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Effect of Climate on Morphology and Development of Sorted Circles and Polygons

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ABSTRACT

Sorted circles and polygons are widespread features of periglacial landscapes, but the controls on their development remain poorly understood, impeding their use as palaeoenvironmental indicators. We investigate the relationship of sorted circles and polygons to altitude in the northern Billefjorden area, central Svalbard. The patterns occur in two distinct elevation zones, below 200–250 m asl and above 600 m asl. The higher-elevated patterns have smaller diameters and shallower sorting depths due to a thinner active layer at higher elevations, suggesting that sorted patterns can indicate climate conditions and ground thermal state when the patterns initiated. Geology is believed to be of less importance for pattern morphology in the study area, causing only its fine-scale variations. The pattern diameter-to-sorting depth ratios have a median value of 3.57, consistent with previous studies and theoretical models of patterned-ground formation involving circulation mechanisms. Large-scale sorted patterns may develop over centennial timescales in this high-Arctic environment. They are probably not in equilibrium with present-day climate conditions and have probably formed throughout the Holocene.

KEY WORDS: patterned ground; sorted circles and polygons; morphology; active layer; Svalbard; high Arctic

INTRODUCTION

Periglacial sorted circles and polygons are common on unvegetated or sparsely vegetated surfaces composed of a mixture of unconsolidated fine and coarse materials (Warburton, 2013). They develop by repeated freezing and thawing of the ground. However, less consensus exists regarding their formation mechanism, developmental dynamics or environmental controls (Ballantyne, 2013, and citations therein).

Advances in determining the environmental factors and limits of patterned ground have been made using statistical modelling on spatially variable binary data representing patterned-ground occurrence or activity (e.g. Luoto and Hjort, 2005; Hjort and Luoto, 2006; Feuillet, 2011). However, the main shortcoming of such approaches is that they group all patterns of the same type, irrespective of their morphology. Although individual pattern types have some common features, which allow classification based on morphology and/or site characteristics (e.g. Treml *et al.*, 2010; Feuillet *et al.*, 2012; Watanabe *et al.*, 2017), high variability of shape and size results from a wide range of environmental settings in which they develop (see Goldthwait, 1976; Washburn, 1980; Grab, 2002). Such variability makes it difficult to draw specific conclusions from a purely binary-data approach. As quantitative data about sorted patterned-ground morphology from areas of permafrost and seasonally frozen ground on a wider scale are scarce (e.g. Holness, 2003; Treml *et al.*, 2010; Feuillet *et al.*, 2012), their environmental controls are still poorly understood, impeding their use as indicators of present and past environmental conditions. Hence, quantitative data about pattern distribution and morphology are needed from a wide range of environmental settings.

Most studies of patterned ground in Svalbard have provided detailed observations of sorted patterns on a local scale, particularly on coastal plains (strandflats) near polar stations, mainly in western and southern Svalbard (e.g. Jahn, 1963; Hallet and Prestrud, 1986; Van Vliet-Lanoë, 1991; Kääb *et al.*, 2014). Less work has been conducted on a wider scale, and still less on patterns at higher elevations. Studies from the interior regions of Svalbard, such as the northern Billefjorden area, are limited, with no detailed observations of sorted patterns published.

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Here, we describe for the first time the distribution and morphology of sorted circles and polygons in the northern Billefjorden area, central Svalbard (79° N), and we investigate their relationship to altitude. We hypothesise about their developmental rates, chronology and relation to active-layer thickness (ALT) and present-day climate conditions.

STUDY AREA

The study area is located around the Petuniabukta and Adolfbukta bays in the northernmost Billefjorden, central Svalbard, between 78°40′–78°44′ N and 16°16′–16°56′ E (Figure 1). Bedrock at patterned-ground sites consists mostly of sandstones with areas of shales, limestones, mica-schists and gneisses (Dallmann *et al.*, 2004). At lower elevations, sparse vegetation is dominated by *Dryas octopetala* and *Saxifraga oppositifolia* communities (Prach *et al.*, 2012), whereas higher elevations lack vegetation (Figure 2).

The area has some of the highest summer air temperatures (Przybylak *et al.*, 2014) and is among the driest regions in Svalbard (Hagen *et al.*, 1993). The nearest meteorological station with long-term observations is located about 50–60 km south from the study area, at Svalbard Airport (28 m asl), near Longyearbyen. Mean annual air temperature (MAAT) there during 1981–2010 was −5.1 °C and mean air temperatures of the coldest (February) and warmest (July) month were −13.5 and +6.4 °C, respectively (Nordli *et al.*, 2014). The inner-fjord climate of the northern Billefjorden, however, shows slightly higher temperature amplitudes and up to about 1 °C lower MAAT based on local short-term studies (Rachlewicz and Styszyńska, 2007; Láska *et al.*, 2012). Total annual precipitation in the area is estimated at around 200 mm (Hagen *et al.*, 1993).

