GEOLOGY AND GEOPHYSICS

The geomorphology of Surtsey Island in 1972

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INTRODUCTION

This report is based on field studies, carried out by the authors in July 1972, aerial surveys of 15 July 1971 and 7 August 1972 (Fig. 1), and comparisons with results of previous investigations by the senior author (Norrman 1968, 1969, 1970, 1972a and b). The aim of the 1972 studies was to map the distribution of tephra soil over the lava areas, to study differentiation in tephra soil by geomorphic processes, to evaluate the use of photogrammetric ground surveys in studies of the morphology of steep walls and finally to determine coastal changes during the last two years.

SOIL STUDIES

Soil distribution

One of the factors that seriously limits the progress of plant colonisation on Surtsey is the mobility of the soil (Schwabe 1970, 1971a, b). The main part of the loose material on the island is made up of tephra either found as originally deposited after volcanic eruptions or redeposited after transportation by slope processes, by wave action or by wind drift. The other soil source is the lava. An unknown part of the glowing lava that flew into the sea was by the rapid cooling fragmented into cubic particles of pebble size. Very coarse material is also produced by wave abrasion of the lava cliffs. The distribution of these shore products is confined to the beaches and the flood deposits of the northern ness. Weathering products from the lava plateau surfaces still play a quantitatively insignificant role.

With regard to the distribution pattern and grain size the tephra produced by the two Surtsey craters — Surtur I and II — may be divided in two original main types. There is on one hand the tephra, that fell down close to the funnels and built up the high tephra cones, and on the other one the material that was blown farther away by the wind and formed covers that gradually thinned out from the source (Thorarinsson 1967, Fig. 5.2,3). The first type is characterized by its wide range of grain sizes from boulders to silt (for size analyses cf. Sheridan 1972), the latter by its narrow range of sand and silt and rather good sorting. Such tephra sand was not only deposited on Surtsey from its own craters but also from the short lived volcanic islands of Syrtlingur and Jólnir. In the south-eastern part of Surtsey all original tephra was covered by the final lava flow from Surtur I.

The interior crater slopes include very little of fine material, and the dominant slope processes are individual particle fall and avalanching as has been found from the stratification in sample pits dug in these slopes. The exterior slopes are alternately affected by mudflows, generated by heavy rains and by aeolian processes in draught periods (cf. Jakobsson 1972, Fig. 1, Norrman 1972a, Fig. 3, and Norrman 1972b, Fig. 1). Erosional as well as depositional forms are created by these agencies. In the summer of 1972 erosional features strongly dominated the northern slope of Surtur II (Fig. 7a).

On the rim and the upper interior slope of the Surtur I tephra crater there is no longer any loose material as the tephra by consolidation and palagonitization has turned into hard rock (Jakobsson 1972), and no new aeolian deposition can take place in this exposed area. Inside the same crater and on the lower parts of the saddle be-

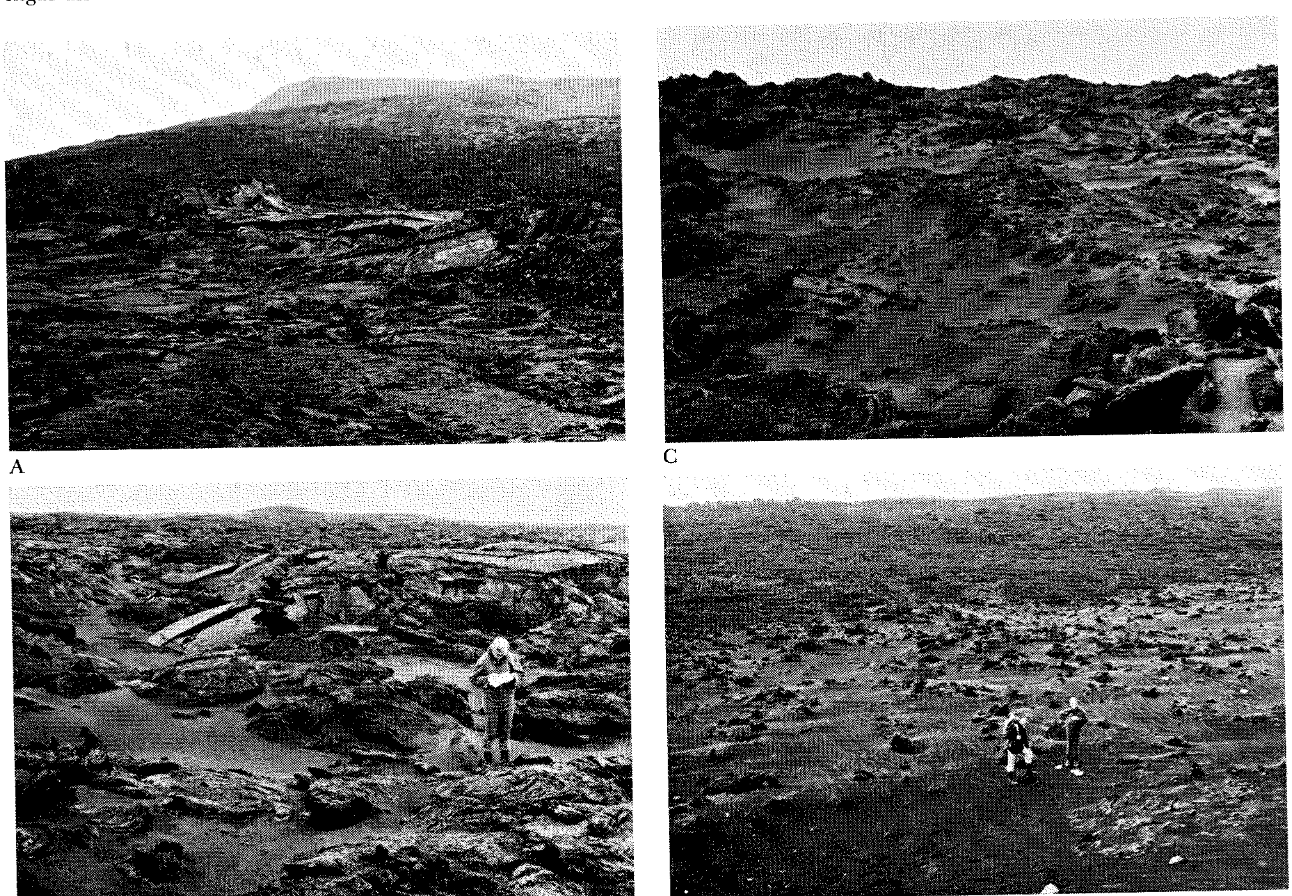
Fig. 1. Aerial photograph of Surtsey Island, 7 August 1972. The nrs. 1-5 denote test areas for terrester photogrammetry. Site nr. 3 is exemplified in Fig. 9. Photograph by Landmælingar Íslands.

