Short-term Periglacial Processes, Vegetation Succession, and Soil Development within Sorted Patterned Ground: Jotunheimen, Norway — **Source link**

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Abstract

Small (1 ≤ m diameter) sorted patterned ground features were studied on the Little Ice Age forelands of three Jotunheimen glaciers. Patterned ground appears to be most active near the ice margins, declining in intensity of activity with distance from the glaciers. Vegetation and soil development are negligible within patterned ground that is "Recent" (decadal time frame). Significant ($P < 0.05$) fine scale differences in vegetation and soil development occur within patterned ground on terrain ~70 yr in age, with patterned ground borders having higher values of vegetation cover and thicker soils than that in patterned ground centers. With increasing age of terrain and patterned ground, soil development and vegetation encroach inward toward patterned ground centers, implying that a short-term, active periglacial zone exists near the ice margin, decaying with time and glacier retreat. Specifically, terrain that has been deglaciated for ~70 years and is approximately ~350–500 m from the ice margin shows a significant decline in frost activity, allowing for the initiation of pedogenesis and vegetation colonization.

Introduction

The exact processes responsible for patterned ground formation are still poorly understood (French, 1996). A variety of theoretical and quantitative studies have sought to explain patterned ground formation (Hallet et al., 1988; Krantz, 1990; Boelhouwers et al., 2003; Kessler and Werner, 2003; Matsuoka et al., 2003), yet the complexity associated with patterned ground has yet to yield a universal explanation. This lack of a universal explanation results from the wide range of environments in which patterned ground can be found; therefore, similar-looking features of different environments do not necessarily share a common genesis (Washburn, 1980).

Many past patterned ground studies have looked at dynamics of frost processes within permafrost regions, processes that may be active for millennia (Hallet et al., 1988; Cook-Talbot, 1991; Kessler and Werner, 2003). However, local factors outside of permafrost regions, such as those found in the recently deglaciated terrain of Jotunheimen, Norway (e.g., microtopography, drainage, exposure of substrate, and distance from the ice margin) can also explain patterned ground formation (Ballantyne and Matthews, 1982, 1983; Harris and Matthews, 1984; Matthews et al., 1998; Ballantyne, 2002a, 2002b). Formation of patterned ground and the duration of periglacial processes can be brief, with formation of patterned ground and subsequent stabilization occurring within a few decades. In the Jotunheimen region, the reworking of glacial deposits into patterned ground has been observed to be most active on terrain bordering ice margins (Ballantyne and Matthews, 1982, 1983; Matthews et al., 1998). Here temperatures and soil moisture appear to be conducive to the rapid reworking of glacial deposits into patterned ground, processes which may then decline with continued retreat of the ice margin. Ice marginal environments of temperate glaciers have been observed to have cooler temperatures as a result of katabatic winds draining onto the immediate forelands (Ballantyne and Matthews, 1982; Obleitner, 1994; Van Den Broeke, 1997). This may then create an edge effect with the occurrence of more freeze-thaw cycles near the ice margin, allowing for the genesis of patterned ground. In these conditions, patterned ground activity can be thought of as short-term and ephemeral. Once disturbance associated with frost activity is reduced

via continued deglaciation, geoecological interactions (Troll, 1971; Matthews, 1992, 1999; Matthews et al., 1998) or interactions between abiotic and biotic processes may then proceed, resulting in vegetation succession and soil development, thus modifying the landscape.

Although patterned ground activity may be brief, its occurrence is often overlooked in landscape studies regarding vegetation establishment and soil development. This study actively sought out patterned ground along recent (i.e., <250 year old) glacial chronosequences to investigate the role of frost disturbance within patterned ground and its role in providing heterogeneity to landscape evolution. Specific goals were to (1) determine whether there is a microscale preference within patterned ground (center vs. border) in regard to vegetation and soil development, and (2) determine if and where along the chronosequence major thresholds occur regarding interactions of abiotic and biotic processes within patterned ground.

