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Morphostructural zones of the Mýrdalsjökull ice cap and its main outlet glacier the Höfdabrekkujökull, Iceland*

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Abstract: The problem of the morphostructures of glaciers is directly associated, certainly as far as its condition and origin is concerned, with topographical, geomorphological and geological rock foundations, surrounding those at the bedrock of glaciers and also, in case of valley and outflow glaciers, with those of the valley slopes. Such differentiation of the bedrock of the Mýrdalsjökull ice cap leads to a classification of its three morphostructural zones: the glaciomorphological centre (A) which has only slightly varied relief ($a_1 - a_4$), a northern homogeneous macro-cone of radial flow (B), and a bipartite, supramarginal surrounding slope (C), which has a significant development of outflow glaciers. This differentiation of the subglacial relief and the rocky surrounding of the Höfdabrekkujökull, are manifested in the distribution of various types of foliation and fissuring on its subaerial surface. These, together with its hypsometric formation, were the basis for distinguishing four morphostructural zones of this glacier ($H_1 - H_4$). The distinctive morphostructural features of the sector of the bottom zone (H_4) of the glacier determine the areas of its particular activity; this reflects the lithogenetic and morphogenetic nature of the subglacial bedrock. The deformed deposits of the bedrock and the nearest forefield represent an important dynamic effect of the glacial system.

Key words: Iceland, ice cap, outlet glacier, morphostructural zones, foliation, types of fissures

Introduction

The main areas of glaciation in Iceland are of cover type. There are four main ice caps: Vatnajökull (8300 km^2, 74% of the island glacial area), Langjökull (953 km^2; 8.5%), Hofsjökull (925 km^2; 8.26%) and Mýrdalsjökull (596 km^2; 5.32%), which are located in the southern and central part of the island. Altogether, they cover nearly 96% of the recently glaciated areas of the country.

The fourth biggest cap, Mýrdalsjökull, is located near the coast, its southern edge being less than twenty kilometres north of the southern coast of the island. It covers an active volcano Katla and its near surrounding.

The location of the Mýrdalsjökull indicates that, within the climatic zone of Iceland, it was formed in a different centre of precipitation culmination than the one over the Vatnajökull (>4000 mm/year), the second biggest in the country. This is quite important in respect of the size, balance and activity of the ice cap. The maximum precipitation level in southern Iceland (Wójcik, 1976; Björnsson, 1979) ranges on average for 60–70 days a year (1971–1980) over the whole area around Mýrdalsjökull. Einarsson (1988) described this as the "east", "south-east" and "south-west" type of weather. The precipitation lasts almost 80 to 100% of days within the period of such atmospheric circulation. It is those frequent and high precipitations in the mountain-upland and coastal areas of the southern Iceland which have produced the Vatna- and the Mýrdalsjökull ice caps. However, the climatic factor has not been the only one that has influenced spatial development and the structure of the ice caps.

Taking the Mýrdalsjökull as an example, the significant role of bedrock hypsometry and the degree of litho-geomorphological variety of the bedrock relief in the spatial development of ice caps in Iceland has clearly been demonstrated, particularly with regards to the formation and the size of its outlet glaciers. Geological, geomorphological and hydroglacial conditions on the surface of the interface between the ice cap or an outlet

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glacier and the bedrock vary significantly in time. This relates to persistent and active subglacial volcanism. Therefore, the role of bedrock elements is equal to or even more important than the role of climatic factors in controlling glacial dynamics and distribution of the ice masses, the amount of transported morainic material, the flow of meltwaters and deformation possibilities of outlet glaciers on the bedrock and adjacent forefield (Eythorsson, 1963; Thorar-insson, 1964; Rist, 1967a, 1967b; Sigbjarnarson, 1970; Price, Howarth, 1970; Jaksch, 1975; Kozarski, Szupryczyński, 1978; Björnsson, 1979, 1988, 1996; Price, 1982; Boulton, Harris, Jarvis, 1982; Heim, 1983; Williams, 1983; Krüger, 1985, 1994; Jania, 1993; Wiśniewski, Andrzejewski, Molewski, 1996, 1997). The complexity of the structure and its location in the south of Iceland are the principal influences for the development of that outlet glaciers as a major part of "outlet" systems of the Vatna- and Mýrdalsjökull ice caps, developed mainly in their south or south-east parts. The Höfdabrekkujökull is the largest outlet glacier of the Mýrdalsjökull ice cap in its south-eastern sector. This is the only outlet tongue of the cap which is a true piedmont type glacier (Björnsson, 1979; Krüger, 1994).

From a knowledge of the surface topography, the internal ice mass structure, the hydrology of the Hofsjökull and the relief of the bedrock of this ice cap, Björnsson (1988) considered that the morphostructural composition and the surface relief of the glacier were directly related to the relief and the structure of the bedrock. Although it is admitted that the present authors have had no access to any bedrock imagery, they nevertheless made an attempt to use the external features of that relationship to establish the relations between the surface relief and the bedrock and morphostructural zonality of the Mýrdalsjökull ice cap and its major outlet glacier i.e. Höfdabrekkujökull.

The concept "morphostructure" in geomorphology and glaciology

It is necessary, firstly, to explain the concept of **"morphostructure"**. In geology, a **"structure"** refers to the internal arrangement of rocks and/or sediments formed within tectonic, sedimentary or stratigraphic, petrographic or mineral units of the Earth's crust. **"Morphology"** is a descriptive term, a geomorphological concept and it is most frequently associated with a particular area or a relief-forming process e.g. "the morphology of the area is of crucial importance for a sedimentation process (...)" or "the morphological types of an area corresponds to the stages of a geomorphological cycle" (Turnau-Morawska, 1954, p. 66). Therefore structural geomorphology, based on geology, which determines the role of geological composition in the formation and durability of the relief, prefers a classical "morphostructural" approach to the basic subject of its investigation. Hence, in geomorphology the term **"morphostructure"** concerns the surface relief of the area being investigated, i.e. such a mode of formation of the "geomorphological horizon" of this part of the lithosphere where a deep structure and a tectostructure of rocks and sediments is particularly characteristic or exists on a large scale. A lineament morphostructure of a surface reflecting a series of large scale faults or straight parts of large valleys is an example of this. As the morphostructure of a geomorphological surface is mainly produced by endogenic factors (mainly tectonic), the concept **"morphostructure"** covers the phenomena of repetition and penetration through consecutive paleomor-phological surfaces (fossil relief) of explicit and older erosion forms, e.g. valley slopes and cliffs. Of course, it is axiomatic that the concept "lineament" is an important geological term as well as a geomorphological and glaciological one. Such concepts as "structural base level", "structural landform", "structural surface" or "structural control in geomorphology" are commonly applied in geomorphology. The latter, distinctive in a genetic sense, means in geomorphology "the influence of geological structures on the development and appearance of landscape" (Lattman, 1968, p. 1074).

In the case of the geomorphology of the lithosphere surface, the problem of the lack of zoning of the structural relief seems to be quite important (especially in case of zones of exogenous origin). However, when a more extensive characterisation of glaciers is necessary, especially in case of the larger caps of cover glaciation, which develop on a varying and endogenously active bedrock, it is possible to use, a morphostructural division into zones, as well as a standard **"glaciological zoning"** determined from the glacioclimatic and glaciohydrological points of view (Jania, 1986, 1987, 1993; Marciniak, Marszalewski, 1991).