tween the two craters there are considerable deposits of wind blown sand with distinctly rippled surfaces. The same type of deposit is also found on the south-western margin of Surtur II.

The cover of sandy tephra on the lava plateau south of the southern crater slopes shows few specific form elements that can be attributed to aeolian reworking.

A substrate map, showing the extent of sand coverage, was published by Fridriksson, Magnusson and Sveinbjörnsson in 1972. The class limits used in their investigation (from 1970) were rather wide, and it was found desirable to produce a map with a more differentiated set of sand coverage classes. In our mapping the percentual coverage was estimated by visual judgement in the field (Fig. 2). The method includes some subjectivity, but from check areas independently classified by two members of the team the distribution pattern in Fig. 3 could be regarded valid.

The primary area of investigation was the southern part of the island south of the tephra cones. The map (Fig. 3) shows, with the exception of the topographically distinct lava front south of Surtur II, a tendency for diminishing



A C B D

Fig. 2. Examples of sand coverage classes. A: < 10%, B:20-40%, C: 40-60%, D: 60-80% (centre), > 80% (foreground). For location of photographs see letters A-D in Fig. 4. Photographs by B. Calles.

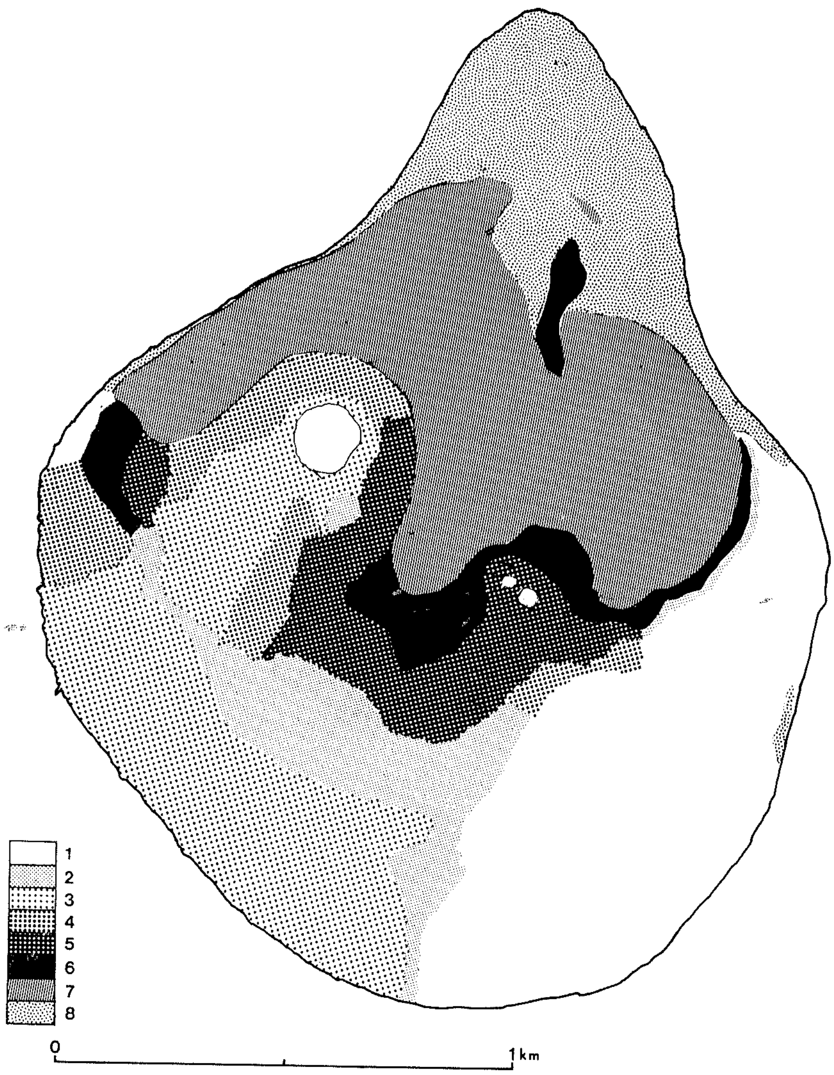


Fig. 3. Map showing the distribution of shore material, primary tephra and lava areas covered by tephra sand. Legend: 1. < 10% sand cover, 2. 10-20%, 3. 20-40%, 4. 40-60%, 5. 60-80%, 6. > 80%, 7. Primary tephra cones, 8. Shore sediments.

amounts of sand with an increased distance from the craters, and then again some increase along the south-western coast. The naked south-eastern plateau, that was covered by the last lava flow from Surtur I in 1967, stands out sharply in contrast to the various coverage in the areas, which received tephra not only from the Surtur eruptions but also from Jólnir. Eruptions from the latter one are most probably responsible for the secondary maximum at the coast. From the map it may be concluded that over the lava area there has been little redeposition by wind of sand since the intense tephra production period. This conclusion is also evidenced by the detailed sand surface morphology, as previously mentioned.

