SURTSEY RESEARCH PROGRESS REPORT

X

SURTSEYJARFÉLAGIÐ

THE SURTSEY RESEARCH SOCIETY · REYKJAVÍK 1992

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Index

INTRODUCTION

The crew on the fishing boat off the south shore of Iceland that peaceful morning on the 14th of November 1963 did not know what was happening when the sea started bubbling. When the column rose they were in no doubt. This was a submarine eruption, the birth of an island, a new land.

The island was given the name Surtsey which in Icelandic means the island of Surtur, who according to old Icelandic belief is the giant who keeps the subterranean fires burning.

The eruption immediately caught the interest of Icelandic and foreign scientists. That led to the formation of the Surtsey Research Committee, later Society, for the purpose of coordinating the scientific work on the island and publishing reports. The island was soon declared a protected national monument. The Society has been entrusted with its management.

This is the tenth progress report published by the Society. They appeared frequently to start with, even yearly when the development of the island was more rapid and the scientific work was intense. Now Surtsey's development has become more settled and the changes slower and accordingly the reports appear with longer intervals. The ninth report was published in 1982.

As for the previous five reports, the scientists Adalsteinn Sigurdsson, marine biology, Eythor Einarsson, botany, and Sveinn P. Jakobsson, geology, have been in charge of the edition of this report. Without such voluntary work this report would not have been published. Guttormur Sigbjarnarson of the Icelandic Natural History Society has managed the publication of the present report.

In order to facilitate the scientific work on Surtsey a house was erected there in 1966. This was made possible by a contribution by late Prof. Paul G. Bauer. The house was named Pálsbær (the house of Paul). It served the scientific community well for years but became a victim of geomorphological changes of the island. In 1985 a new house was built at a more settled and stable site. The widow of Prof. Paul S. Bauer, Winifred, contributed generously to its construction. For that we are indeed grateful. The new house has been given the name Pálsbær II.

As acknowledged in earlier reports the scientific work on Surtsey enjoyed for years financial support from several sources. In later years it has mostly been financed by the Icelandic Government and institutions in Iceland and abroad from where scientists have come to work on Surtsey. The Icelandic Coastguard has continued giving valuable assistance primarily through transportation to and from the island. That is highly appreciated.

Next year Surtsey will be 30 years of age. During those years numerous scientists representing most disciplines of natural sciences pertaining to such a development have worked on Surtsey. The papers and reports on Surtsey published in scientific journals and magazines all over the world are counted in hundreds. A bibliography of geological papers is to be found in this report.

Surtsey has added to man's knowledge of the Earth and will hopefully continue doing so. That is certainly needed if man is to succeed in reversing deterioration and even destruction of his environment, so vital for his own existence.

For the Surtsey Research Society,

Steingrímur Hermannsson,
chairman

BIOLOGY

Soil Respiration on the Volcanic Island Surtsey, Iceland in 1987 in Relation to Vegetation

By

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ABSTRACT

Soil respiration at three different stages of vegetation development was measured in the *Honkenya peploides/Elymus arenarius* community in Surtsey over a three day period in July. The soil respiration rate was lowest (88 mg CO_2 m^{-2} hr^{-1}) in a plot bare of vegetation, slightly higher (110 mg CO_2 m^{-2} hr^{-1}) in a plot dominated by *Honkenya,* but consistently highest (281 mg CO_2 m^{-2} hr^{-1}) in a plot dominated by *Elymus.* Soil properties were similar in the three plots and the respiration rates were related to differences in vegetation cover and root biomass between the plots. Root biomass was found to be relatively low and the organic carbon and nitrogen status of the soil poorly developed.

INTRODUCTION

Surtsey has provided scientists with an unique opportunity to follow biological succession in a terrestrial habitat devoid of life and organic substances in its first stage of formation. Since the eruptions came to an end in 1967 the development of life on the island has been uninterrupted. Early investigations revealed that the fresh volcanic substrate became contaminated with microbial algae, bacteria and moulds within a relatively short time and biologcal activity was established on the island (Schwabe 1970, Smith 1970, Fridriksson 1975). The first vascular plant was found growing on Surtsey in 1965 (Fridriksson 1966), bryophytes became established in 1967 (Jóhannsson 1968) and lichens were first detected in 1970 (Kristinsson 1972). Plants play a key role in soil formation processes, one of the greatest contributions being the addition of organic matter to the soil upon which the decomposer communities are founded.

On Surtsey nitrogen-fixation by blue-green algae has been demonstrated under a variety of conditions (e.g. Henriksson & Rodgers 1978), but their ecological importance in the development of life on the island has been debated (Brock 1972, Henriksson & Henriksson 1982). Development of bryophytes and lichens has been rather slow on Surtsey due to unfavourable substrate conditions. Although they may be locally abundant they have not contributed significantly to the formation of plant cover on the island. The advancement of the vascular plant colonization on Surtsey has, on the other hand, been steady (Fridriksson 1987) and is probably of greatest importance in the establishment of vegetation and soil biota on the island.

The objective of the present study was to investigate the biological activity and soil properties in an area of Surtsey where plant colonization is in a relatively advanced stage of succession. For this purpose measurements of soil respiration were carried out on the island. Soil respiration has been defined as "the sum total of all soil metabolic functions in which CO_2 is produced" (Singh & Gupta 1977). The rate of CO_2 evolution from soil surfaces has been commonly used to measure soil respira-

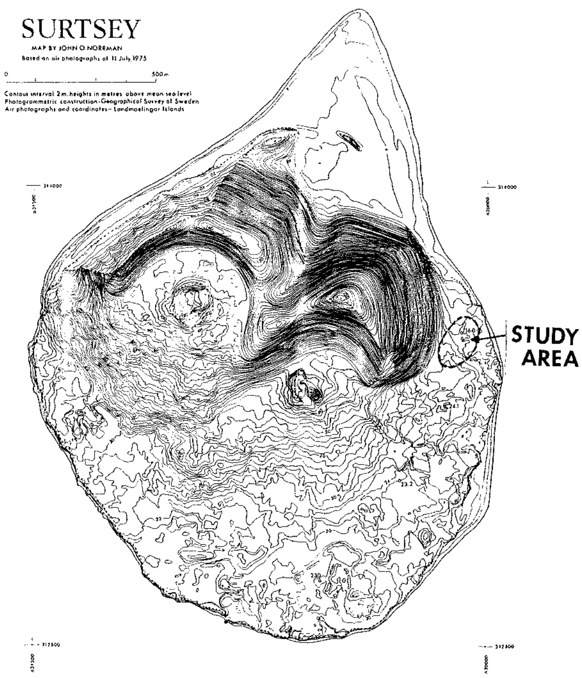

Fig. 1. Location of the study area on Surtsey.

tion. The main source of CO_2 evolving from the soils of most terrestrial ecosystems are microbial, microfaunal and root respiration. Studies of soil respiration have been used to measure and compare soil metabolism in different ecosystems or successional stages within the same ecosystem.

STUDY AREA

The study was conducted on the easternmost part of the island (Figure 1) in an area where windblown tephra and sand has filled the depressions in the underlying lava and levelled the terrain. The area is between 10 and 20 m a.s.l. On this part of the island the vegetation was most developed. The area was invaded by vascular plants in 1968 when the first young plants of *Honkenya peploides, Elymus arenarius* and *Mertensia maritima* were found there (Fridriksson 1975). Of these species only *Honkenya* persisted in the area from the first year of discovery, but *Elymus* and *Mertensia* did not gain a foothold there until 1973 (Fridriksson 1978). The three species have produced seeds and increased in numbers. The population growth has been most prolific in *Honkenya* and it was the most prominent species in the study area in 1987. *Elymus* has also increased considerably in numbers and the oldest plants have formed small sand dunes in association with *Honkenya* plants (Fridriksson 1982). Of *Mertensia* there were only a few scattered plants. Estimations of vegetation cover in the area in 1987 indicated an average plant cover of 8.5%, all of which was attributable to *Honkenya* plants (Fridriksson 1991). Conditions for bryophytes and lichens are poor in the area and they were of no ecological significance in the development of the plant community.

Three study plots representing different stages of vegetation development on the tephra soil were selected for the soil respiration measurements. The plots were distanced approximately 40–150 m apart.

a) Bare plot

The plot was considered as a base-line reference and for it a nearly unvegetated patch within the study area was selected. There were neither mature plants within the plot nor in the immediate viscinity of it. Four small *Honkenya* plants, probably in their second year, with only one shoot each were found within the plot and sixteen seedlings of the same species. One young *Elymus* plant, with stolon and 3 leaves, was also found within the plot. The size of the plot was 15×1 m.

b) *Honkenya* plot

The plot was located in an area considered to be representative of a well developed *Honkenya* colony. In the plot there were numerous mature *Honkenya* plants as well as young plants in their first and second year. One immature *Elymus* plant with nine leaves, and six seedlings of the same species were found scattered within the plot. The size of the plot was 15×1 m.

c) *Elymus* plot

The plot transected the center of a sand dune formed by the largest *Elymus* plant (No. 74-51) growing on Surtsey in 1987. The plant was first recorded on the island as a seedling in 1974 (Fridriksson 1978). In 1979 the plant produced seeds for the first time and in that year it occupied an area of 155x290 cm (Fridriksson 1982). In 1987 the plant covered a circular area with a diameter of about 650 cm. In the dune several *Honkenya* plants grew in association with the *Elymus*. In the center the dune had reached a height of approximately 120 cm above its surroundings. For several years a pair of Great Black-backed Gulls (*Larus marinus*) has bred in the dense *Elymus* cover of the

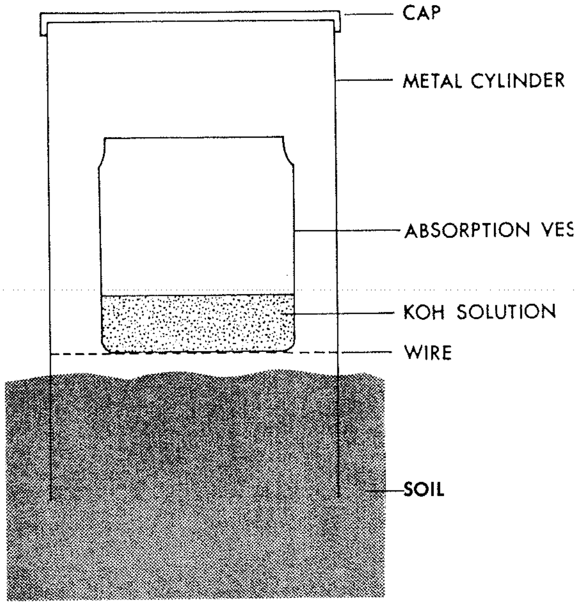

Fig. 2. Schematic drawing of apparatus used to measure soil respiration in the field.

dune and in 1987 the young had recently left the nest when the respiration measurements were carried out. The size of the plot was reduced to 10×1 m in order to match somewhat better the size of the dune.

METHODS

Soil respiration

Carbon dioxide evolution from the soil was determined by using an alkali absorption method (Gupta & Singh 1977). Open ended metal cylinders 10 cm in diameter and 18 cm high were inserted 5 cm into the soil. Green plant material was removed if it occurred within the cylinders. A wide-mouthed glass jar containing 50 ml of 0.2M KOH solution was placed into the cylinders for absorption of CO_2. A wire inside the cylinders kept the jars about 2 cm above the soil surface so they did not interfer with CO_2 evolution from the soil (Figure 2). The cylinders were sealed and left in the ground for 24 hours at a time. Four replicates were used and cylinder positions were randomly selected at the beginning of each 24 hour period. To serve as controls, four cylinders open at one end, and of the same volume above ground as in the active cylinders, were used and these were handled in the same way as the active cylinders. At the termination of each measurement period the alkali solution was poured from the glass jars and into air-tight plastic bottles, in which it was kept until analysis was carried out in the laboratory. The respiration measurements were run for three consecutive days, starting with the first 24 hour period in the afternoon of 2nd of July.

CO_2 absorption was analyzed by titrating the unneutralized KOH with diluted standardized 0.200N HCl after precipitation of the carbonate with excessive (15 ml) 3N $BaCl_2$ and using phenolphthalein as an indicator. The following formula was used to calculate the amount of CO_2 evolved:

$$\text{mg } CO_2 = (B - V)\, N\, E$$

where: V = volume of acid required to titrate the KOH in the active cylinders to the end point; B = volume of acid to titrate KOH in the control cylinders to the end point; N = Normality of HCl; E = equivalent weight, E = 22 if the data are expressed as CO_2 (Strotzky 1965, Magnússon 1986). For each sample the results were converted and expressed as mg CO_2 m^{-2} hr^{-1}. The capacity of the solution used was to absorb 220 mg of CO_2, which is equivalent to 1167.1 mg CO_2 m^{-2} hr^{-1} over a 24 hour period.

