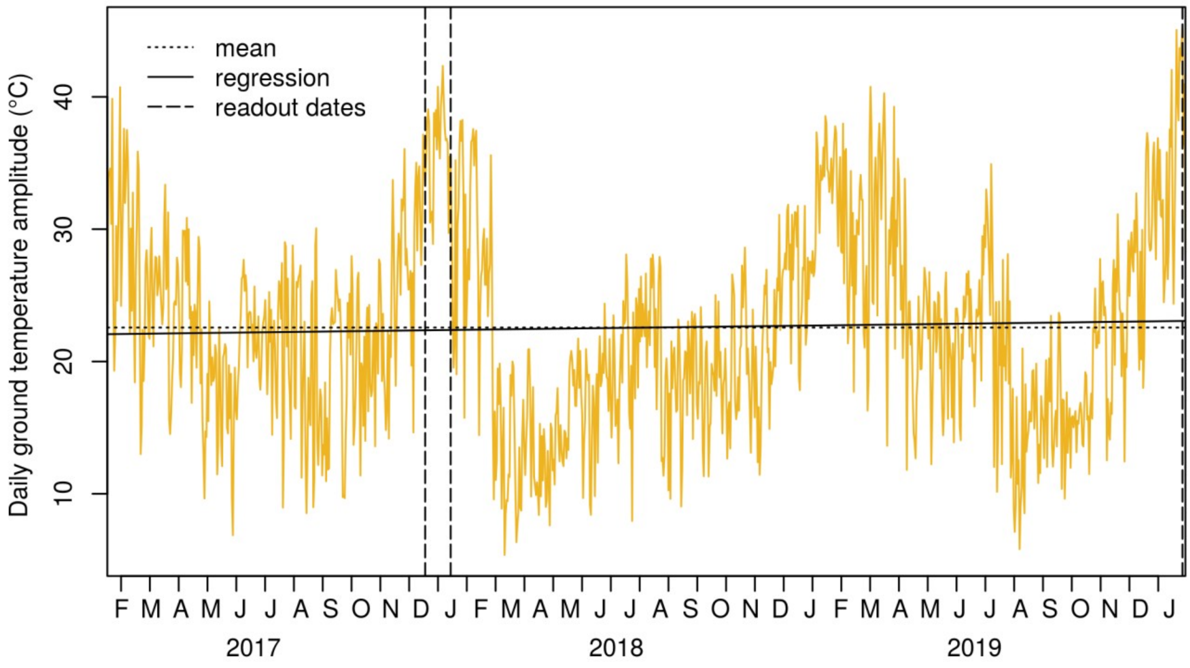
The caption to Figure 4 is a bit misleading I think. It informs the reader that these photos show us the ‘Periglacial environment of the Bale Mnts’. In the first instance, it shows contemporary phenomena of a frozen waterfall and needle ice (i.e. the contemporary environment). These features do not qualify this to be labelled a contemporary periglacial environment as the ground temps show very temporally limited and shallow diurnal freeze only, and the contemporary active cryo-geomorphic environment has a negligible effect on the landscape/landforms today. However, the larger relict landforms show us that this was indeed once a periglacial environment. So the caption could read something like ‘Contemporary seasonal ice phenomena and relict periglacial landforms of the Bale Mnts’

We will follow this suggestions and modify the caption accordingly.

Figure 5: It is problematic to show the location of only one needle ice site and only one frozen water fall locality. Firstly, there were likely other sites with needle ice at the time of observation. . .as also for frozen waterfalls or seepage out of rock at some localities. Secondly, the