Svalbard was largely covered by the Late Weichselian ice sheet during the Last Glacial Maximum (LGM) (Landvik

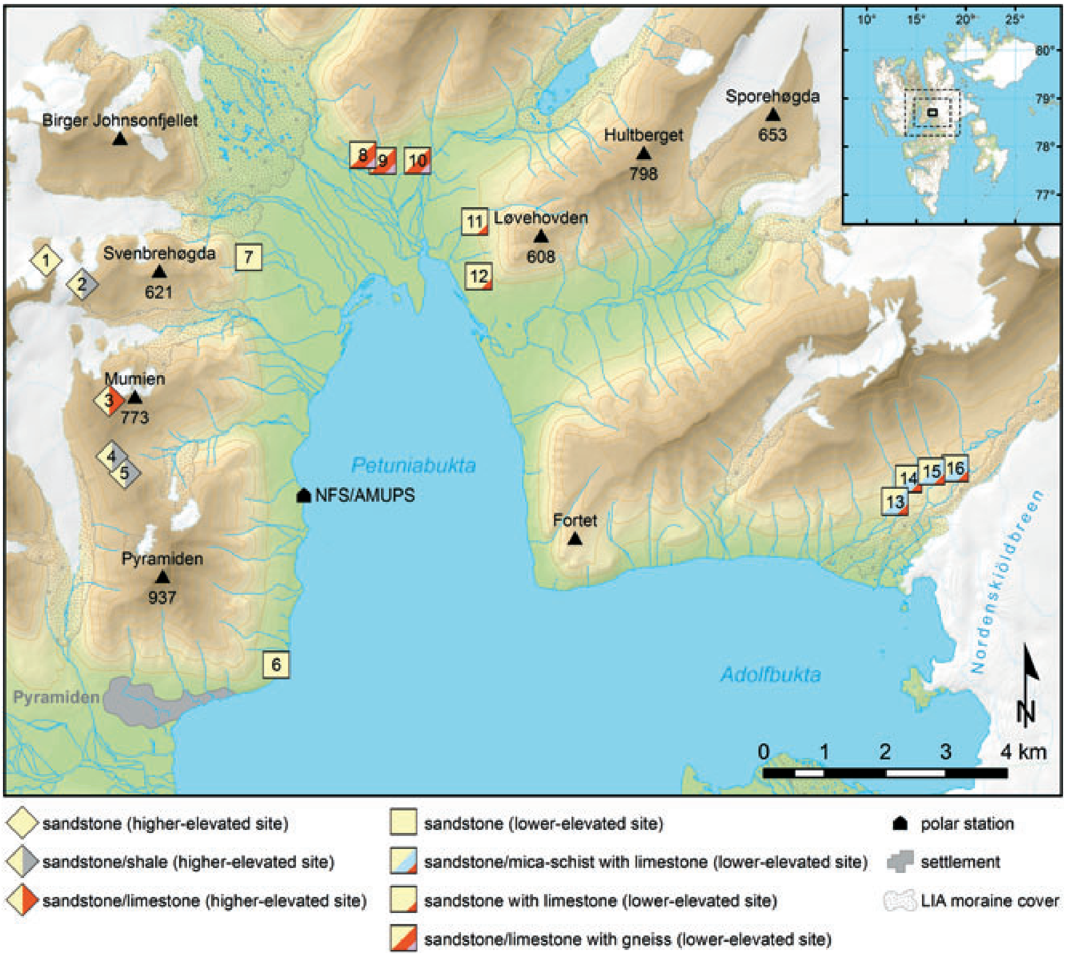

Figure 1 Location map of Petuniabukta and Adolfbukta and the investigated patterned-ground sites. Sites 6–12 are located on marine terraces; sites 13–16 occur on kame terraces. Contour interval is 100 m. NFS/AMUPS are acronyms for the Czech Nostoc Field Station and Polish Adam Mickiewicz University Polar Station, respectively. Inset map shows Svalbard archipelago. Topography: Norwegian Polar Institute®. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 2 Photographs of (a) sorted circles on a flat mountain top at 680 m asl (site 2 in Figure 1); (b) sorted polygons on a raised marine terrace at 80 m asl (site 7); (c) sorted polygons on a kame terrace at 234 m asl (site 15); and (d) sorted circles on the Little Ice Age moraine of Nordenskiöldbreen, approximately 0.5 km south of the site 13. [Colour figure can be viewed at wileyonlinelibrary.com]

