The role of weathering and pedological processes for the development of sorted circles on Kvadehuksletta, Svalbard – a short report

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The presence of silt-rich, fine-grained material at the center of the well-developed sorted circles on Kvadehuksletta, Svalbard, is a precondition for their development. Field work, laboratory work, and data from published studies indicate that the fine-grained material is a dissolution product of the dolomitic bedrock. The silt is accumulated in situ and by slope wash in terrain depressions. Chemical weathering and other pedogenetic processes, such as the translocation of silt, are of great importance in Arctic regions and can create the sedimentological prerequisites for cryogenetic processes, such as frost sorting and cryoturbation. Therefore, the bedrock composition and the composition of surficial material are considered to be important control factors for these processes.

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Introduction

Sorted circles on Kvadehuksletta, situated on the peninsula Brøggerhalvøya, Svalbard, are mainly developed in fossil fluvial and beach sediments. The circles appear nearly unique on Svalbard because they are exceptionally well-developed and unusually large. They were first described in detail by Miethe (1912). On Kvadehuksletta (Fig. 1) the circles form local networks, as shown in Fig. 2. The dynamics of the well-developed circles on Kvadehuksletta have been studied in detail by Hallet and others (Hallet & Prestrud 1986; Andersen 1988; Hallet et al. 1988). Patterned ground in general on the north side of Brøggerhalvøya has been studied in detail by VanVliet-Lanoë (1988). Similar circles on Svalbard have been reported from southern Spitsbergen in the Hornsund area (cf. Jahn 1975).

This report deals with the problem of the regional distribution of this type of patterned ground and the prerequisites for its development on Kvadehuksletta. The genesis of silty fine-grained material, found in the center of the circles, is therefore regarded to be of great importance. On Kvadehuksletta fine material is lacking in the unaltered recent beach sediments but is found in older beach sediments. It is suggested that special geological and hydrological factors may favour frost sorting processes and the development of patterned ground on Kvadehuksletta. This is indicated by the lack of well-developed forms in other similar strand-flat areas on Svalbard which were observed under a surveying project carried out by the Department of Physical Geography, University of Oslo, in collaboration with the Norwegian Polar Research Institute (Sollid et al. 1991).

The fine material is believed to originate as a weathering product, mainly from the dissolution of dolomitic limestone. Carbonate dissolution has been described as an important geomorphological agent in Arctic regions (Helldén 1974; Salvigsen & Elgersma 1985; Åkermann 1973) and is viewed as a major prerequisite for the development of the sorted circles on Kvadehuksletta.

This report is to be regarded as a summary of preliminary results from field and laboratory work carried out in 1987 and 1988 at the Department of Physical Geography, University of Oslo, in connection with detailed geomorphological and Quaternary geological mapping of Kvadehuksletta, scale 1:10000 (Tolgensbakk & Sollid 1987). As a part of this project the genesis of the fine-grained material found in the sorted circles was studied by Etzelmüller (1989) under the supervision of J. L. Sollid. More substantial information about granolumetric and mineralogical analysis of the soils, especially those associated with the sorted circles, will be presented in another report when further laboratory analyses

