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SELECTED FORMS OF FROST SORTING IN THE MARGINAL ZONE OF FLAAJÖKULL (ICELAND)

Abstract

In the moraines of the Fláajökull glacier (Iceland) authors observed many forms that were induced totally or partly by the frost sorting processes. These forms were divided into the following groups: stone filled nests, sorted circles, sorted nets and different kinds of sorted stripes such as: soil-stone, and pebble-stone stripes, and stone filled furrows. The degree of evolution of these forms was noted as well as the frequency of their appearance on the moraine ridges of different age.

INTRODUCTION

In the summers of 1997[1] and 1998[2] the field studies were conducted on the end moraine area of the Fláajökull glacier in Iceland (DĄBSKI, FABISZEWSKI, PĘKALSKA, 1998). The glacier flows from south to east from the Vatnajökull icecap. Its marginal zone is developed on the coastal plane, on the altitude of about 40 m a.s.l. The Icelandic permafrost does not extend on that area.

The moraine ridges were marked with the numbers from I (the youngest moraine and closest to the glacier) to V (the last ridge – about 1.5 km away from the glacier). The latter ridge, as estimated, was created in 1870. Additional calculations of the varves in the clay sediments between the IIIrd and the IVth ridge gave the mean of 87 annual varves. This confirms the previously estimated date of the development of the IVth ridge – the first decade of the XXth century. The IIIrd ridge was formed probably during the years 1930–1934 and the IInd ridge – probably in 1943 (DĄBSKI, FABISZEWSKI, PĘKALSKA, 1998).

The southern part of Iceland is characterised by a cold maritime climate. The meteorological data from the nearest meteorological station in Hólar i Hornafirði (about 30 km from the area of interest) pertaining

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to years 1966–1995 were utilised to approximate the climate of the study area. The influence of the glacier was taken into account. The mean annual temperature is +4,4°C (the mean temperature for January is –0,2°C and the mean lowest temperature is –2,8°C). The mean number of days with the temperature < 0°C for July and August is 0, maximum number of days with the frost in a year occurs in December and is 22. The mean annual amplitude is 10,4°C, the mean daily amplitude is 5,1°C, and the mean annual rainfall – 1474 mm.

THE PURPOSE AND THE METHODS OF THE STUDY

Observation of the frost-originated forms and their variability depending on the duration of their formation was performed in the field. The degree of evolution correlates well with the age of the moraine on which the forms appear. The excavations were performed, the dips and the strikes of the longer axes of boulders were registered, and the samples for laboratory analyses were collected. The findings were registered with the photographs, notes, and drawings. Results of the sieve analyses are presented in the chapter: "Final conclusions" (Fig. 2). In order to register the effectiveness of the upfreezing and then frost weathering, stones with the diameter >30 cm were counted in 12 representative fields of 100 m^2, established on the moraines of different ages. At the same time the degree of frost weathering was registered (Fig. 1).

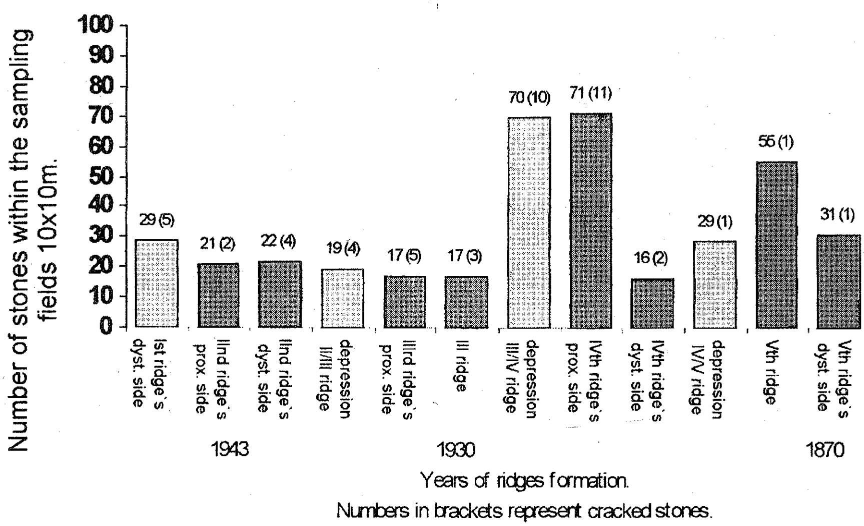

Fig. 1. Stones with the diameter >30 cm, occurring on the moraines of various ages