et al., 1998). Deglaciation of the Billefjorden began after about 12.3 kyr BP (Mangerud *et al.*, 1992). Local glaciers had retreated close to their present extent by the end of the Pleistocene (Baeten *et al.*, 2010) and the glacierized area declined further during the early and mid-Holocene (Landvik *et al.*, 1998). Glaciers started to readvance about 3 kyr BP, attaining their maximum Holocene extent during the Little Ice Age (LIA) (Landvik *et al.*, 1998), implying that the surfaces non-glaciated during this period have been mostly ice-free throughout the Holocene. Since the LIA, air temperatures in central Svalbard have increased substantially, averaging 0.026 °C yr^{-1} (Nordli *et al.*, 2014). This has led to rapid glacier retreat (Rachlewicz *et al.*, 2007; Małecki, 2016) and paraglacial landscape transformation (e.g. Stacke *et al.*, 2013; Ewertowski and Tomczyk, 2015; Strzelecki *et al.*, 2017).

Continuous permafrost underlies the extensive non-glacierized areas (Figure 1) (Humlum *et al.*, 2003), with ALT generally reaching 0.3–1.6 m, and in diamicton occasionally up to 2.5 m (Gibas *et al.*, 2005; Rachlewicz and Szczuciński, 2008; Láska *et al.*, 2010). The ALT has increased about 0.01–0.03 m yr^{-1} since the 1990s in central Svalbard and the thickening is expected to continue along with climate warming (Etzelmüller *et al.*, 2011), but the response may be affected by complex interactions of forcing meteorological variables and their interannual variations (Christiansen and Humlum, 2008).

METHODS

Sampling Strategy, Morphometric Parameters and Grain-Size Analysis

Sorted circles and polygons (Figure 2) were investigated at sites with a continuous network of at least 10 patterns on flat or gently inclined terrain (up to 5°). In total, 290 sorted circles and polygons were examined at 16 locations, at elevations of 28–773 m asl (Figure 1).

Length, width and height of 10 or 20 randomly selected sorted patterned-ground features were measured at each study site, depending on the number of patterns present. The length is defined as a maximum horizontal dimension of the pattern measured between the opposite centres of coarse borders, while the width is the largest dimension in a direction perpendicular to the length and intersecting it at the pattern centre. The height is a maximum vertical distance between the lowest point at the pattern border and the highest point at its updomed centre (*sensu* Křížek and Uxa, 2013).

At three sites at elevations of 31, 598 and 773 m asl (sites 6, 5 and 3 in Figure 1), the sorting depth was determined by excavations as a maximum depth where a distinct boundary between the sediments beneath the fine centre and coarse border was visible.

Grain-size analysis was carried out on eight samples collected at five study sites (sites 2, 3, 5, 6 and 7 in Figure 1) from depths of 0.05–0.15 m at pattern centres. The samples were air-dried, gently crushed and mechanically sieved through a set of sieves up to 0.125 mm, while finer fractions under 0.125 mm were examined by timed sedimentation in a suspension.

Statistical Analysis

All morphometric parameters show a log-normal distribution, and thus they were log-transformed to meet the criterion of normality according to the Shapiro–Wilk test (Shapiro and Wilk, 1965). Accordingly, their median values are reported hereafter. Relations between the morphometric parameters were examined using the Pearson correlation coefficient. Between-group differences were assessed by a one-way ANOVA and *F*-test. Cluster analysis was applied on standardised site averages to search for potential geological influences on patterned-ground morphology. All statistical testing was at a significance level of 0.05, and analyses were done using the software STATISTICA (StatSoft, Inc., 2009).

RESULTS

Altitudinal Distribution and Substrate Characteristics

One group of sorted circles and polygons (69 % of the investigated patterns) is located mainly on raised marine and kame terraces at elevations up to 200–250 m asl. A second group (31%) occurs on adjacent flat mountain tops and ridges above elevations of around 600 m asl (Figure 1). These two distinct elevation zones are separated by steep talus slopes, which are highly unfavourable for patterned-ground formation. Glacier forelands developed since the LIA are occupied only by rare small-scale and poorly developed patterns (Figure 2d) that were not specifically examined in this work.

The sorted circles and polygons at higher elevations are formed within sediments or poorly developed soils derived from *in situ* weathered sedimentary rocks, particularly sandstones associated with shales and limestones. The lower-lying patterns are mostly derived from secondary deposits of weathered materials, which are dominated by sandstones associated with limestones, mica-schists or gneisses (Figure 1). Particles smaller than 2 mm constitute 11–61 % of the samples collected at patterned-ground sites. This fraction contains 5–24 % clay (<0.002 mm) and clay–silt (<0.063 mm) represents 6–49 %. The samples are frost-susceptible (*sensu* Beskow, 1935), although at one site they contain little silt (Figure 3).

