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OPEN FISSURES IN A POLYGONAL NET ON THE NORWEGIAN ARCTIC COAST

INTRODUCTION

In connection with an inventory of large-scale polygonal ground in northern Norway, using aerial photographs, a small area of tetragonally patterned ground was observed at the village of Karlebotn in the inner part of the Varangerfjord (70°10′N., 28°30′E.). The polygons are situated in the distal part of a vast late-glacial delta which has been built up in front of the bordering mountains on the southern side of the fjord (Pl. 1). The delta plain is bounded by a wave-eroded slope. The height of the delta surface at the locality of the polygons is 72—73 m above the present sea level.

SUMMER OBSERVATIONS OF THE POLYGON SURFACE

In aerial photographs on the original scale (1 : 20,000), the pattern appears very faintly but emerges clearly by enlarging the photograph (Pl. 2). In the field it can be identified as shallow furrows (Pl. 3) with a somewhat denser vegetation and a peat layer a few centimetres thick in the bottom.

At the first field inspection (July 1962) the occurrence of open fissures in some of the polygon furrows attracted especial attention. These fissures regularly ran in the middle of the furrow and had a rectilinear course, though smaller irregularities occurred. The fissures did not leave the furrows. In some cases short fissures could be found in places where no polygon furrows existed. The walls of the fissured peat were rough, and the width varied

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accordingly. On an average the fissures could be considered as being 5 mm in width.

The observations represented a summer situation with only little precipitation. It was therefore easy to associate the fissures with the desiccation of the peat. The loss of water from the very wet period during the melting of the snow and the frozen ground to the very dry stage in summer would effectively change the volume of the peat.

The fissures could thus be suspected to be a desiccation phenomenon. In favour of this conclusion were also the facts that the fissure walls were rough and split up and, above all, that the fissures could not be followed downwards into the moister mineral soil. Furthermore no permafrost was found in the 1-metre-deep test pits that were dug.

According to this interpretation, the fissures would have no connection with the polygon formation proper or with a possible ice-wedge formation, which postulates a cracking of the ground. The fissures would only be a secondary feature, due to the occurrence of a substance (the peat) highly sensitive to desiccation.

OBSERVATIONS OF THE POLYGON FIELD IN LATE WINTER

In order to shed light on the problem, it was necessary to inspect the area in a late-winter or early-spring situation. Such an inspection was made in April 1965.

The distal part of the delta plain was on that occasion free from snow. On the bordering slope of the surface there were great masses of wind-accumulated snow. The interior of the delta surface was still covered with snow. Apart from local variations, the snow cover was 10—20 cm thick. This distribution of snow between the distal and interior parts of the delta plain seems to be significative of a more pronounced winter situation. According to information received from the people of the district, the whole surface is as a rule covered with a thin and wind-packed snow layer, but probably the snow cover is thinnest in just the distal part of the plain.

The frost table lay 5—10 cm below the surface in vegetation-covered parts of the plain. Below the uncovered parts it was found at a depth of 20—30 cm. The last few days had been unusually warm and there had been no frost during the night. The melting of the snow and thawing of the ground had thus taken place very rapidly. On this occasion there was melt-water in many of the polygon furrows, effectively reproducing the pattern (Pl. 4).

It showed that fissures occurred to a much larger extent than was observed in the summer situation. In all the examined furrows continuous fissures were found. In some cases the fissures were quite discernible as 5-mm-wide open cracks. In other cases they did not appear clearly, but the vegetation cover indicated a rupture in the ground, which could also be confirmed. If the spade was placed across the furrow and the ground was slowly lifted up, the vegetation carpet and the ground divided without any break along a clear fissure (*cf.* Pl. 4). It was of great interest to note that fissures occurred also in the water-filled polygon furrows.

It was noticeable that the fissures had a knife-sharp character, with quite even walls. In this respect the fissures clearly differed from the rough fissures in the summer situation. They gave the impression of being fresh formations.

The fissures did not diverge from the polygon furrows. Where such a furrow was abruptly cut by another furrow, the fissure also ended. The fissure pattern was thus fully accordant with the polygon pattern.

One might have been misled to consider the dry summer situation as determining the formation of the fissures; there was likewise a risk of classifying the phenomenon as merely a winter phenomenon. However, there are so many indications in favour of the winter alternative that the possibility of their being desiccation fissures can be dismissed. One such indication is the fact that the fissures also occur in the water-filled furrows. Furthermore the fresh character of the fissures means that they cannot be desiccation fissures from the previous summer.

