The geomorphology of Surtsey island in 1980

By

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INTRODUCTION

This report is based on field studies, carried out by the authors in June 1980, along with aerial surveys of Surtsey of July 11, 1975 and August 21, 1980. The objective was to construct a geomorphological map of the island, to study characteristics of tephra sediments which are of importance to transportation and sedimentation processes and finally to determine coastal changes during the last five years.

Topographic maps from 1968 and 1975 have previously been published with 2 m contour intervals (Norrman 1970 and 1978). A map was also published showing the distribution of shore material, primary tephra and lava areas covered by tephra sand divided into six classes from <10% to >80% (Norrman, Calles and Larsson 1974). This substrate map was published to help the interpretation of patterns of plant colonisation, that strongly depend on soil distribution and the mobility of the soil.

A GEOMORPHOLOGICAL MAP OF SURTSEY

General

Maps showing land forms or groups of land forms rather than purely topographical features are often produced to satisfy some specific need. They may for example be made in various scales for planners, geologists or tourists.

In the international discussion on geomorphological mapping the East European countries are making great contributions. This is especially the case regarding medium-scale mapping; scales 1:20000 to 1:1 million. These maps are often presented in many colours to enable the distinction of features both morphologically, genetically and chronologically. In the present work, however, we need to distinguish smaller elements than those shown in ordinary geomorphological maps.

The map of Surtsey is intended to document the morphology as of August 1980. Our symbols are not those found in e.g. „The Guide to Medium-scale Geomorphological Mapping" (Demek and Embleton 1978) because of the finer resolution of the objects mapped.

The geomorphology of Surtsey

The geomorphology of the island may be divided into different scales.

In the *macro* scale one may divide Surtsey into three parts:

I – The tephra cones
II – The lava plateau
III – The sand ness

In the *meso* scale one may subdivide these categories into:

Ia – Surtur I (Surtur senior) volcanic cone
1 – Palagonite tuff (móberg)
2 – Wind eroded areas
3 – Wind deposits
4 – Slump scars and slump deposits.

Ib – Surtur II (Surtur junior) volcanic cone
1 – Palagonite tuff
2 – Wind eroded areas
3 – Wind deposits
4 – Shoe string rilled tephra slopes
5 – Wave abraded sections
6 – Slump scars and slump deposits

Fig. 1. Vertical aerial photograph of Surtsey of August 21, 1980. Photo by Landmaelingar Íslands.

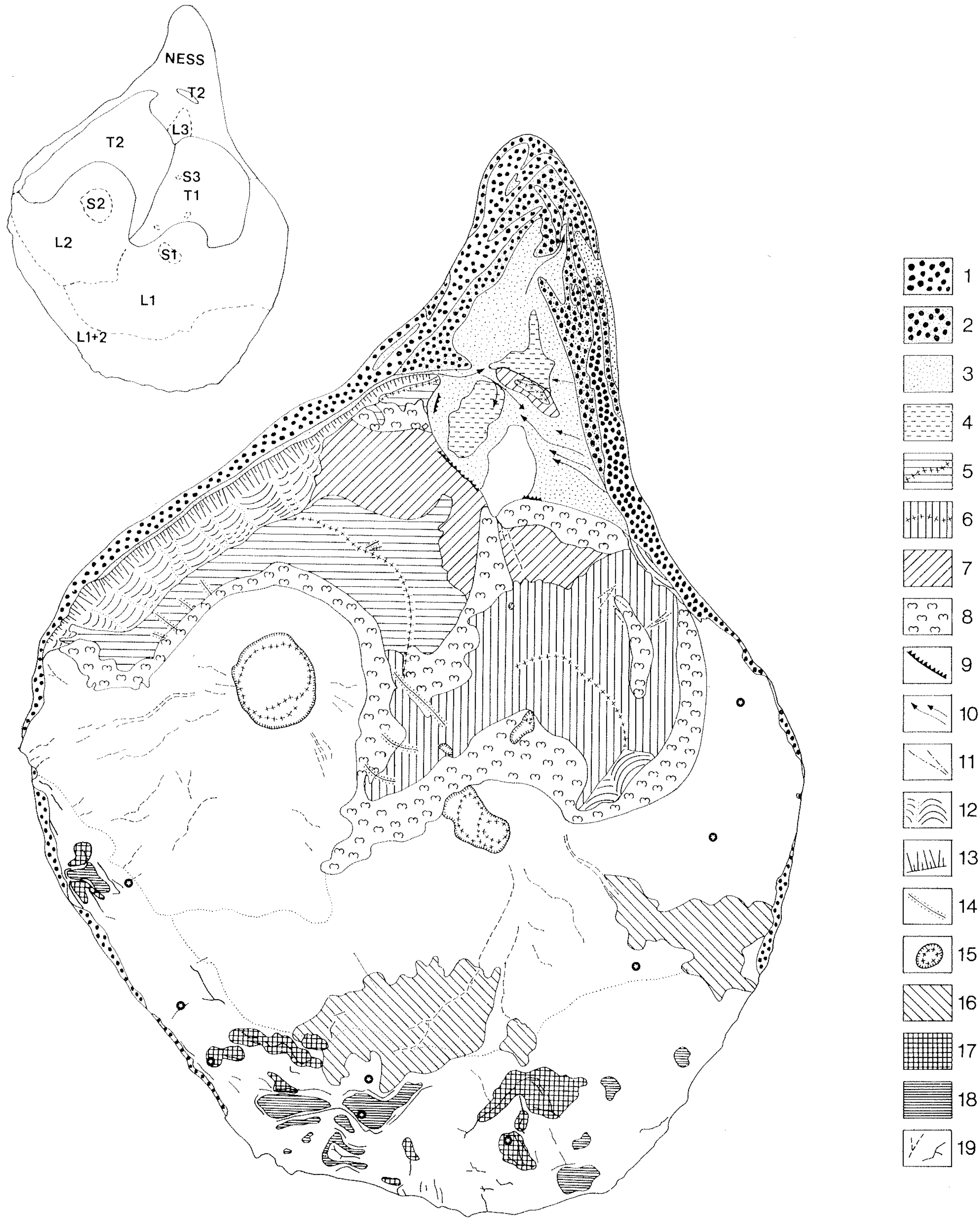

Fig. 2. Geomorphological map of Surtsey. Legend of inset map: S 1—3: the three main crater areas, L 1—3 the lava deposits of the three eruption sites, T 1—2 : tephra deposits.
Legend of main map: 1) Boulders deposited by wave action, 2) Boulders deposited by wave action, partly sand covered, 3) Sand, 4) Temporary lagoon areas (silt and clay), 5) Primary tephra cone with crest line, 6) Primary palagonitized tephra cone with crest line, 7) Reworked tephra surface, 8) Eolian deposits, 9) Highest shore scarp, 10) Overflow channels, 11) Protruding ridges in the tephra, 12) Slump scars; 13) Talus slope, 14) Thermal fissure, 15) Crater area with crest line, 16) Aa lava, 17) Lava dome, 18) Lava depression, 19) Lava flow channel and fissures in the lava. White areas represent extent of pahoe-hoe lava, dotted lines separate different lava deposits. Black circles show position of signals for aerial photography in 1980. Approximate scale 1:10,000.