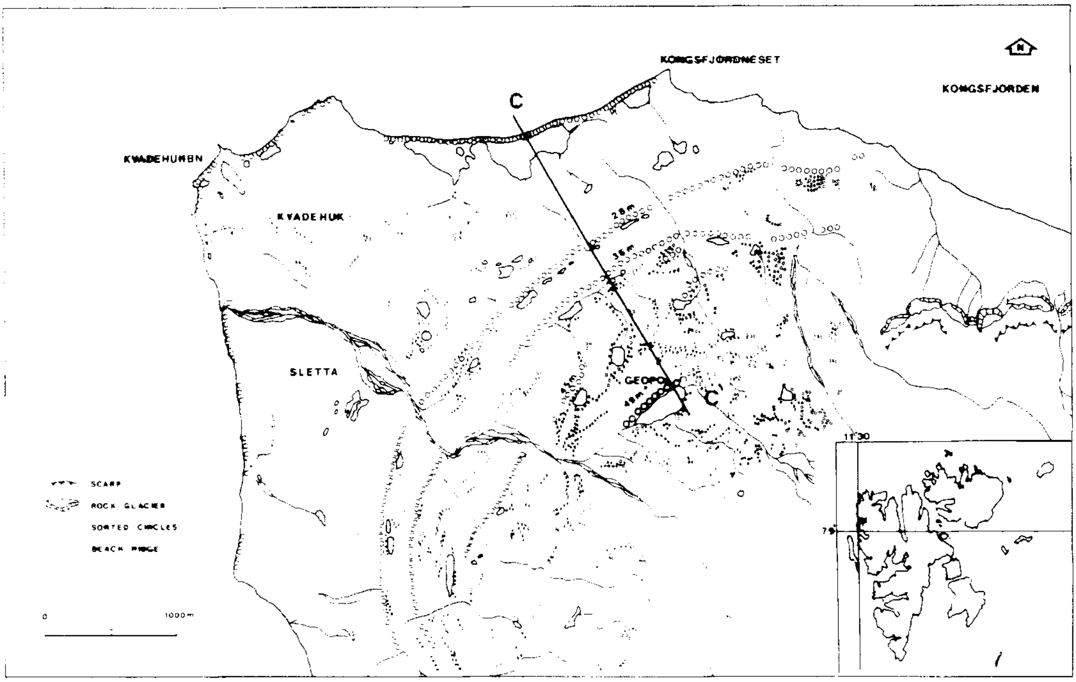

Fig. 1. Kvadehuksletta, located on the peninsula Brøggerhalvøya on the south side of Kongsfjorden. The highest marine limit is about 80 m a.s.l. Only the most pronounced beach terraces and well-developed sorted circles are shown (based on Tolgensbakk & Sollid 1987).

are completed and all data from previous fieldwork have been processed.

Setting

Kvadehuksletta is a strand-flat area on the northwestern point of Brøggerhalvøya, western Spitsbergen (79 °N 12 °E) (Fig. 1). The bedrock of the area consists mainly of permo-carboniferous dolomite and minor areas of younger clastic sediments (Orvin 1934; Challinor 1967).

The climate is high Arctic with a marine influence. Ny-Ålesund, about 10 km southeast of Kvadehuksletta, has an annual mean air temperature of −6.1°C and mean precipitation of 373 mm. On Kvadehuksletta precipitation is assumed to be higher and the summer temperature slightly lower due to the location of Ny-Ålesund in a fjordbasin. The thickness of the permafrost in the area is estimated to be about 200 m based on measurements carried out in front of the glacier Austre Brøggerbreen, about 10 km south of Kvadehuksletta (Liestøl 1977).

A complex of raised beach ridges covers most of the strand-flat area (Fig. 1). The best preserved ridges are located at levels below the shoreline at 45 m, dated to Late Weichsel (about 13.5 ka) by Formann et al. (1987). Large beach ridges are, however, found up to a level of 74 m. According to Formann & Miller (1984) the uppermost beach ridges could be of pre-Weichselian age (130–290 ka). They could suggest an ice-free Kvadehuksletta in the Weichsel, while most recently Mangerud et al. (in press) propose a large Weichselian ice sheet, reaching to the edge of the continental slope in the west. The latter does not necessarily imply that the beach ridges are of postglacial age. Marine or glacial deposits can survive a glaciation under cold-based ice nearly undisturbed, as reported for recent forms from Storøya, Svalbard (Jonnson 1983) or supposed for fossil forms in the southeastern regions of Norway (Sollid & Sørbel 1984).

Geomorphologically, the complex of beach ridges could be divided into two areas, one below and one above 45 m a.s.l. The thickness of marine sediments varies by several metres around the

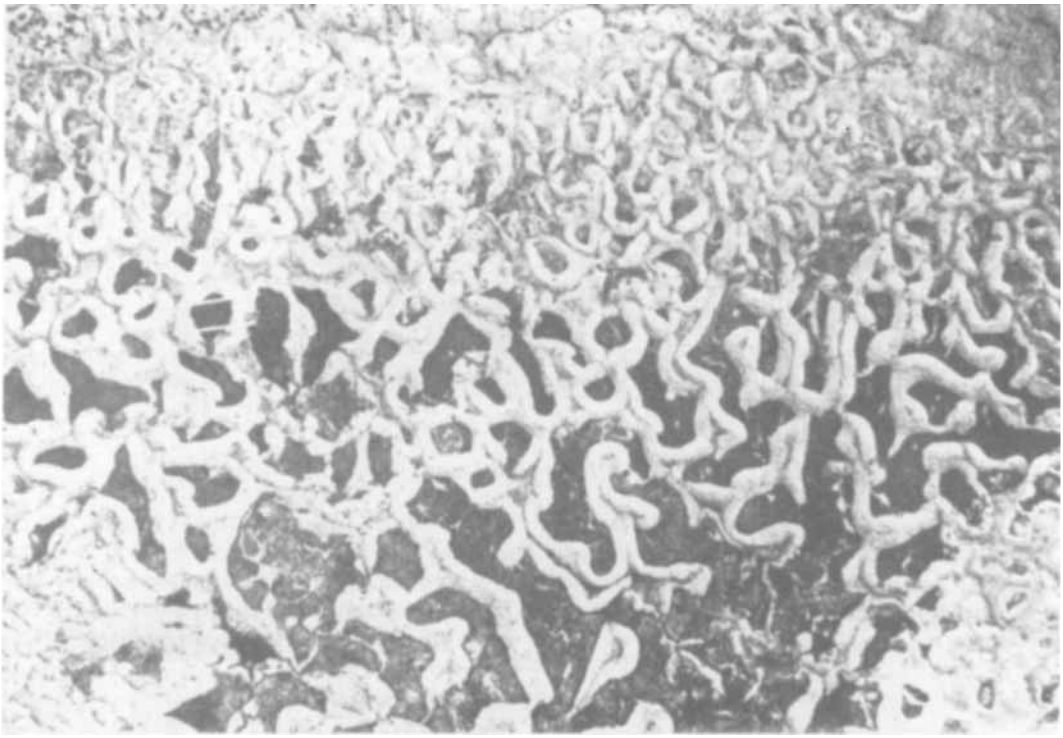

Fig. 2. Network of well-developed sorted circles on Kvadehuksletta, developed in a moist terrain depression. The photo was taken from helicopter (J.L. Sollid 1985). The two parallel stripes across a circle at left-center can be used as a scale; the distance between these stripes is about two metres.