needle ice shown on the map is not a permanent feature at that locality, neither is the ice on the cliff face – which is hence problematic to show on a map. In Contrast, the other geomorphic phenomena mapped are permanent on the landscape (at least for the generation that will read this article) and thus suitable for mapping. Are the waterfalls (as shown in the photo) frozen every year? For how many months each year?
The location marked with an asterisk in the map (Fig. 5a) is predestined for cold air ponding and one of the best sites in the Bale Mountains to observe/study needle ice. Needle ice occurs also along other stream banks, but during our field surveys at the end of the dry season (January to February) most of the smaller streams were already dried up. In the upper Wasama Valley, needle ice can be found at clear nights throughout the dry season each year. That's why this location was included in the map. As far as we have observed, the frozen waterfalls only evolve at the shaded north-exposed cliffs in the Wasama Valley (marked in the map). Our local guides were not aware of any other location where this seasonal phenomenon can be observed. The waterfalls in the Wasama Valley freeze every year at the end of the rainy season (i.e. October/November) and persist until the onset of the following wet season (i.e. February/March). We will revise this figure (and caption) to clearly distinguish between the location of present and relict landforms as well as sites where seasonal phenomena like the frozen waterfalls and needle ice can be (best) observed.
Figure 5b shows 3 exposure age locations but only one age given. '620' requires an indication of scale of age used. Why does the word saturated appear twice on the map? Is this not also a bit problematic. . .unless it is permanently saturated at that locality? Figure 5c three numeric values given. . ....what are these . . .age scale used?
This information is indeed a bit misleading. The word "saturated" appeared twice in the map (5b) since ^{36}Cl reached saturation (concentration where production and decay are balanced) in two samples of the investigated stone stripe on the western part of the plateau when using a time-invariant scaling (i.e. Stone, 2000). The resulting age (>1000 ka) of these two samples (BS05 and BS06) was at the limit of the method and was therefore not explicitly stated. As indicated in the legend, the three numeric values in Fig. 5c represent the exposure ages of three investigated blocks (BS01-03) from a stone stripe on the southern part of the plateau. We will add the sample names in the revised version of the map and provide further information in the caption for clarification. Furthermore, we will recalculate all six exposure ages (samples BS0-06) with the latest version (2.1.) of the established CRONUS Earth Web Calculator (http://cronus.cosmogenicnuclides.rocks/2.1/html/cl/) using the physics-based and time-dependent LSDn scaling framework (Lifton et al., 2014; Marrero et al. 2016). This information will be included in the respective methods section and in the figure caption. References: • Lifton, N., Sato, T. and Dunai, T. J.: Scaling in situ cosmogenic nuclide production rates using analytical approximations to atmospheric cosmic-ray fluxes. Earth Planet. Sci. Lett., 386, 149–160, http://dx.doi.org/10.1016/j.epsl.2013.10.052, 2014. • Marrero, S. M., Phillips, F. M., Borchers, B., Lifton, N., Aumer, R. and Balco, G.: Cosmogenic nuclide systematics and the CRONUScalc program. Quat. Geochronol., 31, 160–

187, http://dx.doi.org/10.1016/j.quageo.2015.09.005, 2016. • Stone, J. O.: Air pressure and cosmogenic isotope production. Journal of Geophysical Research: Solid Earth, 105, 23753–23759, http://doi.wiley.com/10.1029/2000JB900181, 2000.
P17, line 2: the authors say that the deposits are associated with so called ‘frost weathering’. How do you know for certain that it was due to ‘frost weathering’ . . .and not maybe a combination of different weathering mechanisms of which freezing/thawing of water might be one? This would then also imply potential thermal stress (thermoclastis) as an additional weathering type. I think greater scientific caution and rigor is required with statements such as these.
We wrote that these deposits are “[…] associated inter alia with frost weathering […]”. The large size of the clasts (several decimetres to more than one metre) indicates that frost action was probably the most relevant mechanism for producing the scree. However, this statement does not exclude that also other weathering processes were involved. We will rephrase the sentence to make this clear.
Figure 7: When I examine your temperature records over the period 2017 to 2019 in this Figure, I am concerned that your 2cm and 10cm ground temperature data may not actually represent the temperatures at a fixed depth through time because I can see that their amplitudes (in both the positive and negative directions) increases progressively through time. This is of course typical to a situation where your thermistor has shifted upwards through the soil profile.
It is unclear whether the referee refers to figure panel “a” or “b” in Fig. 7 and how he comes to the conclusion that the daily ground temperature amplitude increases progressively over the period 2017 to 2020. Panel “a” in Fig. 7 shows hourly ground temperatures and, thus, allows to infer daily amplitudes. However, the analysis of the evolution of the daily ground temperature amplitude in 2 cm depth shows no significant trend over the period 2017-2020 (see figure below) and also no change after the readout dates (vertical dashed lines). If the last week before the final readout end of January 2020 was ignored in the analysis (this period was characterised by exceptionally high amplitudes), the minimal (insignificant) positive trend would even reverse into a minimal (insignificant) negative trend. This argues against the assumption that the thermistors might have shifted upwards through the profile over time. There is no evidence that the measured ground temperatures do not represent the conditions at fixed depths (2 ± 1, 10 ± 2, 50 ± 5 cm). Panel “b” in Fig. 7 shows seasonal ground temperature variations in 2, 10 and 50 cm depth and indicates that the thermal difference between the dry and wet seasons was more pronounced in the years 2018 and 2019 than in 2017. However, these variations are attributable to climatic fluctuations and cannot indicate a vertical shift of the thermistor as the magnitude of seasonal ground temperature variations is similar in all depth. To make this clear, we will use a simpler smoothing approach than the initial “local regression with a smoothing span of 0.32” to illustrate seasonal ground temperature variations in Fig. 7b.