The **"morphostructural zoning"** of ice caps e.g. Mýrdalsjökull, considers not only the "sedimentary-deformation structure" of the glacier (a), but also its surface relief, where it is formed as a "penetrative reflex of the subglacial bedrock relief, its structure and geomorphological dynamics" (b) which is not the only effect of a zonal record of the ice mass balance. Accordingly, many authors, including Rutter (1965), Jahn (1971), Klimaszewski (1978) and Jania (1993) have emphasised the dynamic character of the ice surface structure (foliation, fissuring). In this case "morphostructural zoning", if not in glaciology but at least in geomorphology (structural), may be regarded as a term closely complementary to the concepts developed by Florensov (1964, 1965; after Gerasimov, 1976b): "relief structure", "geomorphological structure" and even "geomorphological formation".

It will be noted that compositional and morphostructural elements of the surface relief of glacier are themselves of various sizes and genetic ranks. For example large scale, vertical differentiation of hypsometry and a degree of morphographic spatial development of various types of the bedrock relief are reflected in the macroscale phenomena of the relief structure of the glacier, i.e. in the course of morphostructural zoning of the glacier. On the other hand, even elementary vertical and linear components at a small scale, being minor phenomena in the bedrock, and seismic activity result either in smaller structural forms located in particular areas or in intensification of their morphostructural development, albeit at a significantly smaller scale (e.g. fissures). This type of relationship is confirmed by temporal and spatial associations, as well as a similarity in the scale of the earthquake in the vicinity of the Mýrdalsjökull, including that known to have occurred in the vicinity of the Höfdabrekkujökull (Kirki in the north and Skálarfjell in the south) in July and August 1988 and the icequake on the outlet glacier located between those areas (Bransdóttir, Menke, 1989).

Morphostructural zones of the Mýrdalsjökull

The Mýrdalsjökull ice cap and its smaller neighbour, located to the west, the Eyjafjellajökull, must have formed one cap during the Little Ice Age. Williams (1983) identified their extent in a list of thirteen major glacier areas in Iceland, which range from Vatnajökull (from 8940 km^2 in 1844 to 8300 km^2 in 1980) to Snaefellsjökull (from 43 km^2 in 1844 to 11 km^2 in 1980). The part of the list concerning the Mýrdalsjökull and the Eyjafjellajökull is presented in Table 1.

As noted above, the fourth largest area of current cover glaciation in Iceland has developed in a mountain-upland area in the southernmost part of the island in the eastern part of a young rift zone, in which there has been repetitive volcanic and tectonic activity in postglacial period. This has been emphasised by numerous authors, e.g. Thorarinsson & Saemundsson (1979), Saemundsson (1979). Einarsson and Björnsson (1979) regarded the area "near the subglacial volcano Katla in South Iceland" as one of "a few areas of persistent seismic activity" (op. cit., p. 41), which "is located near the southern end of the eastern volcanic zone, south of its junction with the south Icelandic seismic zone". These authors distinguished two epicentres under the ice cap: (a) "one under the SE-part of the Mýrdalsjökull ice cap and coincides with the sites of the latest Katla eruption", (b) "the other is under the SW-part of Mýrdalsjökull, about 15 km W of the first" (op. cit., p. 41). Tryggvason (1973) noted an annual cyclicity of seismic activity for the first time for the period of 1952–1958 in the area of the Mýrdalsjökull (in that period, the frequency of earthquakes was several times higher in the second half of the year than in the first).

Krüger (1994) divided the Mýrdalsjökull ice cap into two regions: (a) the ice cap proper, i.e. that part which descends from the culmination to 1300–1100 m a.s.l. and (b) a peripheral zone, where it divides into separate outlet glaciers. However, in our opinion, the Mýrdalsjökull actually shows three distinctive morphostructural parts. Our scheme is proved by various interrelated factors: balance, hypsometry-exposure, ice movement dynamics of the subaeral surface of the glacier (a) and the relief, lithology and seismic

Table 1. Changes of the areas of Mýrdalsjökull and the Eyjafjellajökull

No.	Surface of glaciers (km^2) and the range of changes in relation to the previous period (%)			Author and the year of issue	Source material
	Mýrdalsjökull – Eyjafjellajökull	Mýrdalsjökull	Eyjafjellajökull		
1.	1100	–	–	B. Gunnlangsson, 1844	map of Iceland, 1:480 000 (unpub.)
2.	1000 (–9.1)	–	–	T. Thoroddsen, 1901	1881–1898 field surveys (unpub.)
3.	1000	–	–	T. Thoroddsen, 1906	maps from 1844, 1901
4.	–	685	101	S. Thorarinsson, 1943	DGI maps, surveyed in 1902–1938
5.	–	701 (+2,33)	107 (+5,94)	S. Thorarinsson, 1958	DGI maps, including post-World War II editions
6.	–	596 (–14,98)	77,5 (–27,57)	R. Williams, 1980	Landsat images, 19.08.1973 and 22.09.1973 (unpub.)
7.	–	596	77,5	H. Björnsson, 1980	Landsat images, 1973 or aerial photos, 1960

and volcanic activity of the subglacial bedrock (b). The bedrock affects the formation and distribution of morphostructural zones on the surface of the glacier by relative increase in the variation and by directing a frame of the structural relief, type of rocks and macrofracture of the subglacial surface. The geomorphological elements of the bedrock (oriented hills and depressions) are especially important for they control distribution of the deeper parts of the glacier and its intrabasal and subglacial waters. They also determine spatial development of sedimentary masses in relation to the solid bedrock, their texture and water content, participating in the distribution and the scale of deformation structures of deposited sediments.

The morphostructure of the Mýrdalsjökull ice cap consists of the following parts: (a) a glaciomorphological centre, (b) a northern macro-cone of a glacial flow from centre to the Slétt and Botn glaciers and (c) a supramarginal steep slope of the cap with outlet glaciers of depressions and glacial valleys (Fig. 1):

a) The main part of the **ice cap centre (A)** consists of two separate **ice domes** (a_1): the bigger and higher in NW, the Godabunga (above 1480 m a.s.l.) and southern, the lower and smaller, the Háabunga (about 1400 m a.s.l.). Both domes cover approximately half the centre area. They are separated by a **col depression** (a_2), which is 5 km long and approximately 1.5 km wide in an ENE-WSW direction. The structure of the centre also contains **ice divide ridges** (a_3), developed mainly along an extension of the Godabunga ice dome. The classic form of such distinction is an ice lobe, the Godalandsjökull, which is directed westwards from the dome towards the neighbouring dome, the Eyjafjallajökull. Another ice divide ridge from Godabunga dome in NE direction termed the Austmannsbunga by Rist (1967a), separates the dome from the glacial macro-cone (B). The form of both domes and the Ausmann-bunga ridge (approx. 1375 m a.s.l.) is quite characteristic. They mark, together with the col (Fig. 1) a vast subglacial area referred to in the literature as the "Katla caldera". A fourth part of the morphostructural division of the glaciomorphological centre of the ice cap Mýrdalsjökull consists of **subdome slopes** and **flats** (a_4). The largest flat is located to the north of the southern dome, the Háabunga, being also a vast direct back zone of the outlet glacier, the Höfdabrekkujökull.