beach ridges and locally to almost zero in some interridge areas. Here weathered bedrock, fluvially reworked material, and patches of wet, richly vegetated tundra are found. The lithological composition of the marine and fluvial sediments on Kvadehuksletta reflect the bedrock geology of the area, with a dominance of carbonates. Samples of pebbles from the recent beach sediments showed a content of about 80% dolomitic limestone and about 5% other carbonates; the remaining 15% were sandstones, conglomerates and metamorphic pebbles. No significant difference in the lithological composition between recent and fossil beach sediments was found.

The hydrological regime of Kvadehuksletta is controlled by the beach ridges and permafrost. Small ponds fed by snow and permafrost meltwater and by surface runoff are formed in terrain depressions behind the ridges.

In spite of the relatively high precipitation, the cryogenetic undisturbed soils developed on the beach ridges are classified as being within the Polar Desert Zone (Tedrow 1977; Ugolini 1986). The arid soil regime is mainly controlled by sedimentological factors, such as the dominance of coarse-grained beach sediments with a thick active layer, which cause good drainage conditions.

Field and laboratory work

The fieldwork for this report was carried out during the summers of 1987 and 1988. Soil sampling and detailed geomorphological and soil mapping were carried out along special profile lines (Fig. 1).

Analysis of the rocktype composition of beach sediments was performed by counting 150 to 200 pebbles of the 8–16 mm fraction. Grain size analysis was done by wet and dry sieving. The fraction smaller than 63 μ was analysed by a Sedigraph 5000 D. Mineralogical analyses were carried ut with a Phillips PW 1729 X-ray diffractor with a Cuα-lamp ($\gamma = 1.54060$ Å). The fraction <63 μ

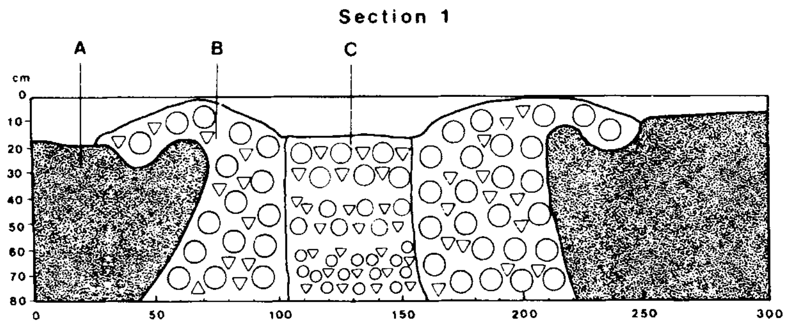

Fig. 3. Section through a typical well-developed sorted circle in moist terrain depression, overlain by beach sediments. A. Domain (gravelly silt). B. Circle border (rounded to subrounded beach sediments, no fines). C. Intercircle area (rounded to angular gravelly beach sediments). Note the distinct border between domain and border, and border and inter-circle area.

was used for a randomly-oriented bulk sample. The clay fraction (<2 μ) was separated by sedimentation methods. At this stage an oriented sample was prepared and treated by standard clay mineral analysis techniques.

Regional distribution pattern

Sorted circles

The stone borders outlining the sorted circles have a maximum height of about 50 cm, with average heights of 20 to 30 cm. The material in the stone borders consists mainly of stones with a diameter of up to a few centimetres. The gravel in the borders reflects the surficial material where the circles are found. The central areas of the circles are dominated by silty fines. The fine domain is limited sharply by the gravel border. The limit extends vertically downwards presumably to the permafrost table. The same vertical pattern was observed between the circle borders and the inter-circle area (cf. Fig. 3) suggesting some kind of vertical movement. The fine domain constitutes a plug under the centre of the borders. Locally, material rich in silt was also found under the circle borders, as has also been described by Jahn (1975) from the Hornsund region.

Detailed geomorphological mapping shows that the well-developed networks of sorted circles (Fig. 2) are concentrated around terrain depressions where the water supply is relatively good, especially surrounding ponds and between beach ridges (Fig. 1). These forms are found both in marine beach sediments and in fossil fluvial material. The age of the deposits does not seem to govern the pattern of distribution significantly. The circles are abundant and well-developed both in the youngest beach sediments and close to the marine limit. However, areas with a network of sorted circles, as shown in Fig. 2, are found mainly behind the 28 m ridge (Tolgensbakk & Sollid 1987) which is dated to about 10 ka (Formann et al. 1987). This distribution pattern is due to topographical and hydrological factors.