Most stones that up-froze to the surface of the moraine were found in a depression between the IIIrd and the IVth ridge and on the proximal slope of the IVth (northern exposition). Instant decrease of the number of the fresh, not weathered stones, towards the Vth ridge is accompanied by the increase in the number of wholly disintegrated forms which were not taken into account (Fig. 1). The next increase in the number of fresh stones on the Vth ridge can be explained by the difference in lithology. Some stones disintegrated due to their strong susceptibility to the frost weathering, leaving only the more resistant ones. On the young moraines, with the tendency to increase in the direction to the glacier, the number of stones partly weathered (such stones were taken into account) is noticeably greater (Fig. 1). The authors are inclined to explain the small total number of stones present on the surface of the IInd and the IIIrd ridge, by the initial stadium of upfreezing. The stones laid there by the glacier are already disintegrated, while the new ones have not had enough time to up-freeze and enrich the surface.

The purpose of the article is to present the chosen frost-sorted forms, that have the most distinct pattern and their composition, and relief seem to univocally suggest their origin.

THE CHARACTER OF THE SELECTED FORMS

From the various structural forms in the marginal zone of Fláajökull glacier the following punctual and linear forms were distinguished: initial forms of moss cracking, stone-filled nests, sorted circles, sorted nets and different kinds of sorted stripes such as: soil-stone and pebble-stone stripes and stone filled furrows. Distinction of those forms makes it possible to present the evolution of periglacial forms in a time cross-section, from contemporarily created forms on the Istridge, to the ones that have been formed during the last hundred years (ridge V).

PUNCTUAL FORMS

Initial forms of moss cracking

The often found moss cracking can be regarded as the initial stadium of some punctual forms (Pl. 1). The main process here is the upfreezing of the boulders and pebbles lying beneath the moss. In most cases the longer axes of the stones are vertical. This fact makes it possible to explain the phenomenon of mesh cracking by the upfreezing mechanism. Moving from the 1st to the IIIrd ridge one can notice the increase in the density of the vegetation cover of moss, lichen or little shrubs. However, going farther towards the last ridge, the vegetation cover decreases in density and

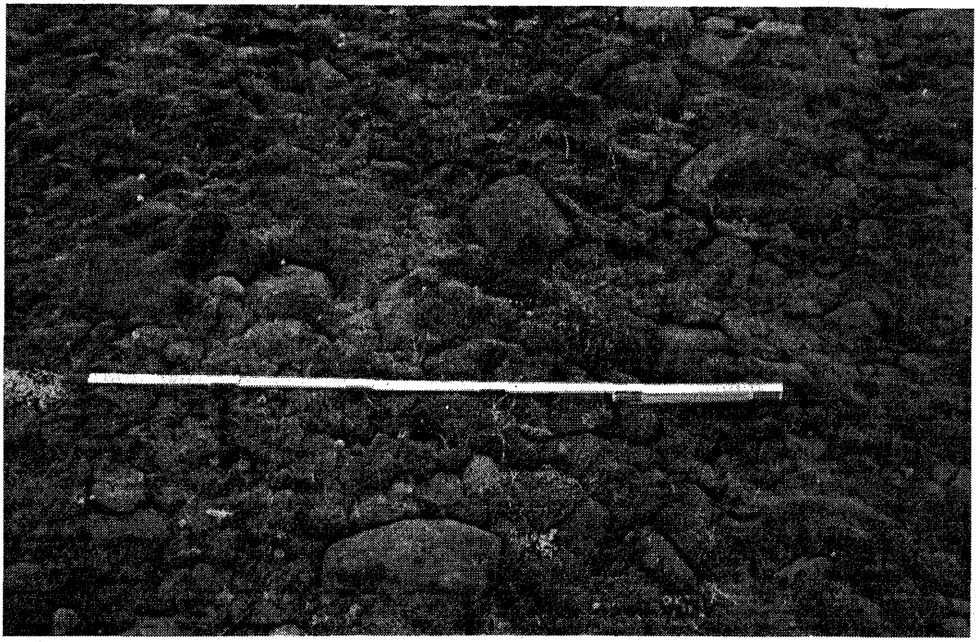

Photo by E. Gryglewicz

Pl. 1. An example of moss cracking

has only vestigial character on the Vth ridge. This is clearly associated with the gradual (the farther the stronger) destruction of the moss by the upfreezing stones. Therefore, there is a logical explanation for the moss cracking to occur most widely in the depression between the IInd and the IIIrd ridge.