Although the alkali absorption method may underestimate CO_2 release it has been found to be well suited for measuring soil respiration due to the relatively simple apparatus used and low cost, which enable extensive replication of measurements in a variety of habitats (Coleman 1973, Singh & Gupta 1977). The results obtained by the method may therefore not give absolute values but rather be a relative measure of the intensity of soil respiration. Such data can however be useful in comparing respiration under different conditions (Reiners 1968).

Soil moisture, temperature and chemistry

For determination of soil moisture, surface samples 14.5 cm deep × 3.5 cm in diameter, were taken underneath the respiration cylinders at the termination of each 24 hour measurement period. The samples were sealed in plastic bags and stored until handled in the laboratory. Moisture content was determined gravimetrically after drying the samples at 80°C for 48 hours, and calculated as % dry weight.

Soil temperature was measured with a maxima-minima thermometer, which was placed horizontally into a 15 cm deep soil pit and covered with the displaced soil. The pit was made outside the study plots and within a 1 m distance of them. Measurements were only made by the bare plot and the *Honkenya* plot. After each 24 hour period, the thermometers were recovered and after reading were reset and put back in place.

The soil samples collected for soil moisture determination after the second 24 hour period of respiration measurements were analyzed for pH and content of organic carbon, nitrogen and potassium. The dried samples were sieved through a 0.5 mm mesh. Measurements of pH were made in a mixture with distilled water, content of organic carbon (C%) by Walkley-Black titration (Jackson 1958), nitrogen (N%) using the Kjeldahl method, and potassium (K) with 1.25% acetic acid suspension and flame photometry.

Plant cover and root biomass

The plant cover was determined using the line-intercept method. Within each study plot a meter tape was laid out twice along the plot at a 33 cm and 66 cm distance from the side line. Plant species that intercepted the line were recorded to the nearest 1 cm. The accumulated length out of the total tape length occupied by plants was used to express percentage cover.

After all soil respiration measurements had been completed, the study plots were divided into four equal parts of 1 m width. In the center of each part the respiration cylinders (10 cm diameter) were driven 20 cm into the soil. All soil and root material within the cylinders was then removed and put on a sieve with a 2 mm mesh size. From the sieve all visible roots were collected and placed in plastic bags. In the laboratory the weight of the root samples was determined by ignition at 600°C for 2 hours. This method was selected due to the difficulties involved in detatching small tephra-grains from fine roots which was considered to result in a loss of root material.

Statistical analysis

The data were subjected to analysis of variance, and means checked at $p=0.05$ level of significance.

CLIMATE

Surtsey, being the southernmost terrestrial part of Iceland, has a rather mild, oceanic climate. At the Vestmannaeyjar meteorological station on Stórhöfdi, Heimaey, which is 22 km northeast of Surtsey, the mean annual temperature during 1931–1960 was 5.4°C. The mean January temperature was 1.4°C and the mean July temperature 10.3°C, which were the coldest and warmest months respectively. The annual precipitation for the same period was 1402 mm. In the driest months (May and June) the mean precipitation was 81 mm, but 156 mm in the wettest month (December) of the year (Einarsson 1976). Meteorological observation on Surtsey in 1967 and 1968 indicated that the climatic conditions on the island do not deviate markedly from those of Stórhöfdi (Fridriksson 1975).

In 1987 the monthly temperature on Stórhöfdi in April, May and June was near the 1931–1960 average. In April and May the monthly precipitation was above average, but June, on the other hand, was extremely dry with a precipitation of only 12.3 mm (Vedráttan 1987). The temperature at Stórhöfdi during the time of the soil respiration measurements on Surtsey on July 2–5 appears to have been near normal (Icelandic Meteorological Office, unpublished records), but the precipitation records indicate a dry period (Table 1).

Meterological measurement were not carried out on Surtsey in 1987, but the following was noted during the stay on the island:

July 2. Calm, cloudy and dry, soil surface dry on arrival at 10.30. Slight rain around noon, but otherwise dry and calm for the rest of the day.

July 3. Started raining at about 00.30 and continued during the night. Eastern breeze, cloudy and dry during the morning, became calm and sunny in the afternoon and evening.

TABLE 1.

Mean daily air temperature and total precipitation during June 26–July 5, 1987 at Stórhöfdi, Heimaey

Day	Temperature °C	Precipitation mm 24 hours
26.6	7.8	0
27.6	7.2	0
28.6	7.9	0
29.6	8.7	trace
30.6	10.8	2.3
1.7.	9.6	0.3
2.7.	9.7	0
3.7.	10.4	trace
4.7.	11.5	0
5.7.	10.2	1.0

July 4, clear and calm during the night. Northwest breeze and sunny during the morning and early afternoon. Became cloudy around 17.00. Slight rain in the evening.

July 5. Rained intermittently during the night and morning. Continuous rain in the afternoon. Wind calm.

RESULTS

The soil respiration rate in the plots ranged from 79.6 to 381.7 mg CO_2 m^{-2} hr^{-1}. The rate was on all days consistently highest in the *Elymus* plot and significantly different from the rates determined in the bare plot and the *Honkenya* plot, which did not differ significantly from each other (Table 2). In the bare plot, however, the respiration rate was lowest on all days. Over the three day period the mean respiration rate was 1.26 and 3.20 times higher in the *Honkenya* and *Elymus* plots respectively, than the rate in the bare plot. There was no consistent change in respiration between days in the different plots. In the bare plot and the *Honkenya* plot there was little spatial and temporal variation in respiration rate. In the *Elymus* plot there was, on the other hand, a considerable variation in this respect, and it was also noted that the respiration rate was higher in the part of the plot which had *Elymus* cover than in spots which were bare of vegetation or had *Honkenya* cover only. The difference in respiration rate between days in the plot coincided with the number of respiration cylinders positioned within the *Elymus* cover, which was 3, 1 and 2 on days 1, 2 and 3 respectively. Over the three day period the respiration rate of the cylinders within the *Elymus* cover averaged 414.0 mg CO_2 m^{-2} hr^{-1}, while the rate of those outside it in the same plot was 148.4 mg CO_2 m^{-2} hr^{-1}.

The soil moisture content ranged from 6.24 to 9.45 dry weight (Table 2). The soil samples lost on the average 10.81 g of weight upon drying, which corresponds to 7.75% of the soil volume sampled being filled with water. The moisture content was lowest in the bare plot and significantly different from that in the other plots. There was a significant decline in moisture content of the soil over the three day period.

The soil temperature at 15 cm depth fluctuated between a minumum of 12.0°C and a maximum of 27.5°C (Table 2). The temperature rose over the three day period, which appeared to reflect the changes in air temperature at Stórhöfdi (Table 1) and a shift from cloudy to sunny weather on Surtsey during the measurements.

TABLE 2

Soil respiration rates, moisture, temperature, plant cover and root biomass under three different vegetation conditions in Surtsey in 1987. Values are x±S.E. for respiration, moisture, chemistry variables and root biomass, N=4.

Plot	Bare	*Honkenya*	*Elymus*
Soil respiration mg CO_2 m^{-2} hr^{-1}			
Day 1 (July 2–3)	79.6±12.2	122.2±10.5	381.7±104.4
range	52.2–110.8	103.1–147.7	132.6–583.1
Day 2 (July 3–4)	85.9±4.4	101.5±2.0	170.9±45.5
range	73.9–94.2	98.0–107.0	98.0–287.7
Day 3 (July 4–5)	98.0±3.8	107.6±5.0	290.9±66.0
range	90.4–105.7	96.8–118.4	137.5–407.4
Day 1–3 mean	87.8	110.4	281.2
Soil moisture % dry wt			
Day 1	7.75±0.59	8.38±0.58	9.45±1.06
Day 2	6.99±0.44	8.30±0.15	8.13±0.70
Day 3	6.24±0.52	7.68±0.28	7.28±0.63
Soil temperature °C -15 cm, min-max			
Day 1	12.0–19.0	14.0–17.0	n.d.
Day 2	13.5–24.5	14.5–20.5	n.d.
Day 3	15.0–27.5	14.5–27.5	n.d.
Soil chemistry			
pH	7.0±0.1	6.9±0.1	7.1±0.1
C% dry wt	0.23±0.03	0.23±0.01	0.28±0.01
N% dry wt	0.008±0.003	0.011±0.002	0.033±0.008
K meq 100 g^{-1}	0.31±0.01	0.30±0.03	0.47±0.08
Vegetation			
Plant cover (%)	0	13.2	70.6
Root biomass g m^{-2} 0-20 cm	0	14.5±5.0	45.9±17.7

The soil chemistry analysis gave similar results between plots for pH and content of carbon and potassium (Table 2). The concentration of these elements was, however, highest in the *Elymus* plot, but the difference was not significant. The nitrogen content of the soil in the *Elymus* plot was, on the other hand, significantly higher than that of the other plots.

Plant cover was not measureable in the bare plot, but in the *Honkenya* plot and the *Elymus* plot respectively 13.2% and 70.6% of the soil surface was covered with vegetation (Table 2). In the *Honkenya* plot all the vegetation cover

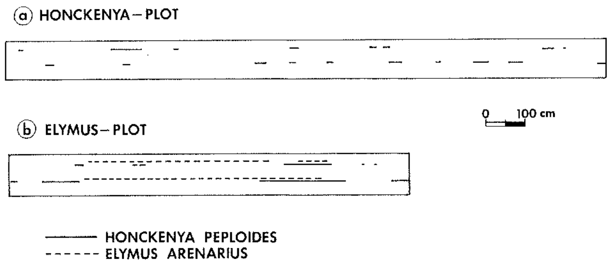

Fig. 3. Occurrence of plants along two longitudinal line-transects in the vegetated study plots on Surtsey, where soil respiration was determined.

was attributable to *Honkenya* plants, which were distributed throughout the plot (Figure 3). In the *Elymus* plot, the total cover of *Elymus* was 56.2%, while that of *Honkenya* plants was 26.6%. Some of the *Honkenya* in the plot formed a layer underneath the *Elymus* cover, which explains the difference in total plant cover and the additive cover of the two species (Figure 3).

Roots were not detected in the soil samples in the bare plot, but in the *Honkenya* plot root biomass was estimated by ignition as 14.5 g m^{-2} in the top 20 cm of the soil, and 45.9 g m^{-2} in the *Elymus* plot. The means were significantly different. The proportional variation in root biomass between samples was similar in both plots (Table 2).

DISCUSSION

The soil respiration rates, 80–382 mg CO_2 m^{-2} hr^{-1}, determined in Surtsey were within the range reported in various studies of soil respiration in dry grassland and open habitats, which vary from 0 to over 1100 mg CO_2 m^{-2} hr^{-1} depending on the season (Walter & Haber 1957, Lieth & Quellette 1962, Kucera & Kirkham 1971, Coleman 1973, Chapman 1979, Gupta and Singh 1981, Parker et al. 1983). The rates from Surtsey are high in comparison to the results of Lieth & Quellette (1962), who reported a soil respiration rate of 57 mg CO_2 m^{-2} hr^{-1} in July in a *Elymetum arenarii* community on gravelly sand, along the sea coast of the Gaspé Peninsula in Quebec, Canada. In other dry open communities the rate was in the range of 55 to 141 mg CO_2 m^{-2} hr^{-1}. The soil respiration rates reported by Walter & Haber (1957) from Germany were, on the other hand, closer to the results of the present work. In a sand dune without vegetation on the Rhine the soil respiration rate was 89 mg CO_2 m^{-2} hr^{-1} in July, and in an *Agrostis* meadow on sand the rate was 315 g CO_2 m^{-2} hr^{-1} during July to October. The soil respiration rates measured by Chapman (1979) in a lowland *Calluna* heathland developed on sand dunes in southern England were considerably higher than the rates observed on Surtsey, but at a soil temperature of 10–18°C they ranged from approximately 220 to 950 mg CO_2 m^{-2} hr^{-1}.

The difference in soil respiration rate between the three plots studied in Surtsey presumably reflects their vegetation condition. The observed variation in moisture content, temperature and chemistry of the soil between the plots was minor and did not correlate well with the soil respiration rate, which the vegetation variation, however, did. The respiration rate measured in the bare plot was relatively high, taking into account that no roots were extracted from the soil within the plot and the absence of surface litter, the low organic matter content and low status of microbial and faunal activity og the tephra soil in Surtsey (Henriksson & Henriksson 1974, Henriksson & Rodgers 1978, Broady 1982, Bödvarsson 1982, Ólafsson 1982). The soil is probably well aerated near the surface due to its low organic matter content, relatively coarse particle size and low water holding capacity. Therefore diffusion of atmospheric CO_2 into the soil and uptake in the respiration cylinders may have occurred and could explain to some extent the high respiration rates measured in Surtsey. Assuming that the CO_2 uptake in the bare plot represents mostly non-biological sources of CO_2 in these soils, then the average soil respiration rate over the three day period would be about 20 and 190 mg CO_2 m^{-2} hr^{-1} in the *Honkenya* and *Elymus* plots, respectively. Further studies are, however, needed to verify this.