Single sorted circles are found over the entire strandflat area in various degrees of development. They are even found on dry areas and in dolomitic weathering material in terrain depressions where surficial material thickness is small and water supply is present. The borders of these circles are built up of angular stones from bedrock weathering debris.

Cryogenetic undisturbed soils

The well-drained soils developed on the beach ridges are described in previous works (Formann & Miller 1984; Mann et al. 1986; Sletten 1988). A major feature of these soils is a 15 to 40 cm thick silt accumulation horizon (B_1) which underlies an A-horizon showing extensive dissolution signs on pebbles (Fig. 4). In and beneath the silt horizon secondary carbonate precipitation is found on the bottom side of the gravel. The chemistry and kinetics of the solution and precipitation of carbonates in these soils is described by Sletten (1988). Soil morphology and soil water chemistry indicate that this pedogenetic silt is mainly a residual of the dissolution of dolomitic gravel.

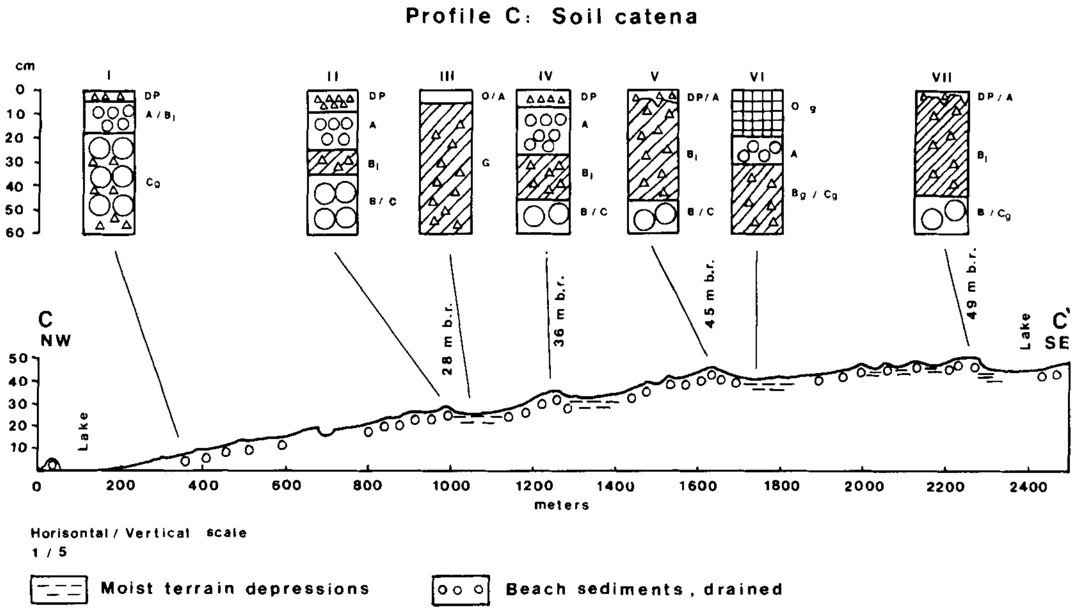

Fig. 4. Soil catena along profile line C-C' (cf. Fig. 2). DP = desert pavement. A = horizon with obvious signs of carbonate dissolution (angular to subangular pebbles). B_1 = silt accumulation horizon (notation according to Formann & Miller (1984)). A/B_1 = horizon which shows beginning of silt translocation (siltcaps on pebbles). B/C = transition between silty B-horizon and parent material. G = water-saturated horizon (gleyic). O = organic horizon. (g) = temporally water saturated.

The silt is translocated down through the soil column by percolating pore water and enriched in a silt horizon (Formann & Miller 1984). The translocation of fines is described by Tedrow (1977) and Ugolini (1986) as an important pedological process in well-drained polar soils, and reported from other areas, for example in morainic material in Arctic Canada (Locke 1986) and in polar soils of Antarctica (Campbell & Claridge 1987). Formann & Miller (1984) attempted to use the degree of silt accumulation in the soils developed on the beach ridges as a relative dating tool for the marine deposits. In the youngest beach ridges, silt is mainly accumulated as silt caps on pebbles, while on older beach ridges the pebbles are totally imbedded in the silty soil matrix (Fig. 4). The border between the two typical morphological features is the 45 m beach ridge.

Silt-rich horizons are lacking on the recent beach ridges between Kvadehuken and Kongsfjordneset. There are no signs of silt accumulation, even by eolian or by pedogenetic processes.

Silt rich soils were observed in wet inter-ridge depressions, found outside the well-developed sorted circle areas. In these areas hydromorph soils have formed, with a gravelly O- and A-horizon and a silty gleyic B-horizon saturated with water (Fig. 4).