Morphology

Horizontal dimensions of the sorted circles and polygons range from several decimetres to 4.5 m, with median values of 1.8 and 1.4 m for the length and width, respectively (Figure 4). Because the patterns occur on flat or gently inclined surfaces, both characteristics are highly correlated (r = 0.90, $p < 0.0001$) and the length-to-width ratios show low values (median of 1.25). The median height is 0.15 m (Figure 4), but it reaches up to 0.5 m depending on the pattern size (for length r = 0.50, $p < 0.0001$; for width r = 0.53, $p < 0.0001$). The median height-to-width ratio equals 0.1 (Figure 4).

Sorting depths of the sorted circles and polygons range between 0.44 and 0.64 m. The diameters (averages of the length and width) of the respective patterns range between 1.64 and 1.77 m, resulting in pattern diameter-to-sorting depth ratios of 2.77–3.73 (median 3.57) (Figure 5).

Higher elevations generally host patterns with significantly smaller horizontal dimensions than lower elevations (Figure 6). Likewise, shallower sorting occurs at higher altitudes, although the sample size is not representative. In contrast, sorted circles and polygons with significantly larger heights and height-to-width ratios occur at higher elevations (Figure 6).

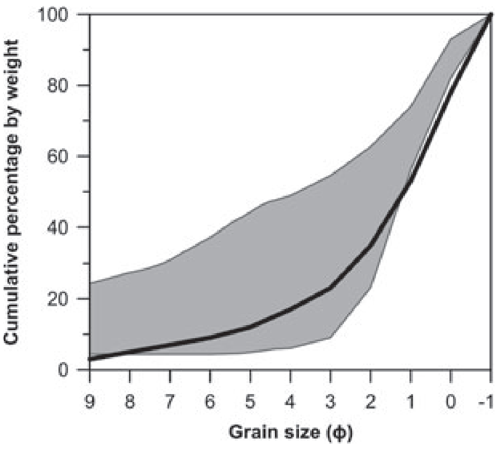

Figure 3 Grain-size envelope for eight sorted patterns in comparison with the frost-susceptibility limit of Beskow (1935) (thick black line).

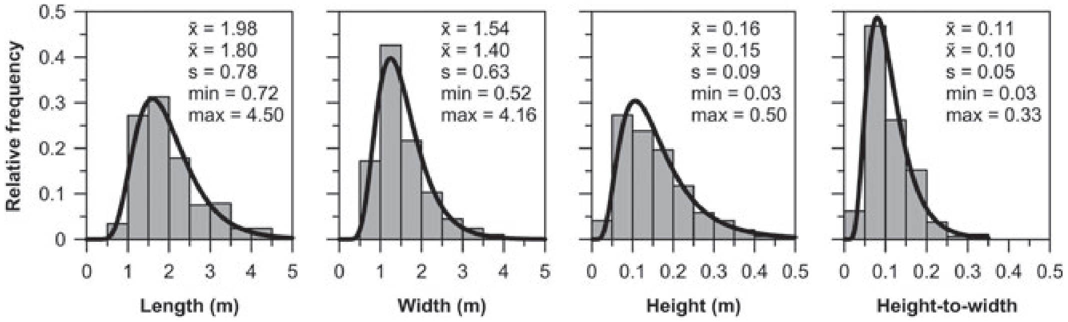

Figure 4 Histograms of the length, width, height and height-to-width ratio of sorted circles and polygons (n = 290) showing typical log-normal distributions. x̄ – average; x̃ – median; s – standard deviation; min – minimum; max – maximum.

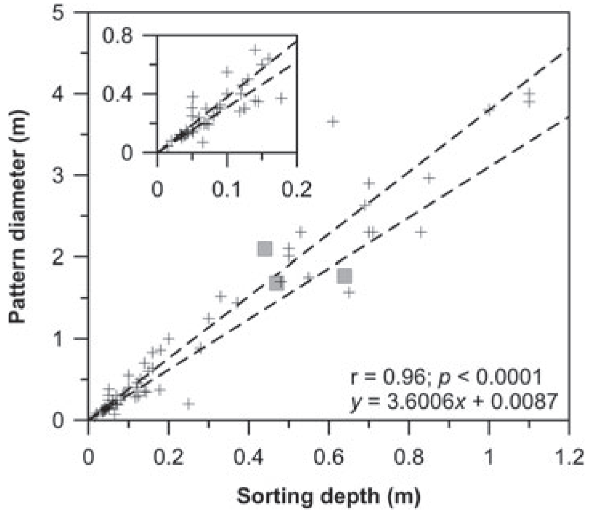

Figure 5 Scatterplot of relation between pattern diameter and sorting depth. Squares mark sorted circles and polygons investigated in the present study. Crosses are 67 previously published values for sorted circles and polygons found in Troll (1944), Furrer (1955), Henderson (1968), Freund (1971), Ellenberg (1976), Ballantyne and Matthews (1982), Ray *et al.* (1983), Gleason *et al.* (1986), Wilson and Clark (1991), Wilson (1992), Ballantyne and Harris (1994), Love (1995), Kück (1996), Grab (1997, 2002), Humlum and Christiansen (1998), Holness (2003) and collected by other personal observations on two small-scale patterns located on an LIA moraine in the Petuniabukta area. The dashed lines define theoretical limits of pattern diameter-to-sorting depth ratios (3.1–3.8), based on model predictions (e.g. Ray *et al.*, 1983; Gleason *et al.*, 1986; Hallet and Prestrud, 1986). Although the individual data points are scattered around the theoretical limits, the general strength of the relationship is remarkable. The median value of all 70 data points is 3.54.