Grain size distribution of tephra sand

Samples for grain size analysis were collected from 14 different sites in areas outside the tephra cones (Fig. 4). For comparison a sample from the outer slope of Surtur II has been added. The cumulative distribution curves are shown in Fig. 5.

In order to avoid bias effects from very local surface phenomena channel samples from the upper 5 cm of the soil were taken. Each sample consisted of 200 to 500 grammes of soil.

The material was dry sieved on U.S. Standard 8-inch. sieves with one phi intervals. For the parts of the samples finer than 4 phi units pipette analysis according to Andreasen was used. The

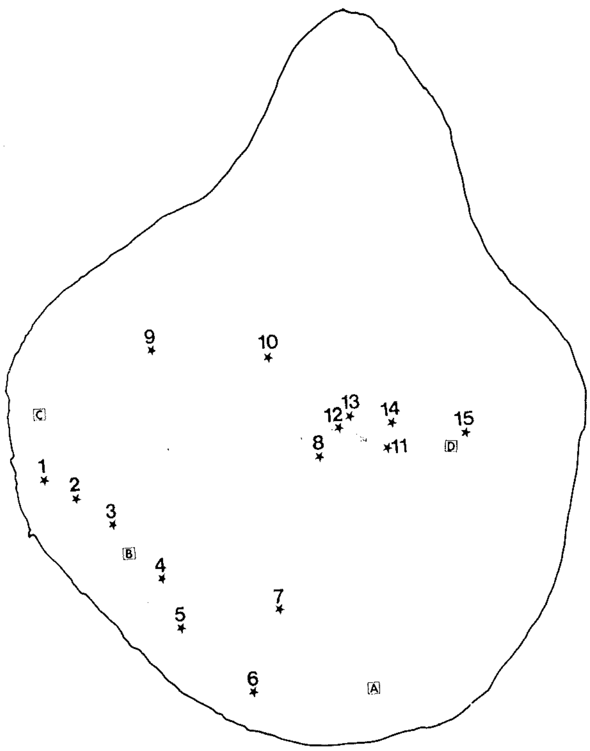


Fig. 4. Sampling sites for grain size analyses (1-15) and location of photographs shown in Fig. 2 (A-D).

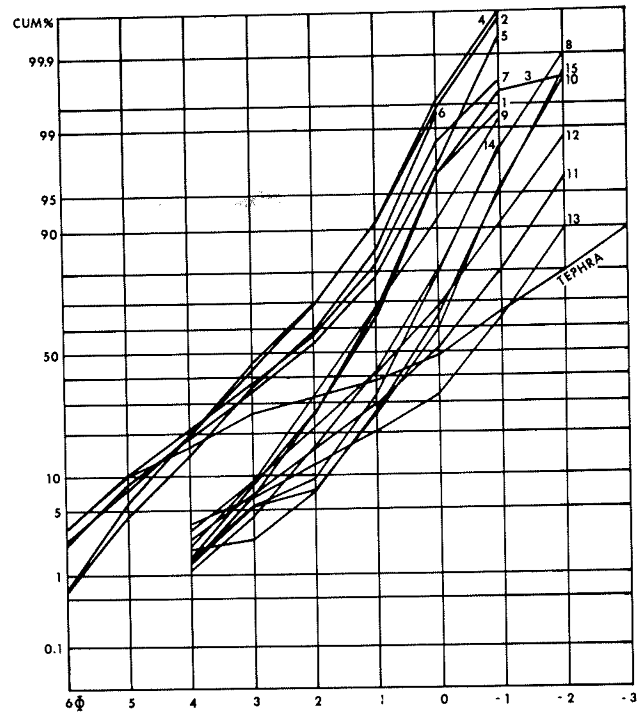


Fig. 5. Grain size distribution curves for samples from tephra sand in the lava area (1-15) and for one sample of primary tephra from the cone of Surtur II. For sampling locations see Fig. 4.

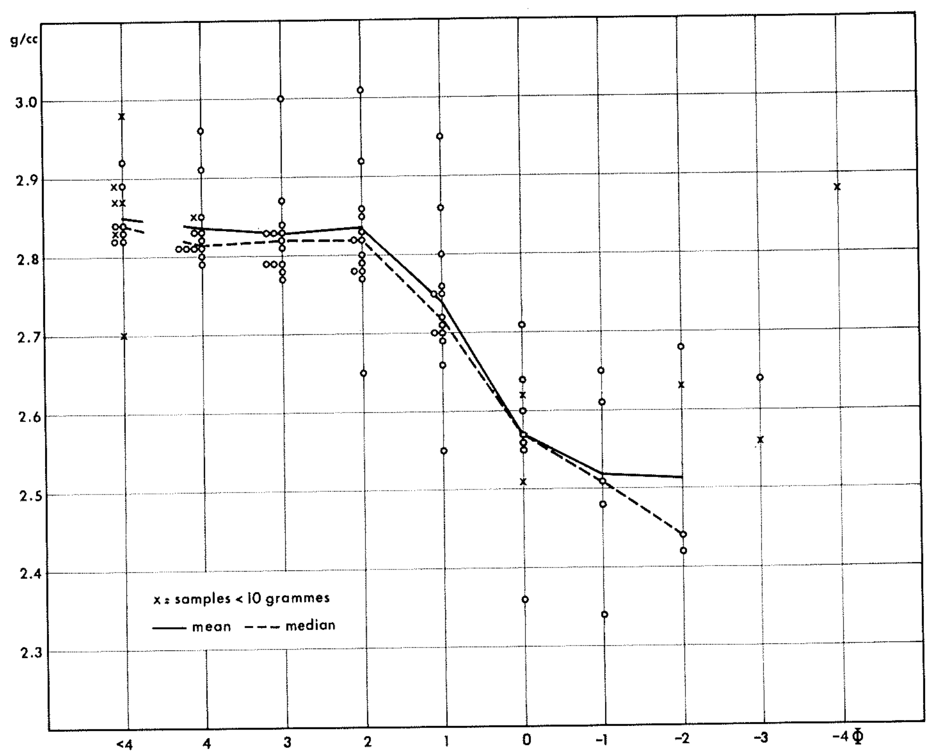


Fig. 6. Density determinations for individual grain-size classes of samples nrs. 1-14.