(b) The northern **glacial macro-cone (B)** is fan-shaped and is slightly inclined towards the north. Its vertical range is 1240–1200 m a.s.l. at the outlet from the glacial centre and 820–625 m a.s.l. at the marginal foot of the forehead of the Slétt and the Botn glaciers. This morphostructural sector of the Mýrdalsjökull, with its delta-fan plan form, resembles the radial piedmont sheet flows of Alaskan glaciers. The only significant difference is the lack of a rock boundary on both sides above a classical piedmont foot. It is replaced in the east by an ice mass of a steep supramarginal slope of the cap (C). In the west, it is separated from the Mekurjökull glacier by a narrow zone of rock ridges of the Enta massif which appeared above the ice when this part of the Mýrdalsjökull was lowered at the end and after of the Little Ice Age. It is also characterised by a direct contact with the source of this structural sector in NE part of the glaciomorphological centre and a lack of a narrowed tongue at the back of the fan. The northern part of the cap is thus not typical of a piedmont glacier. As a part of the morphostructure of the Mýrdalsjökull ice cap it is a glaciomorphological transitional form between the central area and the morphostructural slope (C) which is the next zone of the glacier.

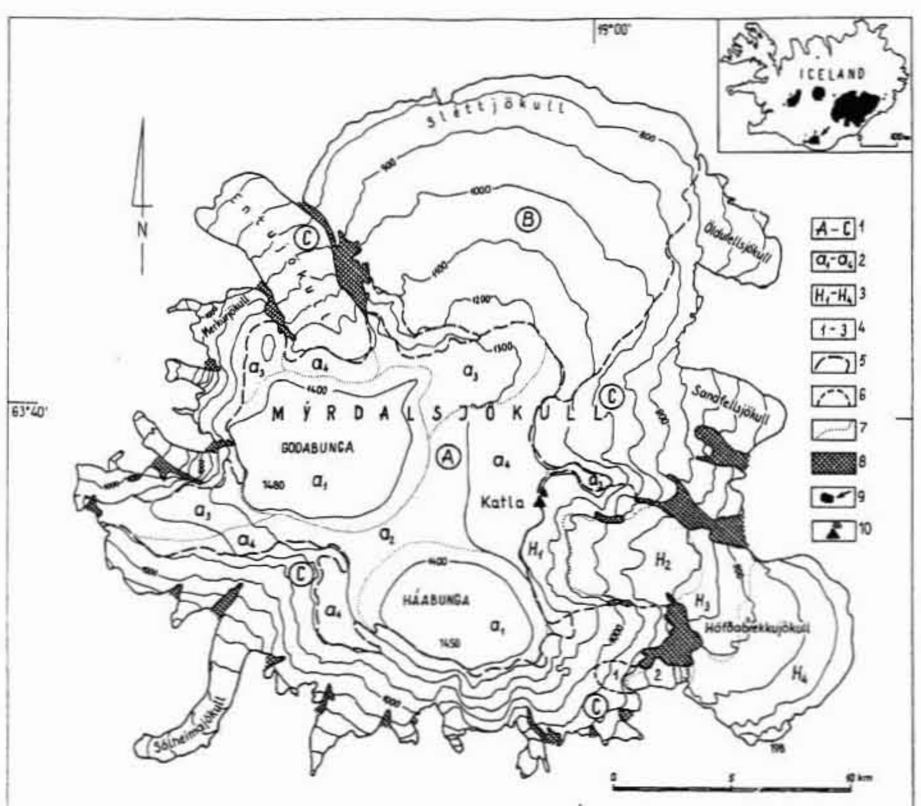

Fig. 1. Division of the Mýrdalsjökull ice cap into morphostructural zones.

1 – main morphostructural zones of the ice cap: A – a glaciomorphological centre of the cap (a_1 – ice domes of the glaciomorphological centre, a_2 – a depression col, a_3 – ice divide ridges of the centre spreading out from its ice domes, a_4 – sub-dome slopes of the centre); B – the northern cone of the glacial outflow; C – a supermarginal slope of the ice cap; 2 – sub-zones of the glaciomorphological centre of the cap; 3 – morphostructural zones of the outlet glacier; 4 – zonal division of the ice mass of the lateral tributary of the Höfdabrekkujökull; 5 – limits of the distinguished morphostructural zones of the Mýrdalsjökull ice cap; 6 – limits of the lateral range of the Höfdabrekkujökull tongue; 7 – major limits of the sub-zones of the central area of the cap; 8 – nunataks and major rock massifs significantly dividing the cap rim; 9 – major glaciers in Iceland.

Such a position in the morphostructural division of the cap is imposed by the central-peripheral location (a), medium hypsometric range between the central areas and the most dynamic outlet glaciers (b), the character of its subareal relief in most of the area located in the ablation zone (c), constant descent of its longitudinal profile (d) and the longest, completely lobar form of the glacier forehead (e). In combination, these features prove that this part of the glacier cap Mýrdalsjökull is based on a relatively poorly cut and smoothed subglacial internal slope which corresponds to the prominence of the Katla caldera.

(c) Steep, relatively narrow and rugged, **supramarginal slope (C)** of the Mýrdalsjökull cap is peripheral. The continuity of the slope is broken in the north by the macro-cone of radial ice flow (B) of the Sléttjökull-Botnjökull fan. This morphostructural zone of the Mýrdalsjökull ice cap occurs at the western, southern and eastern margins.

The outer slope of the ice cap consists of two parts: **the slope proper (C_1)** surrounding the centre and **the outlet glaciers (C_2)**. The relative altitude of the former is variable. In the NW, in the Merkurjökull zone, it is relatively even at 350 m, but in the S it varies from 1400 to 880 m a.s.l.; over the rocky and flat Gvendarfell on the eastern part of the cap, in the southern vicinity of the Öldufells, it varies from 980 to 820 m a.s.l (Fig. 2).

Several glacial outlets (C_2) of differing size and dynamics extend form this zone. The valley tongues of the outlet glaciers are larger and more active. The latter type of glacier is represented by Entujökull in the NW, Solheimajökull in the SW and Höfdabrekkujökull in the SE. There are also smaller glacial outlet forms such as hanging ice-patches or short, passive, tension-collapse V-shaped ice overhangs. Glacial outflows extend from the cap on NW, S and E sides, i.e. on that size of the Mýrdalsjökull where a well developed supermarginal zone of the cap exists (C). According to an Icelandic map at the scale of 1:100 000 (the Þórskmork/Landmanalaugar sheet; 1995), there are at least 30 significant, longer than 0.5 km, outlets there. These range in size from 0.14 km², the nameless outlet eastwards from Sandárhöfud to the largest one, the Höfdabrekkujökull, at the SE edge of the Mýrdalsjökull cap.

