Surface and bedrock topography of the Mýrdalsjökull ice cap, Iceland: The Katla caldera, eruption sites and routes of jökulhlaups

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Abstract – *Radio echo soundings have revealed a large caldera beneath the Mýrdalsjökull ice cap. The caldera encircles an area of 100 km^2, is 600 to 750 m deep and its highest rims reach 1380 m a.s.l. Three major outlet glaciers have eroded 300 to 600 m deep breaches into the caldera rim. The northern part of the caldera floor, where an area of 25 km^2 is below 800 m, is smoother and lies deeper than the southern part, which is characterized by subglacial ridges and individual mounts rising from 750 m a.s.l. to about 1100 m. A number of ridges radiate out from the caldera, however, none toward south. One ridge strikes west toward the neighbouring volcano Eyjafjallajökull, and a second ridge strikes E from the eastern rim of the caldera. Ridges also radiate from the caldera rim toward NW, N, and NE. A linear depression, bounded by steep slopes, 200-250 m deep and 1.5 km wide, strikes NE toward the volcanic fissure Eldgjá. Twenty eruptions have been documented from the caldera during the last 1100 years, all causing catastrophic jökulhlaups. Over the last four centuries eruptions have occurred on single vents and volcanic fissures trending both E-W and S-N. We suggest that the largest eruption of the last millennium (1755 A.D.) took place on a several kilometers long fissure trending east from Goðabunga; and the eruptions of 1823 and 1918 on a northerly striking ridge from the eastern rim of Háabunga. At present, meltwater drains southeastward, down to Mýrdalssandur, from an area of 60 km^2 within the caldera. All but two of the 20 recorded jökulhlaups in historical times have taken this path. An area of about 20 km^2 within the caldera drains to the southwest, down to Sólheimasandur. Two jökulhlaups are known to have taken this route to the river Jökulsá á Sólheimasandi in historical times. A third route, northwestward into Fremri Emstruá and the Markarfljót river, was taken by a prehistoric jökulhlaup in 1600 B.P. Presently, geothermal activity is displayed by several small cauldrons, 0.5-1 km in diameter on the glacier surface. Meltwater accumulates beneath two or three of these cauldrons and is frequently drained in small jökulhlaups.*

INTRODUCTION

The Mýrdalsjökull ice cap is the fourth largest glacier in Iceland, with a total area of 600 km^2. The glacier rises 1300-1500 m above the surrounding lowland (Figure 1), receives heavy winter precipitation, has high rates of summer melting and is thus drained by many rivers. Located at the southern tip of the propagating Eastern Volcanic Zone, the ice cap is underlain by a highly active central volcano containing a large caldera. The caldera, together with a 80 km northeast-trending fissure swarm, comprise the Katla volcanic system (Jakobsson, 1979; Jóhannesson *et al.*, 1990). The volcanic system has been active over several hundred thousand years and the basal mountains consist of hyaloclastites from glacial periods (Robson, 1957; Jakobsson, 1979). The caldera subsidence may date from the Pleistocene (Sæmundsson, 1982) and ash layers originating from the volcano have been identified in the GRIP ice core dating from 75,400 and 77,500 years B.P. (Grönvold *et al.*, 1995). An eruption producing more than 10 km^3 of tephra in 12,000 years B.P. may have contributed to its formation (Lacasse *et al.*, 1995; Sigurðsson *et al.*, 1995). During the Holocene 150 to 200 eruptions may have taken place in the volcanic system both on short volcanic fissures and single vents (Larsen,

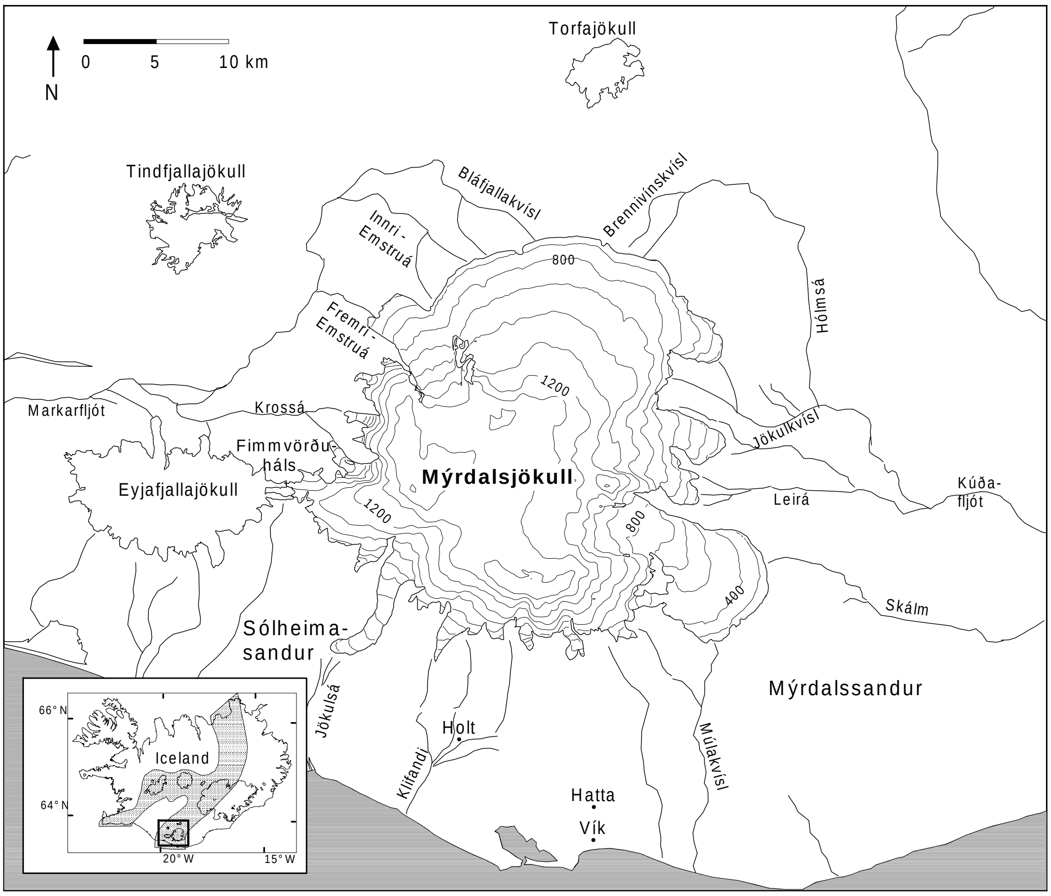

Figure 1. Location map of Mýrdalsjökull and surroundings; outwash plains and glacial rivers. Insert map of Iceland showing the location of the neo-volcanic zone. – *Mýrdalsjökull og nágrenni, jökulsandar, jökulár og lega gosbeltisins á Íslandi.*

1993, 2000), producing 30-35 km^3 of tephra, erupted subglacially, mainly from the caldera (Þórarinsson, 1975), and 15 km^3 of lava, largely originating from the fissure swarm (Jakobsson, 1979).

The central volcano is one of the most seismically active in Iceland. The epicenters are bimodal; one seismic zone lies within the caldera but the other beneath its western rim at Goðabunga (Einarsson, 1977, 1983, 1991; Einarsson and Björnsson, 1987; Einarsson and Brandsdóttir, 2000).

Since the settlement of Iceland (870 A.D.), twenty volcanic eruptions, on average two per century, have been traced to the Mýrdalsjökull volcanic system. Eruptions under the ice cap rapidly melt large volumes of ice, triggering enormous jökulhlaups from the glacier margins, frequently breaking off large blocks of ice (Pálsson 1883, 1945; Eyþórsson, 1945; Þórarinsson 1957, 1967, 1975; Rist, 1967a; Einarsson *et al.*, 1980; Larsen, 1993, 2000; Tómasson, 1996). The jökulhlaups have threatened human population, damaged vegetation, disrupted roads on the alluvial plains surrounding the ice cap and even generated flood waves in coastal waters. During 18 of the 20 documented eruptions the associated jökulhlaups flowed southeast down to the Mýrdalssandur outwash plain (Figure 1), but in two cases jökulhlaups flowed southwest to the Sólheimasandur outwash plain; the third route, northwestwards into the river Markarfljót, was taken by a jökulhaup in 1600 B.P. (Haraldsson, 1981). During the jökulhlaups, a mixture of water, ice blocks, volcanic products and sediment, frequently hyperconcentrated, surges over the outwash plain. Velocities of 5-15 m/s, peak discharge of 100-300,000 m^3/s reached in a few hours, and total volumes of 1-8 km^3 have been suggested (Jóhannsson, 1919; Þórarinsson, 1957, 1959, 1975; Hannesson, 1934; Maizels, 1993; Tómasson, 1996; Karlsson, 1994). These jökulhlaups, along with heavy fallout of tephra, make the Mýrdalsjökull volcano the most hazardous one in Iceland.