Fig. 3. The northern end of the western tephra cliff (140 m high). Note the rill marks in the upper part of the large slump scars and the well developed talus covering large parts of the high winter berm. Oblique boulder berms are formed by the unrefracted waves. Photograph by B. Calles, June 1980.

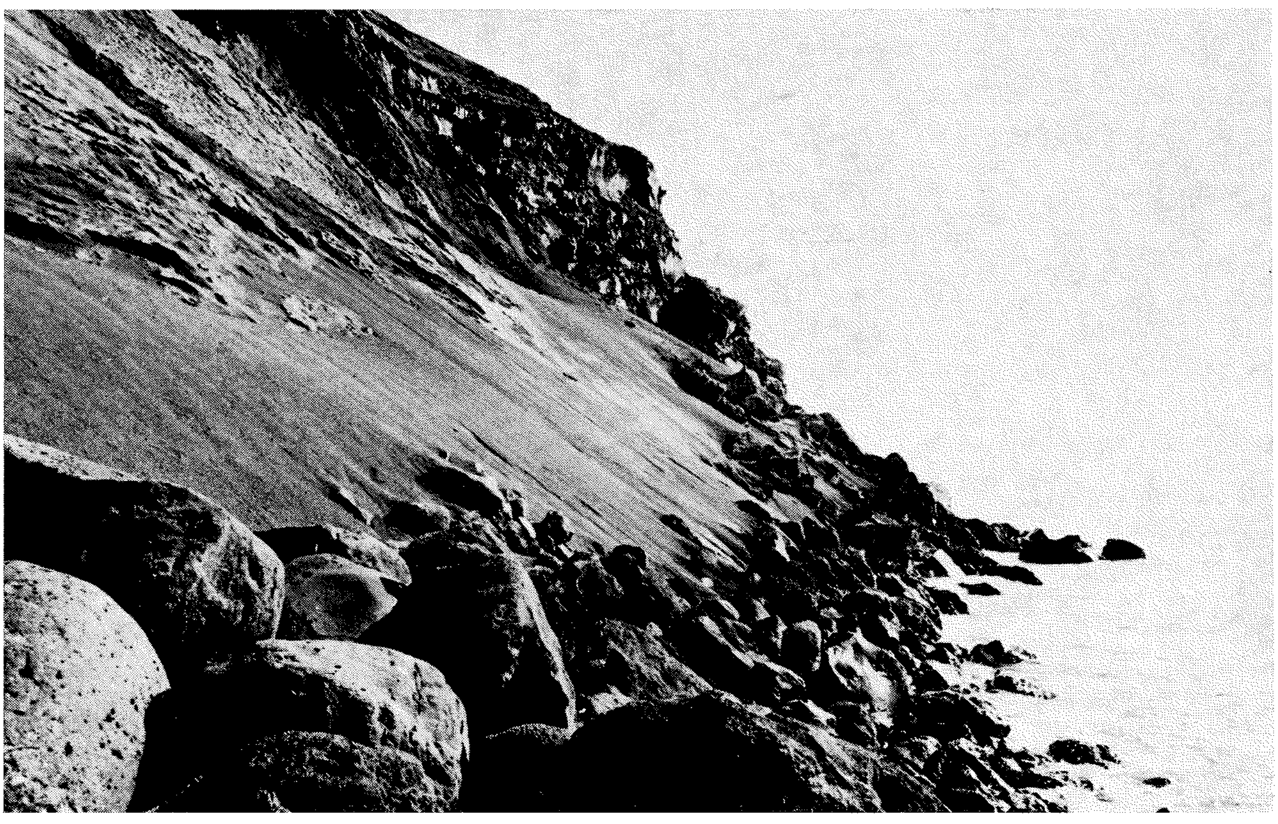

Fig. 4. The southern end of the western tephra cliff with a steep lava cliff in the background. Most of the shore terrace has been eroded by north-bound longshore drift and the talus material is gradually slipping into the sea. Note the angularity of the lava boulders abraded from the nearby cliff. Photograph by B. Calles, June 1980.

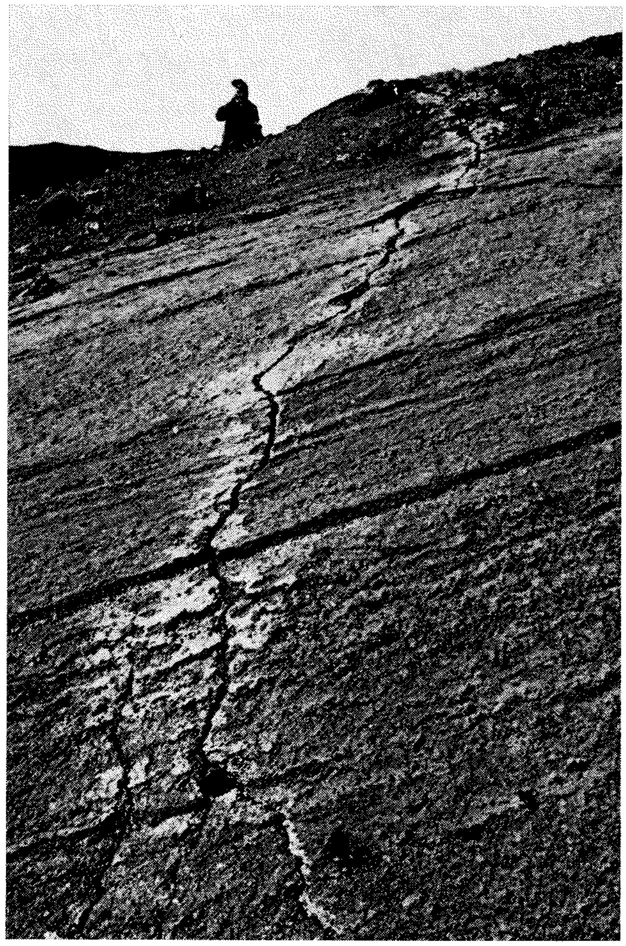

Fig. 5. Thermal fissure in palagonitized tephra (tuff) in the eastern cone. Photograph by B. Calles, June 1980.