Transitions between cryogenetic undisturbed soils and sorted circles

Transitions between silt horizons and sorted circles are observed especially on the slopes of the beach ridges and in wet depressions. It is obvious that silty hydromorphic soils dominate in areas saturated by water, while sorted circles are formed in areas not constantly saturated by water but having a good water supply. This confirms observations by e.g. Jahn (1975) in the Hornsund region and by Van Vliet-Lanoë (1988) along the northern coast of Brøggerhalvøya. Transitions between pedogenetic silt horizons and poorly-developed sorted circles on the top of beach ridges have been observed locally. Several excavations show that the B_1-horizon locally reaches the surface, showing an early phase of development of sorted circles, even on dry areas as represented by the top of the beach ridges. Transitions between horizontal silt horizons and mudboils or

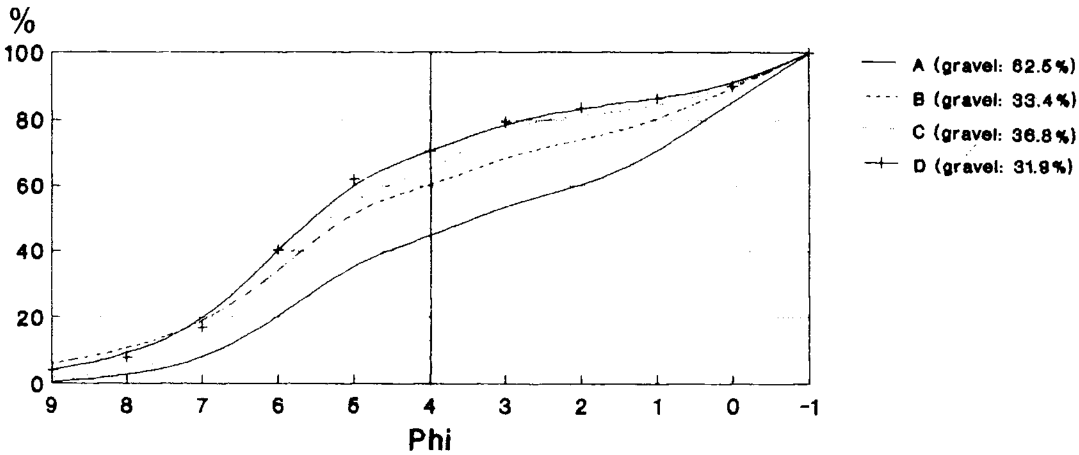

Fig. 5. Grain size distribution from silt-rich fines. Soils sampled from the fine-grained center of sorted circles and from nearby areas. Gravel was removed from the samples; the amount of gravel removed is given in brackets. A = Silt accumulation horizon of soil developed on 36-m beach ridge. B = Domain from section 1. C = Domain from circle developed in weathering material. D = Silt accumulation in undisturbed hydromorph soils (33 m a.s.l.).

poorly-developed sorted circles observed on the slopes of beach ridges seem to be the result of slope-wash and translocation of silt by percolating pore water. Such subsurface drainage is confirmed by observations referred in Van Vliet-Lanoë (1988) where these features can occur in zones with drainage concentration. Subsurface drainage down the slopes of the beach ridges on Kvadehuksletta can concentrate on the permafrost table, especially in late spring and early summer.

Some results from soil sampling and analysis

Most work was carried out on the material rich in silt, sampled in soils from the fine-grained centre of sorted circles and from adjectant areas. As one of the aims of this work was to find evidence of the origin of fines in the circles, the samples were divided into silt collected from sorted circle sites and silt collected from other sites for comparison. The first group was subdivided into fines from circles developed directly on beach terraces and from circles developed in moist depressions between terraces.

The most striking feature is that the pedogenetic silt found in the silt horizons of the cryogenetic undisturbed soils and the silty material in the sorted circles located nearby do not show any signficant difference, either in grain size distribution or in mineral composition. The fines here consist mainly of medium-coarse to coarse silt with a relatively small amount of fine and medium sand and clay (Fig. 5).

Mineralogical analysis of the fines shows that the silt is mainly composed of dolomite and quartz, with a varying amount of feldspar and mica. The quantitative distribution of the main minerals in the silt is found to be nearly the same as for the local unweathered dolomitic bedrock, with slightly higher values for quartz due to the dissolution of carbonates (Figs. 6 and 7). The silt in sorted circles developed directly from weathering material does not show any significant mineralogical difference to unweathered bedrock (Fig. 6). Feldspar and mica are therefore inherited from sandstones and conglomerates found in the surficial material.

Fines in sorted circles developed in moist depressions show small variations in grain size distribution and mineral compositions of the silt and clay fraction over the entire study area. Almost the same values of these parameters, which are close to those of unweathered bedrock, have been measured both in forms nearby the recent coast line and nearby the highest marine limit, about 80 m a.s.l.