DISCUSSION

Sorted Patterned-Ground Morphology in Relation to Altitude

We recorded a relatively narrow range of pattern diameter-to-sorting depth ratios (Figure 5) that are consistent with other field data and theoretical models of patterned-ground formation based on linear stability theory (e.g. Ray *et al.*, 1983; Gleason *et al.*, 1986; Hallet and Prestrud, 1986; Peterson and Krantz, 2008). According to these studies, patterned ground shows a fixed pattern diameter-to-sorting depth ratio (for an overview refer to Figure 5) where the pattern size is controlled by the thickness of the active layer in permafrost areas or by the freezing depth in seasonally frozen ground areas, respectively.

Because climate acts as a first-order control on ALT (Bonnaventure and Lamoureux, 2013), we assume that the active layer thins towards higher elevations because of the temperature lapse rate. Thus, a thinner active layer can explain the smaller diameters of patterns at higher elevations (Figure 6). The validity of this interpretation is further underpinned by similar relations between pattern diameter and altitude reported from other continuous (Marvánek, 2010) and discontinuous (Kling, 1998) permafrost areas and also from regions with former permafrost (e.g. Křížek and Uxa, 2013). Consistent with theoretical considerations, the opposite altitudinal trends have been observed in seasonally frozen ground areas (Holness, 2003; Feuillet *et al.*, 2012) because of increasing freezing depth towards higher elevations. All these observations suggest that the morphology of sorted patterns can indicate climate conditions, while the altitudinal trends can indicate ground thermal state (i.e. permafrost or seasonally frozen ground conditions) when the patterns initiated (*sensu* Peterson and Krantz, 2008).

Nevertheless, site-specific factors such as geology and ground material can also influence pattern size. For instance, pattern diameter tends to be positively correlated with the amount of fine material (Treml *et al.*, 2010; Feuillet *et al.*, 2012). Likewise, clast size, which has been stated to be interconnected with pattern size (Goldthwait, 1976; Feuillet *et al.*, 2012), or differences among pattern types (e.g. Kling, 1998; Treml *et al.*, 2010) could interfere in this relationship. However, no clustering into morphologically homogeneous groups corresponding to identical geological conditions was found for both the lower- and the higher-elevated pattern sites (Figure 7). This is probably due to the general abundance of sandstones that more or less predominate at most sites, while other components are less represented. Accordingly, we believe that geology causes only fine-scale variations in pattern morphology in the study area, and thus is of limited importance for the investigated patterns.

The occurrence of patterns with significantly larger height and height-to-width ratios at higher elevations

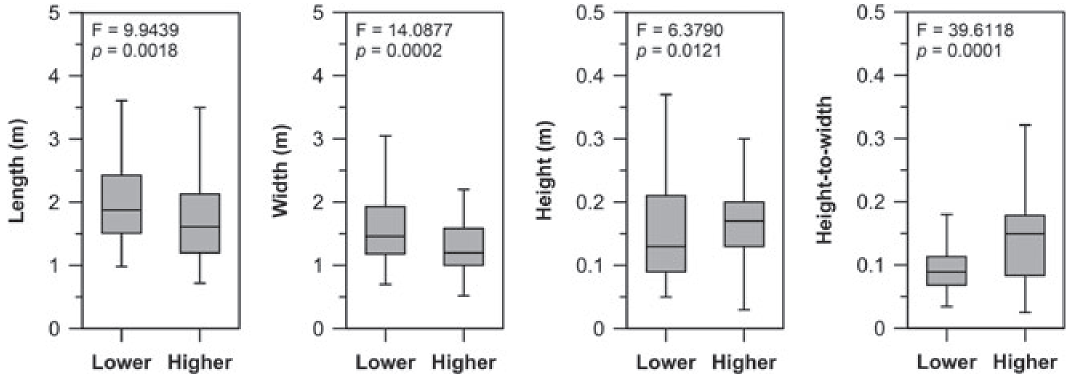

Figure 6 Boxplots showing morphological differences between the lower- and higher-elevated groups of sorted circles and polygons (n = 290). The boxes show median values (thick horizontal line) and the first and third quartiles (bottom and top of boxes, respectively). Whiskers represent minimum and maximum values, excluding outliers (values lying 1.5 interquartile ranges below and above the first and third quartiles, respectively).