In Surtsey, the roots and the associated rhizosphere micro-organisms were probably the primary sites of biological activity in the soil and sources of respiratory CO_2. A build up of a litter layer at the surface has not occurred in the young and exposed habitat and the organic matter content of the soil is extremely low, and therefore the contribution from these sources to that total soil respiration is probably still negligible. Estimates of contribution of root respiration to total soil respiration vary considerably (Chapman 1979), which reflects both differences in methodology as well as in the plant communities and soil types studied.

Phillipson et al. (1975) attributed only 3–4% of soil respiration to roots in a beechwood, while Chapman (1979) estimated root respiration as 70% of total soil respiration in a *Calluna* heathland. The root biomass, 14-46 g m^{-2}, in the young plant community in Surtsey was relatively low in comparison to results of studies from grasslands and dry open habitats, where root biomass has been determined to be in the range 100 to 1900 g m^{-2} (Perkins et al. 1978, Richards 1986). It must, however, be borne in mind that sampling of roots below 20 cm was not carried out in Surtsey.

The study showed that the tephra soil of Surtsey has the characteristics of immature soils, as was expected. In freely drained grassland soils in Iceland the pH is commonly 5.4–6.3, orgainc carbon ranges from 5–15% and nitrogen from 0.4–0.8% (Helgason 1968). Studies of the properties of soils of denuded highland areas in Iceland (Arnalds et al. 1987) indicate that they are somewhat lower in pH and richer in organic carbon and total nitrogen content than the soils of Surtsey. The carbon and nitrogen status of the soil in Surtsey was similar to that found in soils of mobile coastal dunes with a *Elymo-Ammophiletum* community in southern Norway (Lundberg 1987), which have a very low organic, nitrogen and moisture content in comparison to the soils under the communities of the older fixed dunes. Studies of succession on dunes in Britain have shown that a build up of soil organic content is a very slow process and centuries rather than decades are needed for distinct changes to occur (Chapman 1976). The total nitrogen concentrations determined in the soil in Surtsey in the present study are within the range found in studies on the island in 1974 and 1976 (Henriksson & Rodgers 1978), which indicates that the nitrogen status of the soil has not improved markedly over the last ten years.

The soil in the *Elymus* plot was richer in nitrogen than the soil of the bare plot and the *Honkenya* plot, and also its carbon and potassium content was relatively high. It is probable that the higher nutrient status in the *Elymus* plot was due to the effects of bird faeces and food remains from the pair of nesting gulls in the dune, rather than to the difference in vegetation development. The enrichment of the soil by the birds may also have affected the biological activity of the soil directly and the soil respiration rate in the plot. In recent years there has been a considerable increase in the number of breeding gulls on Surtsey, in particular Lesser Black-backed Gulls (*Larus fuscus*) and Herring Gulls (*Larus argenteus*), which nest in colonies and revisit them year after year. Defecation has been shown to be of importance in enhancing soil-nutrient concentrations in Herring Gull colonies (Sobey & Kenworthy 1979). The breeding birds may in the future have profound effects on the rate of vegetation development and soil formation on Surtsey.

ACKNOWLEDGMENTS

The Surtsey Research Society provided logistic support for the study, and the work was also supported by the Agricultural Research Institute. Transport to and from the island was in the hands of Icelandic Coast Guard helicopter personel. The assistance of these agencies is greatly appreciated. The author would like to thank Dr. Sturla Fridriksson and Jón Gudmundsson for their valuable assistance and companionship during the stay on the island.

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Vascular plants on Surtsey 1981–1990

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INTRODUCTION

A yearly study has been made of the vascular plants on Surtsey since the first plant was discovered growing on the island in 1965. Reports on this investigation have been given in the Surtsey Research Progress Reports. The last one covered the period 1977–1980. (Fridriksson, 1982a). An overview of the study of colonization of life on Surtsey, including the recordings of plants, has been presented in other journals for the period up to 1988 (Fridriksson 1982b, 1987, 1989). Reports of the studies have as well appeared in newspapers and magazines (Fridriksson 1984). These review papers gave an account of the species found on Surtsey in the various years since the birth of the island in a submarine volcanic eruption in 1963. However, in order to maintain continuity in the reports of the study of vascular plants on Surtsey in this journal, a description is given here covering the period 1981 to 1990.

RESEARCH METHODS

The methods used in studying the vegetation of Surtsey have been described in previous papers of the Surtsey Research Progress Report. The individual plants were at first all recorded and marked on a map with the aid of an aerial photograph. These maps bore a grid of a coordinate system with quadrats of 100×100 m (1 ha), marked numerically and alphabetically. In 1979 the *Honkenya peploides* plants had become so numerous that detailed records of individual plants could no longer be kept. Instead their frequency had to be estimated in quadrats or on transects. However, individuals of any new species discovered would still be marked on maps and staked.

The distribution patterns of the plants were investigated and a description made of their flowering and seed setting. Where associations were being formed a detailed study of their development was carried out. Photographs have been taken of individual plants and associations to document their appearance and characteristics. Aerial photographs were used to facilitate the marking and mapping of plants on a chart showing vegetation of the island (Figure 1).

GENERAL DESCRIPTION

Of the 20 species of vascular plants that had been found on Surtsey from the time the island was born only 13 were growing there in 1980. This shows that the conditions on the island are not too favourable for plant growth. In the following year 1981, there was even a decrease in the number of species and during the period up to 1985 no additional species were discovered. Then in 1986 three new species were found growing on the island, two of which had apparently been there the previous year without being noticed. In 1987 two more species were observed and in 1988 some of the earlier colonizing species that had failed to grow there for a few years reappeared among the plants on the island. Thus there were 18 species growing there in 1988. In 1990 four new species were discovered and that year a total of 25 species of vascular plants was found.

During the 27-year period of the island's existence a total of 28 species of plants had been recorded growing on Surtsey at one time or another, but some of them were not repre-

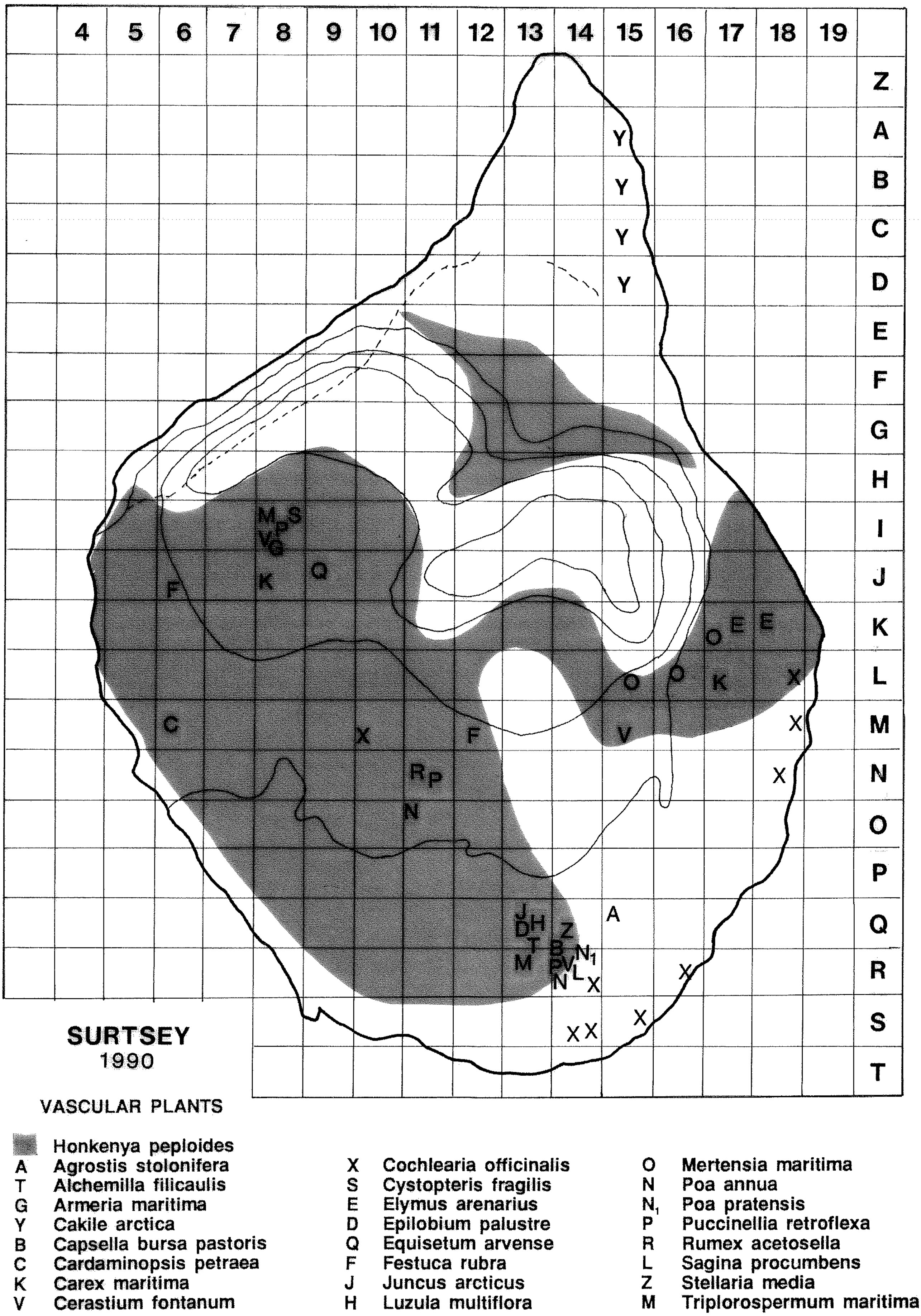


Fig. 1. Distribution map for plants on Surtsey.

sented at the end of the study period. There is apparently seasonal variation in the amount of dispersing seed to the island and seed of some of the colonizing species is not annually dispersed or manages to germinate.

INDIVIDUAL SPECIES

Agrostis stolonifera L.:

One plant of this common grass species of Iceland was discovered in Surtsey in 1987 and has been found growing there ever since. It was originally found at the edge of a patch of *Sagina* on a flat spot on the lava shield in the southern part of the island in quadrat Q-15. It flowered during that summer with eight panicles being produced. This plant has developed further but new individuals of the species have not been found. The patch covered an area of 5×10 cm in 1987 and had increased to 10×15 cm in 1990 with three distinct centres.

Alchemilla filicaulis Buser:

One individual of this species was discovered in the spring of 1990 near the gull breeding colony on the southern part of the island (Einarsson 1990).

The plant has most likely grown from seed carried by a bird to the island.

Angelica archangelica L.:

This species which is common on the cliffs of nearby islands has been represented on Surtsey by two seedlings in 1972 and 1973. It has never been found since on the island. It is a possible future occupant of the bird cliffs on the southern edge of the lava.

Armeria maritima (Miller) Willd.:

In 1986 a single plant of this species was discovered growing high upon a narrow shelf in the southern rim of the Lava crater. The plant was then flowering with three heads. Its seed had apparently been brought to this remote location by ravens that frequently visited this spot and were obviously preparing to use the shelf as a site for their future nest. The birds had brought to this place pieces of strings, bones and wooden sticks intended for nest building and beside this debris the plant grew and increased in size during the following years. It had developed 31 heads in 1987 and was flourishing. In 1990 two plants were found growing side by side at this same location and both were in flower (Figure 2).

Fig. 2. An *Armeria* plant on a shelf of the rim of the Lava crater with moss on the crater floor.

Atriplex patula L.:

A small plant was found growing in 1977 at the high-tide-line, by the north-eastern shore. This species, which is common on the nearby islands, has not been rediscovered on Surtsey.

Cakile arctica Pobed. (syn.: *Cakile edentula* (Bigel) Hooker; *Cakile maritima* Scop.):

This species was the first to colonize the shore of Surtsey in 1965. The species, being an annual, has not managed to establish a firm foothold on the island and has only been found growing there in 13 years during this 27-year period. The plants have mostly been at the high-tide-line, as were the approximately 120 specimens found on the island in 1990, where they are favoured by the fertile environment of the sand mixed in with the decaying sea weed. Although some of the plants have been able to flower and develop seed their production has not been sufficient to ensure the preservation of the species on the island. The existence of the species on Surtsey is therefore almost exclusively dependent on seed dispersal from neighbouring sources.

This may be variable between years due to differences in the amount of seed produced on the neighbouring islands as well as the south coast and may depend on the prevailing winds following the fall of seeds.