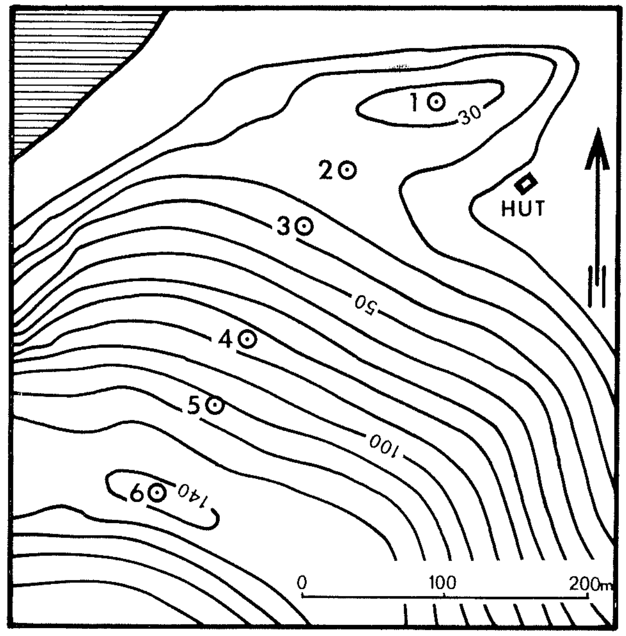


Fig. 7. A. Mud flow rills in the tephra slope SW of the research hut have been eroded by wind drift transverse to the slope direction. Aerial photograph of 7 August 1972. B. Sample sites for pH and conductivity determinations. Height contours of 1970.

percentual cumulative weight distribution was plotted on a log-probability scale (phi units), and the statistical parameters (TABLE 1) were graphically determined according to Inman (1952). As can be seen from the graphs (Fig. 5) the distribution generally differ from the log-normal (straight line) by being slightly upward concave.

All samples from the lava plateau at the southwest coast except nrs. 1 and 3 have a median value of 2.2-2.8 phi and contain ca. 15-20% material finer than 4 phi (Fig. 5). Samples 1 and 3 have a median of 1.3-1.4 phi and contain less than 2% finer than 4 phi. The samples nrs. 8-15 from deposits close to the crater slopes have all but one a median coarser than 0.8 phi and contain 1-4% finer than 4 phi.

The first set of samples has a suspended load character and can be regarded mainly to contain particles permanently settled already during the active eruptive phase. There has been some erosion, and silt from dust clouds, carried by wind from the tephra slopes, may have been added. The second set consists of material, that has generally been transported a short distance and close to the ground in jumping and rolling motions. This material has gradually accumulated since the end of the eruptions not only by deflation in the interior crater slopes but also by transportation from the northern part of the island along the eastern outer slope of Surtur I. This transport route is marked by the narrow curved strip of highest coverage (black) in Fig. 3.

TABLE 1

Median, mean, standard deviation and skewness (in Φ-units) of grain-size distributions for sand samples from the lava area (nrs. 1-15) and from the original tephra of the northern slope of Surtur II (nr. 16).

Sample	MdΦ	MΦ	σ	α
1	1.40	1.51	0.91	0.12
2	2.70	2.80	1.42	0.07
3	1.30	1.54	0.94	0.26
4	2.80	2.81	1.39	0.01
5	2.18	2.51	1.70	0.20
6	2.32	2.48	1.41	0.11
7	2.40	2.70	1.73	0.17
8	0.80	0.98	1.05	0.17
9	1.52	1.52	1.09	0.00
10	0.29	0.48	0.99	0.19
11	0.07	0.40	1.57	0.21
12	0.70	0.90	1.50	0.13
13	–0.55	–0.11	1.59	0.28
14	0.65	0.73	0.86	0.09
15	0.39	0.49	0.96	0.10
16	–0.08	0.83	3.20	0.28

Variation in density with grain size

Because of the visible presence of gas bubbles in the tephra grains there was reason to suspect the density of the material to vary with grain size. For grain size analysis using sedimentation methods it is essential to know if there are systematic variations, and therefore some tests were carried out. This preliminary study gave such variable

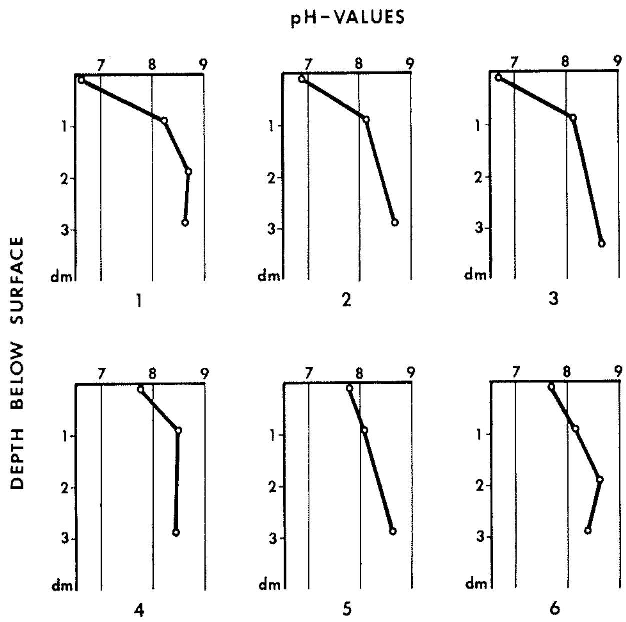


Fig. 8. pH values at different levels in the sampling pits.

densities, that a systematic investigation on different size classes was thought necessary.