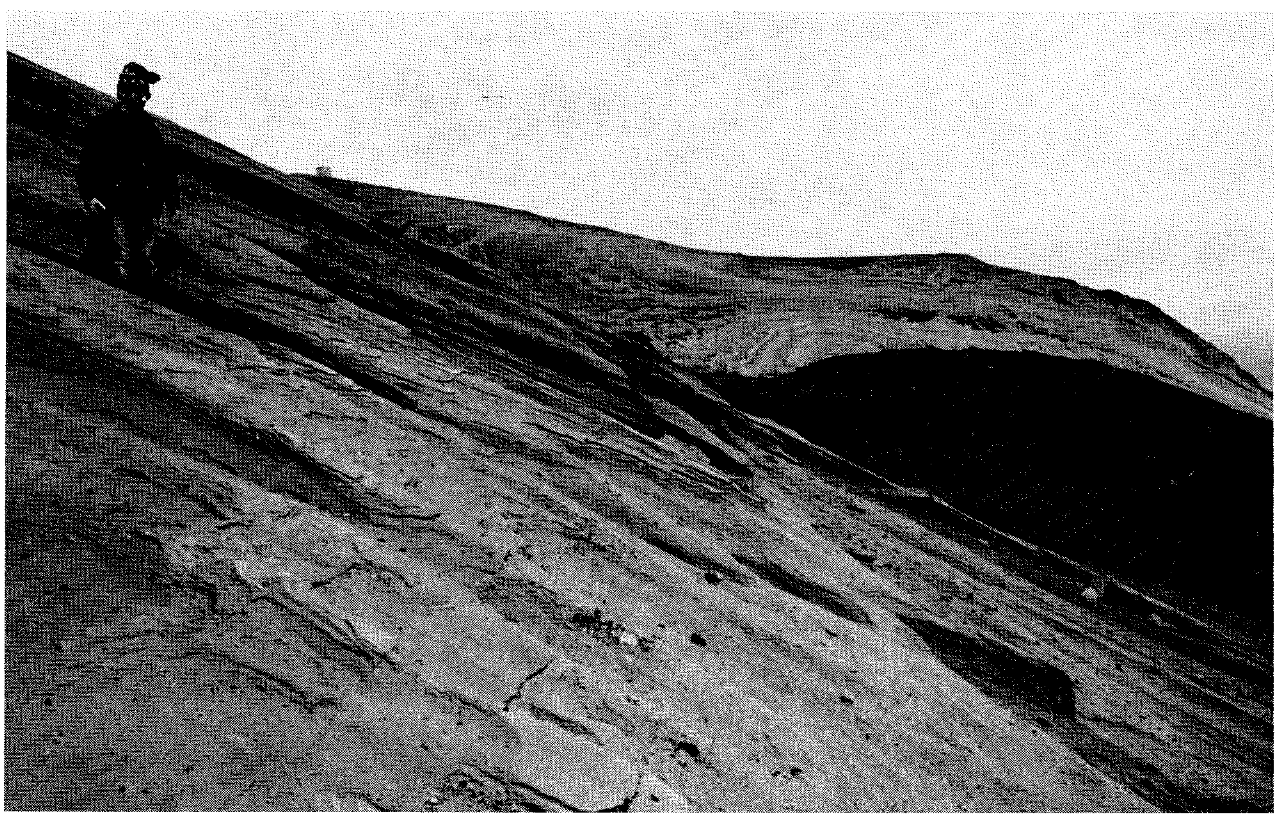

Fig. 6. Wind deflation of palagonitized tephra (tuff) in the eastern cone. Photograph by B. Calles, June 1980.

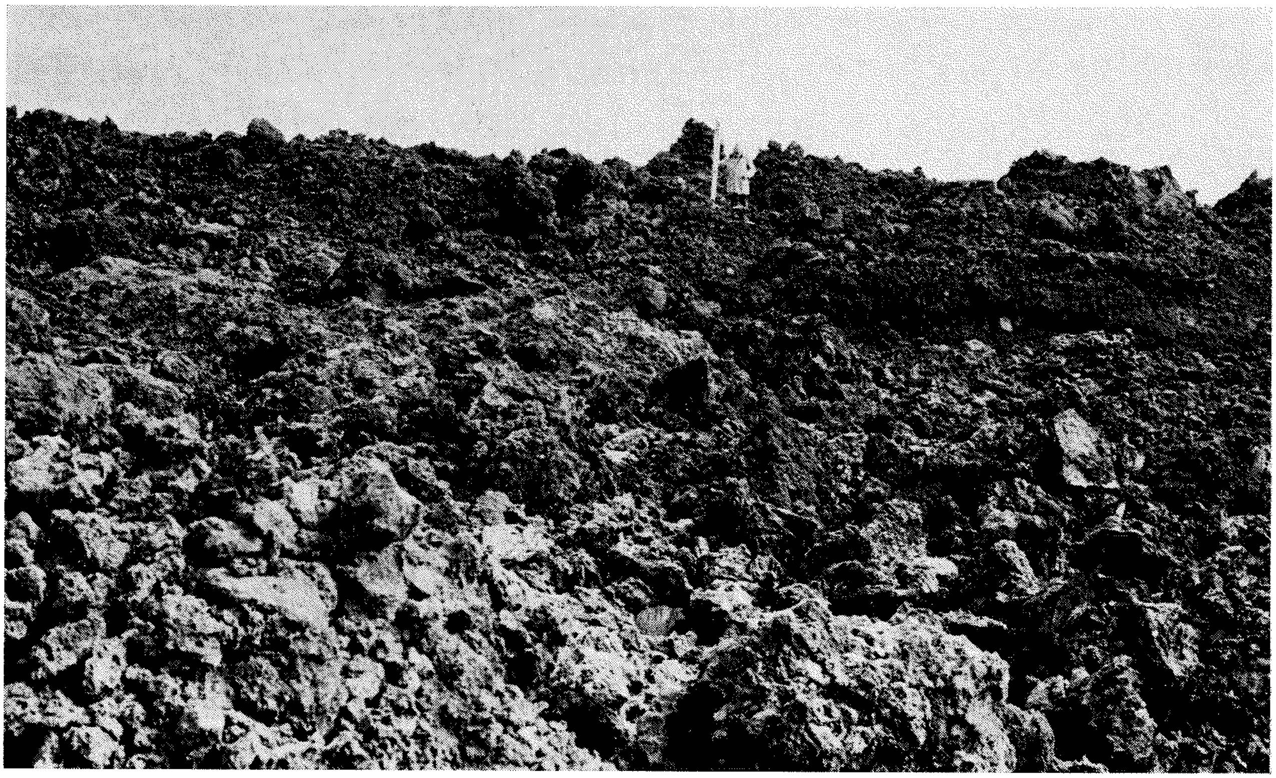

Fig. 7. Aa lava to the south of the eastern cone. Photograph by K. Lindé, June 1980.

Fig. 8. The lava formed by the western crater. Wind-blown sand has later partly covered the lava. Photograph by B. Calles, June 1980.

Fig. 9. The eastern end of the northern ness with very large boulders in the foreground. The height of the summer berm is indicated by the darker tint of newly wetted boulders. Photograph by K. Eriksson, June 1980.