The diffraction pattern of the silts directly connected to beach terraces indicates an increase of quartz, feldspar and mica content relative to dolomite with the age of the beach terraces, both

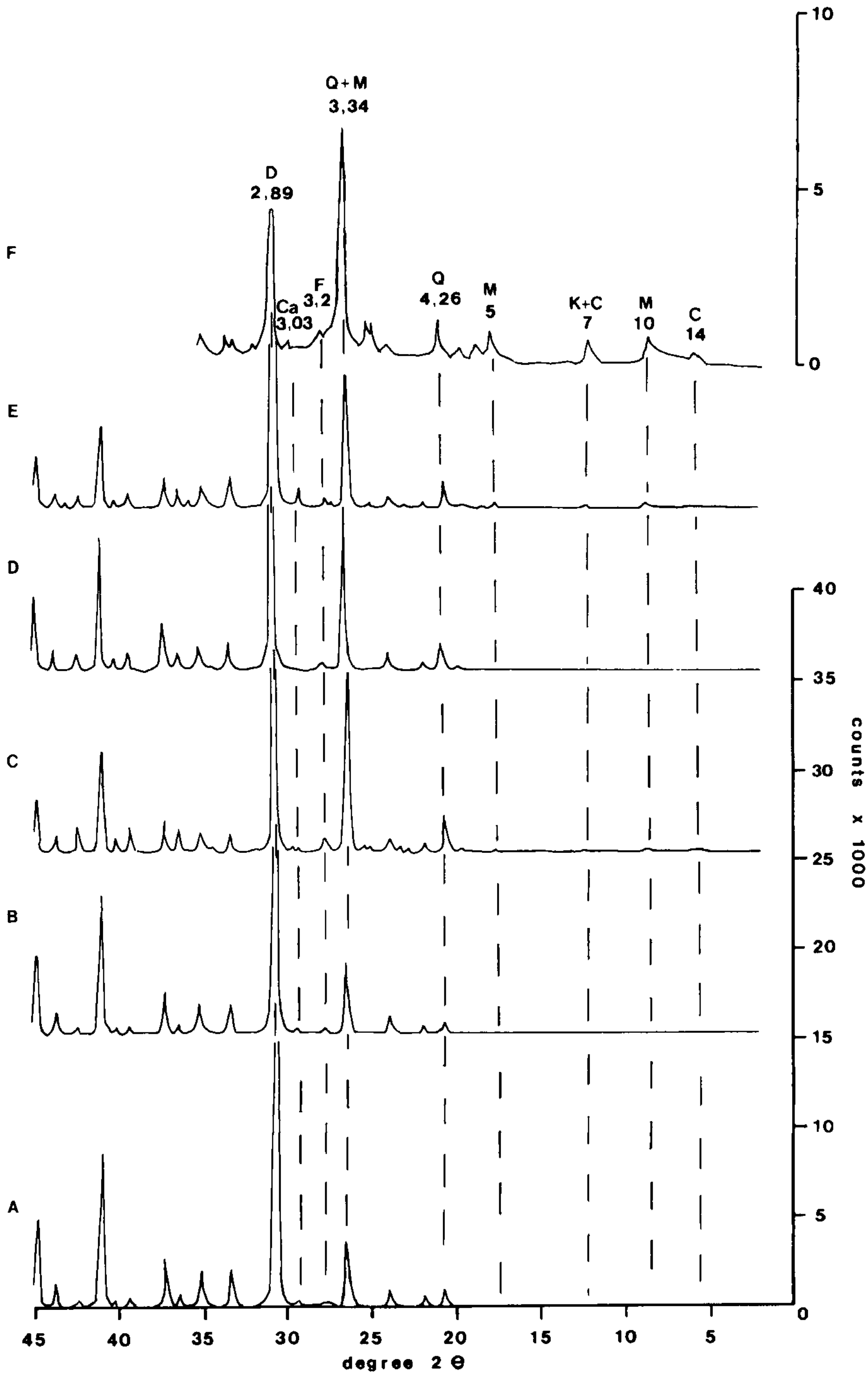

Fig. 6. X-Ray diffraction pattern of fines from soil horizons and sorted circles. Samples A to E, pulver sample (<63 μ). Sample F, oriented sample of clay fraction, untreated. A = dolomitic bedrock. B = domain from circle developed in weathering material. C = domain from section 1 cf. Fig. 3. D = silt accumulation in hydromorph soil (33 m a.s.l.). E = silt accumulation horizon of soil developed on 36-m-beach ridge. F = same as E, but fraction less than 2 μ. Labels of the peaks: M = mica, K/C = kaolinite and chlorite, Q = quartz, F = feldspars, Ca = calcite, D = dolomite.