The density measurements were made with a Beckman Air Comparison Pycnometer, using the mean of five determinations for each sample. The mean and median was calculated for each size class on the samples larger than 10 grammes. In all 85 sampes were analysed, whereof 73 larger than 10 grammes. The total range of densities on individual samples was found to vary from 2.34 to 3.01.

From the results presented in Fig. 6 it can be seen that there is little variation between the size classes for material finer than 1 phi, the average size of this material being of the order of 2.82-2.84. For the material coarser than 1 phi, there is a systematic decrease of density with size. For the coarse sand left on the -1 phi sieve the average density was found to be 2.52.

pH and conductivity measurements

In order to study leaching as a step in the soil-forming process, a number of soil samples were taken in the northern slope of Surtur II above the research hut. The location of the sampling sites is shown in Fig. 7b. On every site a pit was dug and samples collected at different levels down to approximately 30 cm below the surface.

The sites nrs. 1 and 6 are both situated on crests, which have been lowered by deflation. In the area from site 5 to site 3 material has moved downslope by mudflows, and in the mudflow rills there has been wind erosion as well as deposition (Fig. 7a). The thickness of the disturbed layer on top of primary tephra does probably not exceed ¼ m. Site nr. 2 is situated in a saddle, where material from mudflows and aeolian deposits have accumulated and partly flowed farther downslope towards the hut.

The determination of the pH-values was made according to a standardised procedure. A sample of four grammes was shaken with destilled, dejonised water and left over night. The pH of the clear fluid above the settled soil was then determined with a standard pH-meter.

The results of the measurements (Fig. 8) indicate that there is little leaching below ca. 20 cm. The three lower sites seem to be far more affected than the three upper ones.

Surface samples from the same sites were also analysed with respect to conductivity and the following results were obtained

Site nrs.	1	2	3	4	5	6
micromhos/l	8.0	13.2	30.8	15.0	10.2	6.2

The consequent increase from the highest site to the foot of the slope (site 3) could be interpreted as a combined effect of decrease in sea water spray with altitude and downslope wash of salt with rain water. However, it remains to explain the low value of site nr. 2. The similar conductivity of site 5 and 6 may be related to their crest position.

It may be concluded that the pronounced variation in pH and conductivity found in this very limited study calls for a more general investigation that covers the whole island. It would be desirable to investigate the difference in precipitation and sea-water spray on different altitudes and under different weather conditions in order to establish the basic factors influencing the leaching of the tephra cover. A survey of the amount of reworking of the surface by different morphological agencies could also give a valuable help in determining the rate of leaching and in the long run the soil forming processes.

PHOTOGRAMMETRIC SURVEYS

The mapping of steep and high slopes or walls is often a difficult and even dangerous task. The use of terrestrial photogrammetry can however many times solve the problems in an elegant way. During the field season 1972 metric photographs were taken in five areas of Surtsey (Fig. 1) to document morphological features formed by different processes.

TABLE 2

Objects of terrestrial photogrammetry

Area nr.	Type of object	Type of process
1	Tephra slope N Surtur II	Eolian activity
2	Cons. tephra E Surtur I	Slight eolian activity
3	Tephra wall E Surtur I	High eolian activity
4	Low tephra cliff on the NE part of Surtsey	Eolian activity and occasional abrasion
5	High tephra slope S research hut	Rainwash and eolian activity

The equipment used was a Zeiss terrestrial metric camera (TMK) with a focal length of 60 mm and a picture size of 9x12 cm (glass plates). To get the two scenes forming the stereoscopic model the camera was placed successively on two tripods defining the ends of the photogrammetric base-line. The positions of the necessary control-points in the area to be mapped were determined by theodolite measurments from the same tripods.

To find the proper camera positions in a terrain like that of Surtsey is a difficult problem, especially if the intention is to rephotograph certain sites after a time interval of some years to make possible dynamic studies. The ground has to be firm to keep the tripods steady and must not move or change with time. As the mapping accuracy in the stereoscopic model is decreasing with the square of the distance to the object it is necessary to find camera positions as close as possible to it. At the same time the base-line shall be as long as possible to increase accuracy. It must also be near parallel to the mapping plane, and the ends of it must not differ too much in level. On Surtsey such firm ground is hard to find close to the slopes or walls of interest except of small lava spots or boulders raising somewhat above the tephra surface. Thus detailed indoor calculations before starting terrestrial photogrammetric missions are often of little or no value as terrain realities may change all plans. The tephra wall in Fig. 9 can serve as an example of this. Due to terrain problems (the height of the wall and lack of stable camera stations) the base-line had to be placed as much as 65 m from the foot of the wall giving a theoretical error in point by point measuring of c. ± 0.1 m in the front part of the model and up to ± c. 0.5 m in the rear parts of it.

Another problem, however usually minor, is to find distinct objects in the photographed scene that can serve as control-points or to put artifical signals into the area to be mapped. Even if it is usually possible to adjust metric cameras close to the so-called normal case of photogrammetry, it is necessary to know the exact position of at least three points in the stereoscopic model. In Fig. 9 a vertical rod may be seen in the lower right part of the photo, indicating the z-axis of the map coordinate system as well as being a scaler besides some natural objects of known position. When terrain-objects are used as control-points the risk for identification mistakes is high. A Polaroid camera is often a useful tool as the point then can be marked in the photos directly in the field.

The mapping from the metric photographs has been done in the stereo-plotting instrument Wild A9 at the Department of Physical Geography in Uppsala. A description of this photogrammetric equipment was given in a report from the institute (Larsson and Sundborg 1972). As the photo axis is horizontal the contours plotted show equal perpendicular distances from the base-line, it is not possible to plot "ordinary" height contours from these photos in the equipment used, as the y- and z-axis of the instrument can not be interchanged.