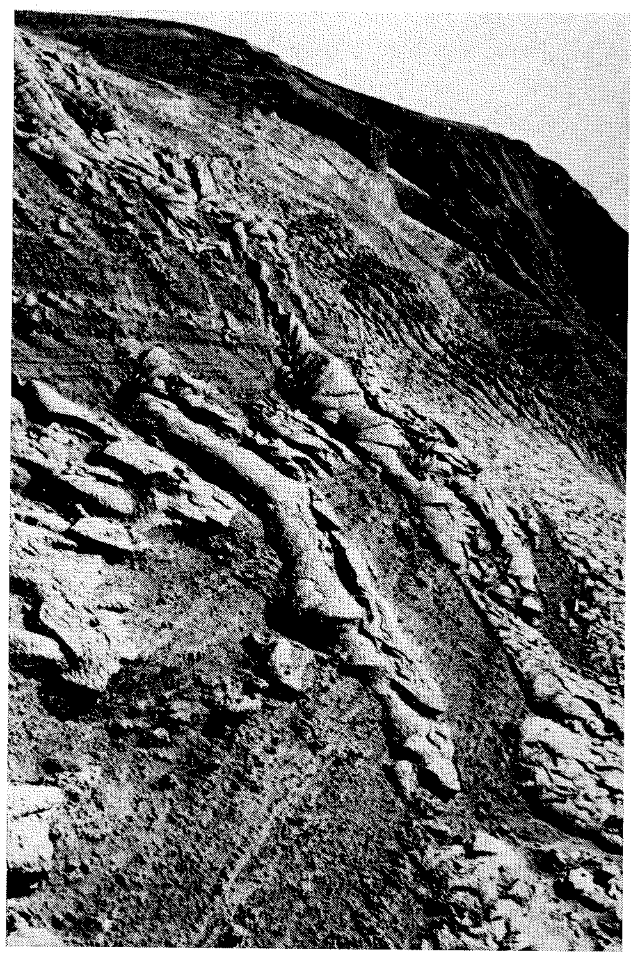

Fig. 10. Structures formed by wind action on a wet and silty material along the tephra wall of the western shore. The primary tephra structure is visible between the silt patches. Photograph by B. Calles, June 1980.

Ic — Volcanic vents of different age and size and their related minor lava flows.

IIa — Pahoe-hoe lava areas — rope lava, lava domes, lava depressions, roofed and open lava flow channels.
IIb — Aa lava areas
IIc — Lava flows near vents
IId — Fissures, primary or due to wave shock

IIIa — Boulder ridges and berms
IIIb — Temporary lagoons — daily or seasonal

Mapping equipment

The geomorphological map of Surtsey was prepared at the Department of Physical Geography in Uppsala, Sweden. It is based on an interpretation of aerial photos taken in black and white by the Icelandic Geodetic Survey (Landmaelingar Íslands). Three sets of photos were used: one vertical in approximate scale 1:7000 taken at an altitude of 1050 m and one vertical taken at 2100 m. One set of oblique photos was taken at only 460 m. The photos were taken on August 21 1980 at approx. 1435 local time. The weather was clear, the shadows and contrasts were sharp.

The mapping of contours is best done using small scale photos, while detailed morphological mapping should be done using the larger scale photos. The oblique photos were used as a support in „difficult" areas. Ground pictures have also facilitated the interpretation as have notes and other records from a visit to Surtsey in early June 1980.

The aerial photos were interpreted in pairs with Carl Zeiss, Jena, Interpretoscope. This instrument allows the photos to be viewed at magnifications 2X—15X. The stereoscopic models obtained in the instrument cover an area of about 1.8 km^2. The area of the island is about 2 km^2, but its shape makes it necessary to inspect several stereomodels.

The resulting map

The aerial photos were placed in the Interpretoscope and a working map was made on a transparent sheet directly over a photo. The mapped elements can be placed in either of the previously mentioned categories. Distinctions were made among as small details as possible, regarding photographic resolution and mapping technique. The detection of an object depends on its size, shape and contrast to the surroundings.

The elements marked on the working map were transferred to a sheet lying on a vertical photo, the scale of about 1:5000. The large scale features are presented on a small scale map, while the smaller features are presented on a larger scale map. These maps have legends in only black and white. Some morphological elements are further shown in photos (Fig. 3-11).

The tephra cones are mapped as being of palagonite tuff or of primary, unsolidified tephra. Their crests are shown on the map. Where erosion has occured it is shown with a diagonal hatching regardless of the process involved — rill wash or eolian. The wind driven sand and silt which cap the lower parts along with other parts in the lee are indicated. The abrasion scarps on the sides of the cones are given a special symbol like the smaller scarps marking the upper shore of the seasonal lagoon just to the north of the cones.

Areas lying in shadow are dark and do not display any morphological details. The photos from 1980 were originally requested to be taken late in the afternoon so that the sun would shine on the western cliff. This was unfortunately not done. It would have made it possible to distinguish between individual slump scars. The more than 100 m high cliff is formed of tephra material that was previously abraded by westerly waves. Now (1980) it seems as if the abrasion has halted at least temporarily, by a boulder ridge covering the foot of the cliff and by the continual hardening of the tephra.

In the micro scale a large number of features may be observed and mapped. Our map scale, however, does not permit their reproduction. On the tephra cones one may observe thermal fissures where water vapour is leaking out. Microstructures due to differences in hardness of the palagonite tuff and wind eroded tephra layers can be seen on the side of both cones. The mud-flow rills on Surtur II just above the hut can be subdivided into erosional and depositional parts. Wind ripples in the sand and wind driven silt can be reported from most areas where the wind has not been purely erosive.

Small cracks can often be seen in the lava field. They are situated on the roofs of lava domes, channels or tunnels, which are often thin enough to collapse under the weight of a walking person.

Microfeatures of great interest are the fractures in the basaltic lava close to the southern cliff. Some of them are seen in aerial photos, but not all. They are formed due to wave shock