Of great importance for the morphogenetic interpretation of the fissures is the fact that the mineral soil is found to contain a vertical ice-vein. This formation appears when the thawed peat layer is removed (Pl. 5), and it corresponds exactly to the situation and direction of the fissure. The ice-vein forms the direct continuation of the fissure down into the mineral soil.

The ice-vein is only locally constituted by pure ice. Mostly it is mixed with mineral particles but forms a quite clear ice filling, somewhat raised above the frozen ground surface.

PROBLEMS AND DISCUSSION

The fissures of the polygon furrows are doubtless the result of frost processes. The somewhat wider and rougher fissures from the summer observations are to be interpreted as winter fissures, subject to erosion and widening by the drying of the peat during the summer. The desiccation is thus only a secondary process.

The ice-vein which was regularly exposed on the removal of the peat shows great concordance with the fissure fillings and „ice nipples" that Péwé (1962, p. 70 ff.) described from recent ice-wedges in Alaska. Péwé found in his analysis of ice-wedge polygons a confirmation of Leffingwell's hypothesis "that foliated ground-ice masses form in seasonally recurring thermal contraction cracks in the perennial frozen ground" (Péwé, 1962, p. 74).

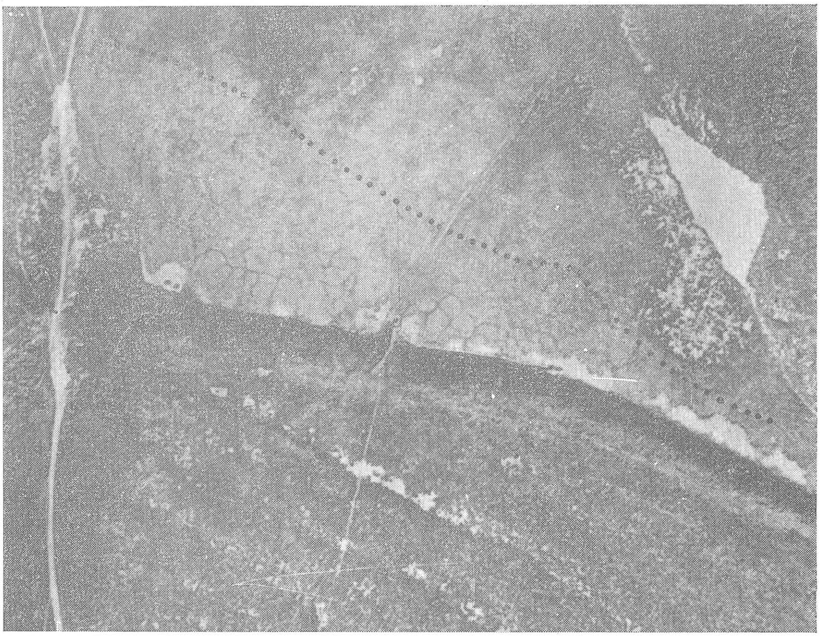
Against that background the occurrence of open fissures in the bordering furrows of the polygons gives us reason to discuss some questions of a climatomorphological character, such as: (1) Is the formation of the polygons a permafrost phenomenon? (2) If there is no permafrost present, may the fissures then represent the regeneration of cracking in fossil ice-wedge zones? (3) Is the formation of the polygons and their bordering furrows an active process? The second question is motivated by the occurrence of fossil polygons containing ice-wedge casts on the coast of the Varangerfjord (Svensson, 1962a and b, 1963).

(1) Of specially fundamental importance is the possible occurrence of permafrost. Permafrost occurs frequently in the peat bogs that cover large parts of the low-lying areas in the inner portion of the Varangerfjord. The permafrost here has the morphological appearance of up to 5—6 m high hummocks (palsas) (Svensson, 1962c). The nearest palsa area is situated only 700 m from the polygon field. The existence of palsas indicates sporadic permafrost, and it may be suspected that the area is situated so near to the marginal conditions for the formation of more general permafrost (even in minerogenic material) that the annual *tjäle* in suitable localities and/or in favourable years may be converted into permafrost. This may mean that the polygons in question are a recent or subrecent phenomenon.