In this paper we present detailed ice surface and bedrock topography data from Mýrdalsjökull, and describe the morphology, size and shape of the Mýrdalsjökull volcano with reference to its eruption history. Furthermore, we present new information regarding the location of eruptive vents, ice and water drainage basins and subglacial flowpaths of jökulhlaups during eruptions.

Previous mapping of the glacier surface and bedrock topography

The first maps outlining with some accuracy the coverage of Mýrdalsjökull were surveyed by the Danish Geodetic Institute in 1904-1907 (the southernmost margins) and during 1937-1938 (the main ice cap). The maps were published in a scale of 1:100,000 (Nørlund, 1944). However, the indicated ice-surface elevation on these maps was not based on the surveying data, except along the glacier edge. Instead, the contour lines were drawn with reference to oblique air photos and show, according to Nørlund (1944), the shape of the ice surface rather than its elevation. In later editions of these maps, the position of the glacier edge has been revised using aerial photographs.

The first triangulation surveying on the ice cap was carried out in 1943 by Steinþór Sigurðsson, who compiled a surface map, later published by Rist (1967a). The next maps of the ice cap were produced by the U.S. Army Map Service in a scale of 1:50,000 on the basis of aerial photographs taken in 1945-46, and the triangulation system previously surveyed by the Danish Geodetic Institute. The ice-surface contours along the marginal areas of the ice caps (some few km up from the edge) were compiled from aerial photographs; but higher up, the contours were identical with those of the Danish Geodetic Survey maps. The surface maps showed the general shape of the ice cap, the outlet glaciers and the caldera depression surrounded by the higher domes of Háabunga and Goðabunga (bunga means dome in Icelandic).

Exploration of the ice thickness of Mýrdalsjökull and its subglacial topography began in 1955 when seismic reflection soundings were carried out at 9 locations on the ice cap, showing an ice thickness of 300-400 m (Rist, 1967a). In 1977 a few radio echo-sounding profiles on Mýrdalsjökull showed considerable variations in bedrock topography. An ice thickness of 500-600 m was observed in the central part of the ice cap (Björnsson, 1978) confirming the presence of a deep depression (caldera) beneath the central part of Mýrdalsjökull. ERTS Landsat-images from the early 1970's also revealed surface forms which strongly suggested that the Mýrdalsjökull ice cap covered a prominent volcanic caldera (Sigbjarnason, 1973; Sæmundsson,1982).

SURFACE AND BEDROCK TOPOGRAPHY OF THE ICE CAP AS MAPPED BY RADIO ECHO SOUNDING

In May in 1991 the ice surface and bedrock elevations of Mýrdalsjökull were mapped in detail. Ice thickness profiling was carried out by continuous radio echo sounding (Figures 2 and 3). Navigation on the ice cap employed GPS and Loran-C and position of the sounding equipment was logged at 50 m intervals with an accuracy of 50-100 m. Most of the sounding lines run along longitudes or latitudes, but some were placed perpendicular to the trend of the buried subglacial structures in order to minimize lateral reflection. Crevasses prevented sounding on the steepest outlet glaciers, flowing to the east, south and northwest. A total sounding line length of 900 km was used in the compilation of the maps.

Glacier surface mapping

The ice surface elevation was measured by precision barometric altimetry and recorded automatically at 50 m intervals along the sounding lines. Corrections were made for the effects of temperature, and variations in atmospheric pressure were logged by a control barometer at a base station within the caldera.

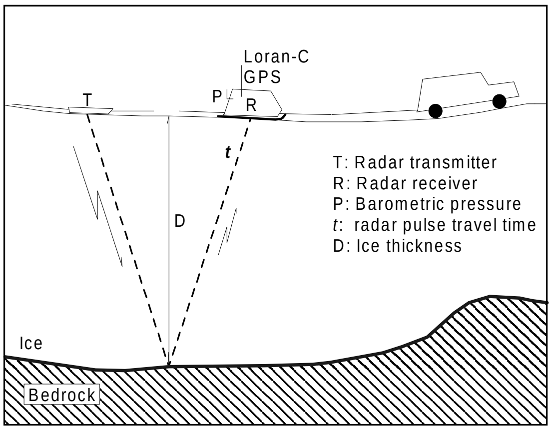

Figure 2. Schematic illustration of the survey technique of ice thickness, position and elevation.– *Skissa af tækjum sem mæla ísþykkt, staðsetningu og hæð jökulsins.*

Elevations were calculated from the standard barometric altimeter equation:

$$z - z_o = (T_o/\beta)[1 - (p/p_o)^{R\beta/g}] \qquad (1)$$

in which T_o and p_o are the absolute temperature and the atmospheric pressure, respectively, at elevation z_o (elevation of base camp), β = 0.0065 K/m is the temperature lapse rate for an international standard atmosphere (i.e. $T = T_o - \beta z$), and p is the observed pressure at the elevation z. For height reference a 40 km long optically levelled profile was surveyed, traversing the ice cap from SSW to NNE and tied to benchmarks of the Icelandic Geodetic Survey on both sides (Fig. 3). The elevation accuracy along this reference line was close to 1 m. Other survey lines were tied to 15 reference points on the optically levelled line and neighbouring mountain peaks. In addition, the elevation was measured at about 230 gravity measurement points, spread over the ice cap. The absolute accuracy in elevation is considered to be ± 5 m on the sounding lines, whereas the relative elevations are accurate to ± 3 m.

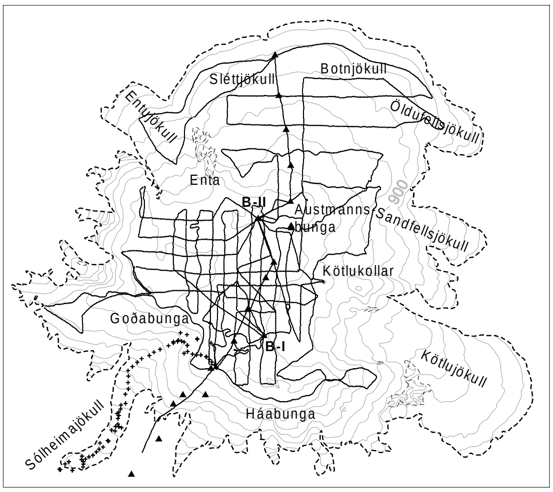

Figure 3. Data source map. The position of the sounding lines and the optically levelled profile (▲) across the ice cap, the location of radio echo soundings (+) by Mackintosh et al. (2000), base camps (B-I and B-II). Names of the main outlet glaciers. – *Gagnasafnskort og nöfn skriðjökla. Lega mælilína og sniðs sem landmælt var yfir jökulinn, mælipunktar við íssjármælingar á Sólheimajökli, lega bækistöðva.*

Radio echo sounding measurements

The radio echo sounder consists of a mono-pulse system (Sverrisson *et al.*, 1980). Pulses of 0.2 μs duration are transmitted into a 30 m long resistively-loaded dipole antenna at the repetition rate of 1 kHz. The reflected signal is picked up by an identical antenna and fed into a receiver which has a 1-5 MHz bandwidth. The transmitter and the receiver are placed on sledges at the centre of the antennae and towed on a line along the glacier surface by a tracked vehicle. The intensity modulation (Z-scope display) of the received signal is recorded photographically with a 35 mm camera. The speed of the scanning beam is proportional to the velocity of the receiver sledge, measured with a bicycle wheel odometer. The velocity of electromagnetic waves in ice was assumed to be 169 m/μs. This same value was also used for the surface firn layer, as its maximum thickness is only about 20-30 m. The vertical thickness of the ice was computed from a digitized sounding record using general inversion techniques as described by Harrison (1970). The sounder sees a strip along the bed of width typically 100-200 m (defined by the first Fresnel zone for a pulse length of 34 m, Björnsson, 1988). Along each sounding line the recorded data represents a moving average of the real bed profile on a strip beneath the line. The accuracy of the absolute ice-thickness measured along the sounding lines is considered to be ±15 m or 2%, whichever is greater. Echo returns were obtained over the whole glacier, however, they were faint in some places adjacent to and south of the northeastern caldera rim, Austmannsbunga, where the ice thickness reaches 600-680 m. Data from Mackintosh *et al.* (2000) were used to compile the map of the Sólheimajökull outlet glacier. The bedrock elevation was obtained as the difference between the ice surface altitude and the ice thickness.

Map compilation

Digital elevation maps (DEM) of the bedrock and surface topography, with equal grid spacing of 100x100 m, were compiled by interpolating data from our soundings and existing geodetic maps of the area surrounding the ice cap. Outside the surveyed area, the final glacier surface map is based on the DMA-series of the Iceland Geodetic Survey (1990). The residual between elevations on our survey lines and the DMA-map was calculated and a new map produced by adding the calculated residuals to the DMA-map. The outlines of the glaciers are the same as on the DMA-series.