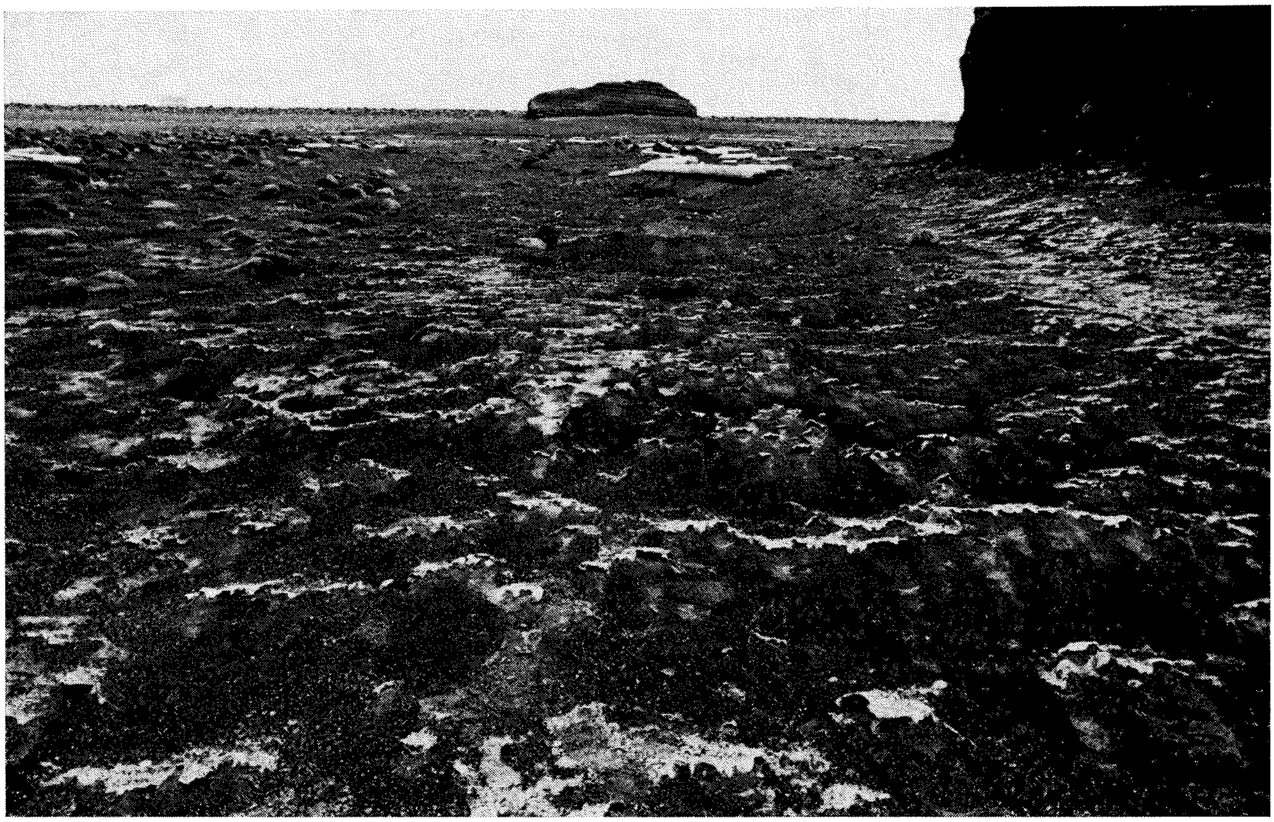

Fig. 11. View along overflow channel draining into the centre of the northern ness from the western shore. Driftwood stranded at 5 m above mean sea level. Flakes of wind-eroded silt left on the gravel bars. Photograph by B. Calles, June 1980.

in the lava which has low elasticity. When the cliff is undermined by storm waves hitting the lava cliff, boulders are broken off along these parallel and perpendicular fractures.

The elasticity of the lavas is low when compared to that of the palagonite tuff. This can be seen from the fact that most of the islands in the Westman Islands group consist mainly of palagonite tuff (móberg). The tuff is a petrified tephra. The hardening process was discussed by Jakobsson (1972) and Jóhannesson (1978). In 1975 this process had cured most of the tephra cones and it was believed to have been completed in a few years' time. The western cliff of Surtur II was then hot and should thus be hardened since then and thereby able to better withstand the attacks of the sea waves.

The aerial photos reveal some of the larger fissures in the lava plateau, but most of them are discovered only by ground control. Easy to see, on the other hand, are caved-in tunnel roofs of small width but of a greater length than that of the fissures. The patches of aa-lava are discerned by their dark colour. This lava is not necessarily darker than the flat lava areas, but it is so broken that the reflection of light is reduced and it appears dark in the photos. These areas of aa-lava are very difficult to cross because of the ruggedness and sharpness of the blocks. Some lava domes and depressions in the pahoehoe lava are marked on the map. Near the cliff are several systems of fissures caused by the shocks of breaking waves.

On the innermost part of the sand ness is an ephemeral lagoon. It is probably filled with water only for short periods of the year during and after winter or spring storms. A similar lagoon is seen to the north of the tephra „ship" on the ness. A small scale feature that can be seen in the photos is stream lines of the water which has run into and out of the ephemeral lagoons at shallow depth. Probably due to the low relief one can not see the stream lines on the ground, but they are clearly visible in the pictures.

The ness is bounded by boulder ridges that in places are of considerable height. Close to the tip of the ness boulder ridges do not form the beach proper. This is formed by sand which is moving with the shoaling waves. The sand ness is dominated by these high boulder ridges, but also in a smaller scale by rippled sand surfaces. Another interesting feature in the very small scale is formed by the wind driven silt which drapes many irregularities and protruding objects (Fig. 10, 11). The silt streamlines

Fig. 12. Oblique air photo of Surtsey from northeast of August 21, 1980. Photo by Landmaelingar Íslands.

the objects so that they look like „roches moutonnées". These silt formations are shaped by the wind, they are also seen as deformations on the shoe-string rills on the sides of the tephra cones. These are particularily clear on the northern side of Surtur I.

SOME PHYSICAL PROPERTIES OF THE SURTSEY TEPHRA

Introduction

Individual particles of the tephra produced during the eruptions that created Surtsey and Jólnir contain heterogenous voids. From a sedimentological viewpoint, a number of questions about the physical properties of the tephra arise. How does the density of the tephra differ from that of other natural materials? Does the shape and surface texture of the particles affect the critical erosion velocity of individual grain sizes? How do the tephra particles behave during sedimentation? At what angles can the tephra be deposited?

Density

A comparison was done between the density of individual grain sizes (½ phi intervals) of Surtsey and Jólnir tephra and that of a Swedish fluvioglacial (granitic) material. Measurements were performed using an air comparison pycnometer. The density of each grain size was tested five times in order to reduce experimental errors and the mean value was calculated.

The variation of tephra densities is not necessarily a result of a different chemical composition but probably a function of the number and size of voids contained in individual grains. Very fine particles contain few, if any, voids and consequently exhibit a high density. The high values for coarse particles may be explained by