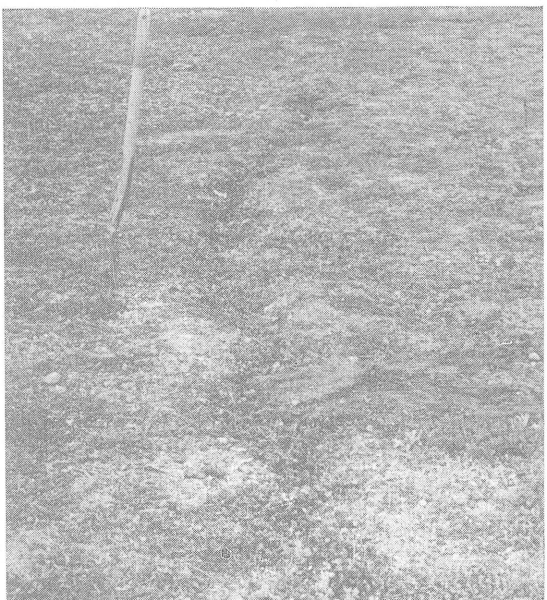
In climatological judgements of the possibilities of permafrost the mean annual temperature is often used as a starting-point.

Photo Wideröes flyveselskap, Oslo

Pl. 1. Aerial photograph from Karlebotn, Varangerfjord, with the delta surface at the top of the figure. Appr. scale 1 : 10 000. The situation of Pl. 2 is marked by a rectangle

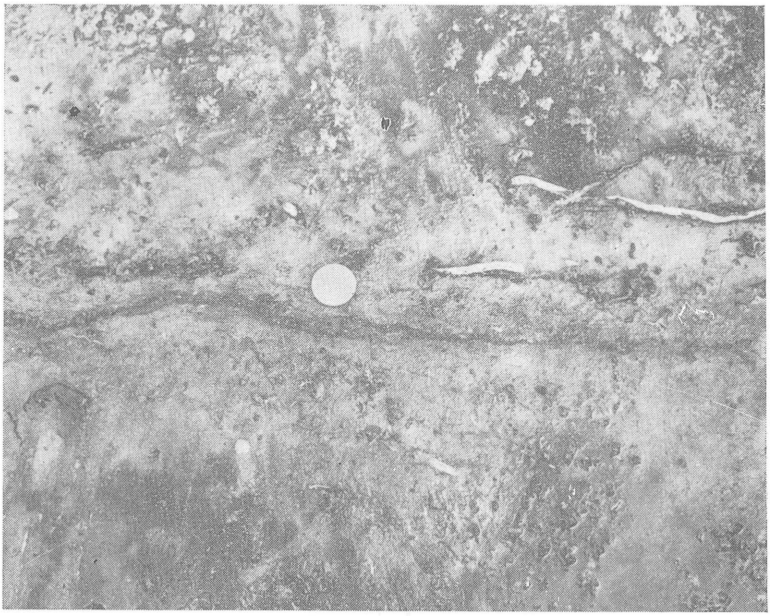


Pl. 2. The front part of the wave-cut delta surface with the polygonal net. Appr. scale 1 : 4000

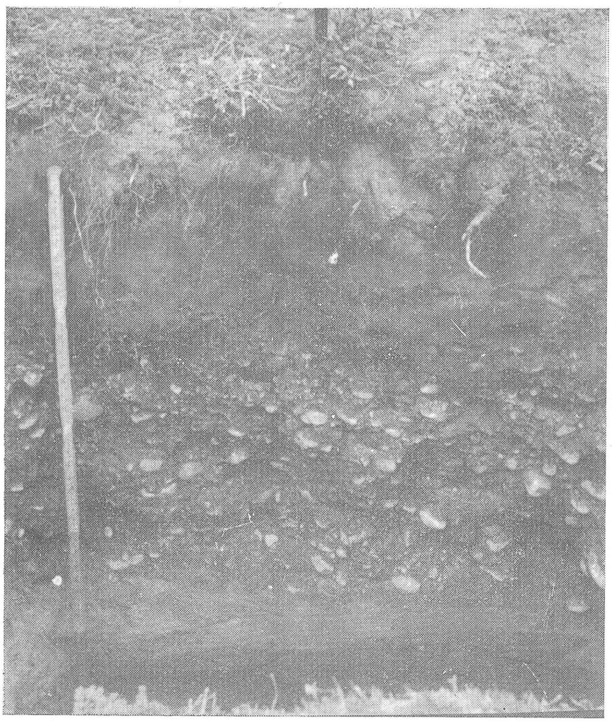


Pl. 3. A polygon furrow in the delta surface (July 10th, 1962)

Pl. 4. Part of the polygon surface. The polygon furrows are filled with water (April 23rd, 1965)



Pl. 5. View on the horizontal, frozen soil surface after the removal of the covering peat. The dark band through the picture (below the coin) is an ice vein (April 23rd, 1965)



Pl. 6. Vertical section below a polygon furrow (September 11th 1965)

In the area of investigation there is unfortunately no meteorological station to-day. At the nearest stations, Tana (20 km to the northwest) and Kirkenes (60 km to the southeast), the mean annual temperatures (1901—30) are 0.0 and 0.1°C respectively. At the Nyborg station (8 km north of the area) a mean annual temperature of —1.5°C has been reported for a short period comprising 6 years (with interuptions) in the second part of the 19th century. The mean annual precipitation for Tana is 423 mm and for Kirkenes 402 mm. 30—35% of the precipitation falls in the period November—March.