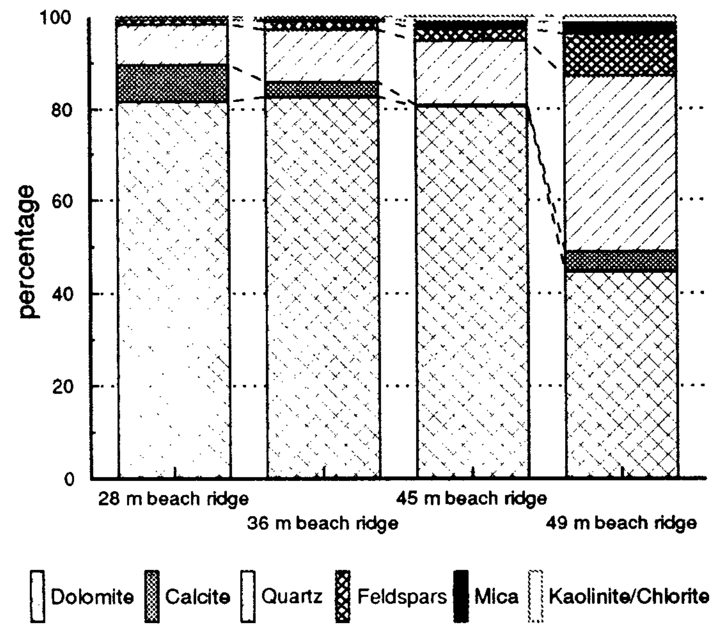

Fig. 7. Relative intensities of randomly oriented bulk samples (fraction < 63 μ) of the B_1-horizon of undisturbed soils developed on the main beach ridges on Kvadehuksletta. The relative intensities are expressed in percentage of the total sum of the intensities of the shown minerals.

in the randomly oriented bulk samples (Fig. 7) and in the oriented samples of the clay fraction. The amount of clay minerals is almost negligible in the Late Weichselian and Holocene areas of Kvadehuksletta, excepting some mica, kaolinite and chlorite inherited from bedrock. In this fraction dolomite and quartz dominate, with a higher quartz content relative to dolomite. The relative amount of clay minerals and feldspar seems to increase in the silt developed on older beach terraces above 45 m a.s.l. A possible time dependence of the mineralogical contents of the fines will be discussed in a later paper.

To test the hypothesis of the silt mainly being a residue of carbonate dissolution, a dissolution test was carried out. Here crushed dolomite rock fragments and pebbles from beach sediments (fraction 4–8 cm) were treated with a light acid (pH 2.5) over a period of one week. After this period a considerable amount of residue was produced, which could be analysed by grain size and mineral distribution. Knowing that the chemical conditions of the test did not represent natural conditions, the results of the analyses showed, however, similar values as those obtained from field samples, with a low clay content and the mode of the distribution in the medium to coarse silt fraction. The test indicates that the dissolution of the dolomitic bedrock on Kvadehuksletta preferably produces a residue rich in medium to coarse silt.

Discussion

Goldthwait (1976) defined the sedimentological prerequisites for the development of frost-sorted patterned ground as primarily being the existence of poorly sorted, heterogenous sediments with a relatively high amount of silt and clay (more than 15%). According to Washburn (1980) the amount of silt and clay is important for effective frost heave and frost sorting. Most sorted forms described in different studies are observed in areas dominated by till; till normally satisfies the above-mentioned granolumetric conditions (e.g. Ballentyne & Matthews 1982; Harris & Cook 1988; Karte 1979).

Fines are originally lacking in the marine beach deposits on Kvadehuksletta. The accumulation of silts in areas where networks of sorted circles are abundant can be explained as being an older sediment layer, the result of secondary translocation processes by slope wash or sub-surface drainage, or the result of in situ weathering. The silts can be of marine origin, deposited before the Pleistocene beach sediments. A *stratigraphic silt-rich layer* beneath the beach sediments was, however, not verified elsewhere in the study area. Sections along the rivers show the beach sediments resting directly on the bedrock. The terrain depressions behind the fossil beach ridges represent a similar coastal environment as observed around the recent beach ridges, with the existence of lagoon lakes behind a beach berm. There, one would, theoretically, expect to find fluvial or lacustrine sedimentation of silt rich fines. If this is the case, one would expect stratigraphic silt layers in or on top of beach sediments with a relative high degree of sorting. This was not observed in the field. Hand-augering on several sites shows that the silts are accumulated as pore fills in the gravelly surficial material, resulting in low sorting values of the material. Drilling in the present lagoon lakes would give a better answer to the last proposed theory. The above observations indicate, however, that the silt accumulation is due to other processes than marine or lacustrine sedimentation.

Field observations and laboratory analysis indicate that the silt in the centres of the sorted circles is of the same origin as the pedogenetic silt described in the soils developed on the beach ridges. The fines in the domains of the sorted circles are therefore also inferred to be originally a weathering product due to chemical dissolution of the dolomitic bedrock and dolomitic gravel in the surficial material. The feldspar and mica content indicates, however, that frost shattering occurs as well as the proposed dissolution of carbonates, since these minerals are considered to be inherited from the clastic pebbles in the surficial material. Formann & Miller (1984) assume, however, that chemical dissolution produces more silt-sized material on Kvadehuksletta. That processes other than frost weathering can be of importance in cold climates, at least in carbonate sedimentary rocks, is confirmed by the results of laboratory studies obtained by Fahey & Dagesse (1984), who showed that adsorption-related processes during oscillations of relative humidity and temperature can contribute to particle disintegration.