Stone-filled nests with distinct boulder centre

The stone filled nests with a distinct boulder centre are found only on the IInd ridge (Pl. 2). The more developed forms of the nests are found farther away from the glacier in depressions, between ridges and on their edges. Between the IIIrd and the Vth ridge the nests also can be found on the slopes exceeding 10°. They are characterised by asymmetric structure and distinct content of sediments on their uphill sides. The diameter of such forms can reach 80 cm and the longest axis of the central boulder can measure up to 40 cm. A well-developed nest can usually be found around the biggest central boulder formed by vertically or obliquely lying smaller stones and pebbles (diameter – 20 cm). Two distinct phases of evolution of these forms were noticed: the young and the mature one. A shallow layer of fine gravel underlies the young forms found on the IIIrd and the IVth ridge (the big central boulder together with the stones consti-

Photo by E. Gryglewicz

Pl. 2. A stone filled nest with a distinct boulder centre

tuting the nest). This structure characterises all forms developed on a relatively young moraine. Another characteristic feature of young forms is a vertical segregation of the stones constituting the nest. The mature forms are found on the IVth and the Vth ridge. What distinguishes them from the young forms is a thick layer of gravel and pebbles under the central boulder as well as under the whole nest (Pl. 3).

The stone filled nests without a distinct boulder centre

These forms are similar to the previously described ones except that they do not have a distinct boulder centre (Pl. 4). Their centres consist of a few smaller boulders, none of them being distinctly the biggest. Such nests are found in depressions between ridges and on their edges. Two distinct stadiums of evolution of these forms were noticed. Young forms are found on younger moraine (ridges 3 and 4) and they are smaller: about 30 cm in diameter and about 35 cm deep. Their centre consists of a stone, relatively big comparing with the diameter of the whole form. The mature forms are found on the Vth ridge and they are much bigger. The diameter of the mature forms reaches 80 cm and the depth – 50 cm. The absence of the distinct boulder in the centre, together with a long diameter probably

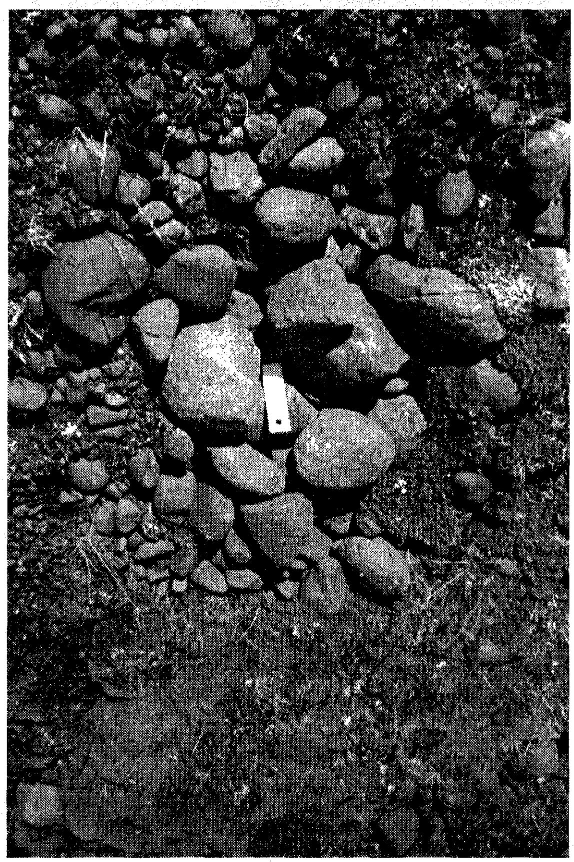

Photo by E. Gryglewicz
Pl. 3. A layer of gravel and pebbles underlying the central boulder

Photo by E. Gryglewicz
Pl. 4. A stone filled nest without a distinct boulder centre

weakens the forms, making them less stable. This is the reason for sinking of the surface of the forms down to about 5 cm. The common feature for the mature nests found on the Vth ridge is a distinct and thick layer of pebbles and gravel. All nests without a distinct boulder centre, irrespective of their age, are well vertically and horizontally sorted.