In investigations in recent permafrost areas, estimations have been made of the mean annual temperature required to produce perennially frozen ground. The temperature values differ, which is quite natural, because of the other parameters, such as snow cover, moisture conditions of the ground, and type of soil or terrain, that are integral to the conditions for permafrost. Temperatures of 0 to —2°C are often advanced. Brown (1966, p. 11) gives the —1°C mean annual air isotherm as the limit of discontinuous permafrost in southern Canada.

The climatological conditions required to produce permafrost are more rigorous than those which are needed to maintain permafrost, and for the formation of ice-wedges, as shown by Péwé (1962, p. 68), still lower mean annual temperatures are required (—4.7°C in the Galena area). In his paper on the palaeoclimatic significance of fossil ice-wedges, Péwé gives —6° to —8°C as the mean annual air temperature for the area of active ice-wedges in Alaska.

The occurrence of permafrost in minerogenic soil is still very little known in Scandinavia. The most detailed investigation has been made by Annersten (1965) in Padjelanta (*cf.* Rapp & Rudberg, 1964 p. 79 ff.), an area of the Scandinavian mountain range (67° N). By making temperature measurements at different depths in the ground Annersten has discovered permafrost in plateau surfaces about 700 m above sea level. The mean annual air temperature is supposed to be —3°C to —4°C and the mean annual precipitation maximally 1200 mm. The formation of permafrost in this locality is facilitated by the high proportion of silty sediments (*cf.* Rapp, *et al.*, 1962). In Iceland Thorarinsson (1964) has observed ice-wedge polygons in areas close to the 1°C mean annual isotherm. These polygons are formed in loessial soil. Thorarinsson states that „a considerably more severe climate is needed for the formation of ice-wedge polygons in the subsoil of Iceland than for the formation in loessial soil" (Thorarinsson, 1964 p. 335).

In extremely cold years the mean annual air temperature may clearly be below zero in the Varangerfjord. Within the standard period (1901—30) Kirkenes has for some years had a mean annual temperature of about —2°C (—2.5°C being the lowest). The mean annual number of days with frost is as high as 218.3 and 221.0 for Kirkenes and Tana respectively. For comparison it can be mentioned that the mean annual number of days with freezing temperatures in the recent permafrost area at Galena (Péwé, 1962, p. 68) is 228.

The meteorological data available for the area and mentioned above show that the conditions for the formation of more general permafrost (besides that in peat) may not exist, and in any case the climatic conditions are insufficient for the formation of ice-wedges. However, it is not out of the question that the frost may penetrate the even sediment surfaces to such a depth that the *tjäle* may remain during a cold summer to a depth of 1 m or more. This is valid especially for surfaces that only have a thin snow cover or are underlain by finely fractioned sediments.

Experience of digging to a depth of 1.5 m in July, August and September in different years, however, has not given reason to suspect permafrost in the ground in the polygon area. Nor have indications of perennial *tjäle* been observed in the neighbouring gravel pit.

(2) Some test pits have been dug, in order to study the stratigraphical conditions below the polygon lines. Below the sandy peat layer of the furrow, 7—10 cm thick, there followed a 25—30 cm sandy layer with no stratification (Pl. 6). Further down a 45—50-cm thick bed of stone and gravel was met with, which in its turn was underlain by stratified sand. No signs of interrupted or turned layers, as in the pseudomorphoses of ice-wedges, were seen in the section. In such a coarse material as the stone-gravel bed in Pl. 6 it may, of course, be hard to distinguish ice-wedge casts. Experience of ice-wedge polygons in the same material from other parts of northernmost Norway, however, shows that the contours of the casts are discernible (e.g. Svensson, 1962b) and are often also further clarified by the contrast afforded by

precipitated iron oxides between the wedge and the side soil (*cf.* Maack, 1967; and Öhrngren, 1967). The disturbed orientation of stones in bedded sediments (Maack, 1967) may also give indications of indistinct ice-wedges. In the vertical section (Pl. 6) anyhow an ice-wedge would have left clear traces in the well-stratified sand bed at the bottom of the pit.