Due to the large spacing between the sounding lines (typically 500-1000 m), the topographic map does not fully reproduce features smaller than 1-2 km across, but local detail is described along the sounding lines. However, relative resolution of the bedrock data with respect to topographical features is considerably better. Volcanic and tectonic structures of vertical extension of the order of 10 m and larger can thus be resolved, e. g. hyaloclastite ridges and major normal faults but we are unable to delineate fissure zones with small vertical displacements.

The maps are presented in conformal conical Lambert-coordinates with coordinate axes originating at 65°N and 18°W. The rows and columns in the matrix implicitly define the geographic coordinates. Smoothed contour maps were drawn from the digital matrix.

The glacier surface map

The central parts of the ice cap form a plateau at an elevation of about 1,300 m (Figures 3 and 4), surrounded by higher rims at Háabunga (1497 m) and Goðabunga (1505 m), the nunatak Austmannsbunga (1377 m) and Kötlukollar (1320 m). This is the surface expression of the Mýrdalsjökull caldera. Steep outlet glaciers flow in narrow valleys down to 100-800 m on the southern and western flanks. Broader outlets drain eastward down to 200-400 m, and one large ice lobe covers the northern flank down to 600-650 m.

The surface map shows 12 small depressions in the glacier surface that have been created by subglacial geothermal activity. These ice cauldrons are typically 20 to 50 m deep and their diameter is 500 to 1000 m.

The most striking difference between our map and the 1938 map of the Danish Geodetic Institute is that we describe the sharp elongated shape of the ridges Háabunga and Goðabunga. At Háabunga the elevation of the old maps was wrong by up to 200 m, mainly due to misplacement of the dome. In contrast our map is very similar to that compiled by Sigurðsson in the 1940s (Rist, 1967a).

Bedrock terrain and geological structures

The most prominent landform beneath the ice cap is a large volcano with a circular base of a 20 km diameter at 700 m elevation and 30-35 km at the base. The mountain rises up to rims of 1300-1380 m that surround a 650-750 m deep caldera, reaching down to an elevation of about 650 m (Figures 5, 6 and 7). The area of the depression, girded by the highest points on the rim, is 100 km^2. The arcuate ridges reaching about 1300 m elevation, form the caldera rims beneath Háabunga, Goðabunga, and between Enta and the nuna-

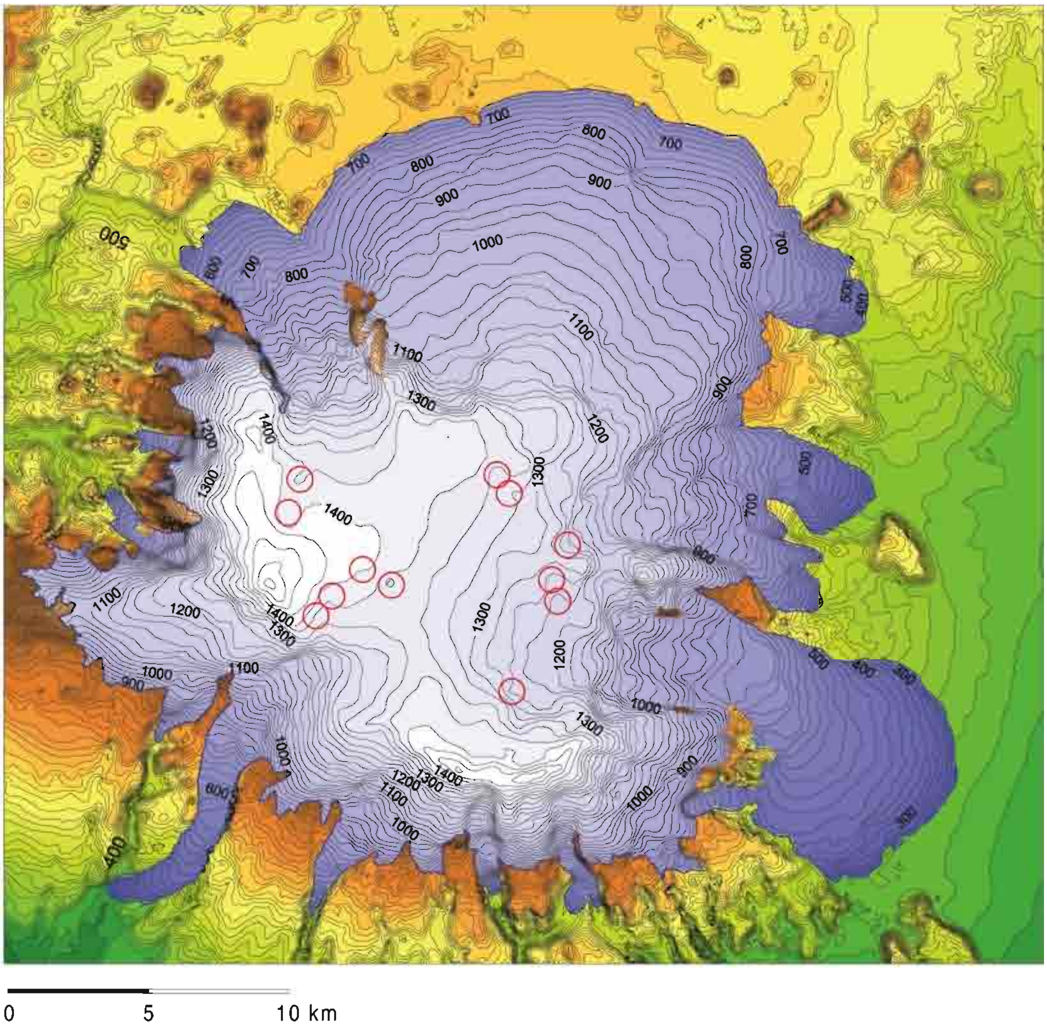

Figure 4. Surface elevation of Mýrdalsjökull in 1991, 25 m contours. Surface depressions (cauldrons) created by subglacial geothermal melting are marked by circles. – *Yfirborðskort af Mýrdalsjökli með 25 m hæðarlínum. Hringir sýna legu sigkatla á jarðhitasvæðum.*

tak Austmannsbunga. The caldera rim has an elliptical outline, with a 14 km long major axis striking SE-NW, and a 9 km long minor axis striking SW-NE. The lower flanks of the volcano are mainly basaltic but rhyolites are exposed on all outcrops that protrude through the ice cover on the caldera rims (Jóhannesson *et al.*, 1990).

The bedrock floor within the caldera has an elevation of 650-1000 m (Figure 5). On the basis of the bedrock topography the caldera floor can be divided into two main parts of almost equal size, on each side of the major axis. The floor is lower and more flat in the northeastern than in the southwestern part of the caldera. In the northeastern part an area of