For temperature measurements and discussion re temperatures – why do you interchange between Kelvin and ◦ C? Please keep to ◦ C.
We used °C for actual temperatures and Kelvin for temperature differences (as it is common in engineering sciences) to avoid misinterpretations, but since this caused confusion, we will consistently use °C for actual temperatures and temperature differences in the revised version of the manuscript.
Way forward I think that the greatest strength this paper has to offer is in showcasing the very unique large sorted stripes and possibly large sorted patterned ground. Showcasing these features and finding a way to show their environmental significance (in a scientifically robust manner), surely merits publication, albeit as a much shorter article than the one submitted currently. I suggest a much trimmed down version of this paper: 1) briefly describing contemporary soil frost dynamics and small-scale contemporary soil frost phenomena – where some of the temperature data could be included, and 2) showcasing the large relict features with mapping data and field based measurement data (I currently do not see the value of the 36Cl and ground penetrating radar data). From these, one could then build an interesting but focused and concise discussion (along the lines of some of the discussion on p25, lines 17-31 – which I quite like). I caution against trying to make too much inference from relict landforms for which we still know relatively little in terms of their mechanisms of formation and thus underlying ground and air climatic requirements. It would thus not be possible to say too much about palaeo-climates for this region, let alone the tropics as a whole as the title of the paper implies. It might be worth saying something about the geo-heritage & geo-tourism potential here given the rarity/uniqueness of the landforms.
As outlined in the responses above, we will shorten and restructure the manuscript. The new structure would be as follows: <u>Results</u> 4.1 Contemporary ground frost dynamics and small-scale ground frost phenomena (including some ground temperature data from the Sanetti Plateau)

4.2 Characteristics of the relict periglacial features (including the ^{36}Cl and GPR data as discussed in the responses above).
4.3 Results of the ground temperature modelling experiment
<u>Discussion</u>
5.1 Comparison of the stone stripes in the Bale Mountains with similar landforms in other regions
5.2 Genesis and age of the stone stripes (discussing two different scenarios: 1. formation due to seasonal temperature variations, 2. formation over several cold and warm phases during the Pleistocene)
5.3 Stone stripes as proxy/indication for regional paleoclimatic and environmental changes

We will shortly discuss the geo-heritage and geo-tourism potential in 5.1.

References: Boelhouwers, J., Holness, S., Meiklejohn, I., & Sumner, P. (2002). Observations on a blockstream in the vicinity of Sani Pass, Lesotho Highlands, southern Africa. Permafrost and Periglacial Processes, 13(4), 251-257. Harris, S. A., & Pedersen, D. E. (1998). Thermal regimes beneath coarse blocky materials. Permafrost and Periglacial Processes, 9(2), 107-120.

Thanks for these recommendations. Will consider both references for the discussion in the revised manuscript.