Nests with a granular disintegrated centre

These forms are found only in the depressions between the IIIrd and the IVth ridge and between the IVth and the Vth ridge. Such nests are characterised by the presence of the disintegrated central boulder of the diameter up to 70 cm forming a bulge up to 15 cm above the surrounding area (Pl. 5). The distinct vertical segregation was observed just like in the other mature forms. In case of the central boulder being not totally disintegrated, the presence of organica on the solid part of the boulder, a

Photo by E. Gryglewicz

Pl. 5. A nest with a granular disintegrated centre

few centimetres beneath the disintegrated surface, was observed. In other cases, if the central boulder was totally disintegrated, organica was not present, but only some moss or grass was observed. The presence of vegetation cover on the forms is an evidence for already inactive form, but on the other hand adds to its farther disintegration down to clay fraction.

This can lead to frost-segregated forms such as sorted circles. Nests with disintegrated central boulders seem to be the final stages of evolution of the punctual forms. Simultaneously, they can change into different forms of patterned ground.

The appearance of the nests in the water-saturated depressions is an evidence of the significant importance of water in their development. Repeated freeze and thaw cycles (the farther away from the glacier, the greater number of the cycles) reflect in the degree of the distinctiveness of the forms. One big boulder, or group of smaller boulders and stones, when freeze up can become a point of concentration of water, therefore increasing the effectiveness of the local frost heave. This hypothesis seems to explain the concentration of smaller stones only around the big boulder. Young moraine ridges, being exposed to freeze and thaw cycles for shorter periods of time, are the areas of the initial stages of the formation of the stone filled nests.

SORTED CIRCLES

The authors use the term "sorted circles" to describe the forms that are more or less circular. The term "sorted nets" could be used in some cases but, in authors' opinion, it would only make the description less clear since the forms vary in shape very much.

Small sorted circles

Sorted circles are commonly found in the area extending from the IInd to the Vth ridge. They occur generally in depressions between the ridges. The biggest circles are up to 60 cm in diameter, with most common size of 15 to 40 cm (Pl. 6). These forms consist of rather poorly developed circles of gravel and pebbles reaching the depth of 5 to 10 cm. It is difficult to say anything about the longer axes of pebbles. The older the moraine, the better-developed net of the circles can be found. The lack of a distinct difference in the composition of an individual sorted circle found on both the older and the younger moraine is an evidence for a short time of their development. However, some sorted circles can develop from the stone filled nests and have a different origin. Water is an important factor, since the circles are most likely to be found in flat depressions. Sorted circles originated probably from the differential frost heaving and frost thrusting processes.

Photo by E. Gryglewicz

Pl. 6. A small sorted circle

Large sorted circles

Large sorted circles are rather unique in the marginal zone of Fláajökull and are rather poorly developed. The biggest forms were found in the depression between the IVth and the Vth moraine ridge (Pl. 7). They are usually in a shape of an ellipse or resample the polygonal pattern. Their diameter is usually 4 to 6 m. The stony circles themselves run along shallow furrows. The internal mesh is usually bulged and covered with vegetation. In a few places one can notice joints between a circle and a stone filled nests and stone filled furrows (see chapter: "stone filled furrows"). Pebbles and boulders constituting a large sorted circle fill a form of a trench, about 30 cm deep and from 15 cm to 1 m wide. The measurement of the longest axes of the stones (6 cm < Ø < 30 cm) inside the trench showed that the most numerous are the vertical ones (50%) while the oblique ones are less abundant (31%). The stones were sorted vertically and horizontally, with the biggest ones situated on the surface and in the middle of the trench. It seems obvious, that in the development of the large sorted circle, the most important process is upfreezing of stones along the furrow. The dominant vertical setting of the stones is the evidence for such a mechanism.