Capsella bursa pastoris (L.) Medicus:

One individual of *Capsella* was discovered in 1990 growing on the sandy deposit covering the lava shield on the southern part of Surtsey at the edge of "Mávaból", the seagull breeding area. A seed of this plant has most likely been carried there by the birds. The plant had produced seven scalps and was blooming with five new flowers. This newcomer will probably have a chance to multiply in the area which is becoming fairly fertile due to bird droppings.

Cardaminopsis petraea (L) Hiit.:

This species is common on gravel beds in Iceland and could be expected to find the environment favourable on Surtsey. Five plants of this species were first found on the island in 1978. They all grew together at the same spot in quadrat M-6 and were marked with a stake No. 78-136. This plant developed and bore seed that fell close by and in 1980 eight plants were growing there together. The plants were not observed during the five following years, but were rediscovered in 1987. At that time seventeen small and three larger plants were recorded at the same location on a 1 m^2 area. This small colony had grown to 25 plants in 1990 and is still isolated at the same spot in the south-western part of the lava flow.

Carex maritima Gunn.:

One plant of this species was first recorded on the island in 1972. Two individuals have both been successful in surviving and developing during this study period. Plant No 78-182 in quadrat L-17 has gradually increased in size by runners and had in 1986 managed to cover an area of 100×70 cm. It had 16 flowering culms, but there were no signs of new seedlings in the neighbourhood. In 1990 it had produced 50 stolons and 26 flowering culms. Plant No 78-148 was growing in quadrat J-8, but has not developed as well as the former. It covered an area of 20×30 cm in 1984 and was rather weak and did not bear flowers in 1990.

In 1986 two new individuals were found in quadrat S-14 on the southern part of the island. One of them was growing in a tuft of 8×40 cm in area and had 13 flowering culms. The other, a smaller plant which was not flowering, was growing in a lava crack filled with sand. Both these individuals probably developed from seed carried by birds. These plants have continued to develop and in 1987 a well-developed plant was found under the north cliff of the Lava crater.

Cerastium fontanum Baumg. ssp *scandicum* H. Gartner:

This species which is common on dry, open land in Iceland has been found growing continuously on Surtsey since 1975 when it was first observed there. However, its population has not increased steadily as regards the number of plants. In some years several young seedlings have started growth but these have often not survived the following winter. There have mainly been two patches or colonies of these plants on the island; one is in a sand-filled depression of the lava in quadrat M-15 which is situated about 20 m south of the present hut. Occasionally there have been several dozens of plants in this colony, but in other years these were fewer and in 1987 and 1988 only one plant was growing there. The other colony of *Cerastium* is on the southern part of the lava shield in quadrat R-14. It grows there in a sandy layer covering a fairly flat surface of lava. The colony consisted of 25 plants in 1987 and 29 the following year. In the summer of 1990 over fifty plants were found growing at this site. Most of them were flowering and producing seeds.

Cochlearia officinalis L.:

Specimens of *Cochlearia* have been found growing on Surtsey ever since the species was first discovered in 1969. Apparently there is a steady dispersal of seed to the island probably carried by birds from nearby sources, but seed is now also produced locally and seedlings have been found in great numbers in some years growing beside the mother plants. However, there has been no major increase of the species on Surtsey during this study period. The older plants have developed and flourished, but the young seedlings seem to have difficulties in surviving. In 1990 there were over 100 individuals recorded on the island. Most of the plants were found in the south and south-eastern part of the lava-apron, especially on the edge of the ocean cliffs where the seagulls perch and feed their young. At the gull-breeding area "Mávaból" in quadrat

R-14 there were three large plants developing respectively with 35, 55 and 60 capsules. In the close vicinity there where 15 younger plants. The soil in this area is becoming quite fertile due to the droppings of the birds and the remnants of their food and other offal, such as feathers, broken eggs and bird carcasses. There is thus a good chance for future development of the species in this habitat. Further to the south along the edge near "Lýsuhóll" in quadrat S-14 around 85 plants were growing in the sand-filled cracks of the lava in 1987. These were again observed prospering in 1990. Thus the species is gradually colonizing the southern fringe of Surtsey. Although this is the site where the species is most common, a few plants may be found farther up in the lava. Thus one large plant, 25 cm high, was discovered in 1987 growing in quadrat M-10. It was flowering and had produced 26 branches with capsules. Another large plant marked No 77-88 growing by the edge had 8 flower stalks. The stalks having on average 25 capsules containing about 15 seeds each, it was thus bearing up to 3,000 seeds that summer. A marked increase in the number of seed of *Cochlearia* is therefore being produced annually on Surtsey.

Cystopteris fragilis (L.) Bernh.:

A few plants of this fern have survived and been recorded in most years since it was first found on Surtsey in 1971. Some individuals were growing in hollows out in the centre of the lava flow. Others were found in the Lava crater marked as quadrat I-8. Here the plants have grown in association with moss that forms tufts on sand deposits in cracks in the lava, so that the plants enjoy shelter and some moisture. Although some of the fronds have been found to be fertile, there has been no increase in the number of this species and in 1990 only five individuals were found growing in the Lava crater of Surtsey.

Elymus arenarius L.:

This perennial grass species is one of the major colonists on Surtsey. It was the second species of vascular plants to take root on the island as it was first found there in 1966 during the third summer of the island's existence. Since then plants have gradually developed, increased in size and multiplied.

During the first 13 years there was not much change in the number of individuals of this species on Surtsey. Seeds were apparently being washed annually up on the shores of the island. Some of them germinated and developed into plants, but there was a high death rate. New individuals were recorded only later to be found wilted, buried by sand or torn up by birds. Thus during the first years the population had to rely on the import of seed to make up for the loss of individuals.

In 1979 there was a marked change in this development. Among the five plants of this species found on the island that year, was a five-year-old plant No 74-51, which was growing on the sand-filled lava surface on the eastern part of the island in quadrat K-18. During that summer the plant started to flower, bearing eight spikes. Again in 1980 it produced some fifty spikes. This flowering and seed setting has continued. The plant has gradually developed in size and the number of spikes has increased as the years have gone by. Thus there has been a great increase in seed production of this individual (Table 1).

In a similar way a slightly smaller plant was growing farther to the west and higher up on the lava in quadrat K-17. It also flowered but bore fewer spikes. Both these plants have considerably increased the availability of *Elymus* seed on Surtsey and thus given the species an additional chance to colonize and spread in this new habitat. Table 1 shows the gradual increase in number of spikes of these two plants. Obviously this seed formation has had a great effect on the *Elymus* population.

The transport of *Elymus* seed to Surtsey was fairly limited. During the first 18 years only ten *Elymus* individuals on the average were found growing annually on the island. Up to 1983 there had been little increase in the number of plants. The death rate of plants must have been almost equal to the rate of new introductions from dispersed seed. Although local seed production started in 1979 it was not until 1983 that new seedlings began developing near the parent plants. In the autumn of 1982 the old plants carried 76 spikes with approximately 4,000 seeds. The following summer there were 38 new seedlings found in the neighbourhood of these older plants which indicates that around 1% of the produced seeds succeeded in developing into mature plants. In the autumn of 1983 there were 240 spikes produced on the old plants which mey have developed some 12,000 seeds. The following summer there were about 150 new seedlings

TABLE 1.

Number of flowering spikes on two *Elymus* plants on Surtsey.

	Years									
Plant no	1979	1980	1982	1983	1984	1985	1986	1987	1988	1990
74-51	8	50	70	115	450	250	300	529	1000	1138
74-78			6	125	520	650	160	280	255	274

found growing in the neighbourhood of these same two old plants, which again suggests that a little over 1% of the available seed had developed into a successful seedling. Now that the *Elymus* seeds are annually being produced on Surtsey in ever greater numbers there is bound to be a steady increase in the number of seedlings in years to come. At first this development will be slow, as the *Elymus* plants on Surtsey do not become fertile until they are five years old. Thus the second generation of *Elymus* plants on Surtsey has just started to become fertile. During the years to come one would expect a major increase in this species. The growing conditions seem to be perfect for *Elymus* and there is plenty of sand and lava which is an ideal habitat for the species. It is therefore likely that in the following years a cover of *Elymus* grass will be formed on the eastern part of Surtsey.

Epilobium palustre L.:

This species which prefers to grow in moist places was first discovered on Surtsey in 1990, when two plants were found near the fertile sea gull breeding area "Mávaból", in quadrat Q-13. These two new plants were both flowering. They both apparently grew from seeds that may have been brought by the birds or rather drifted by air to the island since the seeds are hairy-plumed and light and can easily be carried by wind to Surtsey.

Equisetum arvense L.:

This species which is very common on sand and pumice in Iceland was first found on Surtsey in 1975 but was not rediscovered there until 1990. The first location was in quadrat J-9 on the eastern side of the Lava crater, but the second time it was found growing on the southern brim of the crater in quadrat K-9. This time three groups of plants were found in a colony growing on the ashy surface of the shoulder. The plants were all very small, about 2–4 cm long, with branches growing out of the prothallium. They may have started their growth that same spring from windborne spores. These two locations are peculiarly close together, which might indicate that the substrate there is particularly favourable for this species.

Festuca rubra L.:

This common grass species of Iceland has firmly established itself on Surtsey as it has been growing there since 1973. The plants have, however, not increased in number although they have annually flowered and set seed. Most of the time only one or two patches have been found growing there.

In 1987 two patches were found south of the Hole in quadrat J-6. Plants were flowering at both sites. One had 20 flowers while a smaller patch, further to the north, had 8 flowers. A patch 20×30 cm large and flowering was also found south of the new hut in 1984. The main patch is, however, in quadrat M-12 on a cinder surface. It has covered an area of 50×50 cm and has been flowering annually. In 1990 it covered only an area of 12×10 cm with eight stolons and had only one panicle. Although these fescue plants have borne seeds no seedlings have ever been found in the neighbourhood of the parent plants.

Honkenya peploides (L.) Ehrh.:

Of all the plant species found on Surtsey *Honkenya* is of special importance in forming a vegetation cover. It was the third species to be discovered and was found in 1967 the fourth summer after the birth of the island. Ever since it has been growing on the island and spreading out in its new habitat.

During the first five years the population of this species on Surtsey was dependent on seed dispersal from outside the island. Annually some 20 to 30 new seedlings started growth and the death rate of individuals was 20 to 50%. Most of the losses were due to ocean flooding or the drifting sand that submerged the seedlings during the first winter. Already in the second summer the plants may form a patch 30×30 cm in area and they continue to spread out by runners forming flat mats up to 200×200 cm wide. It took the first plants up to six years to set seed on Surtsey. One out of five flowering plants had female flowers and produced seed in 1971. Of the seeds formed, approximately 1–2% may have germinated and produced successful seedlings. After seed setting started on the island there was a rapid increase in the plant population. The plants produce a large amount of seed. In 1976 a plant was estimated to have 1,000 pods, and in 1985 plant No 76-135 was measured 1.30×1.00 m in area and found to produce about 5,000 fruits, each containing ten seeds. So that this one plant could have given approximately 50,000 seeds. Thus with a 1% seed survival a single plant could produce 500 new seedlings the following spring and with a 50% death rate, the first winter the increase per year could be 250-fold for the largest fertile plants in the population. In reality the growth rate was, to start with, somewhat slower. When the second generation of plants started to produce seed in 1977 after another period of six years there was an even more rapid increase of new individuals. During the following years the population doubled annually in numbers for some time.

With the increase in population the *Honkenya* plants occupied ever new quadrats annually and spread especially out into the sand-filled lava in the south and south-western part of the island following the drifting of sand towards that area. With every year that passed there was an increase both in number of plants and in the size of individual patches. It takes a plant up to seven years to form a patch 1.3×1.0 m in area. Most of the patches do not become larger although one 12-year-old plant in 1983 measured 2.5×2 m or around 5 m^2 in area. The branches of the patches can become 25 cm tall and as the sand may drift in towards their centre a small mound may be formed up to 40 cm high. Sometimes the centre of the plant may be suffocated and a green ring is formed with a sand depression in the middle. The particular size of the plants may be governed by the water and nutrient available for the roots of individual plants that are competing in the habitat.

In 1982 the number of plants and coverage was estimated in fixed transects and in quadrats. In the best developed areas on the eastern part of the island and in a depression in quadrats M-9 and N-10 which with optimism could be named "Grænalág" (the green depression), the coverage was on the average 1 to 1.5% with one plant per square metre. In 1984 the measurements gave around 3% cover in these areas and in 1987 this had increased to 8.5% cover. In 1990 the measurements in three transects from the eastern shore towards the hut showed the cover was 5.2%, 9.2% and 11.6% or around 8.7% in the best-developed areas. It was estimated on the whole that the vegetated area on Surtsey did not cover more than 1%. However, in one sheltered depression "Tröð" south of the hut in an area 10×10 m the cover could be estimated as 60%.