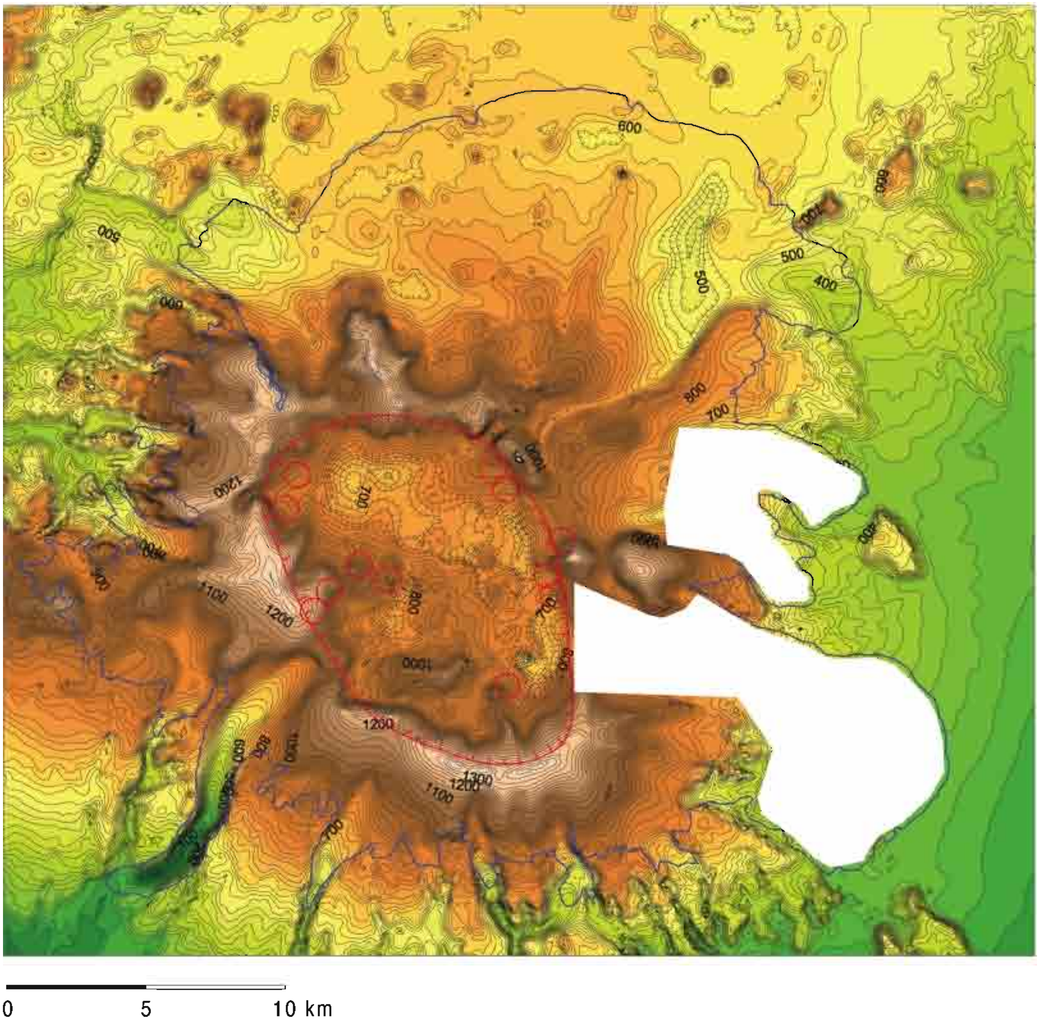

Figure 5. Sub-ice topography of Mýrdalsjökull, 25 m contours. Location of cauldrons marked by red circles and the caldera rim is shown by a red hachured line. – *Kort af botni Mýrdalsjökuls með 25 m hæðarlínum. Hringir sýna legu sigkatla á jarðhitasvæðum og slitrótt lína afmarkar öskjubarmana.*

25 km^2 lies below 800 m. However, a row of peaks, 100-150 m high and trending NNW, is seen 2 km within the eastern rim of the caldera. In the rugged and elevated southwestern floor, subglacial ridges and isolated mounts rise above 1100 m surrounded by depressions that reach down to 750 m. A 3 km long NNW trending ridge strikes from the eastern part of Háabunga and a 5 km long ridge east from Goðabunga. About 3 km north of Háabunga an isolated ridge strikes E-W parallel to the caldera rim. The different morphology of the caldera floor, on each side of the major axis, reflects different production rates of volcanic material after the volcano became covered with ice.

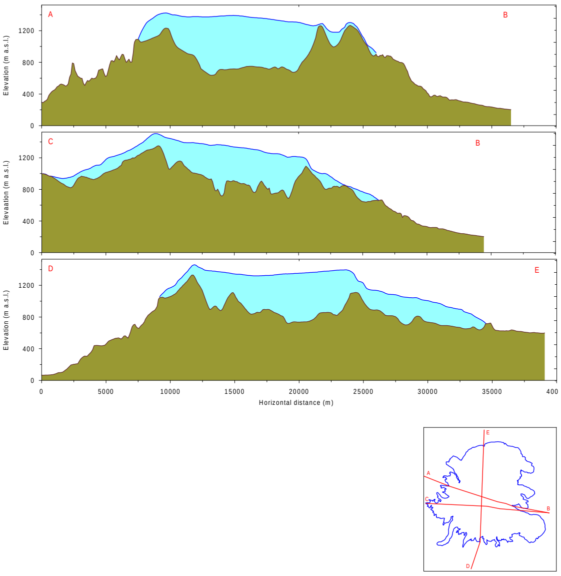

Figure 6. Sections across the Mýrdalsjökull caldera. AB: Goðabunga to Kötlukollar, CB: Fimmvörðuháls to Kötlukollar, DE: Háabunga to Sléttjökull. – *Snið yfir öskju Mýrdalsjökuls*.

Several glacially eroded passes cut the caldera rim but the elevation of their deepest points has not been exactly determined. The lowest pass seems to lie at about 740 m between Háabunga and Kötlukollar, facing southeast to the glacier outlet Kötlujökull. Sólheimajökull drains southwest through a 1050 m breach between Háabunga and Goðabunga. A pass in the northwest at about 1100 m heads toward Entujökull, and a northeastern pass toward Sandfellsjökull. A narrow gorge trending northeast is located just west of Austmannsbunga. This gorge may be a tectonic feature subsequently eroded by water and ice. All these breaches in the caldera rim are potential pathways for jökulhlaups from subglacial lakes at geothermal areas and during volcanic eruptions.

Outside the caldera, several linear structures are prominent on the bedrock map. The topographic ridges that strike outward from the central volcano, presumably consist of hyaloclastites, and crater rows built up on volcanic fissures. On the western side of the caldera margin an E-W trending ridge, Fimmvörðuháls, connects Goðabunga to the neighbouring Eyjafjallajökull volcano. The Kötlukollar ridge on the eastern side of the caldera has the same trend. Entujökull flows between two parallel NW-striking ridges named Enta and Entukollur. In contrast, no ridges strike toward south in the direction of propagation of the rift zone. A ridge strikes N45°E from Austmannsbunga toward Öldufellsjökull, separating Sandfellsjökull and Sléttjökull, and the deep and narrow V-shaped gorge north of Austmannsbunga. This gorge is 200-250 m deep and 1.5 km wide, and bounded by steep slopes. This roughly linear structure is a continuation of the Eldgjá fissure, which produced a lavaflow of 14 km^3 in 934 A.D. and is of tectonic origin. However, it may subsequently have been eroded by jökulhlaups. Beneath Sléttjökull and Botnjökull several isolated peaks bear witness to recent volcanic activity that has created new mountains at a rate, which keeps up with glacier erosion.

Beneath the deeply-eroding Sólheimajökull the bottom dips 50 m below sea level, which is 100 m lower than the terrain in front of the glacier outlet, and is indeed the lowest observed elevation under Mýrdalsjökull (Mackintosh *et al.*, 2000). The region under Kötlujökull, however, has not been sounded.

Ice thickness

The ice thickness of Mýrdalsjökull is highly variable (Figure 8). The maximum ice thickness of about 740 m, is found in the northern part of the caldera where an area of 12 km^2 is covered with more than 600 m thick ice.

Outside the caldera the greatest ice thickness of 450 m was measured on the Eldgjá fissure. The thickness of the ice capping caldera rims is 150 to 200 m at Háabunga and Goðabunga. The main part of Sléttjökull has an ice thickness of 200-300 m, as has Sólheimajökull. The ice thickness of Kötlujökull is unknown. The distribution of the glacier surface area and ice volume for given elevation shows that about 20% of the bedrock of Mýrdalsjökull and 55% of its ice surface lies above 1000 m (Figure 9). The total volume of ice on Mýrdalsjökull is about 140 km^3 and the average thickness only 230 m. Inside the caldera an area of 17 km^2 is below 740 m elevation containing 0.7 km^3. The area and volume of ice inside the rims of the caldera, is 100 km^2 and 45 km^3, respectively.

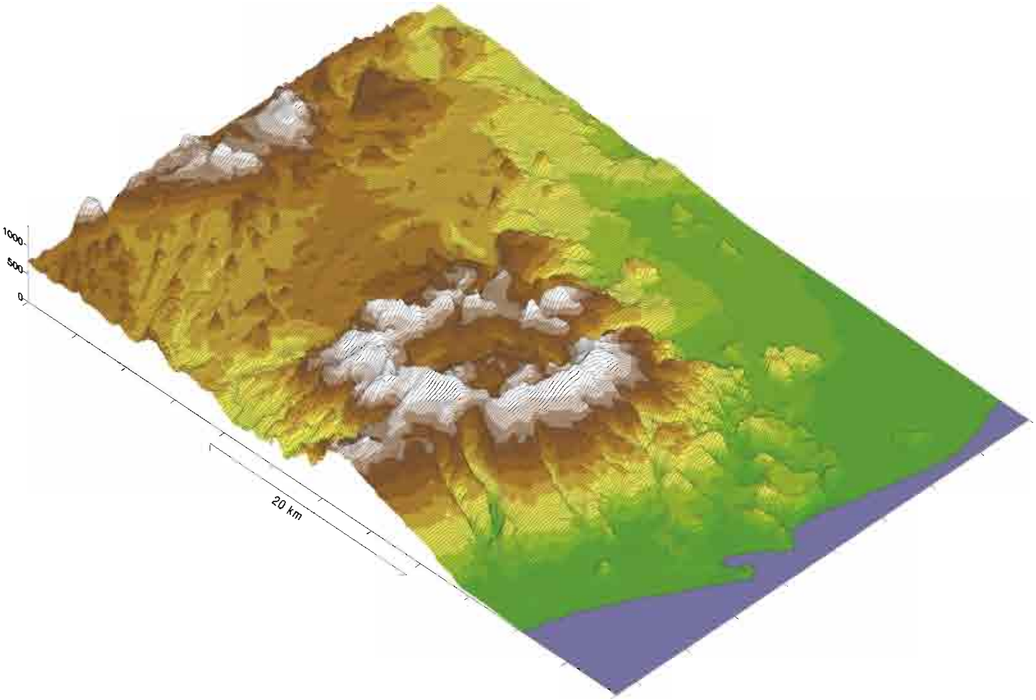

Figure 7. Perspective plot of the sub-ice topography of Mýrdalsjökull and surroundings. View from SW. – *Fjarvíddarmynd af botni Mýrdalsjökuls og nágrenni. Horft í norðaustur.*