In one location on the IVth ridge, a different form of a sorted circle was found. The circle was observed on a slope of 8° and had the diameter

Photo by M. Dąbski

Pl. 7. A large sorted circle

of about 1 m. The stones in a circle with the longest axes (6 cm < Ø < 20 cm) consist of 48% of the vertical ones, and 42% oblique stones. It is worth mentioning that among the oblique stones, the majority was tilted down-slope. This may be an evidence for solifluction. The stones filled a form of a trench 30 cm deep and 30 cm wide. Excavation of stones allowed observation of the uphill edge of the trench build up by the fine sediments.

The small and the large sorted circles seem to have a different origin. The small sorted circles are probably developed by an alternate frost heaving and thrusting. Their occurrence on the old and young moraines is the evidence of the brief period of their development. Possibly, some small sorted circles are developed from the stone filled nests. The stony circles around the large forms are found in furrows, where the upfreezing process is most effective. The initial process of development of the large sorted circles remains unknown. In some cases, when the circle is on a slope, the process of solifluction is distinctly marked.

LINEAR FORMS

In this chapter three types of linear forms are presented. Soil-stone stripes and gravel-pebbles stripes could be described as sorted stripes (Washburn, 1973).

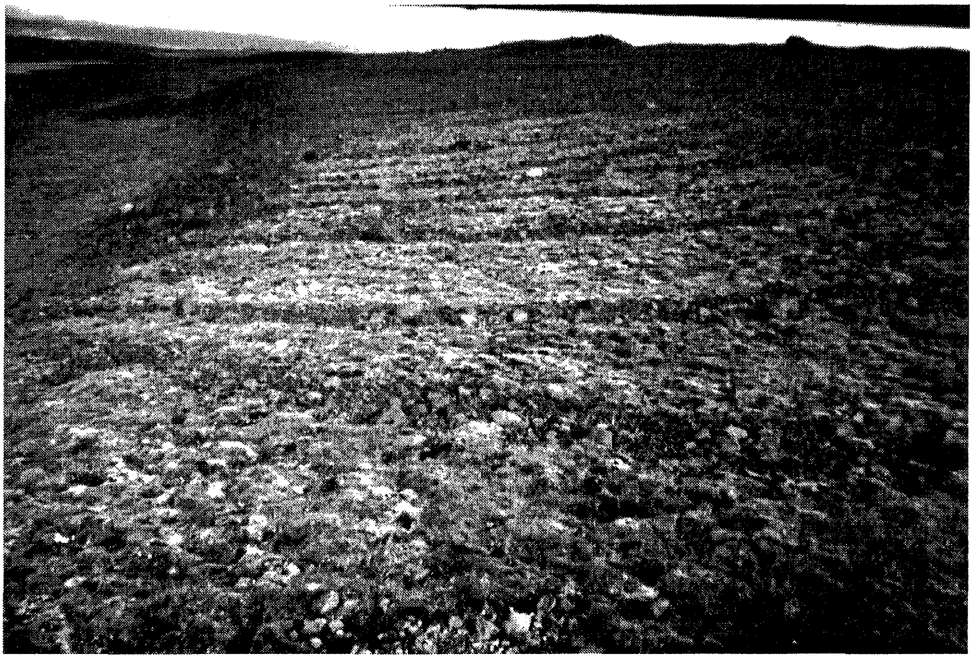

Photo by. M. Dąbski

Pl. 8. A soil-stone stripe

Soil-stone stripes

The dirt-stone stripes are found on the proximal side of the II[nd] ridge (northern exposition). They run, free from vegetation, parallel to the slope in the intervals of 1.5–2 m (Pl. 8). The mean width of the stripes is 60 cm and it ranges from 20 cm to 90 cm. Their maximum length is 16 m and the slope on which they appear is 13°. The stripes consist of sand, gravel, pebbles, and small boulders. The stones (from 6 to 29 cm length of the longer axis) show slight elongation parallel to the slope. The authors observed only horizontal sorting – there are no larger stones in the intervals, they are slightly concave and covered with moss.