The *Honkenya* can definitely be called the leading colonist of the vascular plants on Surtsey. It now grows in 59 of the marked quadrats, which amounts to 43% of the quadrats on the lava and 29% of the total quadrats on Surtsey.

Juncus arcticus ssp. *intermedius* Willd:

In 1975 a young plant of this arctic rush was discovered on Surtsey and in the summer of 1990 one specimen was found there again. This time it was growing on a flat strip of sand in the lava flow near the bird-breeding area "Mávaból" in quadrat Q-13. That single plant was young and not flowering.

Luzula multiflora (Retz) Lej.:

A single plant of this common woodrush was first found in Surtsey during the summer of 1990. Like the former species it also grew near the gull breeding place "Mávaból". Only a few blades were sticking up through the cinder on the lava surface and no flowers had yet been formed.

Mertensia maritima (L.) S. Gray:

This coastal species was among the first four to take root on Surtsey and has also been one of the most common plants, with a population of up to 1,000 individuals in 1990. The first plants were found growing on the eastern side of the lava, where they may have started from sea-borne seed washed up on the eastern shore in quadrat I-18. The colony has spread from there farther up the lava flow towards the west and the plants are now most common in quadrats K, L and M-15 to -17. The colony is particularly dense in quadrat K-17 where 30 plants were found growing in 1985 on an area 10×10 m in flat, sand-covered lava called "Liljuflöt". These have developed further. The large plants measured 30×30 cm in 1987 and have spread out so that three plants growing close together covered an area of 100×180 cm in 1990. Many of the plants are flowering but they are not good seed producers.

Poa annua L.:
This common, annual grass has been found on Surtsey since 1987 when a small mat of 34 plants was found covering a flat surface of aa lava in O-11. At the same spot there were 18 individuals the following year. By 1990 the mat of grass had extended slightly and consisted of some 60 individuals. Plants of this species were also found the same summer growing in the fertile patch of R-14. This place is frequented by sea gulls which have probably brought seed of this species to the island.

Poa pratensis L.:
A few plants of this common grass species have been found growing on the island mostly since 1986 when one plant was discovered in quadrat N-13, growing in the nest of a black backed gull. The following year two plants were found in the Lava crater with six and three panicles respectively and in 1990 five individuals were recorded, one of them being close to the *Rumex* spot in N-11. The seed of this grass has probably been brought to Surtsey by gulls and possibly a raven.

Puccinellia retroflexa (Curt.) Holmb.:
Since 1972 this grass species has been found growing on Surtsey and has been slowly increasing in numbers, mainly for the past four years. The species has established itself at four locations and has achieved the best development in the Lava crater, quadrat I-8 and especially on a flat shield of lava covered with sand in a fertile spot at quadrat R-14.
The plant grew from seeds that probably

Fig. 3. The flat *Sagina* patch with a *Poa* plant left and ropy lava in fore-ground, 1990.

were brought by birds to these spots up on the island.

Rumex acetosella L.:
A few plants of this species had first been observed growing on Surtsey in 1978, when they were occupying a flat surface on the lava in quadrat N-11. In 1980 the colony was still developing with 40 plants on an area of 2 m^2. During the following years there was a gradual increase in the number of plants and in the size of the colony. In 1990 the plants had spread out further so they were then growing in an area of 3×5 m with a few hundred individuals. The plants were occupying the sandy substrate between three patches of *Honkenya* and in some instances the patches of these two species were overlapping. These *Rumex* plants were spreading by stolons, but they were also annually producing a number of seeds. Three metres away from this colony towards the west were 25 seedlings starting a new cluster. However, during the twelve years that the *Rumex* has been growing on the island the species has only been found on this one spot. And although seeds have been formed locally they have not spread out to invade new habitats on the island.

Sagina procumbens L.:
This small, creeping perennial, which had earlier been identified as *S. saginoides* (L.) Karst., had formed a mat of 150 plants on a surface of aa lava in quadrat R-14. This flat lava surface can hold some water following rain and the vegetation there can remain moist for a length of time. The substrate of barren lava is becoming quite fertile by the

TABLE 2

Species and total number of vascular plants recorded on Surtsey during the years 1965–1990.

Species	'65	'66	'67	'68	'69	'70	'71	'72	'73	'74	'75	'76	'77	'78	'79	'80	'81	'82	'83	'84	'85	'86	'87	'88	'90
Cakile arctica	23	1	22	..	2	..	..	1	33	3	5	..	1	0	1	1	..	..	..	..	..	..	3	..	..
Elymus arenarius	..	4	4	6	5	4	3	..	66	26	12	10	8	14	5	5	2	2	15	34	50	200	500	1000	2000
Honkenya peploides		..	24	103	52	63	52	71	548	857	428	500	632	3080	24000	50000	100000	∞	∞	∞	∞	∞	∞	∞	∞
Mertensia maritima		..	1	4	..	..	..	15	25	44	11	6	8	9	8	7	12	24	39	58	100	120	200	400	1000
Cochlearia officinalis		..	..	..	4	30	21	98	586	372	863	501	286	160	91	75	14	3	26	12	4	3	100	25	100
Stellaria media	..	..	..	..	..	4	2	2	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	2	20
Cystopteris fragilis		..	..	..	..	..	3	4	3	3	2	2	2	9	5	5	3	2	1	1	..	..	1	1	5
Angelica archangelica		..	..	..	..	..	..	2	2	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Carex maritima	..	..	..	..	..	..	..	1	1	1	3	2	1	5	2	1	1	2	1	1	1	4	2	2	2
Puccinellia retroflexa		..	..	..	..	..	..	2	1	9	8	8	2	6	40	7	2	2	2	2	2	2	85	30	100
Tripleurospermum maritimum		..	..	..	..	..	..	1	5	2	2	2	1	4	1	1	1	1	1	1	1	1	..	3	6
Festuca rubra	..	..	..	..	..	..	..	..	1	1	2	1	1	5	3	3	1	1	1	1	1	1	2	2	2
Cerastium fontanum		..	..	..	..	..	..	..	..	..	106	99	19	6	97	150	120	100	75	20	20	34	25	29	53
Equisetum arvense		..	..	..	..	..	..	..	..	..	2	..	..	..	..	..	..	..	..	..	..	..	..	..	14
Silene vulgaris	..	..	..	..	..	..	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Juncus arcticus	..	..	..	..	..	..	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	..	..	1
Atriplex patula (?)		..	..	..	..	..	..	..	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	..
Rumex acetosella	..	..	..	..	..	..	..	..	..	..	..	..	..	124	31	40	30	27	28	31	50	80	400	500	800
Cardaminopsis petraea		..	..	..	..	..	..	..	..	..	..	..	..	5	6	8	..	..	..	..	..	..	20	25	25
Poa pratensis	..	..	..	..	..	..	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	1	2	3	5
Sagina procumbens		..	..	..	..	..	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	150	700	1000	5000
Armeria maritima		..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	1	1	1	2
Poa annua	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	36	15	60
Agrostis stolonifera		..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	1	1	3
Alchemilla filicaulis		..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	1
Epilobium palustre		..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	1
Capsella bursa-pastoris		..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	1
Luzula multiflora		..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	1
Unidentified plants		..	..	1	..	..	4	2	1	1	2	1	..	1	..	..	..	..	..	..	..	..	..	..	..
Total	23	5	51	114	63	101	85	199	1273	1319	1449	1132	962	3428	24000	50000	∞	∞	∞	∞	∞	∞	∞	∞	∞

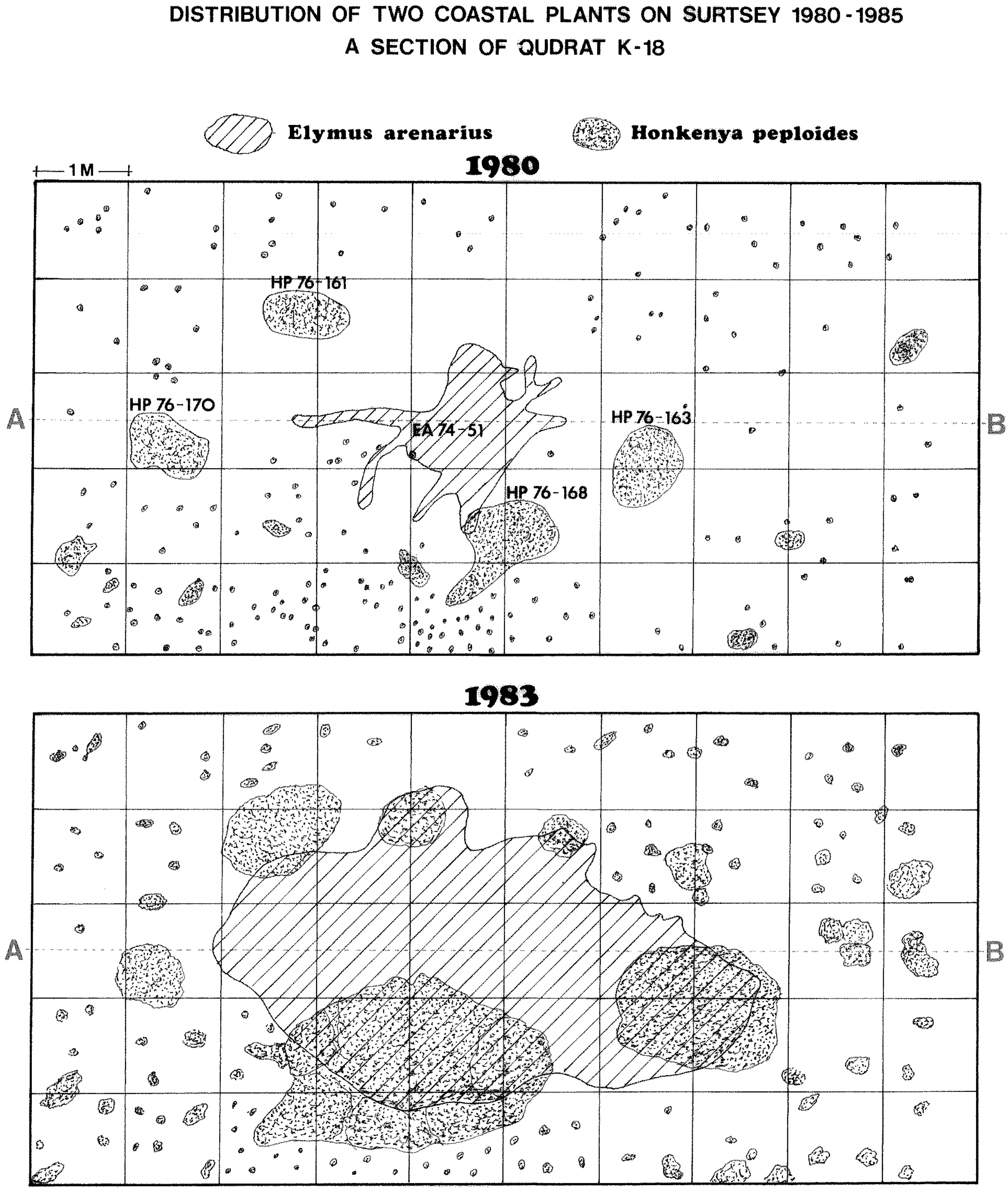
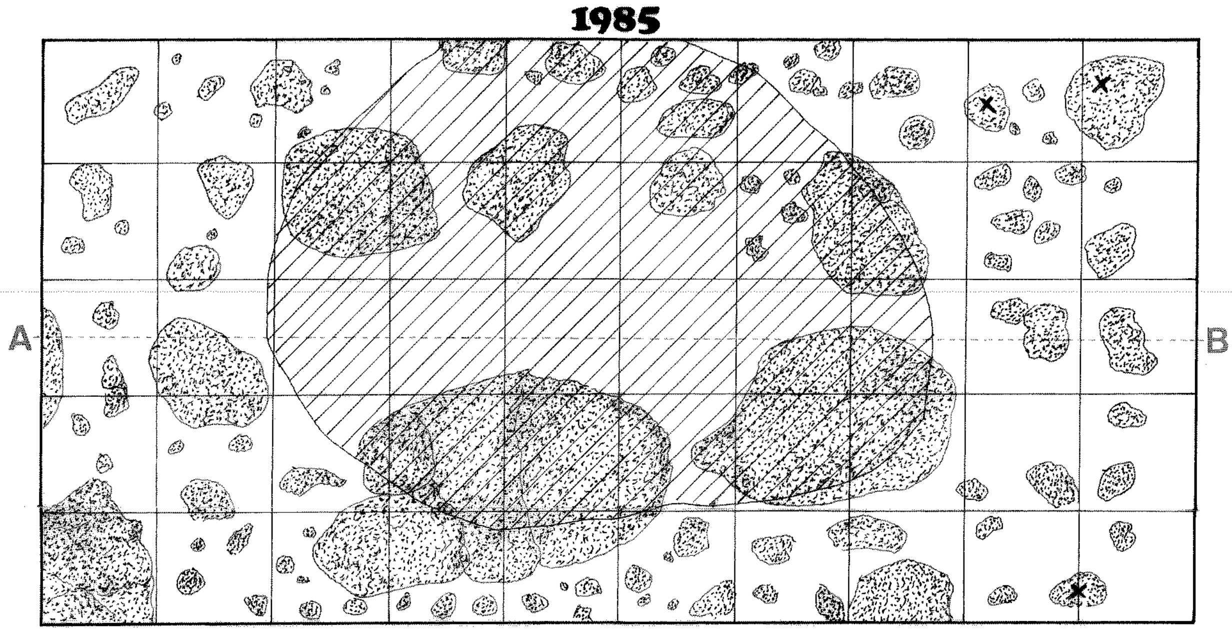
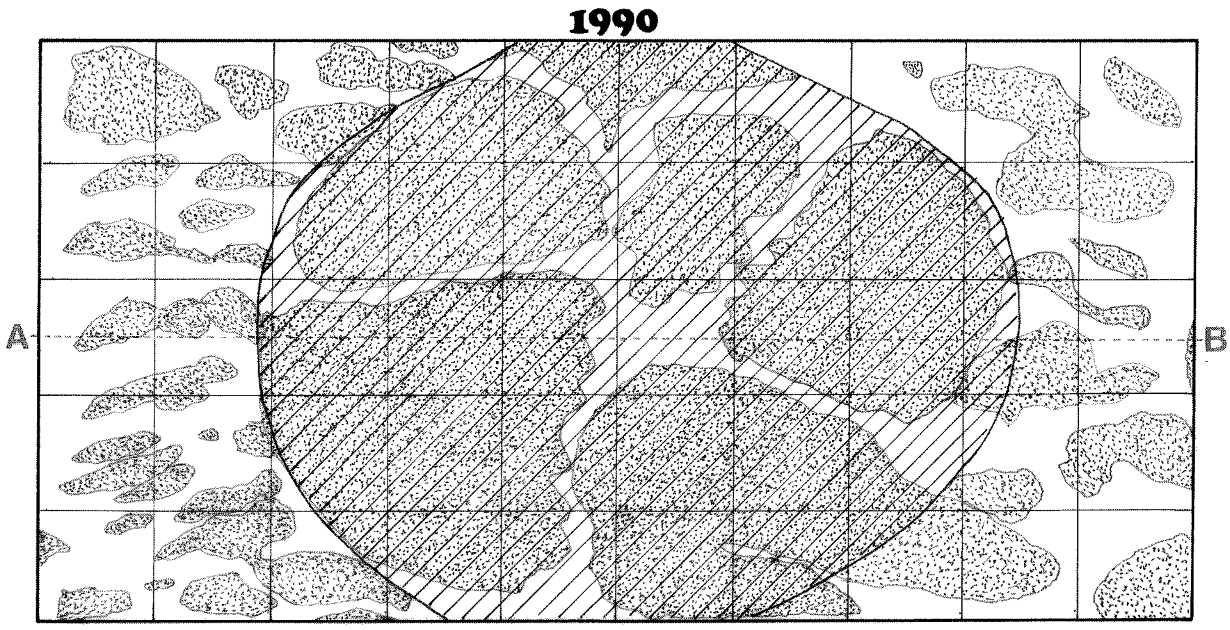