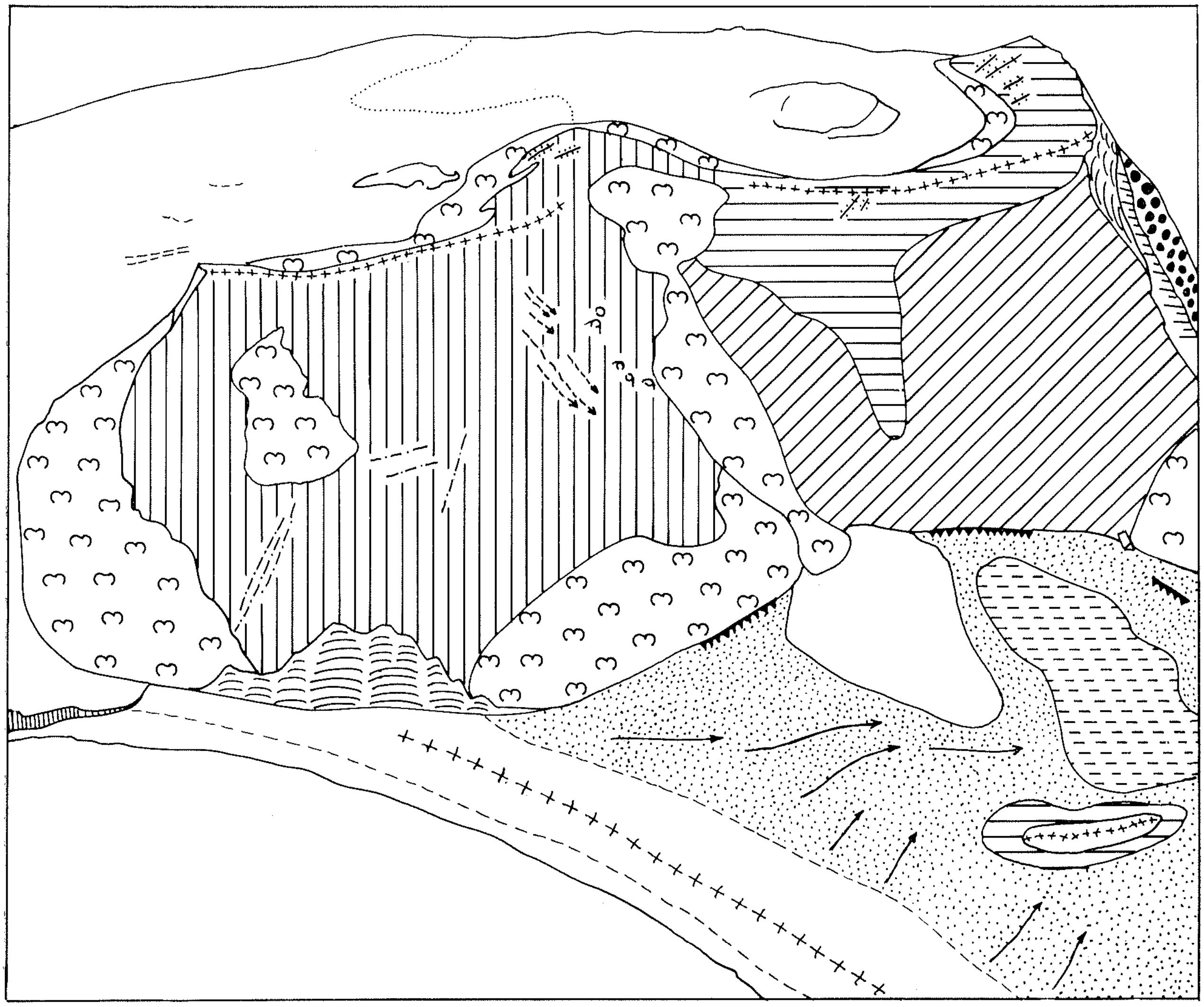

Fig. 13. Geomorphological interpretation of the picture in Fig. 12. For legend cf. Fig. 2. Hatched arrows indicate mudflows. The shore deposits in the foreground are divided into summer shore (foreground) and winter storm deposits with crest line (+++).

few voids. Had the number of voids been higher the particles would have been more unstable and then they would have been broken up into smaller particles.

Settling velocity

It is generally accepted that particles <0.06 mm settle in still water with a velocity that can be expressed by Stokes' equation for settling particles. For particles >0.06 mm the shape of the particle becomes increasingly important. The shape factor is difficult to determine objectively and only empirical data is available on settling velocities of coarse particles.

The voids in the tephra grains produce a rough surface which in combination with the observed densities should result in settling velocities that are at variance with the values which are associated with most other natural materials.

The settling velocities of Surtsey tephra particles and particles of fluvioglacial origin were determined. Individual grains were allowed to settle in a column of distilled water and the time required for a 500 mm fall was measured. In order to get a statistically reliable number of measurements 100 particles in each size class were used. The distribution of settling velocities for individual grain sizes is shown in Table I, median and quartile values of velocities are shown for each grain size and type of material. Tests were also undertaken on several different sizes of glass beads, which exhibited a density of 2.65 g/cc and a very smooth surface. Fig. 15 shows the variation in the settling velocities of the three materials and the variation in the mean values of density in the case of the tephra and the fluvioglacial material.

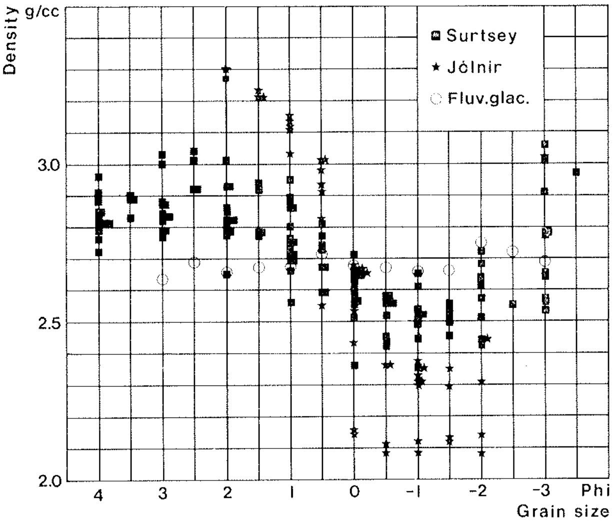

Fig. 14. Observed values of density of individual grain sizes. Samples of tephra from the Surtsey and Jólnir eruptions and Swedish fluvioglacial material of granitic composition.

TABLE I.

Observed values on settling velocity (cm/s) of glass beads, fluvioglacial (granitic) material and Surtsey tephra.

Grain size	Glassbeads			Fluvioglacial			Surtsey tephra		
Phi units	p25	Md	p75	p25	Md	p75	p25	Md	p75
−3.5— −4.0	..	..	..	45.5	52.0	56.8	22.8	27.7	30.6
−3.0— −3.5	..	..	..	40.8	44.5	47.6			
−2.5— −3.0	..	..	..	31.1	33.2	38.2	18.7	21.1	24.0
−2.0— −2.5	41.0	42.3	43.7	28.2	30.5	34.0			
−1.5— −2.0	35.1	36.3	37.3	24.7	27.5	31.0	17.0	18.8	20.6
−1.0— −1.5	26.4	26.8	27.1	20.2	21.5	23.4	14.6	16.3	18.1
−0.5— −1.0	..	..	..	18.6	19.8	21.0	12.2	13.6	15.3
0.0— −0.5	14.9	15.7	16.0	11.4	13.5	14.8	9.8	10.9	12.1
0.5— 0.0	10.0	10.5	10.8	8.6	9.5	10.6	7.6	8.4	9.5
1.0— 0.5	8.8	9.0	9.3	6.7	7.5	8.5	6.1	6.7	7.3
1.5— 1.0	5.7	6.1	6.4	4.6	5.0	5.6	4.2	4.6	5.0
2.0— 1.5	4.1	4.3	4.4	3.5	3.7	3.9	2.9	3.2	3.6
2.5— 2.0	..	..	..	2.3	2.4	2.6	..	..	..
3.0— 2.5	..	..	..	1.5	1.6	1.7	..	..	..

As might be expected the glass beads exhibited the highest settling velocities. The fluvioglacial material exhibited intermediate and the tephra the lowest values. In order to eliminate the effect of variations in density, which were most evident in the tephra, the grain sizes of the tephra were recalculated, using the mass of the particles were assumed to have a density of 2.65 g/cc. Water density was considered to be 1 g/cc. No apparent deviation from the original values resulted from this operation. Thus the differences in settling velocity result solely from differences in shape and texture. It is not possible to draw any conclusions about the relative importance of these two factors.

Critical erosion velocity

The result of a test which was undertaken to determine the critical erosion velocity should be compared with values from generally accepted curves on the critical erosion velocity (e.g. Hjulström 1936, Sundborg 1956). Because of the amount of material available for the tests, and the limitations of the experimental equipment, the reference depth was limited to 0.1 m. For comparison purposes the values from Sundborg's curve were recalculated to apply for the actual densities of the tephra.

One of the serious difficulties attached to this kind of experiment is to determine when the threshold velocity has been reached. It is assumed that this happens when there is a general transport of material over the bed surface. This is a rather vague criterium and can, thus, be assumed to contain a certain amount of uncertainty.