The supramarginal (peripheral) slope of the Mýrdalsjökull (C) covers the area of the largest range of relief; it is intensively dissected by glacial erosion and subglacial melt-water. This is the main zone of discharge of the ice masses and melt-water (including the catastrophic melt water floods, the jökulhlaups) and moraine material from the centre of the Mýrdalsjökull to the outer side of the glacier. Along the extension of the outflows glaciers, the main sandur areas in the surrounding of the Mýrdalsjökull occur. A litho- and morphogenetic role of the morphostructural part of the analysed ice cap and ice masses of similar zones within the other ice caps in Iceland, is very significant. Sigbjarnarson (1983) stated that an alpine type of relief developed over vast areas of Iceland not

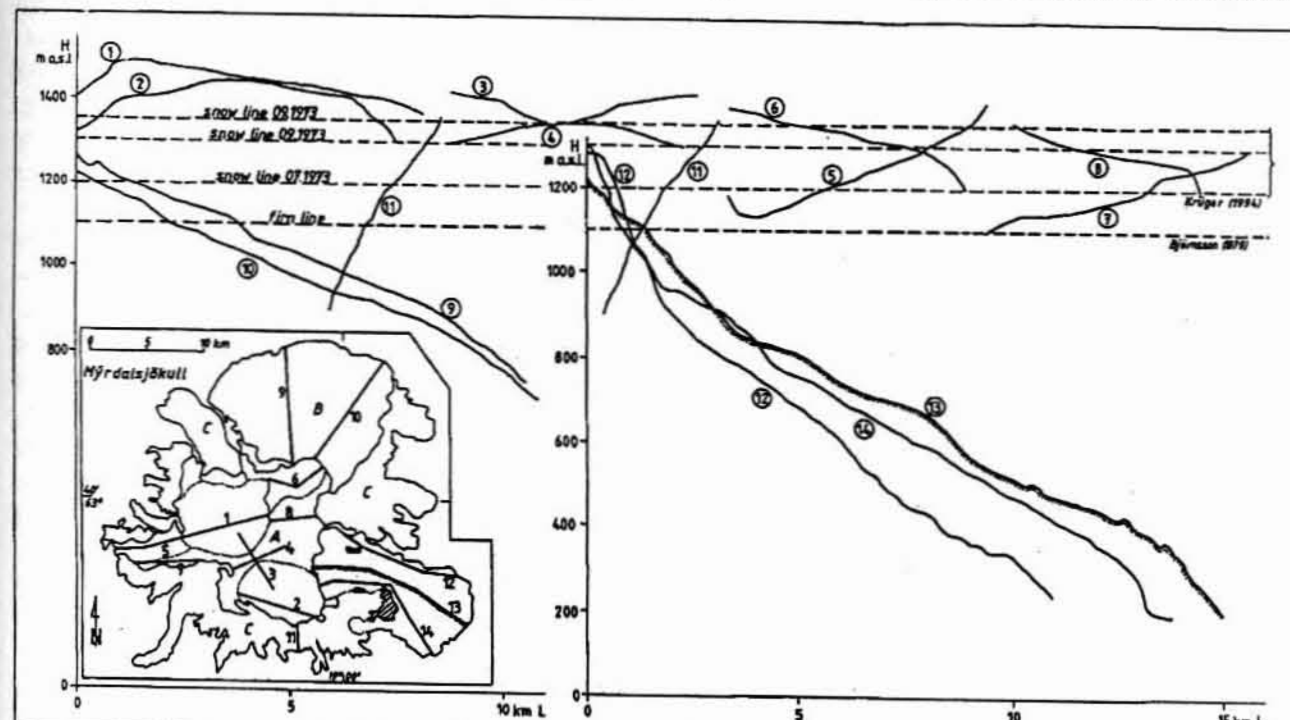

Fig. 2. Hypsometric profiles of the selected morphostructural zones of the cap and their particular parts.

only due to the small separate valley glaciers but mostly owing to the activity of the outlet glaciers of this morpho-structural zone of the ice caps. He determined their total area equal to be about 26 000 km^2, i.e. 25% of the whole island. In the vicinity of the Mýrdalsjökull, the major area of such relief is located close to the Höfdabrekkujökull, mainly in its closest southern borderland.

The glaciomorphostructure of the Mýrdalsjökull described above controls the establishment of particular zones of mass balance and, in consequence, also the zones of basic glaciomorphological and glaciodepositional processes. Therefore the disposition of these zones is also concentric, with a radial trend of directions and dynamics in both time and space. This pattern follows the outflow of ice masses and a pulsating rhythm of advance and retreat of the ice mass over a longer time scale. Analysis of the spatial structure provides more information concerning the places and mode of formation of the following processes: collecting – transporting – deformation – deposition of moraine and fluvioglacial deposits. It also shows possible locations of development of glaciotectonic, glaciodynamic and glaciomelting deformations within the glacigenic deposits. They are directly associated with the zone of the supramarginal slope of the cap (C) and the outlet glaciers.

Surface structures of the medial and lower part of the Höfdabrekkujökull

Aerial photographs taken by Landmalingar Islands (7.08.1992) have been used to analyse the surface structure of a wide area of the Höfdabrekkujökull. Special attention has been paid to sedimentation, sedimentation-deformation and deformation structural elements, particularly:
- lines of foliation,
- areas of supraglacial occurrence of ablation moraines,
- the course of open tension fissures,
- outcrops of shear planes and compression faults.

The obtained image of varied foliation, the range of occurrence of surface ablation moraines (Fig. 3) and different types of fissures (Fig. 4) are a local generalisation of recording of the real structure of the glacier at a particular moment in time.

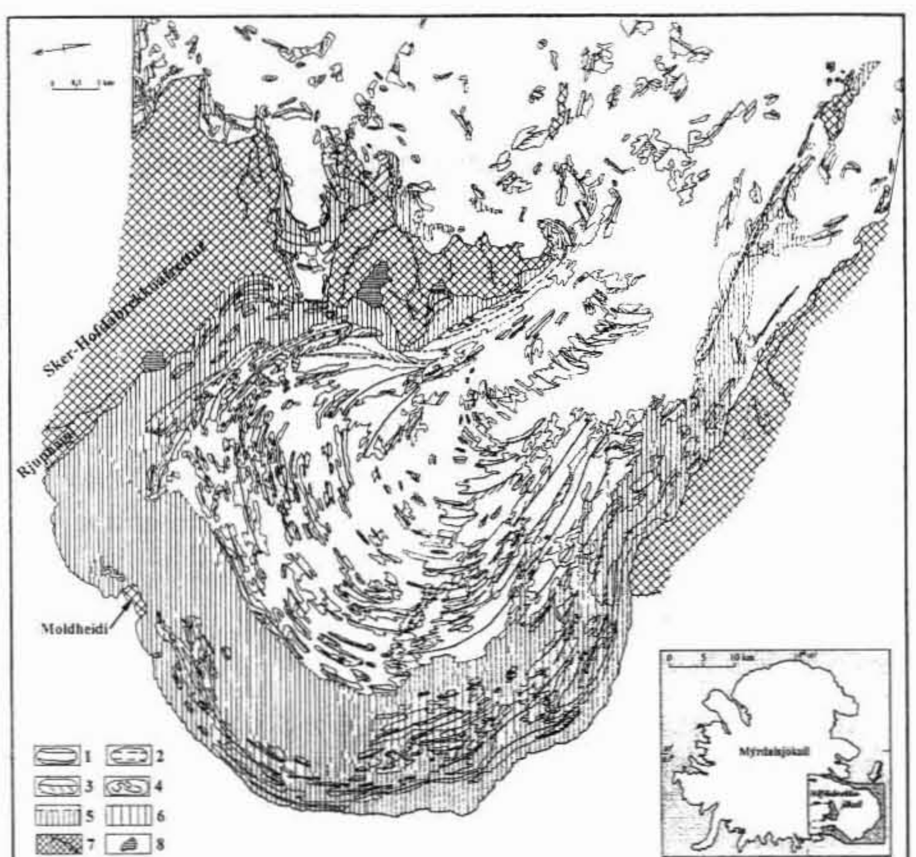

Fig. 3. Areas of varied foliation of the Höfdabrekkujökull and the range of the supraglacial ablation moraine.
1 – a curved foliation; 2 – a parallel foliation; 3 – a discordant foliation (the result of ice mass thrusting); 4 – a deformational foliation; 5 – a zone of regular occurrence of the supraglacial ablation moraine; 6 – a zone of thinner and less compact cover of the supraglacial ablation moraine; 7 – ridges and rock massifs; 8 – lakes.