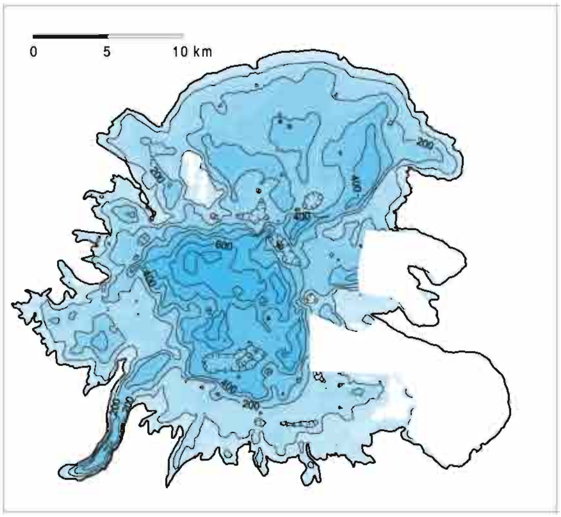

Figure 8. Ice thickness of Mýrdalsjökull, 100 m contours. – *Ísþykktarkort af Mýrdalsjökli.*

ICE CATCHMENT BASINS

The ice flow of Mýrdalsjökull is separated into many distinct ice catchment basins. The boundaries of five main ice catchment basins have been delineated using the surface elevation map (Figure 9, Table 1). We assume that the location of the central flow divide of the ice cap corresponds to the highest ice-surface profile. The boundaries of the major ice drainage basins were drawn manually upstream from the edge to the highest point, perpendicular to smoothed elevation contours.

The main ice divides are located on the southern, western and northern rims of the caldera. Kötlujökull collects ice across the entire reach of the caldera, from an ice divide at the head of Entujökull, from where it flows over 20 km downslope to Mýrdalssandur. The

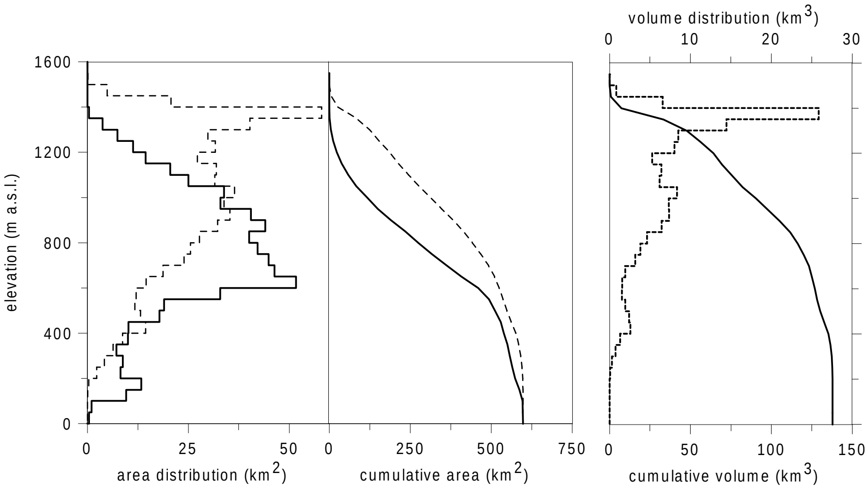

Figure 9. Distribution with elevation of ice surface, bedrock area and ice volume of Mýrdalsjökull. – *Hæðardreifing yfirborðs, botnflatar og ísrúmmáls Mýrdalsjökuls.*

width of the ice drainage basin is 7-8 km in most parts and the ice thickness reaches 740 m. Sólheimajökull drains up to 500-600 m thick ice from a saddle between Háabunga and Goðabunga that extends 1-2 km inside the rim of the caldera. Sandfellsjökull drains ice from the northeastern caldera rims and is separated from Kötlujökull by Kötlukollar. Sléttjökull and Botnjökull drain the northern flanks of the central volcano. The ice catchment basin of one ice cauldron, at the head of Sólheimajökull, about 2 km^2 in area, is shown in Figure 10.

WATER DRAINAGE BASINS

Many rivers drain Mýrdalsjökull. The meltwater reaches the glacier bed through moulins, crevasses and veins, and drains along the base together with basal meltwater produced by frictional and geothermal heat. Subglacial drainage is commonly thought to take place via numerous conduits that may join together forming a few final tunnels, which leave the glacier in a portal. Water that drains out of a number of such portals joins in the foreland to one glacial river.

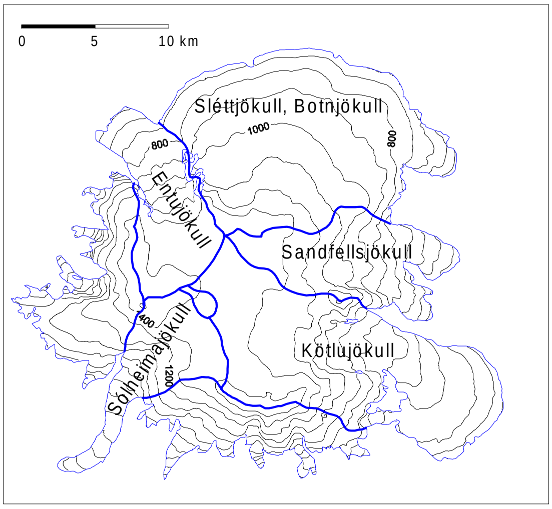

Figure 10. Ice divides of the main ice drainage basins of Mýrdalsjökull. – *Skipting Mýrdalsjökuls í nokkur helstu ísasvæði.*

The watershed on the glacier for this river is drawn as a continuation of the watershed outside the glacier and encircles the individual water drainage basins on

Table 1. Data for five ice catchment basins on Mýrdalsjökull – *Gögn um fimm hluta Mýrdalsjökuls.*

Name	Area Flatarmál km^2	Volume Rúmmál km^3	Mean thickness Meðalþykkt m	Max. elev. Mesta hæð m	Min. elev. Lægsta hæð m
Sólheimajökull	47	12.5	268	1510	120
Entujökull	57	16.2	285	1510	420
Sléttjökull, Botnjökull, og Öldufellsj.	171	40.0	233	1370	620
Sandfellsjökull	66	ca. 15	223	1370	240
Kötlujökull	148	ca. 40	274	1497	200
Mýrdalsjökull	598	140	230	1510	120

the glacier. The watershed at the glacier base is located where the gradient is zero for the fluid potential (expressed as pressure, Pa):

$$\phi_b = \rho_w g z_b + p_w \qquad (2)$$

i. e. the sum of a term expressing the gravitational potential and the water pressure p_w. The symbol ρ_w = 1000 kgm^{-3} represents the density of water g = 9.82 ms^{-2} is the acceleration due to gravity and z_b is the elevation of the glacier substratum relative to sea level. Water flow in an isotropic basal layer would move perpendicularly to the equipotential lines.

The location of the water divides was predicted by a theory of water-filled subglacial conduits (Shreve, 1972; Röthlisberger, 1972). The basal water pressure was assumed to be

$$p_w = k p_i \qquad (3)$$

where p_i = $\rho_i g H$ is the ice overburden pressure, and k is a constant, ρ_i = 916 kgm^{-3} represents the density of ice and H is the thickness of the glacier. This is a first-order approximation of the water pressure and does not describe small-scale variations or fluctuations with the supply of meltwater.

In places where the water pressure is equal to the atmospheric pressure (p_w = 0) location of the water divide, can be obtained directly from elevation contours of the glacier bed, as if no glacier were present. Atmospheric water pressure may occur in steeply-sloping conduits near the edge of the glacier where closure due to the ice overburden pressure cannot keep up with the enlargement due to frictional melting (see Hooke, 1984); thus, the water divides would entirely follow the basal topography.

Under thick ice we expect the water pressure to be close to the ice overburden, at least close to the water divides where the water is flowing slowly and melting of the subglacial tunnels by frictional heat is negligible. On the basis of the predicted potential, ϕ_b, at the glacier bed, according to equations (2) and (3), the Mýrdalsjökull ice cap is divided into three main drainage basins (Figure 11, Tables 2 and 3).