Response to Referee Comment 2 (anonymous)

General comments: This paper presents a detailed account of current and past periglacial landforms and processes of the Bale Mountains in Ethiopia, with specific focus on relict sorted stone stripes. The latter is a very prominent feature and very unique for the tropics and mid- and high-latitudes in general. The characteristics of these stone stripes are described by detailed geomorphological mapping, UAV photogrammetry, ground-penetrating radar and 36Cl surface exposure dating. Palaeoclimatic importance are studied by collecting current ground and air temperature data and modelling a minimum air temperature depression needed to form these landforms. I was pleased to receive the invitation for reviewing this work, which I read with great interest. It is clear to me that the authors have gathered a highly relevant dataset, which would be a great scientific contribution about this topic. However, I agree with previous referee report of Stefan Grab that the paper is very long, in some places lacking focus and it is not always clear what the added value of certain datasets are.
We thank the anonymous referee for his helpful comments and for his contribution to improve the manuscript. In the following, we will respond to the general comments. As outlined in the general response at the beginning and in the response to Stefan Grab, we decided to shorten and reorganise the manuscript in order to improve the readability and structure. We will trim the entire text and remove some of the ground temperature data as well as figures 8-10 (others will be shifted to the appendix). Furthermore, we propose a new title for the revised version of the manuscript (see general response). We will also include subheadings in the discussion as you suggested in one of your comments below.
For example the UAV photogrammetry data – is this just a nice addition or does it actively contributes to your findings? Are grain size distributions based on this imagery as you state in your methodology? This is not clear. I understand that the authors want to describe the features in as much detail as possible, but this does not come forward in the result section of the paper, where it seems that only the geomorphic mapping, the 36Cl surface exposure dating and the temperature measurements and modelling are presented. Results from UAV data and GPR seem to be lacking/could be stated more clearly.
The UAV photogrammetry data are important for the manuscript due to the following reasons: i) The 3D aerial image composed of multiple UAV images (Fig. 6) provides the most realistic view of the stones stripes and helps the reader to get an impression of the landform. ii) The digital surface model served as basis for the analysis of the stone stripes morphology. iii) The orthophoto served for measuring the size of the clasts in the coarse stone stripes. To emphasise the added value of each individual dataset, we will state more clearly in the results section of the revised manuscript how each dataset actively contributes to our main findings.
The way the paper is written now, the temperature measurements and analysis form the core of this work and all other methods are tributary. I strongly agree with Stefan Grab's suggestions on the temperature data used in this paper. The potential presence of air circulation in the blocky material, causing substantial cooling, should be discussed.
Regarding the usage of the ground air temperature date, we would like to redirect the referee to our general response (4.) to the other referee Stefan Grab.

In addition, comparison with current day examples could be more elaborate and is now only briefly touched in the discussion (on p25, L6 you state there are well documented examples from the high arctic). It is also not clear to me why the example of the Falkland Islands is highlighted. Is this the only other site that shows similar inactive landforms, like the ones you observe in the Bale Mountains? Nevertheless, I also agree with Stefan Grab that this work is highly relevant and impor- tant to publish. I therefore suggest that a moderate to major revision of the manuscript is required.
We discussed the stone stripes in the Bale Mountains in comparison with the “stone runs” in the Falkland Islands since this is the only other known location worldwide where inactive stone stripes of similar size have been reported and described. In the revised manuscript, we will dedicate one subchapter to the comparison of the stone stripes in the Bale Mountains with past and present-day examples elsewhere.
Specific comments: - Be careful with absolute statements that are not based on clear references/data. For example: P1 L1: . . .the most prominent features. . . -> one of the most/one of the more prominent features. . . (People studying rock glaciers might disagree with your initial statement. . .). P2 L17: Africa’s largest alpine environment -> one of Africa’s largest alpine environment (also see comment of Stefan Grab). I see that in L22 on p3 underneath study area you have a more detailed statement of this, referring to your manuscript in revision. If you stand by this statement, consider moving this information ore forward in the manuscript.
We will be more careful with absolute statements and will rephrase the first sentence in the abstract. The Bale Mountains represent indeed the largest afro-alpine environment above 3500 m (for a more detailed explanation please refer to the response to the other referee), but we didn’t explicitly mention the elevation in the quoted sentence. We will modify this.
- You are very brief when describing the collected UAV data (L14-20 p6). Normally, at least an error reporting should be done to indicate the reliability of your data. Because UAV data is prone to deformation, especially when using a small amount of ground control points that might not be evenly distributed. If I understood correctly, you did not incorporate ground control points to process the images, but only to georeference the final products (orthophoto, DSM). This is confusing, since normally ground control points are used to correct the geometry in the 3D modelling procedure. Therefore, consider using different terminology. I understand that this is not the focus of your paper and that you refer to earlier work. However, I still think error reporting should be included here (and might not be similar as the errors you achieved on Kanderfirn) if you want to include this data in your paper.
We neglected a more detailed description since the general processing procedure of the UAV images was already presented in a previous publication (Groos et al., 2019), although with a focus on a completely different region (the Swiss Alps...). The absolute georeferencing accuracy of the orthophoto and DSM in not of major relevance in our case as we do not compare our data with any other datasets. However, we agree that an error estimate must always be reported. The horizontal (XY) accuracy of the provided dataset is ~0.5 m (relative to the orthorectified WorldView-1 image) and the vertical (Z) accuracy is ~1.5. m (relative to the SRTM-1 DEM). We will include this