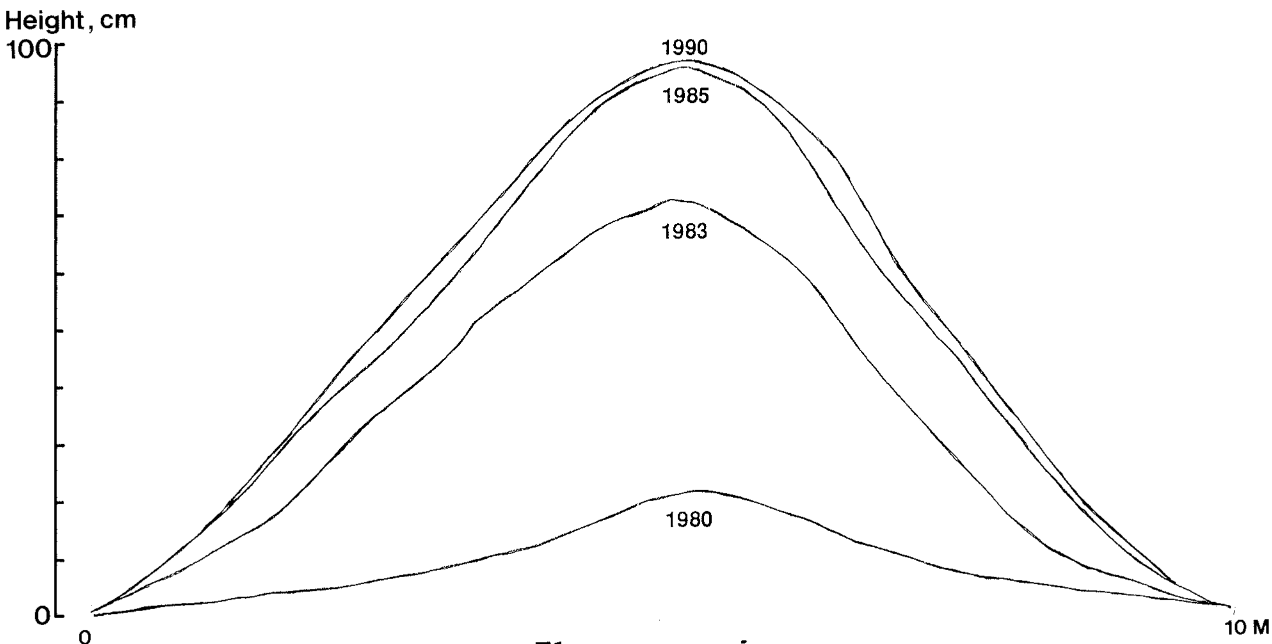
Fig. 4. Charts showing the development of a costal dune of *Elymus – Honkenya* association.





TRANSECT THROUGH DUNE A-B ON SURTSEY

1980 - 1990



Elymus arenarius

bird droppings as the spot is in the gulls' breeding area "Mávaból". There are even two nests of herring gulls just west of this colony and thus the plants are frequently fertilized. Both *Cerastium* and *Puccinellia* plants also grow in this habitat, to which their seed has probably been transported by birds. The vegetation there has achieved up to 100% cover in places and the area which extends over 200 m^2, has on the average 70% cover (Fig. 3).

Stellaria media (L.) Vill.:

This Common Chickweed has been growing on Surtsey since 1988. In 1990 a large plant and up to 19 seedlings were found in the gull-breeding area. This older plant apparently grew from seed brought by the seagulls and enjoyed the fertile sand close to the herring gull's nests.

Tripleurospermum maritimum (L.) Koch:

One plant of this species was discovered in the Lava crater as early as 1972. Since then a few plants have occupied the sand deposited on the crater floor. In 1990 three new plants were found growing at the gull-breeding place on the southern part of the lava. These plants were flourishing in the highly fertile soil there and one of them bore 110 heads. Thus a number of seeds are now being formed locally.

ASSOCIATIONS

In a previous report (Fridriksson, 1982a) a description was given of the first formation of a beach association and a sand dune. Two of the most common species of vascular plants on Surtsey were growing there together, having their territories overlapped. A close investigation was made of the formation of the sand dune and this has continued in the present study period. A section 5×10 m of the sandy area grown with this vegetation has been measured and mapped annually (Fig. 4). This was the first association of vascular plants being formed on Surtsey. The *Honkenya* holds the ground stratum where it enjoys the shelter and can make use of the sunlight in early spring and autumn. Leaves and stalks of the *Elymus* tower over the sward and receive most of the light in the middle of summer. The sward has been built up by the *Honkenya*, thus the soil's top-layer does not dry up as easily as on the black, open sand. The dune is a good example of how species twine together by vegetative growth when occupying the same habitat and thus consolidate into a consociation. These two species also form an association by a somewhat different mechanism.

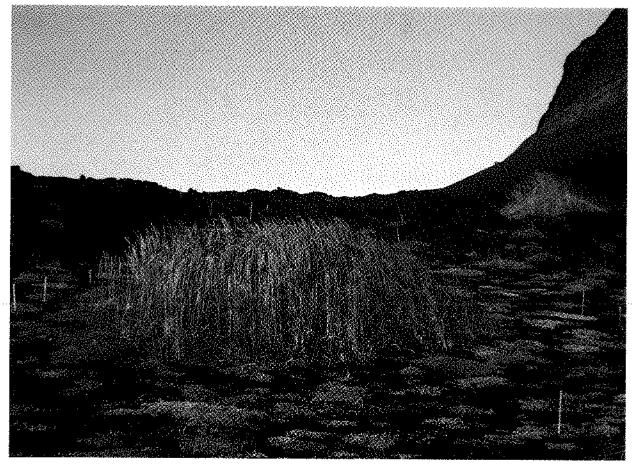


Fig. 5. The *Elymus* plants associated with *Honkenya* in 1990.

In the neighbourhood of the large *Elymus* hill a number of *Honkenya* patches had been established. It was then noticed in 1983 that in the centre of some of these patches a young *Elymus* plant was developing.

The large *Elymus* plant had matured seed the year before and the seeds were distributed in the vicinity. Some were blown away by winter storms; they had fallen into the ocean or on the solid lava, others had been buried too deep in sand or withered on its dry surface and had not succeeded in developing into new seedlings. The Lyme grass seeds that landed in a *Honkenya* patch in contrast encountered more favourable conditions. Such seeds were not buried too deep in sand for successful germination, but they received an even supply of moisture and were better sheltered than on the open sand. This special microhabitat had obviously been favourable for the sprouting of *Elymus* seeds since in the spring of 1983 seedlings of twenty Lyme grass plants were found in the centre of the same number of *Honkenya* patches whereas no new seedlings had developed in the open sand around these patches. The following year in the summer of 1984 this tendency had increased and *Elymus* seedlings were found in patches of *Honkenya* growing at a distance of 350 m from the seed-bearing Lyme grass plant. A total of 100 association patches were thus found that year and twenty more even farther away. In 1986 there were 166 such patches. It is thus possible in this case to look at the *Elymus* as a secondary invader to the primary establishment of the *Honkenya*

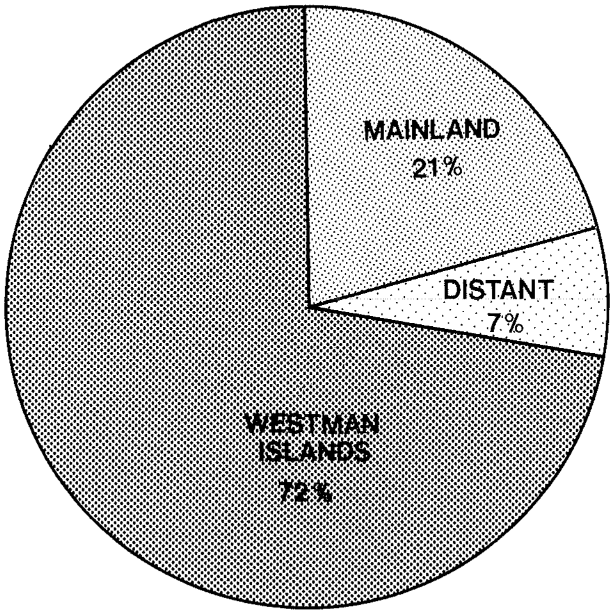


Fig. 6. Source of diaspores found on Surtsey.

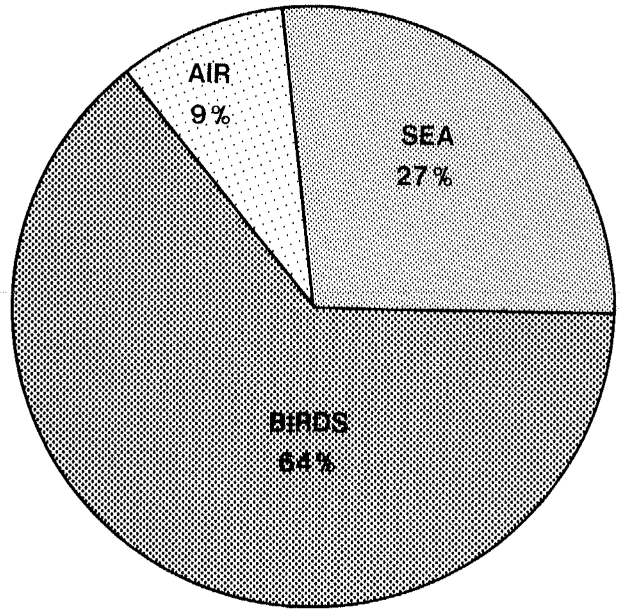


Fig. 7. Likely dispersal routes of vascular plants species found on Surtsey.

pioneer. In addition to the coexistence of these two species in this area *Mertensia* joins them in some places as it also enjoys the same habitat. These three species now form a coastal association on Surtsey (Fig. 5).