Table 2. Water drainage basins on Mýrdalsjökull. Delineation of water drainage basins – *Vatnasvæði á Mýrdalsjökli*

Outwash plain Jökulsandur	Area Flatarmál km^2	Volume Rúmmál km^3	Mean thickness Meðalþykkt m
Sólheimasandur	108	20.3	189
Markarfljótsaurar	167	38.5	230
Mýrdalssandur	323	(79)	(244)
Total	598	138	230

Table 3. Water drainage basins within the caldera rims – *Vatnasvæði innan Kötluöskjunnar*

Outwash plain Jökulsandur	Area Flatarmál km^2	Volume Rúmmál km^3	Mean thickness Meðalþykkt m
Sólheimasandur	19	7.7	401
Markarfljótsaurar	23	12.2	525
Mýrdalssandur	60	28	(467)
Total	102	48	470

The predicted water drainage basins are larger than they would be if the subglacial water pressure were atmospheric. The local gradient in the ice overburden pressure drives water out of the caldera through the passes in the caldera rim. Kötlujökull would collect water from the entire eastern part of the caldera. The watersheds, however, coincide with the ice divides on the sharpest rims of the caldera at Háabunga and Austmannsbunga. Outside the caldera the water divide between Mýrdalssandur and Markarfljótsaurar lies down the central part of Sléttjökull.

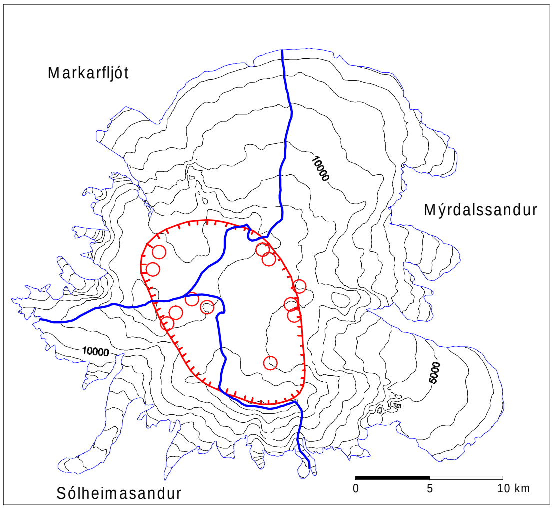

Figure 11. Estimated water pressure potential (ϕ_b) at the ice-bed interface (kPa). Water divides are shown as blue lines. The location of ice cauldrons are marked by red circles and the caldera rim by a red hachured line. – *Mat á mætti sem rekur vatn eftir jökulbotni. Skipting Mýrdalsjökuls í nokkur helstu vatnasvæði. Hringir sýna legu sigkatla á jarðhitasvæðum og slitrótt lína afmarkar öskjubarmana.*

Meltwater is known to have accumulated in subglacial lakes beneath the cauldron west of Kötlukollar and frequently drain in small jökulhlaups under Kötlujökull. Frequent observations of sulphurous smell from Múlakvísl indicates that meltwater may continuously drain from geothermal areas inside the drainage basin of Kötlujökull. The cauldrons east of Goðabunga drain to Fremri-Emstruá. Continuous smell of hydrogen sulphide from Jökulsá á Sólheimasandi indicates drainage of geothermal fluid from beneath cauldrons at the saddle between Goðabunga and Háabunga.

GEOTHERMAL AREAS, ERUPTION SITES AND ROUTES OF JÖKULHLAUPS

Geothermal activity under Mýrdalsjökull is manifested by several ice cauldrons in the glacier surface. The current activity is located just inside the caldera rims, where faults allow rapid vertical transport of geothermal fluid. Accurate and reliable descriptions of eruptions over the last four centuries indicate that they have occurred both on single vents and short volcanic fissures. According to Þorsteinn Magnússon at Þykkvabær in Álftaver (1626, *Safn til Sögu Íslands*, IV, p. 208) many small vents were observed east of the main crater six days after the start of the eruption. Due to melting in the eastern part of the ice cap during the 1721 eruption, black cliffs or a mountain became visible that had been covered by the ice for more than 100 years (p. 228).

In 1755, Jón Sigurðsson (1755, *Safn til Sögu Íslands*, IV, p. 236) reported two vents almost due north from the farm Holt in Mýrdalur. He counted up to five vents two months after the start of the eruption. Three distinct columns of fire side by side were depicted towards the end of the eruption (Eggert Ólafsson, 1772). Based on this description we suggest that this eruption took place on a several kilometers long fissure trending east from Goðabunga (Figure 12). The fissure extended far into the drainage basin of Kötlujökull and therefore meltwater was directed eastward to Mýrdalssandur. This was the largest eruption of the millennium in Mýrdalsjökull after the settlement, producing 1.5 km^3 of tephra (Þórarinsson, 1975). The proximity of the eruption site to Sólheimajökull may have caused the peculiar surge-like behavior of this glacier outlet. Eggert Ólafsson (1772) reported that “during the eruption the glacier went up and down in an undulating motion and finally settled so puffed-up that it became twice as high as before ”. Moreover, the neighbouring Eyjafjallajökull “subsided due to the eruption so two ice free peaks rise above the glacier with a black cliff between them, which nobody has seen as far back as people remember” (Ólafsson, 1772).

Jón Austmann (1845, *Safn til Sögu Íslands*, IV,

p. 255 and 262) described the 1823 eruption site in a detailed diary from the district Álftaver (Figure 1). He also climbed Austmannsbunga from where he portrayed the eruption site at the northern slopes of Háabunga. He described a horseshoe shaped glacier fissure with a SW-NE direction closest to Austmannsbunga but a SE-NW direction close to Háabunga. The bearing from Vík was by the western slopes of the mountain Hatta (p. 268). We suggest that this eruption may have taken place on the 2-3 km long ridge striking NNW from the eastern rim of Háabunga (Figure 12).

In 1918, Jóhannsson (1919, p. 12 and 47) viewed two eruption vents from the south but the location was reported on the northern slopes of Háabunga, 1500 to 200 m north of its highest crest (Sveinsson, 1919, p. 15 and 57). Rist (1967a), however, suggested that the 1919 eruption site was farther north, where two cauldrons suddenly subsided in June 1955 about 3 km southwest of Kötlukollar (Figures 3 and 4), followed by a jökulhlaup under Kötlujökull (Rist, 1967b). Tryggvason (1960) presented seismic data supporting the hypothesis that a small subglacial eruption had taken place in June 1955 where the cauldrons formed. Our radio echo soundings show a 60 m high mound with a diameter of 300 m beneath the southernmost cauldron. The northern cauldron is situated above a depression in the base between two 100-150 m high mounds, that may be the remnants of a crater with an inner diameter of 400-500 m, or a ridge formed during an eruption. The ice there is 400 m thick.

Björnsson (1970) presented bearings of the 1918 eruption site taken from a coastal vessel located to the east of the ice cap that combined with a bearing from Vík gave a location slightly south of the cauldrons (63°37’5”N, 19°3’W). Photographs taken by Kjartan Guðmundsson 23. June 1919 on Háabunga toward Kötlukollar (Þórarinsson, 1959, p. 16, figure 8) show that the crater was neither situated at this position nor where the cauldrons subsided in 1955. Therefore, we suggest that the description of Sveinsson (1919) should be taken literally and that the position of the crater was as shown in Figure 12.

No observations locate sites of eruptions triggering jökulhlaups draining toward Sólheimasandur. During the 1860 eruption a small jökulhlaup drained this way (Hákonarson, 1860) but the main flood went down to Mýrdalssandur. Only one eruption site was reported. However, some melting must have taken place in the western part of the caldera.

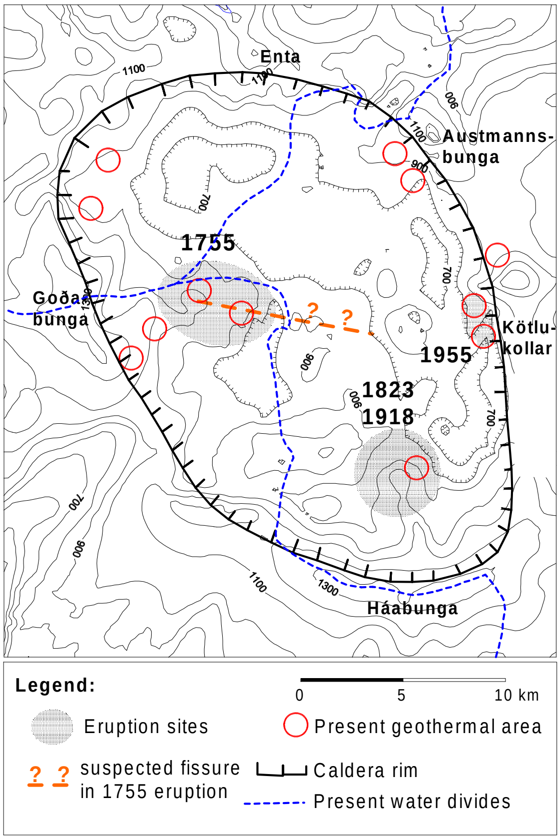

Figure 12. Likely location of recent eruptions in Mýrdalsjökull (1755, 1823, 1918, 1955? A.D.). – *Líkleg lega nýlegra gosstöðva (1755, 1823, 1918 og 1955?).*

Prehistoric eruptions have also drained down Entujökull (Haraldsson, 1981; Sigurðsson, 1988). Extensive flood deposits, found between Öldufell and Kötlujökull, may also be produced by volcanic activity outside the caldera. In 934 A.D. a subglacial part of the Eldgjá fissure erupted and jökulhlaups drained down to Mælifellssandur and south of Öldufell to the river Hólmsá (Larsen, 2000).