In conclusion, it may be stated that the polygons are not caused by recent permafrost, nor are the furrows remnants of earlier permafrost of the ice-wedge type. The recurrent fissuring in the polygon furrows, however, is a recent frost process.

(3) In the literature frost-caused fissure polygons with no ground ice are mentioned by Leffingwell from the Canning river region (Leffingwell, 1919, p. 211). Hopkins *et al.* (1955, p. 139) state that „frost-crack polygons are common in all permafrost zones and may be found locally in the permafrost-free zones of Alaska".

From the terminological point of view it seems appropriate to classify the polygons investigated as frost-crack polygons in the sense of Hopkins *et al.*, who put forward three types of contractional polygons, the above-mentioned frost-crack type and two types of ice-wedge polygons, high-center and low-center polygons. "If the ice fillings of the frost-crack polygon persist through the following summer and become enlarged during subsequent winter freezing cycles, an ice-wedge polygon is formed" (Hopkins *et al.*, 1955, p. 138).

Even in the frost-crack polygons a certain wedging process must take place on the closing of the fissure by ice. Dylik (1966, p. 248) relates an investigation by Pataleiev (1955), who has studied frost-crack polygons in a permafrost-free area in the Far East. Pataleiev has stated that the fissures are filled with minerogenic and organic material, so that the cross-section shows the outline of a bedded wedge. On the basis of this fact Pataleiev gives the following explanation of the formation of the polygon furrows (cited from Dylik, 1966): In the spring, the open fissures become filled with water, carrying fine mineral material and organic remains. This infilling prevents a closing up of the fissures under the pressure of the adjoining masses of seasonally frozen ground, whose volume expands as a result of melting. Inhibited along the walls of the filled fissures, that pressure causes its deformation in the direction of least resistance, as a result of which swellings are formed on the surface, along the fissures—furrows, that border the polygon centers.

In vertical sections of the frost-crack polygons in the Varangerfjord area no „bedded wedge" has been observed. In the uppermost part of the section there are, however, traces of a small funnel-like form in the sandy soil. Below the peat layer, in the middle of the furrow, the brighter, leached sand thus goes down to a tip (Pl. 6). The contour, however, is so indistinct that it cannot indubitably be described as a small wedge formation [1]. It is, however, in just this part of the furrow that the ice-filled fissure (Pl. 5) occurs, and it is an inevitable conclusion that the funnel-like formation is a consequence of the frost-cracking and ice-closing process in the furrow.

The formation of the shallow polygon furrow itself must also be interpreted as the result of this process. Because of its recurrence, the wedging activity of the freezing water will involve a consistent pushing aside of the soil bordering the walls of the fissure. Even though the result of this process each year is very small and infilling may also take place from the side and restrict the result, it will in the long run mean a lateral displacement of the soil in the superficial layers, causing the growth of a shallow, linear depression.

The situation of the polygons in the outer part of the wave-eroded delta surface may give reason for some concluding remarks on the influence of topographical and local-climatological conditions on the formation of frost-crack polygons.

The area was visited after the very severe winter of 1965—66 and it could then be stated that — as in earlier observations — fissures occurred in the polygon furrows. It turned out, however, that the fissures now penetrated further into the plain and thus could be seen where no polygon furrows existed. In Pl. 2 the limit of the observed new fissures is outlined. The distribution of the fissures (and the polygons) is clearly an effect of exposure. The formation of polygons has been initiated from the edge zone of the surface. During normal winters, fresh cracking regularly takes place in this frontal part of the delta and in extremely cold winters is able to continue into the plain.

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[1] A more distinct wedge formation in sand has recently been described in northern Finland by Seppälä (1966). The observation is very interesting, but to classify the form as an ice-wedge seems questionable.

A further effect of exposure can be observed in the fact that the zone in which the fissures occur (and also in the zone of polygons) has no uniform breadth along the delta front but, on the contrary, runs obliquely into the surface (*cf.* Pl. 2). This is due to the fact that an old beach terrace extends in over the delta surface. The white, wind-blown surface of Pl. 2 is a part of this terrace. Below the beach terrace and from its edge out into the plain, snow accumulates in winter. The snow cover thus becomes thinner in the direction of the bordering edge of the delta plain. The insulating effect of the snow consequently diminishes in the same direction and so the most distinct polygons are situated at the very front of the delta surface.

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