Methods

STUDY AREA

Jotunheimen is located in south-central Norway. Regionally the most extensive glaciation since the close of the Weichselian ice age, approximately 9000 yr before present (Andersen, 1980), was the Little Ice Age, reaching its maximum extent during the mid to late 18th century (Karlén, 1973; Karlén and Denton, 1976; Matthews, 1977; Griffey and Matthews, 1978; Matthews and Shakesby, 1984; Erikstad and Sollid, 1986; Nesje and Dahl, 1993; Matthews, 2005). Since then glacial retreat has created a common landscape appearance of a distinguishable Little Ice Age terminal moraine followed by recessional moraines. For this study, patterned ground was investigated on three Little Ice Age forelands. Specifically, patterned ground was studied on small annual push moraines and/or fluted moraines, approximately 1–2 m of relative relief above the surrounding valley floor. The glacial forelands of Slettmarkbreen, Styggedalsbreen, and Vestre Memurubreen lie within the Jotunheimen region between 61° and 62°N latitude, exhibiting Little Ice Age chronosequences (Fig. 1). Glacial snout elevations are ~1270 m, ~1470 m, and ~1625 m above sea level (a.s.l.) and mean annual air temperatures (MAAT) are
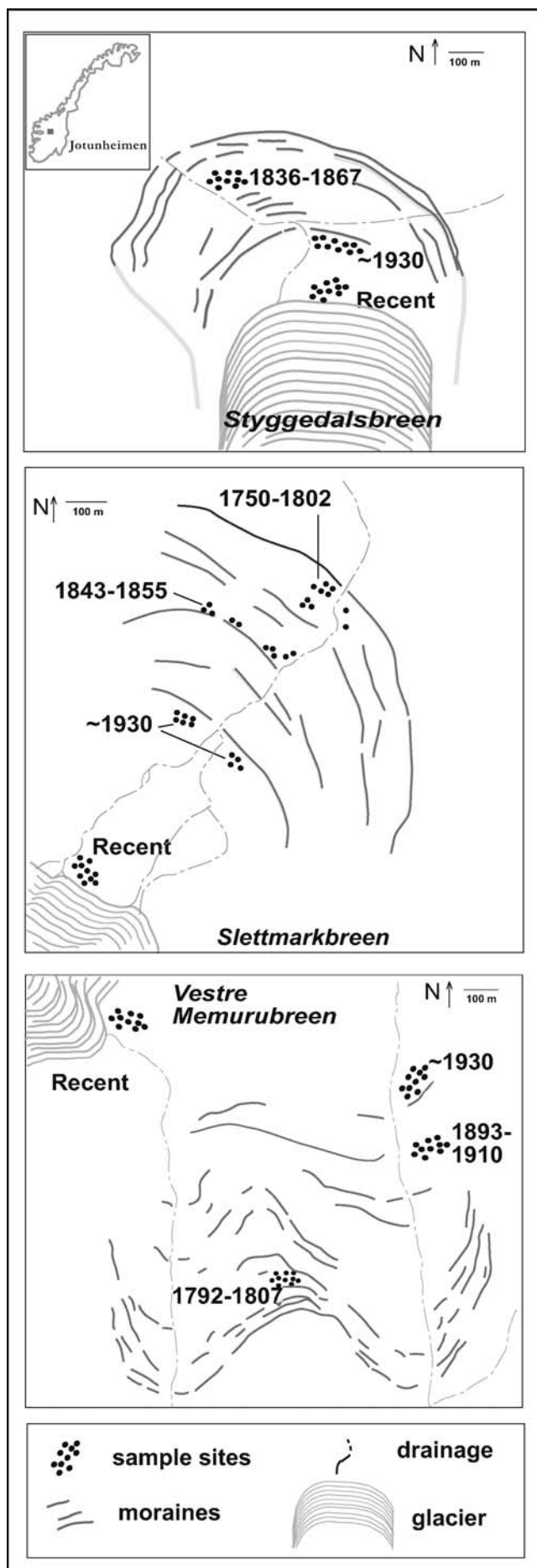
approximately −1.4°C, −2.3°C, and −2.9°C for Styggedalsbreen, Slettmarkbreen, and Vestre Memurubreen, respectively (Bruun, 1967; Messer, 1988; Aune, 1993; Matthews et al., 1998; Matthews, 2005).

Harris and Cook (1986) stated that the zone of discontinuous permafrost starts at 1600–1650 m a.s.l. in Jotunheimen. However, more recent studies have found that the lower limit of discontinuous permafrost is 1450 ± 50 m and corresponds to a MAAT between −2.0°C and −3.0°C (Ødegård et al., 1992; Isaksen et al., 2002). Others have claimed that a −4.0°C MAAT corresponds to the lower limit of mountain permafrost (Tveito and Førland, 1999; Etzelmüller et al., 2003). Consequently, permafrost as a contributor to patterned ground formation is possible for the foreland of Vestre Memurubreen, yet less likely at Slettmarkbreen and Styggedalsbreen. Other mechanisms of formation—seasonal, diurnal activity, and/or proximity to the ice margin—are then likely if permafrost is absent (Ballantyne and Matthews, 1982, 1983; Matthews et al., 1998).