Sagina – Poa – Puccinellia

On the fairly smooth surface of the ropy aa lava on the southern part of the island in quadrat R-14 a colony of the low-growing *Sagina procumbens* plants had been developing since 1986. These plants have been fertilized heavily by the herring gull that breeds in the area. This same habitat is also occupied by the three grass species *Poa annua, Poa pratensis* and *Puccinellia*. This form of association is found on cliffs and bird-breeding grounds by the ocean or even around human dwellings in Iceland. This association will probably become still more common on the flat lava of Surtsey in the future.

The soil of this special habitat has become quite fertile with 60 mg N and 7 mg K per 100 ml of dry matter and 2.9 mg P in 100 ml of dry soil and a rather high acidity of pH 5.3.

DISPERSAL

As the flora of vascular plants on the various members of the Westman Islands is known, it is possible to show the shortest distance for a diaspore to be dispersed in order to reach Surtsey.

The number of potential species to be dispersed is 4 from the nearest rock of Geirfuglasker (5.1 km) and 7 from Súlnasker (11 km). All these species are at present also found on Surtsey. In Fig. 6 it is demonstrated from what sources the plants on Surtsey may have derived. It is obvious that most of the diaspores have come from the nearby Westman Islands, although there have been instances of transportation from the mainland or over greater distances. From various circumstances and from the locations of the new colonists it has also been possible to guess in what way the diaspore may have been transported, whether by sea, air or birds. This is shown on the diagram in Fig. 7 where it is indicated that in most instances birds have been involved in the transport.

THE COLONIZATION

Only the most hardy pioneer species have been able to establish themselves in the immature ecosystem of Surtsey. The vascular species recorded on the island in 1980 were 13 and in 1990 they had increased to 25 (Table 2). Thus there had been an introduction of almost one new plant for every year that has passed since the island was formed.

It is obvious that birds have played a great part in this colonization. Under normal circumstances the establishment of plants on a newly formed inland-lava is a slow process. On Surtsey, however, conditions are different due to the proximity of the ocean and the presence of the numerous sea-birds which both transport plant material and fertilize the substrate.

The diaspores that happen to be dispersed annually to the island were few of any one species and as the casuality rate may be high, only rarely does an arriver establish a new colonist. The species that so far have dispersed to Surtsey do not necessarily represent the best pioneers, others may only have lacked the opportunity of being transported, thus there is often a certain amount of chance involved as to what species becomes established.

Although 25 species form the present members of the vascular flora of Surtsey, the total cumulative number of species that have been found growing there is 28. Thus three species have come and gone. Still other diaspores have been found which have not developed into plants and others may have gone unobserved by our inspection. This is still a small sample or only 6% of the vascular species of Iceland.

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Observations on Seals on Surtsey in the Period 1980–1989

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ABSTRACT

In this paper are presented records of sightings of seals in Surtsey from 1980 to 1989. Seals in Surtsey have been counted regularly, as part of a bigger project of aerial censusing of seals around the coast of Iceland (Erlingur Hauksson 1985 and 1986).

Earlier accounts of seals in Surtsey are rather sporadic and only based on occasional observations. Some of them are mentioned, but many may have been omitted which the author has not been aware of, since observers of seals in Surtsey have not published their records.

INTRODUCTION

The author's first seal observation on Surtsey was in the late summer of 1972, while diving to collect subtidal algae and benthic invertebrates for scientists investigating the colonization of these on the hard substrata bottom. The sighting was of a common seal (*Phoca vitulina L.*) which were quite common at that time.

The author's first sighting of a grey seal (*Halichoerus grypus* Fabricius) on Surtsey, was in 1982 when he was counting grey seal pups in breeding places, from an aircraft, on the coast of Iceland (Hauksson 1985). This is, however hardly the first time grey seals have been observed in Surtsey although there are no written records of other sightings.

Seals, in general, started visiting the island frequently soon after its formation (Fridriksson 1975). It is therefore likely that some grey seals have been around at that time.

Fig. 1. Grey seal pups on the northern sandy spit of the island of Surtsey. The picture is taken by the author from an aircraft on October 19th 1986.

OBSERVATIONS ON SEALS IN 1980 TO 1989

Common seals on the south coast of Iceland have been counted from aircraft in the years 1980, 1985, 1988 and 1989. On most occasions commons seals have been observed in the sea

TABLE 1
Number of common seals (*Phoca vitulina* L.) observed on Surtsey in aerial census, and from a research vessel, 1980 to 1989

Date	Time	Number	Further information
11/08/1980	13.41	20	
22/07/1985	14.45	0	
11/07/1987	–	4	Seen from a research-vessel
11/07/1988	–	0	
21/11/1988	11.30	≈30	All adults
09/05/1989	17.45	0	
22/06/1989	15.30	0	
21/09/1989	17.00	1	

TABLE 2
Number of grey seals (*Halichoerus grypus* Fabricius) observed in aerial census, on Surtsey

Date	Time	Number	Further information
08/10/1982	15.45	0	
19/10/1986	13.14	50	34 pups in lair and 16 adults in the sea (Fig. 1).
16/07/1987	17.11	6	Two adult males and 4 females in the sea.
11/07/1988	12.25	0	
09/10/1988	10.25	2	1 pup in lair 1 adult in the sea.
21/11/1988	11.30	26	15 pups in lair and 11 adults in the sea.
09/05/1989	17.45	0	
22/06/1989	15.30	0	
21/09/1989	17.00	0	
25/10/1989	11.05	4	3 pups in lair and 1 adult female basking on land.
21/11/1989	10.55	35	All pups basking on land, but not all totally white.
13/12/1989	12.00	73	3 white pups and about 70 grown ups basking on land.

around Surtsey or basking on the island's northern spit (Table 1).

Grey seal pups at breeding places on the south coast of Iceland, have been counted from aircraft in the years 1982, 1985, 1986, 1988 and 1989. Grey seal pups have mostly been seen on the northern spit of the island (Table 2).

DISCUSSION

From these observations on seals at Surtsey, it can be deducted that common seals and grey seals have already several years ago started breeding on the island, as well as using it as basking site. They have probably used the sandy northers spit, as a basking site much earlier than they started to breed on it. Fishermen from the isles of Vestmannaeyjar, have noticed seals there regularly, often in great numbers, during the winter-time for many years.

Surtsey is in many respects a good breeding place for seals. The animals there are hardly ever disturbed. Visitors to the island are very few and come to the island mostly in the summertime. The sandy northern spit is low and beaching is easy for the animals, even in windy weather. Close to the island are good fishing grounds for seals. In the summer there is an abundance of saithe, cod and herring just off the cliffs. All year around flatfishes and sea scorpions can be found there to eat.

If the seals in Surtsey continue to get the same protection in years to come, as they have had to date, then a strong breeding stock of grey seals will probably evolve as well as also a sizable herd of common seals. Grey seals are however known to disturb the settlement of common seals. This could happen in Surtsey, so that the island could become a sanctuary for grey seals, as many inhabitable offshore islands and skerries around the coast of Iceland already are.

Common seals are breeding on the nearby shore of the southern part of the mainland of Iceland, in great numbers. However the closest large breeding place for grey seals is on the sandy shores of Öræfi, several hundred km to the northeast, with a small breeding place on Skógarsandur, which is much closer to Surtsey. The grey seal herd in Surtsey has probably been recruited from these herds.

ACKNOWLEDGEMENT

I would like to thank the pilots of the taxi-flight Company Sudurflug hf., especially Einar Gudmundsson, which have skilfully and safely taken the author on several trips over Iceland's most southerly island, Surtsey.

The aerial-census programme for counting seals on the coast of Iceland, on which the results of this paper are based, is sponsored by the Research Committee for Biological Seafood Quality.

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Studies of the Subtidal Fauna of Surtsey in 1980 to 1987 and Changes in Subtidal Fauna from 1964 to 1987

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ABSTRACT

This paper deals with results of faunistic investigations of the subtidal around Surtsey, Vestmannaeyjar, South-Iceland, in 1980 to 1987. Results of species occurrences and faunistic changes are discussed from the time of formation of the island to the present (1987).

INTRODUCTION

After the formation of the new volcanic island, which was given the name Surtsey, in 1963, a unique opportunity was presented for investigating the settlement and succession of the fauna and flora assemblages on this new "land". Such opportunities are rather rare in nature.

The formation of the island makes it possible to study the colonization of algae and animals of the bare rock and formation of subtidal algal forests, which are very common around Iceland dominating the hard substrate of Iceland's sublittoral, which provide shelter and feeding-grounds for the young fish of some of the most important commercial species.

Since the formation of this new underwater "land" marine biologists have been following its colonization by marine flora and fauna. This paper deals with results of faunistic surveys carried out by divers in 1980, 1983, 1984 and 1987. Results of these are discussed in comparison with earlier surveys, to get an idea of how colonization of benthic species has propagated, and how the fauna has evolved with time.

MATERIAL AND METHODS

Sampling

Sampling of subtidal animals was commenced shortly after the eruption and formation of the island in 1963, and has continued to the present (1987). Methods of sampling underwater are described in earlier papers of Sigurdsson (1965, 1968, 1970, 1972, 1974a and 1982) and Hauksson (1982). Underwater sampling in the years 1980, 1983, 1984 and 1987, was performed in a similar manner as earlier, and on the main transects and depths, as far as permitted by limited research-vessel time and bad weather conditions for diving. Results of the surveys in 1980, 1983, 1984 and 1987 are presented in Tables 1 to 4.

Analysis of data

As the main emphasis of the diving work is a faunistic survey only qualitative data is collected. However the same depths and to some degree the same transects are revisited every collecting year, so some information about the distribution of species in respect to depths and subtidal areas of Surtsey is obtained.

Not all animal groups are included in this paper, because they are not yet totally assessed, and are the responsibility of other marine scientists participating in the Surtsey project. Those groups omitted are Amphipoda, Polychaeta, Hydrozoa and Bryozoa and will be treated later.

TABLE 1

Occurrences of species of marine benthic animals on the coast of Surtsey in 1980, in relation to transects and depth

Transects	West coast							East coast					South coast			Southwest coast		
Depth (m)	5	10	15	20	25	30	40	5	10	15	20	30	15	20	30	10	15	25
COELENTERATA:																		
Alcyonium digitatum L.	..	..	x	..	..	x	..	..	..	x	..	x	..	x	x	..	..	..
PROSOBRANCHIA:																		
Margarites groenlandicus (Chemn.)	..	..	..	x	..	x	x	..	..	x	..	..	..	..	..	..	..	x
Nassa incrassata (Ström.)	..	..	..	..	..	x	x	..	..	x	x	x	..	..	x	..	..	..
Onoba striata (Mont.)	..	..	..	x	..	x	..	..	..	..	..	..	..	..	..	..	..	..
Velutina velutina (Möller)	..	..	..	x*	..	x	..	..	..	..	..	..	..	..	..	..	..	..
Gibbula tumida (Mont.)	..	..	..	..	..	x	x	..	..	..	..	..	..	..	x	..	..	..
Skeneopsis planorbis (Fabr.)	..	..	..	x	..	..	x	..	..	..	..	..	..	..	..	..	..	..
Odostomia unidentata (Mont.)	..	..	..	..	..	..	x	..	..	..	..	..	..	..	..	..	..	..
Lacuna divaricata (Fabr.)	x	x	x	x	..	..	..	..	x	..	..	..	x	..	..	..	..	..
NUDIBRANCHIATA:																		
Adlaria proxima (Adler&Hancock)	..	..	..	..	..	..	..	..	x	..	..	..	..	x	..	x	..	..
Doto coronata (Gmelin)	..	..	..	..	..	..	..	..	..	x	..	x+	..	..	..	x	..	..
Dendronotus frondosus (Ascanius)	..	..	..	..	..	..	..	x	..	..	..	..	..	..	..	..	..	x
LAMELLIBRANCHIATA:																		
Heteranomia squamula (L.)	..	..	..	x	..	x	..	..	..	x	..	x	..	..	x	..	..	x
Hiatella arctica (L.)	x	x	x	x	x	x	x	x	x	x	..	x	x	x	x	x	x	x
Chlamys pusio (L.)	..	..	..	..	..	x	..	..	..	..	..	x	x	..	..	..	..	x
Modiola phaseolina (Phil.)	..	..	..	x	x	x	x	..	..	..	..	..	..	..	..	..	..	..
Mytilus edulis (L.)	x	x	x	x	x	x	x	x	x	x	..	x	x	x	x	x	x	x
CIRRIPEDIA:																		
Balanus balanus (L.)	x	..	x	x	..	x	x	x	x	x	..	x	..	x	x	..	..	x
Balanus hammeri (L.)	..	..	..	..	..	..	..	..	..	..	..	..	..	..	x	..	..	..
Verruca stroemia (O.Fr. Müller)	..	..	x	x	x	x	..	..	..	x	..	x	..	..	..	..	..	x
ISOPODA:																		
Munna kröyeri Goodsir	..	..	..	x	..	x	..	..	..	x	..	x	..	..	..	..	..	..
Janiropsis breviremis Sars	..	..	..	..	..	..	..	x	..	..	..	..	x	x	..	..	..	..
DECAPODA:																		
Galathea nexa Embleton	..	..	..	x	x	x	x	..	..	..	..	..	..	..	x	..	..	x
Hyas coarctatus Leach	..	x	x	x	..	x	x	..	..	x	..	x	..	..	x	..	x	..
Eualus pusiola (Kröyer)	..	..	..	x	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Eupagurus bernhardus L.	..	..	..	..	..	x	..	x	..	x	..	..	..	..	..	..	..	..
PYCNOGONIDA:																		
Chaetonymphon hirtum (Kröyer)	..	..	..	..	..	x	..	..	..	..	..	..	..	..	..	..	..	..
ASTERIOIDEA:																		
Asterias rubens L.	..	x	x	x	..	x	x	x	x	x	..	x	..	x	x	x	x	x
OPHIUROIDEA:																		
Ophiopholis acuelata (O. Fr. Müller)	..	..	x	..	..	..	x	..	x	x	..	x	..	..	..	..	..	..
ECHINOIDEA:																		
Echinus esculentus L.	..	..	x	x	x	..	x	..	..	..	..	..	..	..	..	..	..	..
Strongylocentrotus droebachiensis (O.Fr. Müller)	..	..	..	..	..	..	..	..	..	..	..	x	..	x	..	..	..	..
ASCIDIACEA:																		
Styela rustica L.	..	..	x	..	..	..	..	x	..	..	..	..	..	..	x	..	..	..
Halocynthia pyriformis (Rathke)	..	..	..	..	x	..	..	..	..	..	..	..	x	..	x	..	..	..
PISCES:																		
Cyclopterus lumpus L.	..	..	x	..	..	..	..	..	..	..	..	x	..	..	..	..	..	..