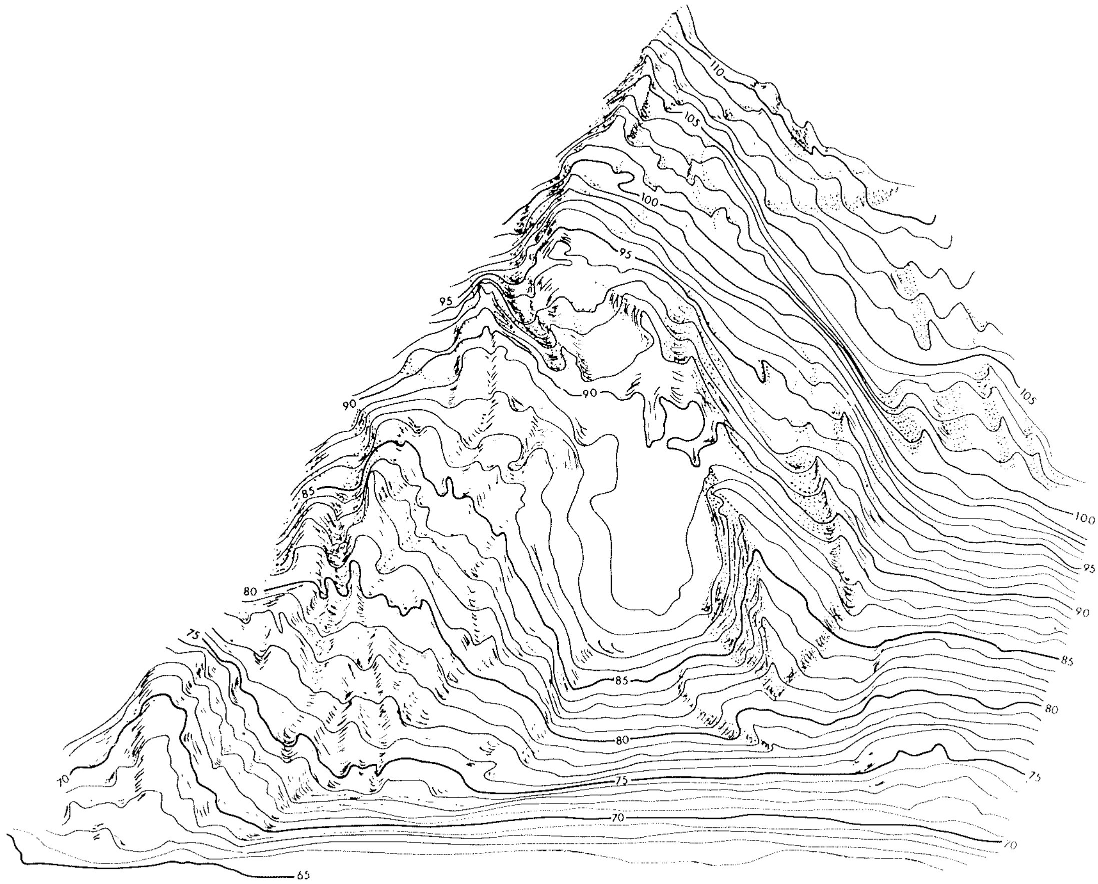
The experiences of the photogrammetric work on Surtsey is positive especially for documentation of steep and inaccessible walls. Repeated photographing can be recommended to be used to follow the rapidly changing morphology of the island in the future.

COASTAL CHANGES

The yearly coastal development up to the summer of 1970 has previously been reported upon (Norrman 1970, 1972a, b). In 1971 aerial stereo-photographs were taken by Landmælingar Íslands on 15 July, but no ground surveys were made that year. In 1972, height stations on the lava already used in 1968 were remounted, a new system of stations was laid out on the sands of the northern ness and the heights of all spots were checked. A set of photographs from a height of 2000 m over the whole island and a series from 600 m, covering the northern ness, were taken by Landmælingar Íslands on 7 August. The 1972 photographs have been utilized for new photogrammetric constructions, by which the coastline and the northern ness have been mapped. The 1971 material has been used for constructing the coastline by stereointerpretation.

The lava cliffs

The south-western cliffs continue to be most strongly abraded (Fig. 10, and cf. Norrman 1972b, Fig. 2) but there is also a considerable retreat all along the southern coast. The high cliffs. forming the western cape, seem to be significantly more resistant and still effectively protect the



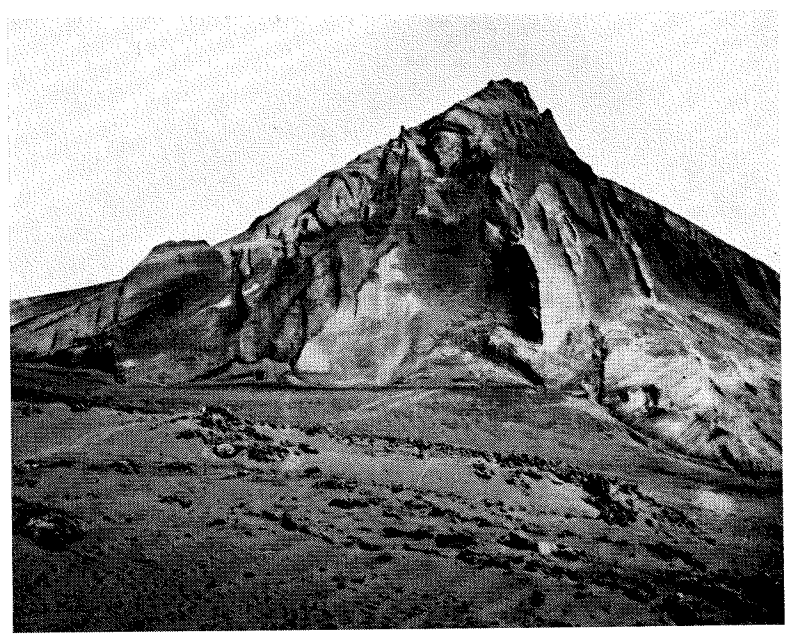


Fig. 9. Distance-contour map and photograph showing the tephra wall E of Surtur I. (No. 3 in Fig. 1). Reproduction scale approx. 1:500. Camera: Zeiss TMK, c=60 mm.