Active and inactive patterned ground is found at the three glacial foregrounds, with active patterned ground being more frequently encountered near the ice margin. Specifically, small (1 ≤ m diameter) sorted to poorly sorted patterned ground was studied. Sorted circles occurred at Slettmarkbreen and Vestre Memurubreen, while sorted nets where observed at Styggedalsbreen. Degree of activity is inferred from lichen and vegetation cover, with cover being inversely related to that of disruptive frost activity. Active patterned ground is characterized by little to no vegetation/lichen cover resulting from intense disturbance associated with frost action (Ballantyne and Matthews, 1982, 1983; Matthews et al., 1998). With increasing distance from the ice margin, vegetation colonization occurs. Initially vegetation colonization occurs at patterned ground borders while centers remain unvegetated, suggesting a microscale differentiation of frost activity, similar to findings by Thorn (1970) pertaining to stony earth circles found in Quebec.

The area is characterized as being alpine, consisting of a mosaic of patches of bare ground and vegetation (Dahl, 1956). Lichens, cryptogamic crusts, and a small variety of perennial vascular plants such as *Poa alpina*, *Trisetum spicatum*, and *Carex* spp. occur, along with dwarf shrubs, on the older more stabilized terrain (Matthews, 1979; Haugland and Beatty, 2005).

Soils within the Little Ice Age forelands are typically shallow, forming from glacially reworked peridotites, pyroxene gneisses, and ultramafic gabbro rock groups (Battey and McRitchie, 1973). Soils tend to thicken with age and distance from the ice margin, grading from Regosol to Brunisols (Mellor, 1986), which translates into Entisols grading into Inceptisols using the U.S. Department of Agriculture Soil Taxonomy (Soil Survey Staff, 1998; Haugland, 2003, 2004).

SAMPLING AND ANALYSIS

Each of the three Little Ice Age forelands was segregated into temporal belts or time units. The time units correspond to a range of lichenometrically determined dates of varying temporal resolutions, signifying the approximate dates of deglaciation (Erikstad and Sollid, 1986; Messer, 1988; Matthews et al., 1998). The forelands of Slettmarkbreen (Fig. 1) and Vestre Memurubreen were segregated

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FIGURE 1. The glacier forelands of Styggedalsbreen, Slettmarkbreen, and Vestre Memurubreen, Jotunheimen, Norway. Approximate location of patterned ground sample sites and terrain age are shown. Ten patterned ground features were studied within each time unit.
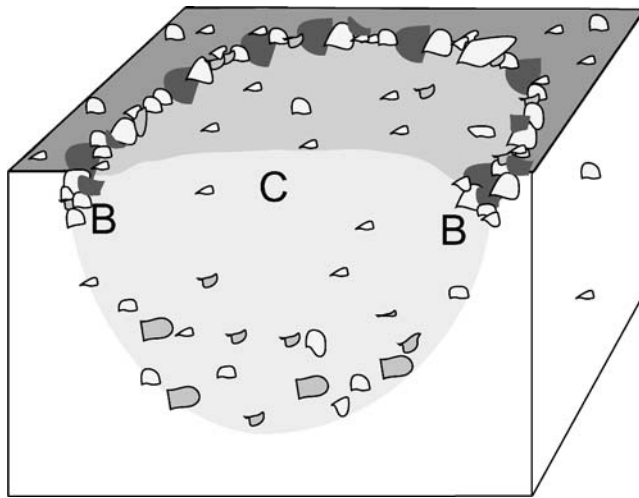
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FIGURE 2. A cross section of a sorted patterned ground feature is shown. The letter C represents the patterned ground center, while the letter B represents border positions. Vegetation cover was sampled at each of the three microsite locations, followed by soil sampling.

Glacier foreland	Time units			
	A.D. 1750–1802	A.D. 1843–1855	A.D. ~1930	Recent
Slettmarkbreen				
Mean diameter (cm)	42.9a	47.9a	45.0a	54.8a
Mean % gravel by depth				
0–6 cm	15.8a	8.6a	10.3a	7.9a
6–12 cm	22.4a	28.2a	23.0a	12.4b
20–26 cm	41.5a	57.1a	38.9a	40.0a
		A.D. 1836–1867	A.D. ~1930	Recent
Styggedalsbreen				
Mean diameter (cm)		42.1a	44.3a	47.3a
Mean % gravel by depth				
0–6 cm		14.2a	7.8b	8.2b
6–12 cm		18.4a	10.7a	16.6a
20–26 cm		53.5a	27.5b	40.0a
	A.D. 1792–1807	A.D. 1893–1910	A.D. ~1930	Recent
Vestre Memurubreen				
Mean diameter (cm)	45.1a	42.5a	45.7a	34.5a
Mean % gravel by depth				
0–6 cm	8.8a	9.7a	9.1a	9.4a
6–12 cm	14.5a	17.5a	15.1a	15.7a
20–26 cm	41.7a	55.0a	54.9a	50.0a