information in the revised manuscript. We had no differential GPS available with us and, thus, could not directly mark and measure ground control points in the field. In principle, the number of five "relative" control points that we used to process the images and georeference the final products are sufficient for such a small area (60 x 80 m) (e.g. Gindraux et al., 2017). Warping (often referred to as "doming" and "fishbowling" effect) can be a problem when processing UAV images, but this is rather the case for larger study areas and not for such a small area as we surveyed. We will revise the respective method section about the UAV data and explain the procedure more precisely. Reference: • Gindraux, S., Boesch, R., and Farinotti, D.: Accuracy Assessment of Digital Surface Models from Unmanned Aerial Vehicles' Imagery on Glaciers. Remote Sensing, 9, 1–15, http://www.mdpi.com/2072-4292/9/2/186, 2017. • Groos, A. R., Bertschinger, T. J., Kummer, C. M., Erlwein, S., Munz, L., and Philipp, A.: The Potential of Low-Cost UAVs and Open-Source Photogrammetry Software for High-Resolution Monitoring of Alpine Glaciers: A Case Study from the Kanderfirn (Swiss Alps), Geosciences, 9, 1–21, https://doi.org/10.3390/geosciences9080356, 2019.
- The text reads sometimes confusing when you talk about temperature measurements. Please check thoroughly throughout the document that you clearly mention when you talk about ground temperature and when you talk about air temperatures. For example: In the caption of figure 1: GT and TM are both ground temperature loggers?
With a few exceptions, we have explicitly distinguished between air and ground temperature throughout the manuscript, but in the caption of Fig. 1 we forgot to mention it. We will revise the caption and will check the manuscript carefully again to differentiate between air and ground temperature where we haven't so far.
- P13 L13: This sentence is lacking a reference. Since you base an important part of your modelling on this value, and the resulting temperature depression, you could give more attention to where you get this value. Is this -1 ◦ C ground temperature purely theoretical (from literature)? Or is this based on other observations in other areas? In your discussion you give an example of Goldthwait 1976, where large sorted landforms are common with air temperatures of -4 to -6 ◦ . How does this stand in relationship with -1 ◦ C ground temperature? Could you compare these air temperatures to the air temperatures depression you found for the Bale Mountains? This needs some clarification throughout the document in both methodology, results and discussion.
As far as we are aware, active stone stripes of similar size like those in the Bale Mountains and Falkland Islands do not exist elsewhere on the globe (or have at least not been reported/described until today). Hence, the mean annual ground temperature that was prevailing during the formation of the stone stripes is difficult to assess. If we assume that frost heave and sorting was one precondition for the formation of the stone stripes, the mean annual ground temperatur at that time was probably about 0 °C or below in the Bale Mountains. Seasonal minimum ground temperatures below 0 °C (and an MAGT above 0°C) might have been theoretically sufficient for the stone stripe formation, but due to the size of the clasts and minor seasonal temperature variations in the tropics, we think a MAGT of 0 °C is an adequate first assumption. Ground temperatures oscillating about 0 °C are also typical for regions where stone circles form (see for example Hallet 2013). The MAGT might have been lower in the Bale Mountains, but it is impossible to make any specific and