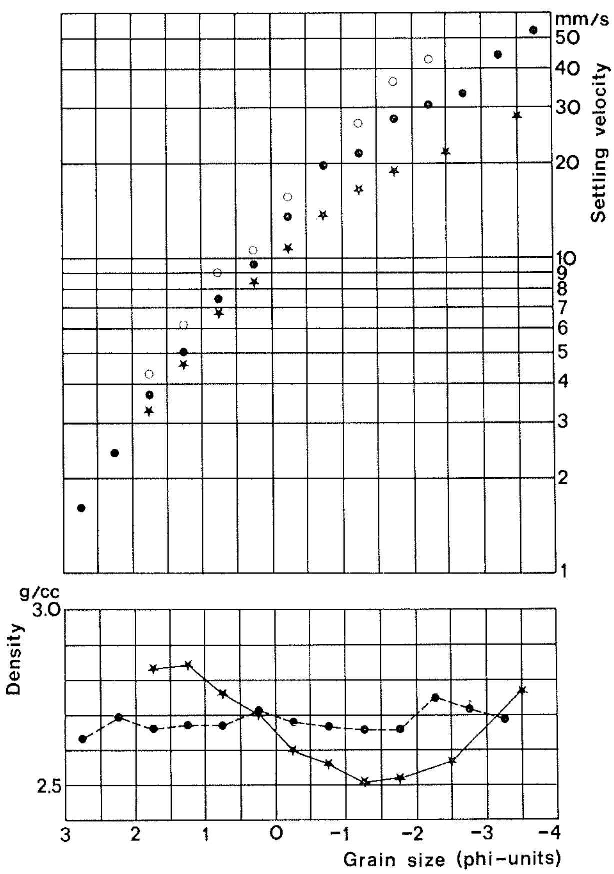

Fig. 15. Settling velocities and density of individual grain sizes. Glass beads: open circles, fluvioglacial material: black dots and Surtsey tephra: black stars.

The tests comprised the grain size range 1 to -2 phi units and the results are shown in Fig. 16. It is evident that, at least for the finer particle sizes, there is no considerable deviation from the calculated values. This implies that the shape and surface texture of the tephra does not exert an important influence on the critical erosion velocity. Variations in density naturally cause differences in critical erosion velocity as compared to natural materials having density values of 2.65 g/cc.

Angle of repose.

The angle of repose is defined as the steepest inclination that a sediment material of a given composition can stand without failure. Factors influencing this value are grain size, density, shape, moisture and organic content. When the angle of respose is superseeded slumping occurs and the slope flattens.

An investigation was carried out in order to determine the angle of repose of Surtsey tephra. To exemplify the different environments in which the tephra occurs the angle of repose was determined both in air and in water.

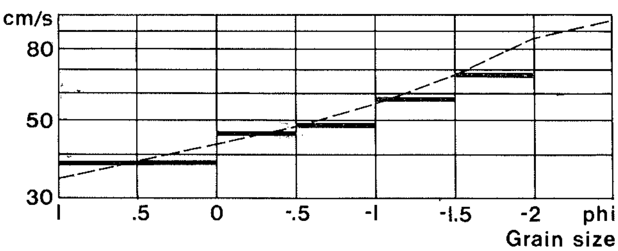

Fig. 16. Observed values on critical erosion velocity of Surtsey tephra compared with values obtained from Sundborg's curve after correction for density (— — —). Reference depth 0.1 metres.

A cone of material was produced in air by letting the tephra fall into the corner of a plexiglass box, producing a cone in the corner with two cuts perpendicular to each other. The same type of test was repeated with a grain size mixture of equal amounts of two adjacent grain sizes to see if this would influence the slope angle. The test was repeated with the box filled with water. The material was carefully flushed into the corner and care was taken to avoid producing turbidity current deposition. The mean values of ten measurements were calculated.

The same material that was used in the cone tests was used in a final test which consisted of putting the material into a plexiglass flume filled with water that was allowed to flow over the tephra, producing a distal slope in the flume. The angle of this slope was measured immediately before slumping occured, giving the maximum angle of repose. The angles of the distal slope differ from the cone slopes due to counter currents at the foot of the slope and the unavoidable impacts which occur when producing cones in water.

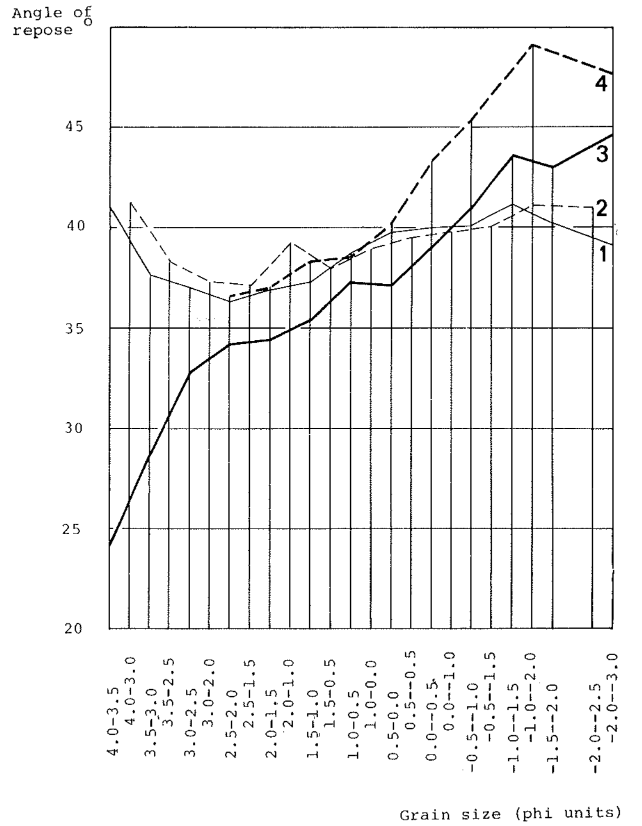

Fig. 17. Angle of repose of Surtsey tephra in different media. 1. ½ phi-units in air; 2. 1 phi-units in air; 3. ½ phi-units in water; 4. Inclination of distal slope produced in running water, ½ phi-units.

Finally, unsieved Surtsey tephra was run in the flume to build up a distal slope consisting of a mixture of grain sizes. The median values of the observed angles of repose are shown in Fig. 17. Both tests in air show a minimum in the grain size range 1.5—3 phi units, with increasing angles both towards finer and coarser material. For the cones built in water the slope angle shows a general decrease with decreasing grain size. For very coarse material the slope angle was even greather than in air probably due to the lower apparent density of the material. The same pattern occured for the distal slopes, the main difference being that values were generally higher than in the cone case. The observed median value for the unsieved tephra distal slope was 41.2 degrees.

Summary

The Surtsey tephra displays an unusual pattern of density variations with varying grain size. The settling velocities of individual grains differ considerably from observed values for fluvioglacial granitic material and glass beads of comparable size. Critical erosion velocities do not deviate from expected values based on previously published data, if the density factor is taken into account. Angles of repose are higher than for other natural materials tested.