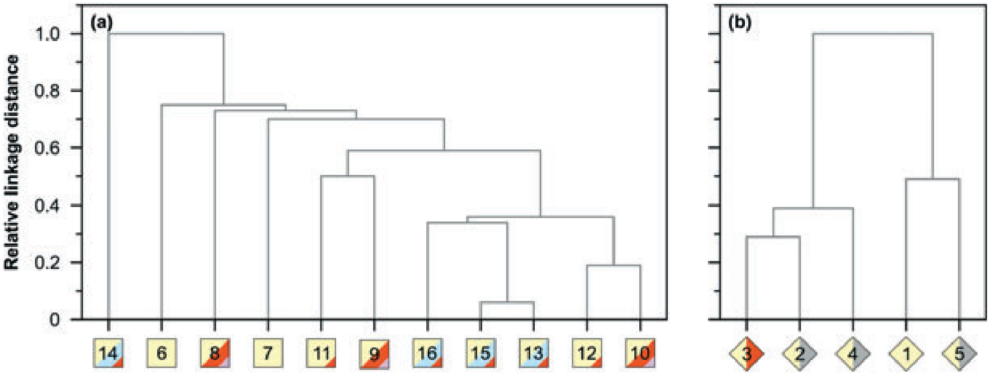

Figure 7 Cluster tree for the (a) lower- and (b) higher-elevated pattern sites based on the single-linkage method and Euclidean distances. Standardised site averages of uncorrelated morphometric parameters (length and heigth-to-width ratio) were used in the analysis. Site numbers and symbols are given in Figure 1. [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 6) is probably due to more severe climate conditions and less moisture. Well-drained sites generally host patterns with better developed microtopography than at poorly drained locations (Van Vliet-Lanoë, 1991). In Svalbard, precipitation tends to increase with altitude (Hagen *et al.*, 1993; Humlum, 2002), but local topographic effects can alter this pattern. Wind redistributes snow across the entire archipelago (Humlum, 2002), and high wind speeds clear snow from exposed mountain summits and ridges in winter (Jaedicke and Sandvik, 2002; Jaedicke and Gauer, 2005). This effect can be reasonably expected in the study area as well (*sensu* Małecki, 2015). Furthermore, a larger fraction of precipitation falls as snow at higher elevations (Hagen *et al.*, 1993; Winther *et al.*, 1998) and can be easily drifted away if neither compacted nor crusted. At lower elevations, most pattern sites are likely to be less wind-affected, and rain occurs more frequently and can quickly soak into the ground. Consequently, the amount of snow and liquid water at the higher-elevated sites is believed to be lower. Naturally, these locations may also be temporarily saturated during the early thaw season and fine centres can even show a thixotropic behaviour (Figure 8a), but as the thaw front descends, they drain progressively and desiccation cracks frequently form on pattern surfaces (Figure 8b). In contrast, lower elevations show higher moisture contents and fewer desiccation fissures. The onset of thawing is also earlier here, which enhances settling of the ground (Hallet and Prestrud, 1986; Hallet, 1998, 2013) and produces rather flat microtopography (*sensu* Van Vliet-Lanoë, 1991).

Developmental Rates

Sorted patterns commonly develop in front of retreating glaciers (Ballantyne and Matthews, 1982; Haugland, 2006) and perennial or late-lying snow patches (Kling, 1998). Because these settings often provide favourable ground material properties, moisture supply, ground thermal regime and topography for patterned-ground formation, sorted circles and polygons can rapidly emerge and develop within a few decades (Ballantyne and Matthews, 1982; Matthews *et al.*, 1998; Feuillet and Mercier, 2012). In Svalbard, the

Figure 8 Photographs of (a) sorted-polygon centre at 773 m asl in a thixotropic state (site 3 in Figure 1); and (b) desiccation cracks developed on sorted-circle surface at 598 m asl (site 5). [Colour figure can be viewed at wileyonlinelibrary.com]