Our model predictions of the delineation of the water drainage basins suggest that from an area of 60 km^2 of the caldera floor, meltwater is drained down to Mýrdalssandur, as did 18 of 20 recorded jökulhlaups in historical times; from about 20 km^2 down to Sólheimasandur as did 2 of the jökulhlaups. The third route down Entujökull was taken by the jökulhaup in 1600 B.P. (Haraldsson, 1981).

The location of the watershed predicted by our data may change during volcanic eruptions. However, if our calculations apply for normal conditions and at the start of an eruption we consider it likely that meltwater from the eruption site will continue to drain through pre-existing channels. After the eruption breaks through the ice cover the basal water pressure will be determined by the water level at the crater and the energy used to transport the water down the glacier.

CONCLUSIONS

We present the first maps of Mýrdalsjökull that describe with known accuracy the surface and bedrock topography. The maps provide basic data for various studies in geology, glaciology and hydrology. They describe the shape of the subglacial part of the Katla volcanic system, the geometry of the central volcano, the location of recent eruptive sites and their connection with structures in the surrounding landscape. The caldera encircles an area of 100 km^2, is 600 to 750 m deep and its highest rims reach 1380 m a.s.l. The northern part of the caldera floor is smoother and lies deeper than the southern part, which in contrast is characterized by subglacial ridges and individual mounts rising from ca. 750 to 1100 m a.s.l. A row of mounts trending NNW, presumably active in recent eruptions, lies 2 km within the eastern rim of the caldera beneath 400 m thick ice.

A number of ridges radiate out from the caldera, however, none towards south. One ridge strikes W towards the neighbouring volcano Eyjafjallajökull, and a second ridge strikes E from the eastern rim of the caldera. Ridges also radiate from the caldera rim towards NW, N, and NE. A linear depression, bounded by steep slopes, 200-250 m deep and 1.5 km wide, strikes NE towards the volcanic fissure Eldgjá.

The maps describe the geometry of the ice cap and its flow and provide data to evaluate the drainage of meltwater from the ice cap during normal conditions and volcanic eruptions. All but two of the 20 jökulhlaups in historical times have taken a path through a pass in the caldera rims southeastward, down to Mýrdalssandur. An area of 60 km^2 within the caldera drains now to Mýrdalssandur, and an area of about 20 km^2 to the southwest, down to Sólheimasandur. Two jökulhlaups are known to have taken this route to the river Jökulsá á Sólheimasandi in historical times. A third route, westward into Fremri Emstruá and the Markarfljót river, was taken by a prehistoric jökulhlaup in 1600 B.P.

The maps form the basis for studies of glacier-volcano interactions and provide a reference datum for monitoring temporal changes in the geometry and flow of the glacier in response to basal geothermal activity as well as to climatological impact. Presently, geothermal activity is displayed by several small cauldrons in the glacier surface, 0.5-1 km in diameter. Meltwater accumulates beneath two or three of these cauldrons and is frequently drained in small jökulhlaups.

Over the last four centuries eruptions have occurred on single vents and volcanic fissures trending E-W and S-N. We suggest that the 1755 eruption, the largest eruption in Mýrdalsjökull of the millennium, took place on a several kilometers long fissure trending east from Goðabunga. The fissure extended far into the drainage basin of Kötlujökull and therefore meltwater was directed eastward to Mýrdalssandur. We suggest that the 1823 eruption took place on the 2-3 km long ridge striking NNW from the eastern rim of Háabunga (Figure 12), and that the 1918 eruption site was situated in the same area.

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ÁGRIP

Yfirborð og botn Mýrdalsjökuls: Kötluaskjan, gosstöðvar og rennslisleiðir jökulhlaupa

Mýrdalsjökull er fjórði stærsti jökull landsins, 1300-1500 m hár, alls um 600 km^2 að flatarmáli (1. mynd). Hann hylur eina virkustu megineldstöð landsins, sem gosið hefur 20 sinnum frá landnámstíð, svo að átján sinnum hafa jökulhlaup fallið niður Mýrdalssand og tvisvar til Sólheimasands. Fyrir 1600 árum féll hlaup norðvestur í Markarfljót.

Fyrstu kort af Mýrdalsjökli voru gerð af danska herforingjaráðinu 1904-1907 (suðurhluta) og 1937-1938 (meginjöklinum) í mælikvarða 1:100.000. Þau voru gerð eftir skámyndum, sem teknar voru úr flugvélum og var ekki ætlað að sýna nákvæma hæð heldur lögun jökulyfirborðsins. Fyrsta kortið sem studdist við landmælingar á sjálfum jöklinum vann Steinþór Sigurðsson árið 1943. Næstu kort voru gerð af kortastofnun bandaríska hersins, U.S. Army Map Service, í mælikvarða 1:50.000. Hæðarlínur við jökulsporðinn voru fundnar af loftmyndum frá 1945-46 en ofar á jöklinum voru þær eins og á kortum Dananna. Þessi kort sýndu aðaldrætti í lögun jökulsins, skriðjökla og dæld í miðjum jökli sem afmarkaðist af Háubungu og Goðabungu. Reyndar lýsti kort Steinþórs Sigurðsonar best skörpum brúnum bungnanna.

Könnun á þykkt Mýrdalsjökuls og landslagi undir honum hófst 1955 með jarðsveiflumælingum, sem sýndu 300-400 m þykkan ís í 9 punktum á hájöklinum. Árið 1977 var 500-600 m ísþykkt mæld með íssjá í nokkrum sniðum á sömu slóðum. Staðfestu allar þessar mælingar hugmyndir manna um að askja væri undir jöklinum.

Kort af yfirborði og jökulbotni. Vorið 1991 var gerður leiðangur á Mýrdalsjökul til þess að kortleggja yfirborð og botn hans svo og rennslisleiðir íss og vatns niður að jökulsporði og jökulám. Mikilvægur þáttur í þessu verki var könnun á eldstöðvum undir jöklinum og mat á því hvert jökulhlaup geta fallið við gos undir honum. Hæð jökulyfirborðsins var mæld með nákvæmum lofthæðarmælingum og þykkt hans með íssjá (2. og 3. mynd).

Fyrstu kort af Mýrdalsjökli sem lýsa af nákvæmni yfirborði (4. mynd) og botni (5. mynd) hans sýna að undir sunnanverðum jöklinum er mikil megineldstöð með hringlaga grunnfleti. Eldstöðin 30-35 km að þvermáli í 200 m hæð og rís upp í 1300-1380 m hæð. Bogadregnir hryggir við Háubungu, Goðabungu og milli Entu og jökulskersins Austmannsbungu (3. mynd) umlykja 650-750 m djúpa öskju megineldstöðvarinnar, sem nær niður í um 650 m hæð. Innan sporöskjulaga barmanna er um 100 km^2 svæði með 14 km langás, í stefnu SA til NV og 9 km skammás, frá SV til NA. Munur á landslagi á öskjubotninum sitthvoru megin við langásinn gæti endurspeglað framleiðslu gosefna eftir að eldstöðin huldist ís. Í norðausturhluta öskjunnar er 25 km^2 flötur neðan við 800 m og botninn er lægri og flatari en í suðvesturhlutanum. Þó er röð NNV-lægra tinda sem gætu verið gígar, um 2 km innan við austurbrún öskjunnar. Í hinum óslétta og hálendari suðvesturhluta eru hryggir og stakir tindar sem ná yfir 1100 m hæð en dældir umhverfis þá ná niður fyrir 750 m. Um 3 km langur hryggur liggur til NNV frá austurhluta Háubungu og 5 km langur hryggur liggur austur frá Goðabungu. Um 3 km norðan við Háubungu er stakur hryggur í stefnu A-V samsíða öskjubörmunum.

Nokkur jökulsorfin skörð eru í öskjubörmunum. Um þau gætu fallið jökulhlaup frá lónum á jarðhitasvæðum og við gos undir jöklinum. Lægsta skarðið er í um 740 m hæð milli Háubungu og Kötlukolla og snýr suðaustur að Kötlujökli. Þótt hæð annarra skarða hafi ekki verið könnuð nákvæmlega má ætla að Sólheimajökull falli um 1050 m hátt skarð milli Háubungu og Goðabungu og hæð skarðs við Entujökull sé um 1100 m. Einnig er skarð að Sandfellsjökli. Norðaustan við Austmannsbungu er 200-250 m djúpt og 1.5 km breitt V-laga gljúfur, á sprungusveim sem teygist frá Kötluöskjunni norðaustur að Eldgjá. Það gæti upprunalega hafa orðið til við jarðskorpuhreyfingar en síðan rofist af vatni og ís, m.a. árið 934 þegar gaus í þeim hluta Eldgjársprungunnar sem er hulin jökli og jökulhlaup féll niður á Mælifellssand og sunnan við Öldufell í Hólmsá. Önnur gos utan öskjunnar hafa einnig hafa valdið miklum jökulhlaupum og gætu mikil hlaupset milli Öldufells og Kötlujökuls vitnað um það.