On the basis of these observations the fines are believed to accumulate both by in situ weathering and by slopewash with later sedimentation in the coarse beach and fossil fluvial sediments in terrain depressions. The grain size distribution of the surficial material then changes from a relatively well-sorted gravelly sediment to a poorly sorted material with a bimodal grain size distribution after the accumulation of fines. This distribution matches the sedimentological prerequisite described by Goldthwait (1976) for the development of frost-sorted patterned ground. When the silt content passes a certain limit, frost action can progress. This limit is estimated to be between 10–12% silt and clay for the beach sediments, and is evidently reached when all macro pores in the gravelly surficial material are filled with fines. The water capacity then increases rapidly and favours further frost processes. The grain-size distribution of the silt rich material of the circle domain and the lower silt limit proposed here correspond with observations from other areas (cf. Ballentyne & Matthews 1982; Goldthwait 1976; Harris & Cook 1988; Nicholson 1976; Washburn 1988). Common for these observations is the presence of silt-rich fines in the circle domain, confirming the importance of the presence of silt-rich fines for the dynamic of frost processes (Washburn 1980).

In more or less constantly moist areas, the lithological composition of the bedrock and the surficial material play an important role, both for frost processes and for the genesis of fines. The hydrological conditions not only govern the frost activity in the ground but also the production of fine-grained material. In terrain depression, in addition to the proposed translocation of silt, there will be a constant water supply from reactive snow and permafrost meltwater, at least in the late spring. This favours carbonate dissolution and in situ production of silty residue from the dolomitic limestone. This process will continue until a supposed upper limit of silt accumulation is reached.

Based on data from published studies, the features described above, and observations from sections dug in undisturbed soils and certain sorted circles in different stages of development, the following development pattern of sorted circles on Kvadehuksletta is suggested (Fig. 8). The sorted circles develop from a stage where gravelly sediments overlie fine-grained material. The fines are originally produced by in situ weathering and accumulated either by soil processes in a silt horizon or by slope wash and sedimentation of fines in terrain depressions. This results in a higher frost susceptibility in part of the soil and leads to vertical and lateral mass displacement or differential frost heaving. A dome of fines is formed, which migrates upwards, eventually reaching the surface, producing patterned ground (Sollid & Sørbel 1988). The concept of vertical and lateral

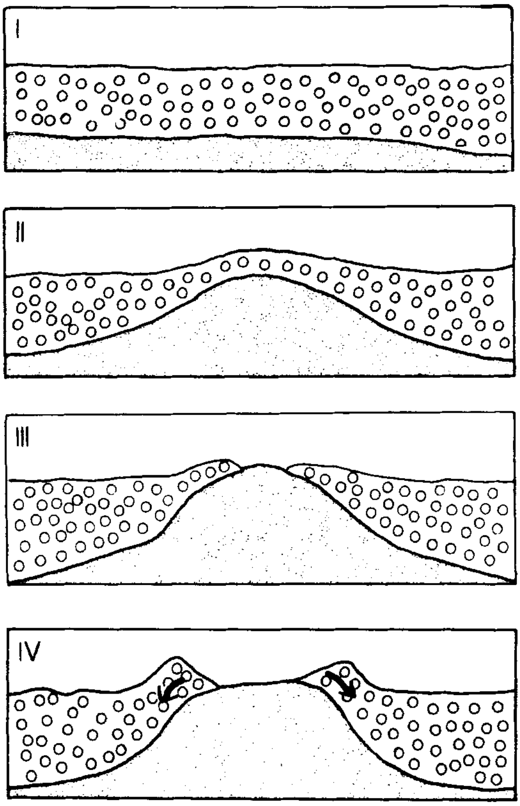

Fig. 8. Stages of the development of sorted circles (from Sollid & Sørbel 1988, modified). I = Initial stage of silt accumulation and vertical sorting. II = Vertical and lateral mass displacement. III = Early stage of the development of sorted circles, forming a mud boil which reaches the surface. IV = Later stage, with development of circle borders.

mass displacement in periglacial soils was discussed by Gripp & Simon (1934) and later used to explain the development pattern of sorted circles and other forms of patterned ground (cf. Jahn 1975; Van Vliet-Lanoë 1988; Washburn 1988). Recently, convective processes due to a density gradient in the soil are suggested to be a main factor in the development of sorted circles (Andersen 1988; Hallet & Prestrud 1986; Hallet et al. 1988).

It is supposed that the sorted circles are initially formed in a relatively short period of time. They probably then reach a mature state with little further change in their pattern. This would explain the small differences of the fine-grained material in the circles covering the study area. It is further suggested that the development of the circles starts after a certain limit of silt accumulation has been passed. The amount of silt accumulated in the surficial material is therefore one of the main factors that influences the development and the pattern of distribution of sorted circles on Kvadehuksletta.

Conclusions

On Kvadehuksletta the development of frost-sorted patterned ground is directly related to the accumulation of fines, which seems to be a residue of the weathering of bedrock and autochtone dolomitic surficial material. This study suggests that chemical dissolution can be an important factor, even for the dynamics of cryogenetic processes. Together with other geomorphological processes, such as slope washing, weathering is a prerequisite and source for later frost sorting and mass displacements in the soils of Kvadehuksletta. The dolomitic limestone is therefore supposed to be a major controlling factor for frost processes on Kvadehuksletta; this emphasizes the importance of bedrock petrography and sediment lithology for the distribution pattern of patterned ground on Svalbard.

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