into four distinct time units, while Styggedalsbreen was aggregated into three distinct time units (Fig. 1). The two youngest time units are identical for the three glacier forelands. The time unit labeled "Recent" has been deglaciated within a decadal time frame and is preceded by ca. A.D. 1930 time unit which represents a period of climatic amelioration producing a characteristic moraine within the region. The older time units are of different ages for the three forelands. A fourth oldest, outer time unit was unobtainable at Styggedalsbreen due to human disturbance associated with construction of a reservoir. Within each time unit 10 patterned features were sampled. For consistency, diameters of patterned ground were measured across the axes, along a north to south compass bearing. Measurements were therefore taken from the innermost side of the north to south stony borders (Fig. 2). Borders are defined as the transition zone between the center cells, dominated by fines, and that of the stony troughs, dominated by coarser clasts. Vegetation and soil samples were then taken at three locations within each of the patterned features: (1) the north border, (2) the south border, and (3) the center.

Vegetation cover was sampled for each of the three sample locations within patterned ground according to life-form category (e.g., grasses, herbaceous species, etc.). Lichen and cryptogamic crusts were incorporated into vegetation totals along with that of vascular species (e.g., Haugland and Beatty, 2005). Total vegetation cover, therefore, is a sum of the various life-form categories sampled. With stratification and multiple layerings of vegetation categories, total vegetation cover may exceed 100% (Kent and Coker, 1992). Initially a plot of 0.25 × 0.25 m made of PCB pipe was to be placed at each of the three patterned ground positions. However, due to the general small size of the patterned features (≤1 m), a smaller microplot was needed. Hence, using string tied across the original PCB pipe plot, a microplot of 8.3 × 8.3 cm was obtained and used for total vegetation coverage.

After vegetation sampling, patterned ground forms were trenched in half along the north to south microtransects, with soil samples being taken at the three locations where vegetation had been sampled. Physical as well as chemical soil properties were measured and printed in Haugland (2004) and Haugland and Beatty (2005). Depth of A horizon (cm), as observed by darkening and incorporation of organic matter, as well as percent gravels with depth, is discussed here. Illuvial B horizons are often the desirable horizon of study, containing valuable information regarding rates of pedogenic development (Birkeland,

1999). However, young soils (i.e., <250 years), as those found in this study, characteristically lack illuvial B horizons; therefore, A horizons were solely focused upon. Percent gravels were estimated visually in the field following the guidelines of Birkeland et al. (1991). For consistency, percent gravels were estimated at three depths: 0–6 cm, 6–12 cm, and 20–26 cm.

Averaged data for position within replicate patterned ground was compared to determine variability across the landscape. Therefore, if vegetation or soil was absent, a value of zero was assigned. A non-parametric ANOVA (Kruskal-Wallis) was performed to determine significant variation in gravel percentages, patterned ground diameter size, vegetation cover, and soil A horizon depths at the microscale (centers vs. borders), and across the time units of each foreland. If the above tests were significant, a non-parametric t-test (Mann Whitney U) was performed to pinpoint microscale or temporal thresholds pertaining to the above variables (Barber, 1988).

Results

GENERAL OBSERVATIONS AND PREVIOUS WORK

Diameters of patterned ground features do not significantly vary with distance from the ice margin for the three forelands (Table 1). Larger patterned ground was found on the crests of the larger recessional moraines, which were approximately 3 m in height above the surrounding terrain. However, the smaller annual and fluted moraines, where patterned ground was studied for this study, did not significantly vary in size across the forelands.

TABLE 2

Microscale variation (centers vs. borders) of vegetation cover and soil A horizon depth for each time unit. A total of 10 patterned ground features were studied for each time unit. Chi-squared values (χ^2) from the Kruskal-Wallis tests are reported, and values in bold represent statistical significance.[a] "B" signifies that patterned ground borders are significantly different in vegetation cover or soil A horizon depth (i.e., higher cover or deeper soils) than that of the patterned ground centers, based on follow-up Mann-Whitney U tests. "C" signifies that the centers are significantly different than borders (i.e., higher cover).

Glacier foregrounds	Time unit	χ^2 vegetation values	χ^2 soil A horizon depth values
Slettmarkbreen	A.D. 1750–1802	**14.63**C	**8.63*B**
	A.D. 1843–1855	0.38	**9.80*B**
	A.D. ~1930	**16.49**B**	**6.91*B**
	Recent	**17.72**B**	0.00
Styggedalsbreen	A.D. 1836–1867	**9.17*C**	**19.71**B**
	A.D. ~1930	**15.81**B**	1.04
	Recent	**18.78**B**	0.00
Vestre Memurubreen	A.D. 1792–1807	**24.52**C**	4.73
	A.D. 1893–1910	0.52	**15.66**B**
	A.D. ~1930	**14.19**B**	**8.36*B**
	Recent	**9.94*B**	0.51

[a] Monte Carlo significance values based on 10,000 sampled tables.