Analogous forms of stripes were found on the eastern side of the roadbed connecting the I[st] moraine ridge with the II[nd] ridge. The stripes observed there run with the wider intervals up to 2.7 m. The stripes are shaped as a spindle and their maximum width ranges from 50 cm to 80 cm. They are 6 to 10 m long and are located on the 10° slopes. The large stones found on the surface of the stripes have the maximum diameter of 15 cm, but gravel and small pebbles outnumber larger clasts. The measurements of the longest axis of stones bigger than 6 cm showed, just like the measurements taken from the previously described stripes, their slight elongation parallel to the slope. Similar stripes were observed in other places of the marginal zone of Fláajökull, but they were not so distinct and well developed. The relief and the structure of the stripes and their immediate surroundings suggest the presence of the snowdrifts functioning during the winter and spring localised in shallow depressions between the stripes. The stripes teeming with larger stones probably develop in the process of accumulation of the coarse material that slides down the snowdrifts. The process of upfreezing enriches the moraine surface with the coarse material, which later on is transported down the snowdrifts and accumulated on the stripes. There are no stripes at the top of the moraine ridge. One can believe that the snowdrifts do not reach the top of the ridge. The fact, which supports this hypothesis, is a small number of days with continuous snow cover – 49 days per year (SZUMSKA, 1998) and the enrichment of the stripes with the coarse material. During the spring melting the stripes can function as a stream. A slight elongation of the longest axes of the stones parallel to the slope can support this hypothesis. In the summer the concave intervals between the stripes maintain the moisture, therefore creating good conditions for moss to grow. The original relief of the moraine ridges is shaped in a vicinity of the glacier. There is an intense linear erosion (the slopes are vegetation free and are 30°). The complex erosion channels found there can serve as an initial factor in the development of the sorted stripes (WASHBURN, 1973).

Gravel-pebbles stripes

In many areas on the proximal side of the Vth moraine ridge (northern exposition) the authors observed narrow sorted stripes that were often connected with the nets of small sorted circles of irregular shapes. The stripes are also found in the depressions between the ridges. The stripes are vegetation free and have varying widths (Pl. 9). The most distinct forms running down the slope can reach 4 m in length. In places where the slope becomes flat, between local culminations, the stripes change into irregular net and loose their distinct shapes. The widths of the stripes range from 20 cm to 50 cm. The widest forms are in places where two stripes merge. The intervals between the stripes are 20 cm to 80 cm wide. The cross sections of the forms showed that the gravel and pebbles stripes fill the trenches 20 cm deep. Distinct horizontal and vertical sorting of the filling is observed, with largest fraction at the surface and in the middle of the trench. The stones with the longest axes (5 cm < Ø < 20 cm) constituting the stripe are in 50–56% oblique, in 33–34% horizontal, and in 11–16% vertical.

In other places authors observed similar stripes connected with nets of small sorted circles (maximum diameter up to 50 cm) from which the stripes commence. Because of the little size of the mesh it can be assumed that the nets originated from the process of desiccation (in the vicinity of

Photo by. M. Dąbski

Pl. 9. A gravel-pebbles stripe

the forms authors observed typical desiccation cracks) and then they were filled with coarse material by the runoff (KRÜGER, 1996) and frost sorting processes which can be supported by the big number of oblique stones. The cracks that run down the slope can function as watercourses therefore getting rid of the fines (WILSON, 1992) and the cracks become trenches which maintain the moisture making frost heaving more effective. Cracks running across the slope become filled with fine material carried away by waters.

Stone filled furrows

Stone filled furrows (Pl. 10) are rather commonly found in the marginal zone of the glacier, but majority occurs on the IVth and the Vth ridge. In general, they are found on ridges between culminations or in depressions between the ridges. In many cases they coexist with stone filled nests and connect punctual forms with little lakes. The stone filled furrows do not create whole sets of parallel running linear forms like the sorted stripes. The stone filled furrow is usually a trench filled with gravel, pebbles and boulders. Its width ranges from 20 cm to 2 m, its length – from 1 m to over 50 m (in places where the form appears in the main stream, between ridges). Stones usually have the diameter of 20 cm

Photo by M. Dąbski

Pl. 10. A stone filled furrow

to 27 cm, but one can also find a boulder larger than 50 cm. The cross sections showed that the trench is about 25 cm and in places where two furrows merge, the depth can reach 65 cm. The set of the stones filling the trenches is mostly oblique, then vertical, and the least numerous – horizontal. In areas considerably deep in the trench, the stones appear to be sorted. The deeper the finer gravel can be found and the axes of the pebbles get more vertical. In a few places authors noted that the longer axes of the stones were parallel to the axes of the furrow and they overlap each other as they were inclined in the direction of the water current.