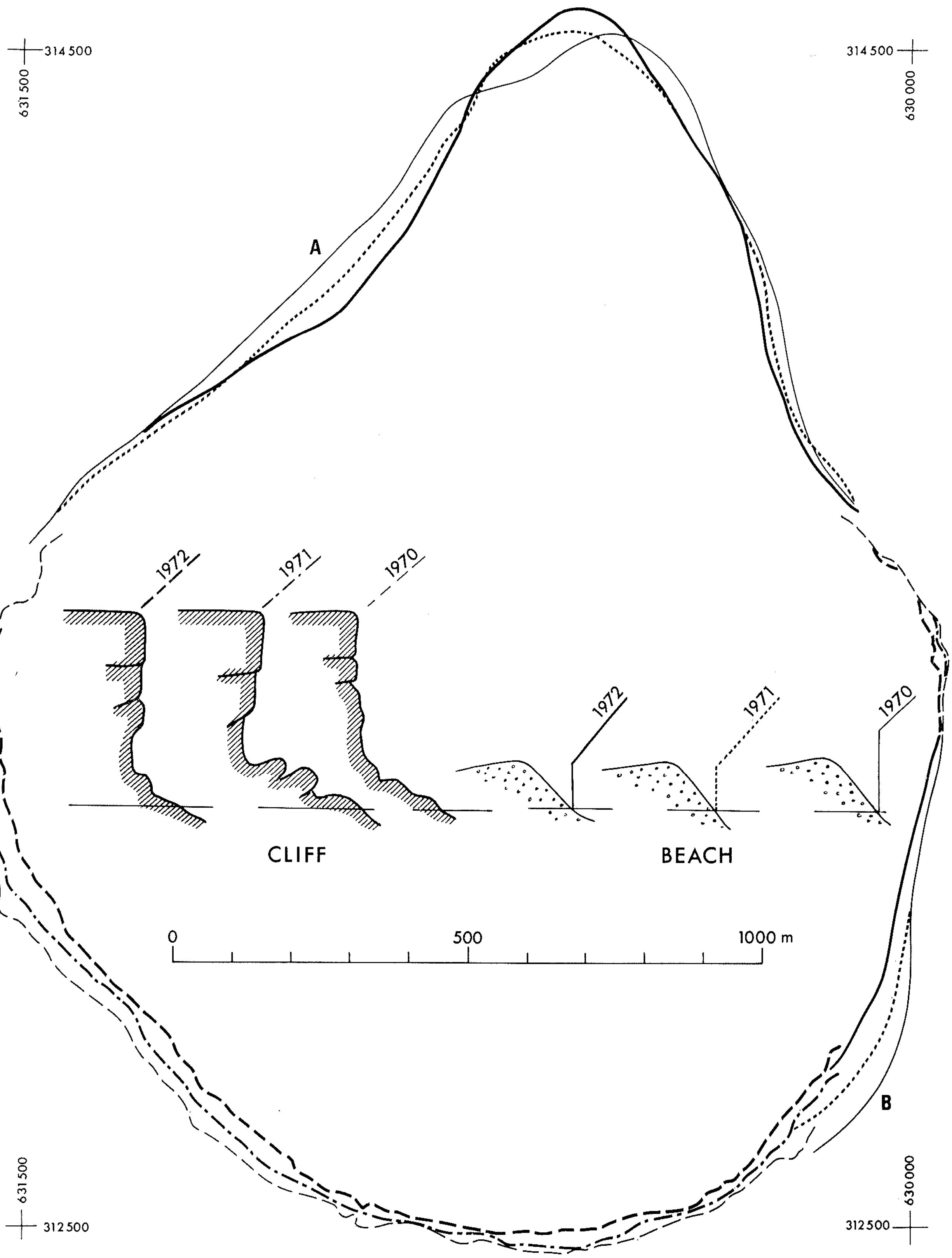


Fig. 10. Cliffline and shoreline of 3 September 1970, 15 July 1971 and 7 August 1972. A: Western boulder terrace, B: Eastern boulder terrace. Photogrammetric construction by Rolf Å. Larsson based on aerial photographs by Landmælingar Íslands and ground control by the authors.

north-western terrace. The bulge of lava from Surtur I on the east coast is now gradually breaking down.

The boulder terraces

There has been a considerable retreat in position of the northern part of the western boulder terrace (A in Fig. 10). The waves have also cut into the foot of the steep tephra wall, which has caused falls and slumps. In the northern area, that has suffered direct wave attack, the crest of the wall has retreated 10 to 20 m from 1970 to 1972.

The eastern boulder terrace (B in Fig. 10) has alternately been eroded and built up from year to year (cf. Norrman 1970, p. 100, 1972a, p. 138 and Fig. 4, 1972b, p. 148 and Fig. 3). During 1971 and 1972 erosion has been predominant, and only a very narrow, straight terrace is left below the indented lava cliff.

The northern ness

In the two previous reports on coastal changes the development of the northern ness has been illustrated by photogrammetric maps with 1-m contour interval from 1968, 1969 and 1970 (Norrman 1972a, Fig. 6 and Norrman 1972b, Fig. 4). The height contours of the 1970 map dramatically record how waves from a westerly storm have overtopped the western berm and how the water has flooded the ness and eroded an outlet channel on the eastern shore. Before the air photographs for that map had been taken, the height station signals on the ness had been swept away. Thus there was no good local support for the stereo model, and levels were uncertain. From the ground control made in 1972 it can be concluded, that the contours of the 1970 map are 1-2 m too high, but the morphological pattern, illustrated by the contours, is still valid.

The 1972 map is based on the 600-m altitude photographs, and for the construction of the photogrammetric model there were 7 height stations signalled and levelled in the area.

From Fig. 10 it can be seen that the ness has been built out towards the north both in 1971 and 1972. There has been some erosion along the eastern shore.