* $P < 0.05$; ** $P < 0.01$.

All time units show a coarsening of percent gravels with depth for patterned ground centers (Table 1). However, percent gravels for the three forelands are generally homogeneous across the forelands at similar depths (i.e., 0–6 cm). Only the Slettmarkbreen and Styggedalsbreen forelands show temporal heterogeneity with percent gravels. The 6–12 cm layer of Slettmarkbreen patterned ground features shows coarsening immediately after the "Recent" time unit and a subsequent stabilization of coarsening thereafter. The 0–6 cm layer of the Styggedalsbreen patterned ground features show a coarsening at the oldest time unit from that of the previous two youngest time units. The 20–26 cm layer shows a decrease of gravels from the immediate younger and older time units.

The general findings of vegetation cover and soil A horizon depth in patterned ground are similar to previous Little Ice Age chronosequence studies of the region (Mellor, 1986; Matthews and Whittaker, 1987; Messer, 1988), studies which generally avoided patterned ground. Vegetation cover is characteristic of the mid- to high alpine vegetation belts, being sporadic and interspaced between patches of bare ground (Dahl, 1956; Haugland and Beatty, 2005). Soil A horizons are absent to thin as befitting the youthful age of the terrain (Mellor, 1986; Haugland, 2004). As with previous studies, both vegetation cover and soil A horizon depth generally increase with time and distance from the ice margin; however, in this study patterned features obtained lower vegetation cover and shallower soil A horizon depth values than that of surrounding unpatterned areas (Mellor, 1986; Matthews and Whittaker, 1987; Messer, 1988; Haugland, 2004). Patterned ground soil chemical properties show less evolution than in surrounding unpatterned areas (i.e., lower acidity, total N, CEC, and percent organic matter) (Haugland, 2003; Haugland and Owen, in press). However, it is evident that microscale heterogeneity occurs within patterned ground of uniform age. Vegetation colonization and soil development initiate at what is assumed to be the less frost-active border positions, with center positions containing relatively lower values. With time and distance from the ice margin, soil A horizon depths generally increase and vegetation cover spreads inwards toward the centers of patterned ground (e.g., Haugland 2004; Haugland and Beatty, 2005).

FINE-SCALE VARIATIONS (BORDERS VS. CENTERS) OF VEGETATION AND SOIL IN PATTERNED GROUND

Fine-scale differences in vegetation cover and soil A horizon depth were investigated in patterned ground of uniform time units. Each of the three chronosequences contains significant ($P < 0.05$) differences in fine-scale heterogeneity between border and center positions (Table 2). For all three chronosequences, border positions typically exhibit higher vegetation cover and soil A horizon depths. In terms of vegetation cover, the two youngest time units for the three forelands (ca. A.D. 1930 and Recent) have significantly higher vegetation covers at one of the two border positions. Fine-scale vegetation cover is either statistically insignificant ($P > 0.05$) and/or reverses trends with the center positions in time units older than ca. A.D. 1930. Significant fine-scale heterogeneity of soil horizon depth tends to lag behind that of vegetation cover, yet does occur within patterned ground at, or immediately after, the ca. A.D. 1930 time units. Center and border soil A horizon depths are initially homogeneous within the youngest patterned ground, with little to no soil development regardless of microsite location. The ca. A.D. 1930 time unit appears to be a temporal threshold for both soil and vegetation in that each of the glacier forelands show a change in fine-scale heterogeneity either at or immediately after the ca. A.D. 1930 time unit, signifying a change or lessening of the abiotic factor of frost disturbance within the patterned features.

TEMPORAL VARIATIONS OF VEGETATION AND SOIL IN PATTERNED GROUND

Mean values of vegetation cover and soil A horizon depth of patterned ground centers were compared among the time units of each glacier foreground, as were the two border positions. For both center (Table 3) and border positions (Table 4), vegetation and soil A horizon depth generally increases with time. An exception is vegetation cover at Vestre Memurubreen. Vegetation increases with age for both center and border positions up through the three youngest time units at Vestre Memurubreen, but decreases significantly within patterned ground of the oldest time unit (A.D. 1750–1802). Patterned features within the oldest time unit occur on an intermorainal area of a protruding knoll. Exposure to desiccating winds may decrease soil moisture levels, a limiting factor contributing to the overall decline in vegetation cover. However, the general findings show that a temporal threshold occurs for patterned ground centers and borders for all three forelands. With increasing age and distance from the ice margin, vegetation cover as well as soil A horizon depth significantly increases at or immediately after the ca. A.D. 1930 time units, implying a change/lessening in disturbance associated with frost action in patterned ground.