After such analysis, five areas of different structural systems have been distinguished on the surface of the foliation structure of the glacier. These are the areas with arch, parallel (longitudinal), discordant (with superimposed strata of the mass ice), and deformational (with a significantly curved course) foliation lines and the areas where foliation has not been observed or has not been clearly marked (e.g. with foliation partly removed by melted moraine sediments) or without it. The zones without foliation may occur in areas of pure ice or in those covered by ablation moraines.

A system of arch foliation is the most common within the surface with foliation structure. It occurs twice as frequently as the discordant foliation (arch-discordant) and three times more often than the deformational foliation. The places where certain types of foliation occur are quite specific. For example, the discordant type occurs mainly in the axial part of the Höfdabrekkujökull glacial

tongue narrowing and in the lower located zone of radial ice flow, where ablation has revealed a transgressive-sedimentary type of superimposion of different ice masses. By contrast, a system of classical deformation occurs mainly in the southern edge of glacier tongue, along the rocky wall Rjúpnagil. Discordant foliation is mostly evident in areas where the bedrock relief is variable and changes greatly and ice masses flow across a rough bedrock and nunataks (a), significant narrowing of the valleys (b) and the zones of overflow (c). Deformational foliation on the surface shows elevations perpendicular to the direction of the glacier movement (a) or it is a response of the glacier to the influence of a lateral rock wall which is thrust against by the glacier at a sharp angle, possibly even at a right angle and with considerable force (b).

In the zone below the equilibrium line, the system of the ablation moraine is typical for valley and outlet glaciers. The extent of the moraine cover varies considerably in the marginal or lateral developments. The width of the zone where moraines are present varies from 2.5–3.0 km at the glacier forehead to a much narrower zone along boundary rock walls; however, this zone extends a considerable distance up the glacier (Fig. 3).

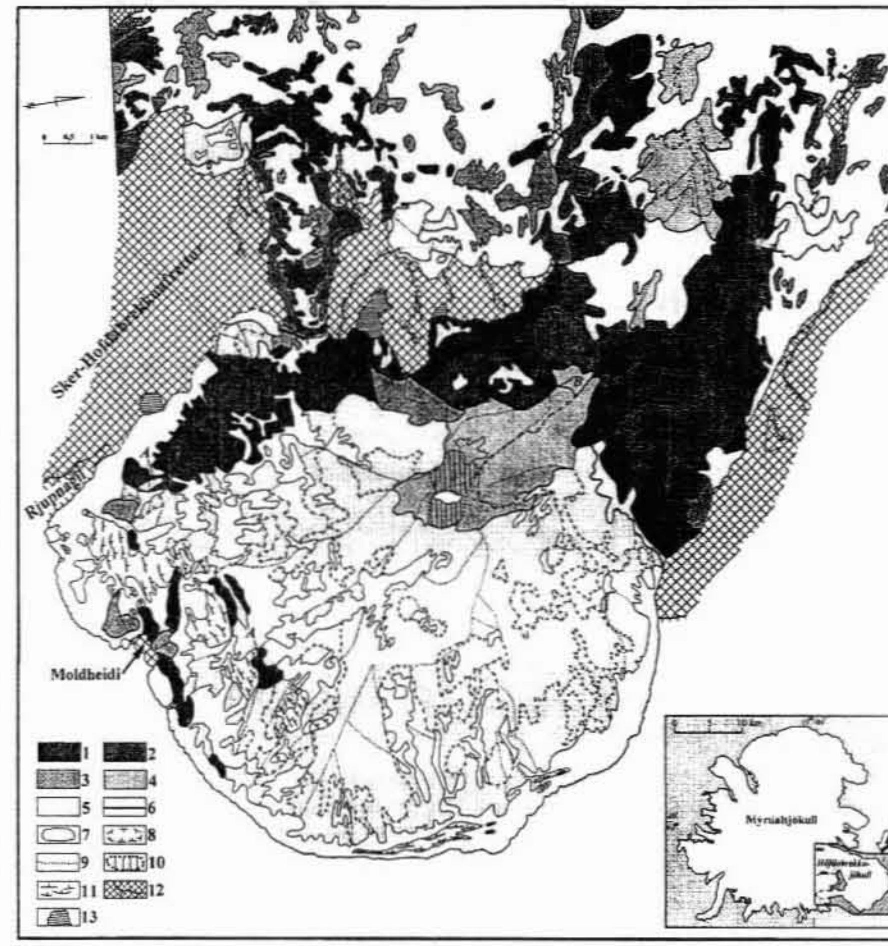

Fig. 4. Zones of occurrence of various types of fissures on the surface of the Höfdabrekkujökull (the areas of various types of fissures superimpos-ing each other: A – transverse and radial, B – transverse and half-opened).
1 – transverse fissures; 2 – oblique fissures; 3 – longitudinal fissures; 4 – half-opened fissures; 5 – radial fissures; 6 – a range of one type fissure; 7 – the area of the glacier without visible fissures; 8 – areas of lower concentration of fissures; 9 – a line of the azimuth changes of the fissures course; 10 – probable area of occurrence of fissures compression; 11 – areas of low ice ridges with a supraglacial cover, formed along compression outcrops of the shear planes; 12 – ridges and rock massifs; 13 – lakes.

Analysis of the character, direction and location of fissures permits the determination of homogeneous areas or complicated, those dominated by a particular type. There are certain places where the structure is more complicated and a system of compression planes co-exists with tension fissures (Fig. 4). The areas with the following types of fissure have been distinguished: transverse, oblique, longitudinal, half-open and radial (which are all more homogeneous in respect to their course) and superimposed fissure areas containing both transverse and radial types (Fig. 4 – A) and transverse and half-opened (Fig. 4 – B). Apart from these, in certain places, particularly in the marginal zone, outcrops of compression shear planes and faults have been observed. Further up the glacier, possible occurrences of compression fissures have also been found.

The spatial arrangement of various types of fissures is quite characteristic. For example transverse types are in the majority in the upper narrower part of the glacial tongue. In certain places, they cover the whole cross-section of the glacier which is then marked by a larger break of the course of the longitudinal profile of the glacier bedrock. Half-open fissures form a characteristic fan system and they are marked by conical outcrops. They are located in several places, mostly along the morphological axis of the glacier surface, in the vicinity of transverse fissures. Their development increases in the direction of the glacier flow. This indicates not only development of a particular glacio-structural trend, but also suggests that the gradient of the bedrock decreases along the area where such fissures occur.