justified assumption. Therefore, we will replace the initially used, but not well-founded, theoretical value of -1 °C by a MAGT of 0 °C. We will justify our assumption and clarify our procedure (as outlined above) throughout the revised manuscript. Reference: • Hallet, B.: Stone Circles: Form and Soil Kinematics, Proc. R. Soc. A, 371, 20120 357, https://doi.org/10.1098/rsta.2012.0357, 2013.
- Section 4.1: make sure the distinction between active and relict periglacial processes is clear. Also add this to the title, for example . . . past and present periglacial processes (needle ice is not really a landform).
We will split the results section (4.) into a subchapter on active (4.1) and a subchapter on relict (4.2) periglacial processes and landforms to avoid confusion.
- Figure 5: I agree with Stefan Grab considering the comments about Figure 5. Reporting single frozen waterfalls and needle ice observation is rather anecdotal. Could you, besides direct observation, also indicate areas where these phenomena are likely, depending on elevation, slope, aspect. . .? Do you have more observations, from for example locals? You could make different mapping categories between permanent landforms and areas were current periglacial processes could be observed. Differ between landforms and processes.
We (and also our local guides) didn't observe frozen waterfalls at any other location. We mentioned this phenomenon in the text (and marked it in the map) because it seems to be the only apparent frost-related process in the Bale Mountains, which is controlled by seasonal rather than diurnal temperature fluctuations. We will add additional locations where needle ice typically occurs (based on observations of our colleagues). Furthermore, we will modify the legend and caption of this figure to clearly distinguish between permanent landforms (active and relict) and areas where periglacial processes can be observed.
- P16 L9: Is there a clear difference in elevation (belts) between relict periglacial features and current periglacial landforms/processes?
No, there is not clear difference in elevation (belts) between the relict periglacial features and current periglacial landforms/processes. What we mainly observed is a difference in the magnitude of the landforms/processes (e.g. active small-scale patterned grounds vs. sorted stone stripes and polygons on the Sanetti Plateau).
- P17, L1: Are the scree slopes really relict? Or could present frost weathering also still contribute to these landforms that are mainly formed in the past?
We cannot exclude that present weathering still contributes to (some of) these landforms, but the return of Erica shrubs/trees between the stones as well as the lack of parent material (i.e. cliffs) at some locations indicates that they mainly formed in the past. We will modify the sentence to make this clear.
- P23 section 4.3: this section could use some rewriting. L9-10 contains your topic sentence, what this part is really about, and I would move this up to the beginning of your paragraph for clarity. At the end of this section you again state that -1 ◦ C MAGT seems critical for the formation of deep seasonal frost. On what do you base this statement? (see also previous comment).

We will restructure and rewrite this paragraph. A MAGT of 0 °C (or previously -1 °C) seems critical for the formation of several decimtre deep frost and the genesis of the stone stripes because of the following two reasons: 1. If the MAGT was above 0 °C (e.g. 1 or 2 °C), seasonal frost could probably not form in several decimetre depth due to limited seasonal ground temperature variations (in the order of only ± 1 °C). 2. If the MAGT was below 0 °C (e.g. -1 or -2 °C), seasonal (or permanent) frost could probably not thaw to a depth of several decimetre due to limited seasonal ground temperature variations (in the order of only ± 1 °C). If the stone stripes formed not because of seasonal ground temperature variations (oscillating around 0°C), but due to temperature fluctuations over several cold (mean multi-annual ground temperatures <0 °C) and warm periods (mean multi-annual ground temperatures >0 °C) during the Pleistocene, the magnitude of temperature change between these phases seems decisive. Will will discuss both scenarios in the revised manuscript.
- P23: Your discussion section could benefit greatly from adding subtitles. Now the structure is not clear and different things are discussed alternatingly, not always grouped coherently. The first paragraph reads more like a conclusion/summary. I can differ the following discussion topics from your current paragraphs: Similar periglacial landforms in other areas/comparison of the Bale Mountains to other area (paragraphs 2-4) Specific environmental settings of the Bale Mountains (paragraph 5, but also 9 and 10) The formation of pattern ground (paragraph 6), discussion seasonal variation (paragraph 7) and sporadic permafrost (paragraph 8) Outreach and future research (paragraph 11)
We will restructure the discussion and consider your suggestion to include subtitles. The first part (5.1) will focus on the comparison between the large sorted stone stripes in the Bale Mountains and similar landforms in other regions around the globe. The second part (5.2) will focus on the genesis and age of the stone stripes and the third part (5.3.) will discuss the potential of the stone stripes as proxy/indication for regional paleoclimatic and environmental changes.
Technical comments: - The English of the paper can still be improved, especially long and complex sentence structures (e.g. multiple commas) should be avoided. Often readability already improves greatly if the sentence structure is reversed, or split into multiple phrases. For example: P2 L7-10 P3 L16-21: turn these two sentences around: The exact timing.. is unknown. . . due to lack of geological maps. . . The central Sanetti Plateau. . . is characteristic for the Bale Mountains. P3 L26-28 P17 L5-8
Thanks for the feedback regarding the written style. We will carefully proofread the manuscript again and revise the sentence structure and choice of words where necessary. We will also ask for professional language editing if that is recommended/requested for final publication.
- Watch out with neglecting articles (a/an, the): P14 L25: the Sanetti Plateau, the highest peaks P20 L20: . . .and the northern valleys. . .
We will check the manuscript and add articles where they are missing.
- Take care of the use of hyphens: P1 L2 and P2 L28: mid- and high-latitudes
We will add hyphens where they are missing.
- Consider putting table 2 and figure 3 in Appendix.
We will remove Fig. 3. Table 2 will be trimmed considerably due to the removal of about two thirds