Discussion

FINE-SCALE AND TEMPORAL VARIATIONS

Homogeneity of diameter sizes across the forelands implies the short-term activity of periglacial processes and the importance of ice margin proximity. With retreat of the ice margin, frost processes decline, inhibiting continuation of significant periglacial processes and the formation of larger patterned ground diameters. Larger patterned ground features were observed on nearby major recessional moraines. They most likely obtain larger sizes from being windswept of snow during the winter months, allowing for deeper frost penetration and

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TABLE 3

Temporal variations of patterned ground centers by time units are shown. A total of 10 patterned ground features were studied for each time unit. Mean values of total vegetation cover and soil A horizon depths are listed. Different lower case letters (i.e., a, b, c, d) show significant ($P < 0.05$) changes in value along the chronosequences (across rows), implying heterogeneity as tested by Mann Whitney U. The same lower case letters (across rows) show nonsignificant ($P < 0.05$) changes in values along the chronosequence, implying homogeneity as tested by Mann Whitney U.

Glacier foreland	Time units			
	A.D. 1750–1802	A.D. 1843–1855	A.D. ~1930	Recent
Slettmarkbreen				
Cover (%)	113.3a	61.3b	18.3c	7.1d
Soil A horizon (cm)	3.1a	1.4b	0.0c	0.0c
		A.D. 1836–1867	A.D. ~1930	Recent
Styggedalsbreen				
Cover (%)		105.5a	9.9b	5.5b
Soil A horizon (cm)		1.8a	0.2b	0.0b
	A.D. 1792–1807	A.D. 1893–1910	A.D. ~1930	Recent
Vestre Memurubreen				
Cover (%)	87.0a	93.0b	14.0c	5.0c
Soil A horizon (cm)	2.5a	1.8a	0.5b	0.1b

TABLE 4

Temporal variations of patterned ground borders by time units are shown. A total of 10 patterned ground features were studied for each time unit. Mean values of total vegetation cover and soil A horizon depths are listed. Different lower case letters (i.e., a, b, c, d) show significant ($P < 0.05$) changes in value along the chronosequences (across rows), implying heterogeneity as tested by Mann Whitney U. The same lower case letters (across rows) show nonsignificant ($P < 0.05$) changes in values along the chronosequence, implying homogeneity as tested by Mann Whitney U.

Glacier foregrounds	Time units			
	A.D. 1750–1802	A.D. 1843–1855	A.D. ~1930	Recent
Slettmarkbreen				
Cover %	79.0a	74.7a	64.6a	36.0b
Soil A horizon (cm)	4.4a	3.5a	1.3b	0.0c
		A.D. 1836–1867	A.D. ~1930	Recent
Styggedalsbreen				
Cover %		76.7a	62.6ab	51.1b
Soil A horizon (cm)		4.6a	0.3b	0.0b
	A.D. 1792–1807	A.D. 1893–1910	A.D. ~1930	Recent
Vestre Memurubreen				
Cover %	71.0a	92.0b	57.0a	16.0c
Soil A horizon (cm)	3.2a	3.2a	1.6b	0.2c

greater longevity of activity (Ballantyne and Matthews, 1982). The smaller size patterned ground features of this study were found on small annual and fluted moraines, less susceptible to being windswept and subsequently blanketed by seasonal snow that inhibits frost penetration and patterned ground growth.

Percent gravels of patterned ground centers across the forelands also imply the importance of ice margin proximity. Patterned ground of this study does not appear to continue the process of sorting with time. At the prescribed depths, patterned ground centers generally do not significantly vary across the forelands. The exceptions that do occur tend to show a reversal, a coarsening with time. In particular, the 0–6 cm layer of the Styggedalsbreen foreland patterned ground features best shows this relationship. A possible explanation for this coarsening is that, with time, pervection, or the downward transport of fines by subsurface flow, as well as deflation leave a desert pavement appearance (Boutlton and Dent, 1974; Matthews, 1992; Ballantyne, 2002b).