In the contour map (Fig. 11) an attempt has been made to illustrate the distribution of boulder covered areas and boulder ridges. In 1968 boulders were found along the western shore of the ness but on the eastern shore there was a beach of gravel and sand. In the 1972 reports on the development 1968-69 and 1969-70 it has been described how boulder berms have gradually been built up along both shores towards the northern end. In the present survey this trend is found to be persistent. The crest of the eastern highest storm berm is about one metre higher than that of the western shore. The crest consists of short obliquely oriented ridges. Because of the coarseness of the material these ridges are rather difficult to identify in the aerial photographs. A lower, well developed berm is found at both shores. The crest of this "summer berm" runs at about 2 m a. s. l.

Scattered drift logs indicate height of floods and two larger areas with an abundance of drift wood (Fig. 11) evidently reflect effects of flow separation in flood stream patterns.

Areal changes

From the photogrammetric maps in the original scale of 1:5,000, areal changes from 3 September 1970 to 7 August 1972 have been calculated (cf. Fig. 10):

The lava cliff of the southern and south-western coast	Loss	8.3ha
The lava cliff of the eastern coast	Loss	0.3
The northern ness and the western boulder terrace	Loss	5.2
	Gain	1.3
	Net loss	3.9
The eastern boulder terrace	Loss	2.9
	Total loss	15.4ha

The above calculation gives an average loss *per year* from the cliff areas of 4.3 ha and from the beach and terrace areas of 3.4 ha. The corresponding figures 1969-70 were 6.5 ha loss of cliff areas and a *gain* of 4.2 ha on the other shores, which may indicate a certain stabilisation of the cliff areas but a continuous instability of the boulder shores and beaches.

ACKNOWLEDGEMENTS

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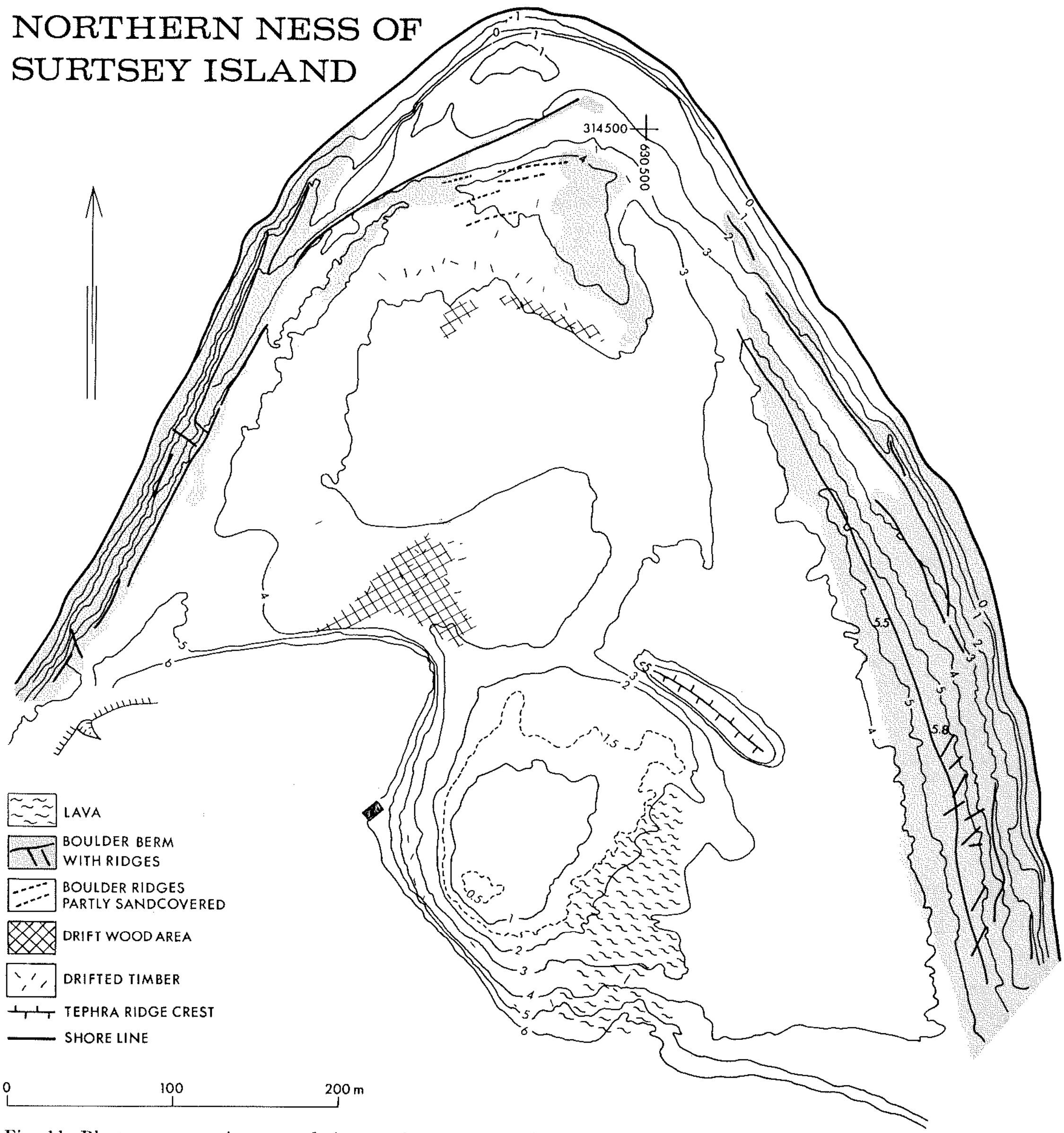

Fig. 11. Photogrammetric map of the northern ness as developed on 7 August 1972. Contour interval 1 metre. Height in metres above mean sea level. Shore line of low tide. Photogrammetric construction by Rolf Å. Larsson based on photographs by Landmælingar Íslands and ground control by the authors.

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