of the ground temperature dataset.
- The use of allow: allow cannot be followed just by a verb, so things like “allow to establish” (L4 p12) are not correct. Allow needs either a noun or a subject and verb, like “allow the establishment of”
Thanks, we will correct this throughout the manuscript.
- Several times you refer to information that is stated later in the manuscript (for example L12, p13, L8, p15). This makes the structure of your paper not always clear to the reader. Consider moving important information more forward.
We will restructure the manuscript accordingly.
- p 17, L7: this sentence is already part of the next paragraph. Move for better structure.
Will move this sentence.
- P22, L3: revise sentence, wrong use of minimal
We will revise this sentence.
- P23, L3: concurrently = simultaneously (?) – long sentence
We will rephrase this sentence.
- P23, L5: what = which
Will be corrected.
- P29 L27: Suggestion to add ‘modern’ and ‘co-exist’ :. . . where relict and modern, frost-related periglacial landforms co-exist.
Will be changed.
- Spelling and grammar flaws are not all flagged, so careful proofreading is still required, keeping the above mentioned comments in mind.
As aforementioned, we will carefully proofread the manuscript to eliminate the remaining flaws.
- Figure captions should be clear independently from the text. Therefore, please clarify: Figure 1: the control points, are they used for georeferencing the UAV data or for satellite imagery? GT and TM are both ground temperatures? The different figure panels require a, b, . . . so the data basis can be referenced more clearly. Consider leaving out the map of Africa indicating the position of Ethiopia and instead mention in the text that Ethiopia is positioned in the horn of Africa. The map of Africa is lacking a scale, as well as your inset of the map of Ethiopia to show the position of the Bale Mts.
We will modify the figure caption to explain more clearly the meaning of the different labels/datasets (control points, GT and TM ground tempeature data logger, etc.). Control points were used for processing and georeferencing the UAV data. GT and TM are the high-quality and low-cost ground temperature data logger, respectively. We will label the different figure panels. We will leave the map of Africa out and include a scale bar.
Figure 5: Consider using a different color code for active and relict periglacial forms (and general geomorphology such as landslides). The distinction between stone polygons and stone nets are not clear, use a different symbol. Make it more clear that panel D is derived from the UAV data.

We will consider all suggestions and revise the figure and caption accordingly.
Figure 8: very long figure caption. Put the information of the columns into the figure (the months for Bega, Belg, Kiremt). No need for mentioning the colours for panel b, this is clear from the column headers. Specify if this displays air temperatures or ground temperature in the figure.
This is a helpful suggestion, but we decided to remove this figure and the corresponding data to shorten the manuscript.
Figure 9: I assume this data is from the AWS stations, mention this clearly. Specify if this displays air temperatures or ground temperature in the figure.
Yes, the data originate from the weather stations, but we forgot to mention this in the caption. It is explicitly stated in the caption that air temperature lapse rates are displayed. However, this figure will be removed to narrow the focus of the manuscript.
Figure 10: I assume this data is from your loggers, mention this clearly. Specify if this displays air temperatures or ground temperature in the figure.
It is explicitly mentioned in the figure caption that ground temperatures are displayed and that the data originate from the installed loggers. However, this figure and the corresponding data will be removed to trim the manuscript.