Statistically significant ($P < 0.05$) fine-scale variations in vegetation cover and soil A horizon depth (Table 2) could be attributed to a lessening of the abiotic factor, frost intensity. Patterned ground within the three chronosequences appear to be more frost active within younger time units near the ice margin, and at the microscale in center positions. Fine-scale differences in frost intensity occur with border positions becoming relatively stable prior to that of center positions, as suggested by significant ($P < 0.05$) increases in vegetation cover and soil A horizon depth compared to that of center positions (Table 4). Following a geomorphic approach, the temporal and fine-scale trends could be attributed to a geomorphic edge effect (Phillips, 1999), where glacial retreat lessens the intensity of frost action, abiotic factors conducive for frost disturbance retreat with the ice margin. However, the biotic component should not be overlooked regarding frost intensity (André, 2003). With primary succession and increased vegetation cover, disturbance associated with frost action may decline due to stabilization and changes of thermal properties (Anderson and Bliss, 1998). Regardless of whether changes in the abiotic or biotic factors are primarily responsible for the apparent patterned ground

stabilization, there does appear to be an active zone or edge in terms of periglacial processes near the ice margin. This pattern of behavior may be modeled.

THEORETICAL MODEL

The theoretical model below (Fig. 3) summarizes this study's findings on patterned ground development. This model is a microscale developmental one that addresses post-deglaciation development of small patterned ground forms. However, it must be recognized that some elements of the model may be forced by mesoscale factors (e.g., regional scale warming).

Regardless of the cause for deglaciation, the model suggests that abiotic factors initially drive the primary processes associated with patterned ground. On a time scale of decades, frost action processes rapidly rework glacigenic material into patterned ground (Fig. 3A and B). These processes are not necessarily associated with permafrost but are perhaps influenced by increased soil moisture and freeze/thaw activity near the ice margin (Ballantyne and Matthews, 1982, 1983; Matthews et al., 1998) or periglacial zone. With time and continued deglaciation (Fig. 3C), the local environmental parameters associated with that of the ice margins decline, leading to a reduction in frost activity (Fig. 3D). For instance, soil moisture may decrease with distance from the retreating ice margin as formally saturated substrates drain and consolidate, inevitably reducing frost action processes (Matthews et al., 1998; Ballantyne, 2002b). Also, microscale improvements in drainage may result from the impacts of previous lateral sorting of what initially was poorly drained, unsorted material within patterned ground, reducing the effects of frost action (Thorn, 1976; Rissing and Thorn, 1985). For these reasons, the abiotic effects of cryoturbation begin to decline at stage D (Fig. 3). A temporal and spatial gradient can loosely be applied to the model with each successive letter representing an increase in age and distance from the ice margin. Yet, the amount of time needed to get to stage D is fairly small, favoring the microsite locations of patterned ground borders
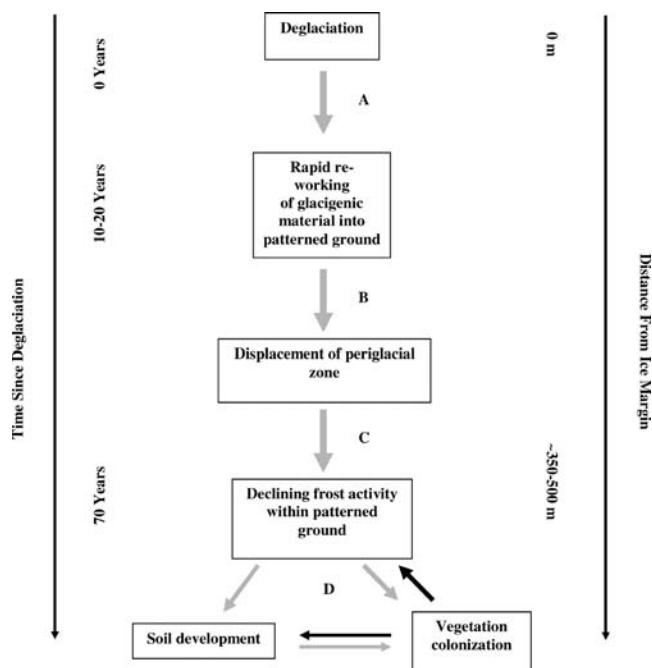
FIGURE 3. Theoretical model of microsite landform development across three Little Ice Age chronosequences in Jotunheimen, Norway. Lighter arrows represent abiotic influences, while darker arrows represent biotic interactions. Arrows show relative strength (thickness) and direction of relationships. An approximate temporal and spatial scale is provided on the sides. The model is a generality of the three glacier forelands studied and is site specific to the Jotunheimen region.

within ~70 yr (ca. A.D. 1930 time units) of deglaciation. Reduced frost action at border positions appears to produce a more stable environment, allowing primary succession to occur (Fig. 3D). This rapid temporal reduction in frost activity could also signify an end stage in terms of patterned ground growth, explaining the relatively small sizes of patterned ground found in Jotunheimen (Ballantyne and Matthews, 1982, 1983; Matthews et al., 1998).