A very characteristic radial system covers most of the lower, wider part of the Höfdabrekkujökull tongue. However, the analysis of the genetic types of glaciers and their spatial relations shows that the piedmont-type flow of the glacier is far from homogeneous. It certainly does not indicate a wide opening and uniform flattening of the bottom of the glacial valley in its outlet zone. A zone of transverse fissures along the rocky wall Rjupnagil on the southern side of the glacier (a) and several smaller fields of such fissures in the marginal zone of the glacier flow, to the rear of Moldheidi rock (b), are quite significant. Between those two areas of transverse fissures the main centre of compression crack outcrops appears. These form small ridges and low, compression ice-hangs which are covered by an ablation moraine. Perhaps not unexpectedly, the area covered by marginal compression fissures along the glacier forehead decreases along the rocky wall of Rjúpnagil and towards the central part of the piedmont-type flow (Fig. 4).

The outline of morphostructural zones of the Höfdabrekkujökull

The Höfdabrekkujökull originates on the eastern edge of the glaciomorphological centre of the Mýrdalsjökull ice cap. Gentle, flat, ice slopes of the centre (a_4), which cover an area of 30 km^2 and the dome of Háabunga (a_1) is the direct source to the west (Figs. 1, 5). The source of the glacier is evidently in the vicinity of the subglacial volcano, Katla (Figs. 1, 2).

(a) Starting at the altitude approximately 1200 m a.s.l. there is a concentric run off of the ice with the major direction trend towards east. This is a steep **spring zone (H_1)** of the Höfdabrekkujökull. Its plan form is broken-oval in shape. It is 6–7 km long (N-S) and the width of the ice stream is 4–2 km (W-E). The surface source zone is squeezed between the Háabunga ice dome (in SW) and a small dome of the ice divide ridge (Fig. 1, a_3) at 1310 m a.s.l.; this is located to the east of Katla (from NE). The slope gradient is high. It may be as much as 15% and in small parts of the slope, i.e. 600 m long, even 30%. The narrow spring zone of the Höfdabrekkujökull corresponds to the subzone of the morphostructural slope of the Mýrdalsjökull dome (c_1), but with a significantly reduced width. Here, to the NE of the Háabunga ice dome, below the source zone (H_1) a small, young crater of volcano Katla (Figs. 1, 5) was located by Björnsson, Sverrisson and Jóhanesson (1978).

(b) The source zone borderlands beyond the base of the glacier tongue Höfdabrekkujökull. This is the **upper zone (H_2)** of the glacier of parallel orientation. It is 5.5 km long. It consists of three main and locally four courses of ice flow. The width of the tongue in this part, between the naked rock ridges 1047 m a.s.l. (N) and 1087 m a.s.l. (S) is 3.5 km. It widens to 4.2 km when it is joined by the northern stream flowing from the base of the dome at 1310 m a.s.l. At the lowest profile of this morphostructural zone of the glacier, it is only 2.8 km wide. This is the narrowest part of the whole longitudinal profile. The run of the glacier valley is straight and parallel in this place and the system of fissures shows axial symmetry beginning from the open fissures in the central line, through two zones of the transverse fissures up to two zones of the oblique fissures at the edge position of the transversal profile along the rock walls (Figs. 4, 5).

(c) At this line the Höfdabrekkujökull glacial tongue turns towards the SE. Significant changes of the type of movement and orientation of the ice mass are evident in this direction. The change is visible on the line of the transversal profile located above the lateral ice mass tributary of the main glacier on the south side. There are signs of compression movements in the SW-NE profile on the south side; a significant cone of open fissures appears in the central part, while in the northern part, transversal fissures are dominant in the higher part of the area and radial fissures occur in the lower part. The zone shows significant morphostructural variations on the glacier surface. They may be caused by an increase of the gradient of the glacier surface slope in the longitudinal profile, thereby directing the main stream of ice towards the S/SE together with an ice movement which follows the curve marked by the oblique, subglacial ridge at the rocky bed. Its occurrence at the bed is reflected on the surface by the central swell on the glacier surface. The difference in altitude of the two longitudinal profiles: northern (Fig. 2: 12) and southern (Fig. 2: 14) also demonstrates the existence of such relief.

In the lower part, the central swell of the tongue is significantly closer to the southern ice stream. The separation of the southern and the central streams is not so distinct here, which indicates a conjunction of the courses of the ice flow and a widening of the subbasal bed of the glacier. This is the **middle zone (H_3)** of the Höfdabrekkujökull tongue. It is marked from the top by the 700 m a.s.l. contour and from the below by 500 m a.s.l. in the south-west side and 430 m a.s.l. in the northern lateral part. The gradient of the surface slope is particularly steep, especially in the northern part of the middle zone (Figs. 1, 5); from 12.6% (640–400 m a.s.l.) up to 13.8% along the section 1.3 km long. The steep surface slope of this part of the glacier is an indication of the surface glaciomorphological structure that a significant threshold zone occurs in the path of the ice flow. The lower part of the middle zone of the tongue again reaches a width of 4.2 km.

The transversal middle zone of the Höfdabrekkujökull is the most important zone of dynamic activities and development trends of geomorphological and sedimentation phenomena in the direct vicinity of the bed. Further, it stimulates the dynamics in the lower,

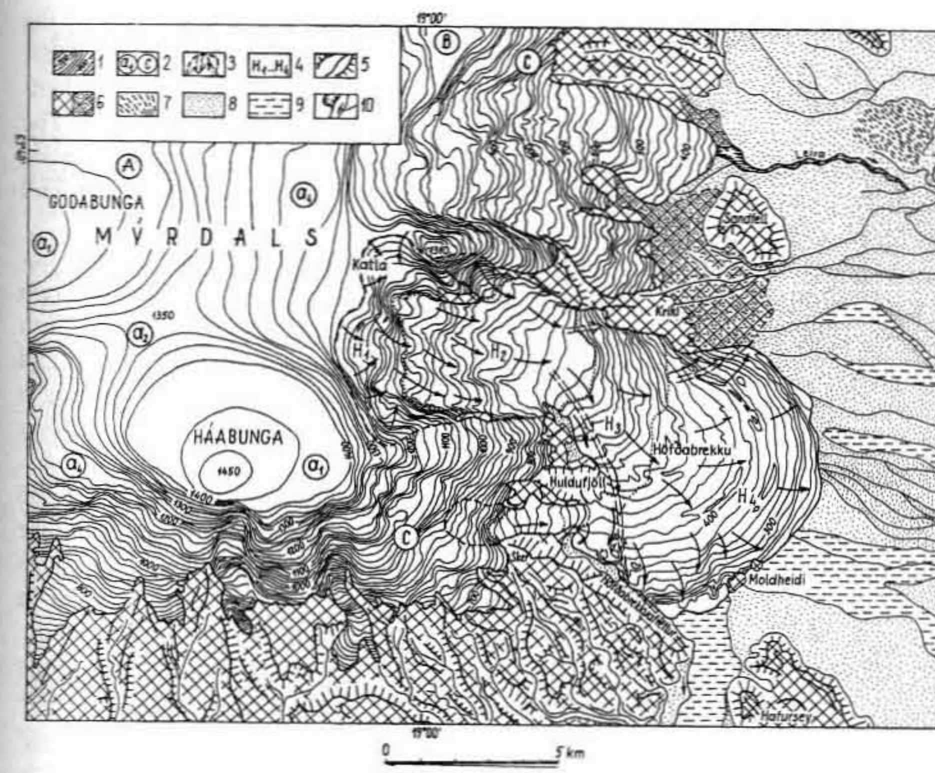

Fig. 5. South-east part of the Mýrdalsjökull ice cap with the outlet glacier Höfdabrekkujökull.
1 – contour line drawing of the glacier surface; 2 – morphostructural zones and parts of the Mýrdalsjökull ice cap: A – glaciomorphological centre of the cap (a_1 – ice domes of the glaciomorphological centre, a_2 – col depression, a_3 – ice-divide ridges of the centre spreading out from the ice domes, a_4 – sub-dome slopes of the centre), B – the northern cone of the glacial outflow, C – a supermarginal slope of the ice cap; 3 – the range of the upper part of the Höfdabrekkujökull, limits of its morphostructural zones and directions of surface outflows of ice (black arrows), and catastrophic flood outflows – jökulhlaups 12.10.1918 (wide arrows); 4 – morphostructural zones of the Höfdabrekkujökull (H_1 – spring zone, H_2 – upper zone, H_3 – middle zone, H_4 – lower, piedmont zone of complicated structure); 5 – mountain ridges and steep slopes; 6 – volcanic rock massifs and the zones of their shallow location under the glacial deposits; 7 – surfaces of volcanic rocks in sandur areas; 8 – sandur deposits; 9 – wet sandur areas; 10 – lakes and rivers.