Undir hinum djúpa og rofna Sólheimajökli nær botn 50 m niður fyrir sjávarmál, eða 100 m lægra en landhæð við jökulsporðinn og lægsta land sem mælst

hefur undir Mýrdalsjökli. Botn undir Kötlujökli hefur hins vegar ekki enn verið mældur.

Ísstraumar. Þykkastur er Mýrdalsjökull um 740 m í nyrðri hluta öskjunnar þar sem 12 km^2 svæði er þakið meira en 600 m þykkum ís (8. mynd). Utan við öskjuna er jökullinn mest um 450 m þykkur, yfir geil í framhaldi Eldgjárinnar. Á öskjubörmum Háabungu og Goðabungu er jökullinn 150 to 200 m þykkur. Meginhluti Sléttjökuls er 200-300 m þykkur eins og Sólheimajökull. Um 20% af botni Mýrdalsjökuls og 55% af yfirborði hans eru yfir 1000 m (9. mynd). Heildarrúmmál Mýrdalsjökuls er um 140 km^3 og meðalþykkt 230 m.

Meginísaskil liggja á börmum öskjunnar að sunnan, vestan og austan (10. mynd). Kötlujökull flytur ís frá meginhluta öskunnar, allt frá ísaskilum við Entujökul. Sólheimajökull er allt að 500-600 m þykkur ís þar sem hann teygist 1-2 km inn fyrir rima öskjunnar á söðlinum milli Háubungu og Goðabungu. Sandfellsjökull flytur ís frá norðausturhluta öskjunnar og Kötlukollar skilja hann frá Kötlujökli. Sléttjökull og Botnjökull skríða niður norðurhlíð megineldstöðvarinnar en flytja ekki ís úr öskjunni.

Vatnasvæði, sigkatlar og jarðhitasvæði. Mýrdalsjökull veitir stöðugt vatni í margar ár en einnig safnast bræðsluvatn undir sigkatla á jarðhitasvæðum og hleypur þaðan í smáskvettum. Á yfirborðskortinu frá 1991 mátti greina 12 sigkatla, sem höfðu myndast vegna jarðhita undir jöklinum, 20 til 50 m djúpa og 500 til 1000 m að þvermáli (4. mynd). Af botnkortinu sést að jarðhitavirknin er rétt innan við öskjubarmana þar sem bræðsluvatn nær að hripa niður lóðréttar sprungur í berginu. Stöðug brennisteinslykt af Jökulsá á Sólheimasandi bendir til sírennslis undan sigkatli á söðlinum milli Goðabungu og Háubungu (sjá safnsvæði á 10. mynd, 2 km^2). Í Fremri-Emstruá hleypur hins vegar frá sigkötlum austan í Goðabungu og undan þremur kötlum vestan við Kötlukolla koma smáhlaup í Múlakvísl og Leirá. Vatn virðist ekki safnast fyrir í öskjubotninum heldur renna þaðan suðaustur niður Kötlujökul.

Vatnaskil við jökulbotn eru dregin upp frá vatnaskilum við jökuljaðarinn og umlykja þau svæðið sem veitir vatni að einstökum jökulám (11. mynd, 2. og 3. tafla). Við mat á legu þeirra var reiknað með að vatnsþrýstingur við jökulbotn væri jafn ísfargi. Þrjú meginvatnasvið eru innan öskjunnar: að Kötlujökli (60 km^2), Entujökli (20 km^2) og Sólheimajökli (20 km^2). Sé litið á allan jökulinn fellur vatn af um 310 km^2 svæði til Mýrdalsjökuls, 110 km^2 svæði til Sólheima- og Skógasands og 170 km^2 að Markarfljóti.

Gosstöðvar. Öll gos sem lýsingar eru til um hafa orðið í austurhluta öskjunnar og jökulhlaup fallið niður á Mýrdalssand (árin 1625, 1660, 1721, 1755, 1860, 1918). Frásagnir benda til þess að gosin hafi orðið á einstökum gosopum og sprungum. Árið 1625 færðust gosopin til austurs frá megingígnum meðan á gosi stóð (Þorsteinn Magnússon (1626, p. 208). Við gosið 1721 lækkaði jökullinn svo vegna bráðnunar að íslaus klettur kom í ljós, sem hafði verið hulinn jökli í meira en 100 ár (handrit í Safni til Sögu Íslands, p. 228; Eggert Ólafsson, 1772).

Árið 1755 kom gos fyrst upp á tveimur stöðum og var annar í norðri frá Holti í Mýrdal (1. mynd), en tveimur mánuðum eftir upphaf gossins sáust fimm gígar (Jón Sigurðsson, 1755, p. 236; Eggert Ólafsson, 1772). Af þessu má ætla að gosið hafi á sprungu innan öskjunnar, sem teygði sig að vesturbrún hennar. Hér er þeirri tilgátu varpað fram að sprungan hafi náð að hryggnum austur úr Goðabungu, en við upphaf gossins hafi vatnsrás opnast austur að Kötlujökli svo að hlaupið hafi farið þá leið (12. mynd). Gosstöðvar nálægt upptökum Sólheimajökuls gætu hins vegar hafa valdið auknum vatnsaga undir honum og hleypt honum fram, því að „meðan á gosinu stóð gekk jökullinn líkt og í bylgjum, hækkaði ýmist eða lækkaði og að lokum belgdist hann svo upp að hann er nú helmingi hærri en áður“(Eggert Ólafsson, 1772). Við gosið hitnaði einnig undir Eyjafjallajökli svo að íslausir tindar risu upp úr jöklinum og svartir klettar sáust milli þeirra. Gosið 1755 er talið stærst allra frá Kötlu frá því land byggðist. Upp komu 1.5 km^3 af gjósku (Sigurður Þórarinsson, 1975).

Árið 1823 lýsti Jón Austmann, (1845, p. 255 og 262) gosstöðvum í suðaustanverðri öskjunni, norðaustan í slakka frá hæstu brún jökulsins (Háubungu, innskot höf.). Þetta gos gæti hafa orðið á 2-3 km löngum hrygg NNV frá austurbrún Háubungu (12. mynd).

Af lýsingu Gísla Sveinssonar (1918) og Guðgeirs Jóhannssonar (1919) má ætla að gosið 1918 hafi komið upp á svipuðum stað og 1823. Sigurjón Rist (1967a) varpaði þó fram þeirri hugmynd að gosstöðvarnar hefðu verið mun norðar, þar sem miðketillinn er suðvestan við Kötlukolla (3. og 4. mynd). Ljósmyndir Kjartans Guðmundssonar, teknar frá Háubungu, sýna hins vegar að gígurinn var ekki þar sem katlarnir eru nú og því er hér lagt til að treysta lýsingum Gísla og Guðgeirs, sjá 12. mynd. Hins vegar gæti lítið gos hafa orðið í júní 1955 þar sem sigkatlarir eru. Þá hljóp skyndilega undan tveimur syðstu kötlunum (Sigurjón Rist, 1967b) og Eysteinn Tryggvason (1960) setti fram jarðskjálftagögn sem studdu þá tilgátu. Á þessum slóðum er 400 m þykkur ís og undir miðkatlinum er 150 m djúp kvos en um 60 m hár hóll undir syðsta katlinum.

Við gosið 1860 var ekki getið um fleiri en einn gíg. Lítið hlaup kom þó undan Sólheimajökli (Magnús Hákonarson, 1860), svo að einhver bráðnun varð vestarlega í eldstöðinni, þótt meginflóðið félli niður á Mýrdalssand.

Lokaorð. Kortin af yfirborði og botni Mýrdalsjökuls eru grunnur að margs konar rannsóknum í jarðfræði, jöklafræði og vatnafræði. Auk þess að lýsa flæði jökulsins nýtast þau til viðmiðunar á viðbrögðum hans við eldvirkni, jarðhita við botn og loftslagsbreytingum. Lega vatnaskila undir Mýrdalsjökli er metin af núverandi lögun jökulsins. Þar sem líklegt er að við upphaf goss haldi bræðsluvatn frá gosstöðvum áfram að renna um rásir sem fyrir eru gæti mat á núverandi legu vatnaskila nýst við spár um hvert jökulhlaup falli, bendi jarðhræringar til þess að gos sé að brjótast upp undir jöklinum.

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