Considerably greater share of the oblique and vertical stones is an evidence of the upfreezing process taking place. Simultaneously, the appearance of the stone filled furrows in the stream and the parallel setting of the stones show that the water flow is also a shaping process. Lowering of the furrow's surface in some places can be an evidence of rillwork along the furrow. The linear water erosion that enlarges the trenches creating optimal conditions for accumulation of the upfrozen stones, is a possible cause of the development of some furrows. Solifluction potentially also has its share in shaping of the furrows. In a few locations, the authors noted fine sediments partly covering the stone filled furrows.

The linear forms in the marginal zone of Fláajökull can be divided into tree categories: the soil-stone stripes, the gravel-pebbles stripes and the stone filled furrows. The process of desiccation should be considered as a possible cause for the development of some of the forms as well as the process of linear erosion that shapes the Ist moraine ridge. Further development of linear forms depends on the processes of frost segregation and work of flowing water setting the longer axes of stones and the rillwork. Some of the linear forms are developed due to the gravitational accumulation close to the snowdrifts or on the foothills of moraine ridges. The process of solifluxion should also be taken under consideration as one of the processes shaping the linear forms.

FINAL CONCLUSIONS

The occurrence of the frost segregated forms in the middle and sub-polar latitudes, outside of the permafrost range, has been noted previously (RAPP, RUDBERG, 1960; WASHBURN, 1973; WILSON, 1992; BALLANTYNE, 1996). Mainly THORARINSSON (1953, 1964) has undertaken the issue of the periglacial forms in Iceland.

Upfreezing plays a significant role in the development of the stone filled nests, sorted circles, stripes of different kinds, and stone filled furrows in the marginal zone of Fláajökull. Upfreezing is a swift process, and its results are visible in the moraines that are only 80 years old. The vertical and oblique settings of the stones and the granulometric com-

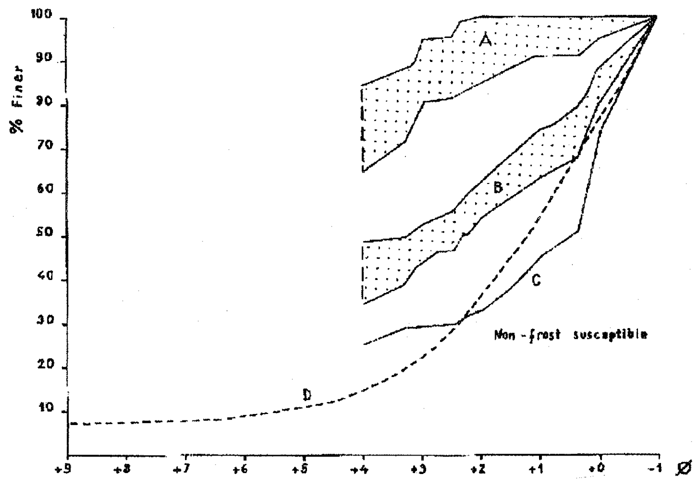

Fig. 2. Comparison of the results of the sieve analyses with the Beskov's curve (P. WILSON, 1992)

A – the range of the cumulative curves for 7 samples from the frost generated forms; B – the range of the cumulative curves for 6 samples from the forms generated through the frost processes, linear erosion, and solifluction; C – a cumulative curve for a sample from a form created by rillwork; D – Beskov's curve depicting the lower limit of the material's susceptibility to the frost processes position of the samples (Fig. 2) are the evidence supporting the hypotheses that the frost processes are crucial in the formation of the mentioned above structures. The graph shows a clear correlation between the prevalence of the fraction susceptible to the frost weathering and the forms created only through the frost processes (Fig. 2A). Successive decrease of the content of this fraction is consistent with the formation processes involved – frost weathering, surficial and linear, erosion and solifluction (Fig. 2B, C). Local climate, with many fluctuations of the temperature around 0°C and a high annual rainfall, creates suitable conditions for the frost processes to occur. Simultaneously, small amplitudes of the temperature < 0°C make it impossible for frost cracking to occur. The initial process of creation of the forms can be the desiccation cracking, the rainfall and the melt waters. The processes of desiccation cracking and rillwork can direct and strengthen the process of frost segregation.

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