The onset of stage D also shows the initiation of geoecological processes where abiotic and biotic interactions begin. The interactions of stage D are shown to be multidirectional. The thicknesses of the arrows suggest relative importance, implying that the displacement of the periglacial zone (Fig. 3C) is essential before stage D begins. At this point, bryophytic or cryptogamic crusts are the dominant form of vegetation cover (Haugland and Beatty, 2005). Once stage D is established, vegetation may then impact the degree of frost activity. For instance, organic crusts have been shown to ameliorate surficial thermal properties, and vegetation cover in general can exert control by physically binding the surface (Anderson and Bliss, 1998; Gold, 1998; Matthews et al., 1998; Eldridge et al., 2003). Yet, vegetation must also be able to withstand disturbance damages (Goulet, 1995). Therefore, the emphasis and strength of the relation between declining frost activity and vegetation colonization can be thought of as a "chicken and egg" phenomenon. This study does not have the data to support adequately the direction of the scenario (chicken vs. egg). Yet, Ballantyne and Matthews (1982) suggest that declining frost activity is a priority for vegetation colonization within sorted circles of the Slettmarkbreen forelands, and the decline was noted with distance from the ice margin. Thorn's (1970) model of stony earth circle evolution may be relevant as well. Thorn observed that the coarsening of circle margins improved drainage which in turn reduced heaving, allowing vegetation to colonize. Proximity to ice margins, as noted by Ballantyne and Matthews (1982) and Matthews et al. (1998), as well

as microscale improvements to drainage, as noted by Thorn (1970), are not mutually exclusive in terms of explaining patterned ground formation and duration of activity within the Jotunheimen region. As Washburn (1980) states, patterned ground can have a polygenetic origin.

Unlike vegetation, the relationship between soil development and reduced frost action (Fig. 3D) is a one-way interaction. If frost action is too strong, horizon forming processes are retarded. Frost activity within patterned ground has also been noted to affect the soil chemistry (Jonasson and Sköld, 1983; Jonasson, 1986; Haugland and Owen, in press). Compared to surrounding more stable terrain, heaving mechanisms associated with active patterned ground features provide fresher supplies of parent material. By comparison, less frost-active surrounding terrain has undergone more intense leaching through time, resulting in higher levels of acidity.

The end of the model (stage D) illustrates the two-way relation between soil development and vegetation colonization within patterned ground. The two processes are intimately related, yet frost action must subside before significant interactions can occur. For instance, heterogeneity of frost disturbance, with a decline in intensity at borders of ~70-yr-old patterned ground, partitions vegetation and soil development to the less frost-active border positions. Border positions show increased soil A horizon depth and development while simultaneously obtaining the greatest vegetation cover (Tables 3 and 4). Meanwhile, frost-active centers typically obtain minimal to no soil development or vegetation cover. With time, distance from the ice margin, and lower levels of frost action, relations between soil and vegetation increase and encroach toward the centers of patterned ground.

The formation of patterned ground supports the geoecologic concept (Troll, 1971; Matthews, 1992; Matthews et al., 1998; Matthews, 1999) because a multidirectional relationship between abiotic factors (e.g., severity of frost action impeding vegetation colonization and subsequent soil development) and biotic factors (e.g., vegetation colonization impeding frost activity) could be occurring. It does appear that an active periglacial zone occurs at the most recently exposed terrain with a noted outward decline in activity, a decline first observed on all three forelands at the ca. A.D. 1930 time units.

Conclusion and Future Work

The above model illustrates how abiotic processes can quickly modify recently deglaciated terrain into a heterogeneous landscape of small patches. The genetic processes responsible for patterned ground initially appear to be associated with the ice margin/edge and are of such severity that biotic processes are minimal to absent. Inevitably, the abiotic processes decline with displacement of the periglacial zone, and vegetation begins to colonize. However, it does so at the microscale, initially at patterned ground borders following Thorn's (1970) model. With this vegetation establishment, a variety of biotic and abiotic interactions begins to occur in patterned ground. The interactions themselves are not unique in terms of landscape development, yet the rate and delayed arrival of these interactions when compared to the surrounding landscape are. Patches of patterned ground can provide heterogeneity to the landscape by delaying normal processes associated with vegetation colonization and pedogenesis.

Future work pertaining to landscape evolution should continue to investigate fine-scale features. A direct improvement to the above study would be to investigate the said interactions within patterned ground as well as those findings at the coarser scale. A multi-scale (fine and coarse) investigation of the chronosequences would give a more complete picture of the processes responsible for landform evolution.

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