COASTAL CHANGES

Aerial surveys undertaken almost every summer by the Icelandic Survey Department (Landmaelingar Islands) provide the basic documentation of coastal changes. The regular documentation of summer conditions (Norrman 1970, 1972a, 1972b & 1978) means that the net effects on the beaches of the storms of the preceding winter are recorded with only minor modifications from recent more modest wave activity. Very little is known about how widely the beaches may vary within the winter season. The trend of annual coastal changes in the volcanic period 1963-67 as well as in the postvolcanic period from 1967 to 1975 was summarized by Norrman (1980).

The coastal contours of 1967, 1975 and 1980 are shown in Fig. 18. There has been a consistently strong erosion of the south-west facing lava coast and the least erosion of the lava cliffs on the eastern coast, which more reflects different exposure to heavy waves than variation in erosional resistance. By the rapid erosion of the lava cliffs along the south-western coast the amount of boulders necessary to keep a protective rampart along the foot of the western, high tephra cliff has been sufficient (Fig. 3), but a slower recession of the lava cliff in recent years may soon change this situation (Fig. 4). Strong rather well balanced longshore drift along both shores of the northern ness in combination with a negative mass balance has elongated and narrowed its shape. Shore material is lost in slump motions down the hundred metres deep submarine slopes, but is also washed into central parts of the ness by storm waves overtopping the berms (Fig. 11). The storm flood level at about 5 m above mean sea level is well marked in the inner parts of the ness by drift wood and an erosional scarp (Fig's 2, 9).

The boulder terrace at the south-eastern coast has proved to be far less stable than the other terraces. This may be explained by exposure to some very hard storms and by a lesser and more irregular supply from longshore drift.

Areal Changes

From the photogrammetric maps in the original scale of 1:5000 areal changes from July 11 1975 to August 21 1980 have been calculated (Fig. 18). The following figures were obtained for different parts of the coast (Table II).

TABLE II.
Areal changes 1975—1980 (hectares)

The lava cliffs of the southern and southwestern coast	Loss	11.9
The lava cliff of the eastern coast	Loss	0.7
The northern spit	Gain	1.2
The northwestern boulder terrace	Loss	3.0
The northeastern boulder terrace	Loss	2.6
The southeastern boulder terrace	Loss	2.1
Total change		—19.1

In the entire postvolcanic period 1967—75 the areal decrease has been 60 hectares, whereof cliffs are 50 and beaches 10 hectares. This means an average annual loss of 7.5 hectares. In the last five years the average annual loss has been half that, which indicates a stabilization of the lava cliff areas, but which also may predict increased erosion of the beach areas.

ACKNOWLEDGEMENTS

The 1980 field study was supported by the Swedish Natural Science Research Council and the Surtsey Research Society. Dr. Bengt Calles and Mr. Krister Lindé shared the responsibility for the geomorphological map, Dr. Calles carried out the tests on the tephra material and Dr. John O. Norrman was responsible for investigations on coastal changes. Dr. Rolf Å. Larsson handled the photogrammetric work. The maps were drawn in the Dept. of Physical Geography, Uppsala University by Miss Kjerstin Andersson and Dr. Calles.

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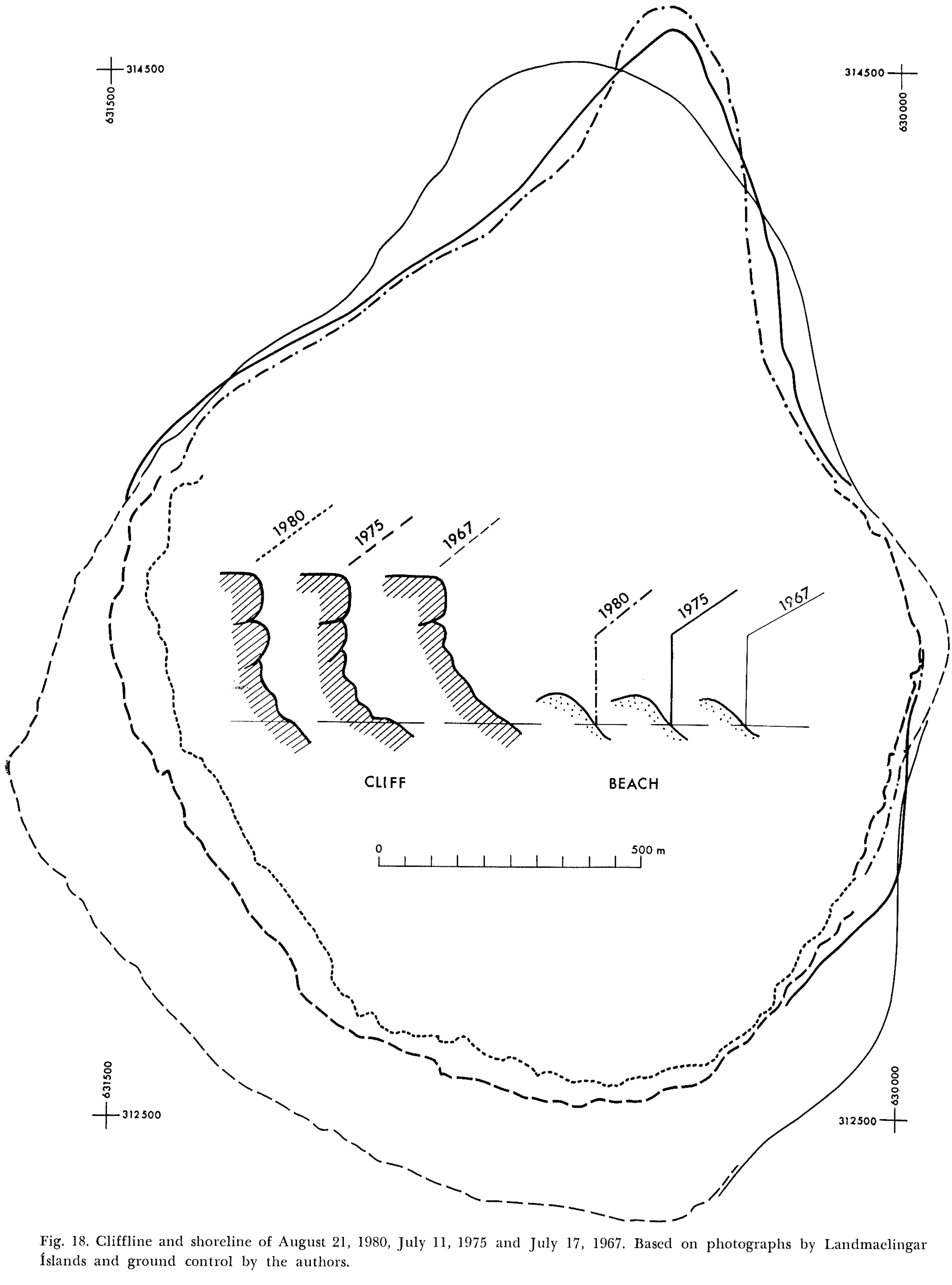

Fig. 18. Cliffline and shoreline of August 21, 1980, July 11, 1975 and July 17, 1967. Based on photographs by Landmaelingar Íslands and ground control by the authors.

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