distally adjacent, and morphostructurally complex piedmont zone of the glacier.

(d) After passing the side blocking the Huldufjöll rocks (below the contour 500 m a.s.l. in south-west and the contour 430 m a.s.l. in north-east), the laterally unrestrained glacier widens significantly. It enters not only the ablation zone of maximum saturation but also the submountain area of radial flow. As previously noticed, the piedmont part is not a homogeneous glacial structure. Its narrower southern part, located between the Rjúpnagil rock wall and the marginal ridge of the Moldheidi rocks is an extensively deformed marginal part of the lower zone of the glacier. So much is indicated by numerous cross fissures, the outcrops of the compression shear planes and the maximum development of deformation-type foliations. Conditions of unrestrained glaciodynamic outflow dominate in the central and northern sectors of the lower part of the glacier. Despite the previous remarks concerning its complex morphostructure, that whole area is determined as the lowest area of the glacier tongue, i.e. **outlet zone (H_4)**. The wall of the rock massif Sker-Höfdabrekkuafréttur, located on SW side of the tongue which, as mentioned, significantly hinders the zone of piedmont flow in that part of the tongue, also constrains ice movement after the glacial charge S from Huldufjöll (Figs. 1, 5). Convergent stream flow, as described by McIntyre (1985), clearly occurs there, thereby increasing the erosional capability of the glacier in this particular part of the bed, i.e. along the rock wall Sker-Höfdabrekkuafréttur. It also significantly influences the development of topographic deformation of both the upper and lower surface of that part of the glacier. It is concerning its closely lateral – marginal belt of glacier ice with about 1 km width. It is obvious that higher glacial strains caused intensive development of deformation structures of the bed sediments in this area and in its nearest forefield. The width of the piedmont zone varies from 2.4 km to 4.5 km.

The front of the Höfdabrekkujökull, which is 12.6 km long is marked in the north by the 310 m a.s.l. contour and, in the south, by the outflow of the Remundargilsá river at approximately 198 m a.s.l. The base of the glacier edge descends from N to S by over 110 m. The unimpeded part of the front descends to 197 m a.s.l. in the axial part of the glacier tongue. From there, up to the basalt ridge Moldheidi, where it currently projects out of the glacier, the piedmont front runs at an altitude of 200 to approximately 210–215 m a.s.l. Close to the marginal outcrops of the partly subglacial Moldheidi Hill, it lies at an altitude between 200 and 280 m a.s.l. on the proximal slopes of the massif. A second rise of the glacier front occurs from the direction of the glacier pressure. The SW slope of the glacier front descends by 60 m in a distance of 300 m. It descends to 220 m a.s.l. and the descent ratio at the foot is as much as 20%. Such maximum inclination of the foot of glacier front follows the direction of the ice mass movement in the southern part of the marginal massif Molheidi (Figs. 1, 2 – B). The 2.2 km long part of the glacier front reaches its southernmost, and also most distal, marginal position (197 m a.s.l.) between the massif and the rock wall Höfdabrekkuarfréttur (SW from the tongue). The distance from the source zone to this end of the glacier tongue is the longest (14.8 km).

The outline of division of the Höfdabrekkujökull into morphostructural zones principally includes the topomorphological variations of its upper surface. But a complete presentation of the morphostructural zonality must also include the relief of the basal layer of the glacier – the negative reflection of the bed relief. As it has been determined by Macheret and Zhuravlev (1982), in the case of 84 glaciers mostly from West Spitsbergen, such an approach enables us to determine more accurately the so called "morphological type" of glaciers, in relation to its sizes: surface, and volume as well as maximum and average thickness.

Conditions of dynamics and deformation of the bedrock deposits of the Höfdabrekkujökull

From an analysis of the general structural situation, morphology and topography of the subaerial surface of the investigated glacier, and an estimation of the directions of the ice movement, together with the arrangements and character of the relief of its surroundings indicate that the factors (glaciodynamic, paleotopographic, and geomorphological) causing the development of deformation structures of deposits of various origins are located along the longitudinal axis. This is the case especially in its southern part and in the extension of the zone in the outwash plain which is also the farthest recent reach (Heim, 1983) of the strong thrust and deformation of the bedrock of the Höfdabrekkujökull. This conclusion is also supported by the fact that the main stream of the water mass of the catastrophic, autumn jökulhlaups of 1918 as described by Larsen and Ásbjörnsson (1995), was also directed along the southern, dynamic ice stream. The main flood water escaped along the path of the previous intensive glacial grooving, i.e. to the west of the Moldheidi-Hafursey line.

From the southern side, towards the Höfdabrekkujökull glacier, the massifs of Huldufjöll (788 m a.s.l.) and Höfdabrekkuafréttur, which descend down steeply, forming the rock wall Rjúpnagil 150–300 m high, are built from Pleistocenic hyaloclastic rocks. The same formations represent the marginal and mutonised massif of the Moldheidi (Figs. 1, 5) which exceeds 300 m a.s.l. and the higher and more extensive massif of Hafursey (582) m a.s.l. located 1.75 km SE from the mentioned rock obstacle. The analysis of distribution of harder rocks in the vicinity of the Höfdabrekkujökull indicates that the border between the older acid igneous rocks of the upper part of the valley bed (H_2) and less resistant younger hyaloclastic rocks, tuffs and basalts, is located in the glacier bedrock under the middle part of the tongue (H_3). The rocks of hyaloclastic formation also comprise the main part of the piedmont foot of the Höfdabrekkujökull (H_4).

The Moldheidi massif currently emerging from under the glacier front (Figs. 1, 5) divides them into two parts: a southern, shorter one (approximately 2 km long), with a significantly compressed glacial mass and the longer one in its mid-northern part, forming a gentle semicircle (almost 10 km long), which outflows laterally. The distribution of longitudinal tension fissures close to the front of the glacier, W of the Moldheidi rocks, suggests the introduction of the ice mass into the zone of lateral compression; the fissures are certainly more extensive (Fig. 4). Hereabouts, in the basal layer of the glacier, it also cogenerates a more significant outflow of the frontal part which occurs when passing the rock obstacle. The massif is a submarginal precursor of the more extensive Hafursey Hill. Both the rock ridges determined in the past e.g. in the late Vistulian or during the Little Ice Age, the outflow of glacial masses along the partly subglacial ice divide of Moldheidi-Hafursey.