LIA ended rapidly in the early 20th century (Hagen *et al.*, 1993; Svendsen and Mangerud, 1997; Isaksson *et al.*, 2005) and, since then, land-terminating glaciers in the northern Billefjorden have continuously retreated at a rate of 5–15 m yr^{-1} and exposed extensive areas (Rachlewicz *et al.*, 2007). Many of these proglacial areas are composed of ice-cored sediments with thick active layers (Gibas *et al.*, 2005) and experience highly dynamic topography changes (e.g. Ewertowski, 2014; Ewertowski and Tomczyk, 2015), potentially disturbing the patterning processes. However, stable surfaces occur here as well. These sediments also have favourable grain-size composition (e.g. Stankowska, 1989; Pleskot, 2015) with high frost-susceptibility, as it is at the investigated sites with sorted patterns (Figure 3). Furthermore, they can provide sufficient moisture for pattern formation, even at places more distant from the moisture-supplying glacier and influenced by strong katabatic winds, which accelerate desiccation of the ground. Nevertheless, despite favourable conditions and about a century to develop, patterns on the LIA moraines and glacier forelands in the northern Billefjorden are rare, small-scale and poorly developed (Figure 2d). Large-scale (>1 m in width) patterns are common in locations immediately adjacent to proglacial areas, but on pre-LIA terrains (Figure 1). Although small-scale sorted circles and polygons may occur on these surfaces as well, they are much more typical for post-LIA glacier forelands and other fresh surfaces. Similar distribution patterns are reported from other regions of Svalbard (e.g. Jahn, 1963; Cannone *et al.*, 2004; Dąbski, 2005; Szymański *et al.*, 2015).

We hypothesise from the above findings that large-scale sorted patterns in Svalbard develop on centennial timescales. This is an order of magnitude longer than previous estimates based on sorted patterns across glacial chronosequences (e.g. Ballantyne and Matthews, 1982; Haugland, 2006; Feuillet and Mercier, 2012). The latter are valid particularly for small-scale sorted patterns and mid-latitude alpine climates, characterised by well-developed seasonal and diurnal temperature variations and numerous freeze–thaw cycles. However, high-Arctic climates are dominated by a strong seasonal cycle, with weak diurnal variations and fewer freeze–thaw cycles (Fraser, 1959; French, 2007).

Measurements of ground motions in large-scale sorted patterns support the hypothesis of their development over centennial timescales. In Kvadehuksletta, western Svalbard, radially outward movements of 10–30 mm yr^{-1} were observed within the fine domains of large-scale sorted circles as a surface imprint of cell-like circulation (Hallet and Prestrud, 1986; Hallet, 1998; Kääb *et al.*, 2014). The surface travel times required to reach the centre–border interface have been estimated to be up to 100 years (Kääb *et al.*, 2014), while the entire circulation may take 300–500 years or longer, assuming decreasing velocity towards depth (Hallet, 1998; Kääb *et al.*, 2014). Thus, it may take up to 100 years for large-scale patterns to emerge in a poorly developed form and hundreds more years to achieve higher developmental stage, consistent with our observations from northern Billefjorden. On the other hand, most sorted patterns we have observed lack distinctly raised stone rings (Figure 2) typical of sorted circles in Kvadehuksletta, and therefore their dynamics may differ. In addition, the above measurements were performed on mature patterns that are among the best developed on Earth (Hallet, 2013). Since frost sorting progressively alters the grain-size distribution in pattern centres and increases their frost-susceptibility (Ballantyne and Matthews, 1983), the displacement rates within well-developed patterns are likely to be faster than those within poorly developed or initial forms, consisting of poorly sorted materials (*sensu* Křížek and Uxa, 2013). Although the non-linear formation mode is likely (e.g. Kessler *et al.*, 2001; Peterson and Krantz, 2008), it lacks a strong experimental support. However, if our hypothesis is valid, then the actual transition time from initial to well-developed patterns should be longer than the above estimates (cf. Hallet, 1998; Kääb *et al.*, 2014).

Chronology

The patterned-ground sites on marine terraces between 20 and 45 m asl may have been continuously exposed to periglacial conditions for most of the Holocene, and those on beaches up to 80 m asl since the Late Weichselian. The northern Billefjorden region was glacio-isostatically uplifted in response to local deglaciation, and associated sea level fall was up to 90 m during the Middle to Late Weichselian and the Holocene (Salvigsen, 1984; Kłysz *et al.*, 1988, 1989; Szczuciński and Rachlewicz, 2007). Dating of marine shells and sediments showed that marine terraces above 20 m asl, where all the investigated lower-elevated sorted circles and polygons occur, formed before *c.* 8.7 cal kyr BP, the terrace sequence up to 40–45 m asl dates from *c.* 10 cal kyr BP (Long *et al.*, 2012) to 12.8 kyr (van der Meij *et al.*, 2016), and terraces up to 80 m asl are attributed to the Middle Weichselian (Kłysz *et al.*, 1988, 1989). However, the highest terrace sequence was probably ice-covered during the LGM (Landvik *et al.*, 1998). The kame-terrace sites probably post-date the major advance of Nordenskiöldbreen (Figure 1), which took place after 18 kyr (Landvik *et al.*, 1998). They may also have formed after its early Holocene readvance about 8–9 kyr, referred to as the Thomsondalen Stage (Kłysz *et al.*, 1988), but this event finds no support in more recent work (e.g. Rachlewicz, 2010). There is no geomorphic evidence that the higher-elevated pattern sites were glaciated during the Late Weichselian. However, summer temperatures were probably constantly below 0 °C during this period and therefore at least a thin perennial snow cover was probably present at these sites. Since patterned-ground formation was highly improbable under these conditions, its origin is probably limited to warmer conditions allowing summer snow melting. Hence, the upper age limit of sorted patterns at most sites is probably the Pleistocene–Holocene transition.

The climate of Svalbard was up to 1–2 °C warmer than at present during much of the early and mid-Holocene (Svendsen and Mangerud, 1997), which would result in MAAT values of *c.* −5 to −3 °C in the study area. These values are almost at the upper limit proposed for development of large-scale sorted circles and polygons in permafrost regions (Goldthwait, 1976; Washburn, 1980; Grab, 2002). Thus, the most favourable conditions for patterned-ground initiation in northern Billefjorden probably occurred shortly after local deglaciation or during the Holocene glacial readvance after 3 kyr BP (Landvik *et al.*, 1998) when temperatures were lower than present. Initiation during the LIA is unlikely for such well-developed patterns because of the limited time available. Accordingly, the sorted patterns are probably several thousands of years old, consistent with morphostratigraphical considerations (Hallet and Prestrud, 1986) and rare ^{14}C data from large-scale sorted circles (Hallet *et al.*, 1988; Cannone *et al.*, 2004) in western Svalbard, which suggested an age of hundreds or thousands of years. Likewise, large-scale sorted circles and polygons in Jotunheimen, southern Norway, are thought to have formed soon after deglaciation in the early Holocene, based on relative-age and Schmidt-hammer exposure-age dating techniques (Cook-Talbot, 1991; Winkler *et al.*, 2016), although this environment is not a perfect analogue to that of high-Arctic Svalbard.

Relationship to Active-Layer Thickness

In permafrost areas, sorting depth is confined by the base of the active layer (e.g. Ray *et al.*, 1983; Hallet and Prestrud, 1986). The frost table was observed only at one excavation site near sea level (31 m asl; site 6 in Figure 1) and reached 1 m at the end of the thawing season (end of August 2014), which is 0.36 m below the sorting depth. At other two excavation sites at higher elevations (558 and 773 m asl; sites 5 and 3 in Figure 1), the frost table was not encountered up to 0.1 m below the sorting depth, even though the thaw depth still might have not been at its maximum (cf. Christiansen and Humlum, 2008; Rachlewicz and Szczuciński, 2008). The ALT varies interannually by up to tens of per cent (Shur *et al.*, 2005). In 2014, summer air temperature at Svalbard Airport (https://www.ncdc.noaa.gov) was *c.* 1 °C above average for the period 1981–2010 (Nordli *et al.*, 2014), and the positive MAAT anomaly was even more pronounced, which probably typifies the mode of the current Svalbard climate (cf. Kääb *et al.*, 2014; Przybylak *et al.*, 2014). However, the thaw depth at the lowest excavation site exceeded the sorting depth by *c.* 56 % at the time of excavation. It is reasonable to assume that the sorting depth of active sorted patterned ground in steady-state conditions is slightly shallower compared to the active layer, although evidence for this is lacking. Nevertheless, the observed difference is probably too large. Therefore, we believe that at least at lower elevations, sorted circles and polygons are not in equilibrium with present-day climate conditions, which also favours their non-recent origin. On the other hand, it raises further questions about the significance of sorted patterns located in present-day periglacial environments under a changing climate.

CONCLUSIONS

Based on the investigations of 290 sorted circles and polygons in northern Billefjorden, central Svalbard, we draw the following conclusions:

1. The sorted circles and polygons form two distinct elevation zones, which significantly differ in pattern morphology.
2. Patterns at higher elevations have smaller diameters and shallower sorting depths because ALT decreases as elevation increases, suggesting that sorted patterns indicate climate conditions and ground thermal state (i.e. permafrost or seasonally frozen ground) when the patterns initiated. In contrast, the heights and height-to-width ratios of higher-lying sorted circles and polygons

are larger. Bedrock lithology is believed to cause only fine-scale variations in pattern morphology.

3. The ratios of pattern diameter-to-sorting depth in sorted circles and polygons have a median of 3.57, consistent with previous studies (median of 3.54; Figure 5) and theoretical models of patterned-ground formation involving circulation mechanisms. This allows estimation of the sorting depth based on patterned-ground surficial morphology, which can be used to reconstruct former active layers and associated temperature conditions.
4. Sorted circles and polygons in this high-Arctic environment may develop over centennial timescales, unlike those in lower latitudes.
5. The sorted circles and polygons are probably not in equilibrium with present-day climate conditions.
6. The sorted circles and polygons have probably been forming throughout the Holocene.

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