After the recession of the front of the Höfdabrekkujökull out of the range of the Little Ice Age, also in the 20th century (Krüger, 1994), a significant difference of the dynamics of the glacier front SW and N of the Moldheidi-Hafursey line occurred. Analysing the map of the Höfdabrekkujökull, which shows the geomorphological situation of the glacier forefield in 1960, Krüger and Humlum (1981) observed a tendency of the southern part of the glacier front to form a delicate lobate system. Three small, but significant curves of the lobate arches, including that squeezing between the Moldheidi rocks, are located in close proximity. However, the southern and the northern lobes contrast to the smooth shape of the mid-northern part of the glacier terminus. Krüger's comparison (1994) of the positions of the glacier front in the years 1904–1945–1960–1980 revealed a complete contrast of glacier dynamics on each side of the Moldheidi rocks. In the 20th century, the front of the glacier has undergone larger changes in the area between the massif and the rock wall Rjúpnagil than in its central and northern part, e.g. N from Moldheidi. For example in the years 1945–1980, directly NE from the southern outcrop of Moldheidi (Fig. 5), over the distance of 2 km, the front of the glacier was almost stable, except for a change of the position about 1955 (Heim, 1983). In comparison, SW from Moldheidi, closer to the rock, the whole front was pushed forward, thereby covering the zone to a wide of 770–860 m (in the area closer to the Rjupnagil wall it was 500–600 m wide.)

Conclusions

Analysis of the problem in relation to the Mýrdalsjökull ice cap and its main outlet glacier Höfdabrekkujökull leads to reach the following conclusions:

1. Distinguishing morphostructural zones of the glacier, beside hydroclimatic including events, topographic, geomorphological and lithological factors of its bedrock and lateral features of its rock borders enables us to classify the ice cap Mýrdalsjökull differently from Krüger (1994). Three morphostructural zones have been distinguished: the glaciomorphological centre (A) with a slightly varied relief (a_1–a_4), the northern macrocone of radial outflow (B) and the bipartite, supramarginal surrounding slope (C), with a significant development of outlet glaciers.

2. The outlet glaciers (c_2) are the most active in the whole subglacial area of the Mýrdalsjökull ice cap, through the main part of the morphostructural zone of the slope (c_1) in the following fields: erosion, deformation, transportation, transformation and sedimentation. The Höfdabrekkujökull is the largest, geomorpholgically most active and the most sedimentologically productive glacier of the ice cap.

3. The glacial trail of the Höfdabrekkujökull marks also the route of catastrophic melt floods (jökulhlaups) caused by subglacial eruption of the Katla volcano. The bottom of the grooved valley depression, Höfdabrekkujökull, is cross-cut by obstacles in the upper part of the floor and by oblique and longitudinal forms, caused mostly by water erosion, in the middle and southern part, i.e. the lines of the catastrophic jökulhlaups of the 20th century and older ones.

4. Variations of the foliation structure on the surface of the glacier, i.e. sequences of different geometric and structural foliations within a small area or the existence of a foliation deformation system indicate significant variations of the bed rock relief of the given ice mass. This includes the marginal and/or the lateral zones.

5. The pattern of fissures on the surface of the Höfdabrekkujökull and their physico-genetic type might be interpreted as giving general information about the bed rock relief and the spatial dynamo-structural reaction of the ice mass to changes in the geometric system of the rocks surrounding the glacier.

6. The structural system of fissures formed in particular conditions in a given place may be modified elsewhere. The ice mass transporting into the area "a load of structures" formed earlier obtains also a new orientation and a genetic character forced by different conditions of the relief or different geological formation. Determination of the role of the Höfdabrekkujökull bed-rock relief for the morphostructural character reflected on the surface of the glacier supports earlier studies by Shumskij (1955) in terms of structural glaciology and by Boulton (1982) and Jania (1987, 1993) in terms of the relation between the bed rock and the glacier.

7. Four morphostructural zones have been distinguished within the area of the Höfdabrekkujökull: a spring zone (H_1), an upper zone (H_2), a middle zone (H_3) and a lower zone (H_4) of complex piedmont and semi-piedmont character.

8. The relief system in the southern part of the lower morphostructural zone Höfdabrekkujökull (H_4), along the rocky wall Rjúpnagil, determines the morphostructural difference of the lateral sector of the outlet zone of the glacier (a). It also marks the area of the significant activity of that part of the glacier (b) and also determines location of the zone covering the forefield ridge with significant development of deformation structures in deposits (c).

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The deformational structures of the deposits on the Höfdabrekkujökull forefield, Mýrdalsjökull, Iceland*

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Abstract: The deformational structures of the developing subglacial (a) substratum deposits and the near Höfdabrekkujökull forefield (b) are the characteristic dynamic parts of the glacio-sedimentological system. These occur in different geomorphological situations: a) under sandur deposits, on the periphery of the fossil embankment of the frontal moraine, on both its distal and proximal slopes, and in the backside depression of this form and b) within the dead ice kettle which was formed in the surface part of the fluvioglacial deposits of the VI sandur level. The older, sub-sandur glaciotectonic discordances, which occur below sandur deposits, represent dynamic structures of two separate glacial advances. Independently of these, deformations of gravitational type also occur. In contrast, the deformations of melt-denudational deposits of the dead ice kettle, surrounded by fluvioglacial deposits, belong to younger (at least several tens years) distortions of gravitational type.

Key words: Iceland, glacier, deformational structures, sub-sandur and dead-ice kettle deposits

Introduction

The dynamics of the Höfdabrekkujökull on the south-east edge of the Mýrdalsjökull (Björnsson *et al.*, 1978; Björnsson, 1979; Jónsson, 1982; Humlum, 1985; Krüger, 1994), and the nature and relief of the bedrock determine the spatial distribution of the moraine and glaciofluvial deposits and the scale of the deformation structures. The deposits of various glacial and glaciofluvial facies display numerous types of deformations in the southern part, close to the forefield of the Höfdabrekkujökull. Structural-lithofacial analysis of these may help to elucidate the glacial processes which control the dynamics of the development and decay of the Höfdabrekku Glacier in the forefield of the main frontal moraines (Heim, 1983). An exposure in the steep slope of the sandur level (VI) revealed below fluvioglacial deposits, a fossil frontal moraine ridge, parts of its disturbed forefield and a thick development of backfield deposits as well as the glaciotectonically-deformed deposits of a proglacial basin represented by numerous sedimentary facies. Also, the younger (at least more than a decade) deposits of a kettle in the proximal part of the sandur (VI) were analysed in structural-lithofacial terms. This enabled the authors to determine the glaciodynamic history of the advances and decay of the frontal part of the Höfdabrekkujökull, with details of the hydrological and morphogenetic changes in the marginal area of the glacier.

Due to the degradation of the so called main moraines, their forefield was free from glacial forms (Heim, 1983; Krüger, 1994). It was completely covered by the levels connected with fluvioglacial activity. Therefore, by means of geological (lithofacial, structural) investigation, it is important to determine the dynamics and position of the front at its older limits rather than in the line of the end moraines.

Glacial and fluvioglacial relief of the south-eastern part of the closer glacier forefield

Jóhannesson (1985) determined the position of so-called outer ("Y") frontal moraines associated with the Older Dryas. As measured in the 1980s, these were situated about 8–18 km from the glacier edge. This

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