* eggcapsule
\+ juvenile

RESULTS

Occurrences of benthic species

Coelenterata

The dahlia anemone, *Tealia felina* L., was found for the first time in 1987, on the east, south and west coast at 20 to 30 meters. It has however most probably colonised earlier than that, but without being noticed.

The Stauromedusae *Haliclystus octoradiatus* (Rathke), was found for the first time in 1983,

TABLE 2
Occurrences of species of marine benthic animals on the coast of Surtsey in 1983, in relation to transects and depth

Transects	East coast						West coast
Depth (m)	5	10	15	20	30		30
COELENTERATA:							
Haliclystus octoradiatus (Rathke)	..	x	..	..	..	..	..
Alcyonium digitatum L.	..	..	x	x	..	..	..
PROSOBRANCHIA:							
Margarites groenlandicus (Chemn.)	x	..	x	..	..	..	..
Nassa incrassata (Ström.)	x	..	x	x	..	..	..
Lacuna divaricata (Fabr.)	x	x	x	x	..	..	..
NUDIBRANCHIATA:							
Adlaria proxima (Alder & Hancock)	..	x	..	..	..	..	..
Doto coronata (Gmelin)	..	..	x	..	..	..	x
Dendronotus frondosus (Ascanius)	..	x	..	..	..	..	..
Aeolidia papilosa (L.)	x	..	..	..	..	..	..
LAMELLIBRANCHIATA:							
Heteranomia squamula (L.)	..	..	..	x	..	..	..
Hiatella arctica (L.)	x	x	x	x	..	..	x
Chlamys pusio (da Costa)	..	..	..	x	..	..	..
Mytilus edulis (L.)	x	x	x	x	..	..	..
CIRRIPEDIA:							
Balanus Balanus (L.)	..	x	x	x	..	..	x
Verruca stroemia (O.Fr. Müller)	..	..	x	x	..	..	..
ISOPODA:							
Munna kröyeri Goodsir	..	..	..	x	..	..	..
DECAPODA:							
Hyas coarctatus Leach	..	x	x	x	..	..	..
ASTERIOIDEA:							
Asterias rubens L.	..	x	x	x	..	..	..
OPHIUROIDEA:							
Ophiopholis acuelata (O.Fr. Müller)	x	..	x	x	..	..	..
ASCIDIACEA:							
Styela rustica L.	..	..	x	x	..	..	..
Halocynthia pyriformis (Rathke)	..	..	x	x	..	..	..

at 10 meters depth on the east coast. It was found on algae.

Alcyonium digitatum L., is the only octocoral occurring at Surtsey. It was found first in the year 1969, four years after the formation of the island and has been found on every sampling occasion since then. *A. digitatum* is now widely distributed around the island, except on the south coast. It is very dominant at depths of more than 20 meters, but may also occur in water as shallow as 15 meters. Its most likely path of dispersal to the shallow grounds around Surtsey, is from below, from the original surrounding bottom, which the eruption did not disturb.

Prosobranchia

Buccinum undatum L., was first found in 1974 and also in 1977, but has not been found later than that. It occurred at one station on the west coast at 10–18 meters depth. It must therefore be rather rare on Surtsey. Its dispersal to the island is probably hindered by its method of propagating which is by laying egg-capsules, but not having pelagic larvae. *B. undatum* seems much less common on Surtsey, than on the southwest coast of Iceland, where it is a very common and conspicuous conch in the lower littoral and sublittoral zone.

Margarites groenlandicus (Chemn.), was first found in 1977, and has been appearing in the samples since then. It is mainly found at depths of 15 to 30 meters and does not inhabit the most shallow water. It is very common in the littoral and upper sublittoral zone on the southwest coast of Iceland. The late arrival of *M. groenlandicus* to Surtsey may due to it not having pelagic larve.

Margarites olivaceus (Brown), was first found in 1984 and then again in 1987, on the east, west and southeast coast, at depths of from 10 to 30 meters. It seems therefore to be a recent inhabitant on the coast of the island.

Margarites helicinus (Fabr.), was first found in 1987, at the east, south and west coast and seems to be a new inhabitant of Surtsey. As *M. olivaceus* it is quite common on the coast of Iceland so it does not come as a surprise that it has colonised the sublittoral hard rock of the Surtsey.

Nassa incrassata (Ström.), occurred first in the samples taken by divers in 1977 and has appeared in samples since then. It has been found at 30–40 meters depth on the west and east coast, but not at the south coast. In Iceland this whelk only occurs on the southern shores and in shallow waters.

Onoba striata (Mont.), is a small and inconspicuous gastropod occurring at a few depths on the west coast in 1980. Its small size may explain its rarity on Surtsey. It is easily overlooked by divers collecting samples and is most often brought to the surface with other animals or algae by chance.

Velutina velutina (Möller), was found the first time in 1974 and constantly since then. It is found in the lower region of the sampling area at 25 to 30 meters depth and only on the east and west coast. It is rather uncommon at Surtsey.

TABLE 3

Occurrences of species of marine benthic animals on the coast of Surtsey in 1984, in relation to transects and depth

Transects	South east coast					West coast			North east coast				South coast		
Depth (m)	5	10	15	20	30	10	15	20	5	10	15	30	10	15	20
COELENTERATA:															
Haliclystus octoradiatus (Rathke)	..	..	..	..	..	..	..	..	x	..	..	..	..	..	..
Alcyonium digitatum L.	..	..	x	x	x	..	..	..	..	x	..	..	..	..	x
PROSOBRANCHIA:															
Margarites groenlandicus (Chemn.)	..	..	x	..	..	..	..	..	..	..	..	..	..	..	..
Margarites olivaceus (Brown)	..	..	..	x	x	..	..	..	..	..	..	..	..	..	..
Lacuna divaricata (Fabr.)	..	..	x	..	..	..	..	..	..	x	..	..	x	x	..
Acmaea testudinalis (Müller)	..	..	x	..	..	..	..	..	..	x	..	..	..	..	..
NUDIBRANCHIATA:															
Adlaria proxima (Alder & Hancock)	..	..	..	x	x	..	..	..	..	x	x	..	x	x	x
Doto coronata (Gmelin)	..	..	x	x	..	..	..	..	..	..	..	..	..	..	..
Dendronotus frondosus (Ascanius)	..	..	x	..	..	..	..	..	..	..	..	..	..	..	..
Aeolidia papilosa (L.)	..	..	..	x	x	..	..	..	..	..	..	..	..	..	..
LAMELLIBRANCHIATA:															
Heteranomia squamula (L.)	..	..	x	..	x	..	..	..	..	x	..	..	..	..	..
Hiatella arctica (L.)	x	x	x	x	x	..	x	x	..	x	..	..	..	x	x
Mytilus edulis (L.)	x	x	x	x	x	..	..	x	..	x	..	..	..	x	..
CIRRIPEDIA:															
Balanus balanus (L.)	..	x	x	x	..	..	..	..	x	x	..	..	..	x	..
ISOPODA:															
Janiropsis breviremis Sars	..	..	x	x	..	..	..	..	..	..	..	..	..	x	..
DECAPODA:															
Galathea nexa Embleton	..	..	..	..	x	..	..	..	..	..	..	..	..	..	..
Hyas coarctatus Leach	..	..	..	x	x	..	..	..	..	x	..	..	..	..	..
Eupagurus bernhardus L.	..	..	..	..	..	..	..	..	..	..	x	..	..	..	..
ASTERIODIDEA:															
Asterias rubens L.	..	x	x	x	x	..	..	..	..	x	..	x	..	..	..
OPHIUROIDEA:															
Ophiopholis acuelata (O.Fr. Müller)	..	..	..	..	x	..	..	..	..	x	..	..	..	..	x
ASCIDIACEA:															
Halocynthia pyriformis (Rathke)	..	..	..	..	x	..	..	..	..	..	..	..	..	..	..
PISCES:															
Liparis montagui (Donovan)	..	..	..	..	x	..	..	..	..	..	x	..	..	..	..

Gibbula tumida (Mont.), was first found in 1977. It is only found on the west coast at 30 to 40 meters depth.

Skeneopsis planorbis (Fabr.), was found in 1980 at the west coast, at 20 and 40 meters, but not since then, a fact surely explained by its small size since it gets easily overlooked by the collectors. This is however a very common gastropod in the littoral and sublittoral zone of Iceland and it is probably still rare on Surtsey.

Odostomia unidentata (Mont.), was found in the years 1969 to 1980 on the west coast, but not since then, which is hard to explain. This is however a rather small gastropod and could be overlooked. It was only found in deeper water (40 m) on the west coast, and this part of the island, as well as the deeper diving depths, has not been as well sampled in later years.

Lacuna divaricata (Fabr.), was found as early as 1968 and has appeared since then. This is a very common gastropod in the more shallow waters, found frequently on algae and stones. Its egg-capsules are also very conspicuous on the *Laminaria* fronds. It is widely distributed on Surtsey, and is to be found on hard surfaces more or less all around the island.

Lacuna pallidula (Say), occurred first in 1987. It is only found on the west coast, at 10–20 meters depth. It is probably a new inhabitant of the fauna and limited to the west coast, and is still rather rare.

Aporrhais pes-pelicani (L.). One juvenile was found in 1968 at 15 meters depth on the northern shores (Sigurdsson 1970), but has not been found again since then.

Acmaea testudinalis (Müller), was first found at Surtsey in 1984, at 15 meters depth on the southeast coast and 10 meters on the northeast. It was not found however in 1987, so it is probably rare on the island, because it is rath-

TABLE 4
Occurrences of species of marine benthic animals on the coast of Surtsey in 1987, in relation to transects and depth

Transects	East coast						South coast						West coast				
Depth (m)	5	10	15	20	25	30	5	10	15	20	25	30	5	10	15	20	30
COELENTERATA:																	
Tealia felina L.	..	..	..	..	..	x	..	..	..	..	..	x	..	..	..	x	x
Alcyonium digitatum L.	..	..	x	x	x	..	..	..	..	x	x	x	..	..	x	x	x
PROSOBRANCHIA:																	
Margarites groenlandicus (Chemn.)	..	..	x	x	x	x	..	..	..	x	x	..	..	..	..	x	..
Margarites olivaceus (Brown)	..	..	..	..	x	..	..	..	..	..	..	..	..	x	x	x	..
Margarites helicinus (Fabr.)	..	..	..	..	x	..	..	..	..	x	..	..	..	x	..	..	..
Nassa incrassata (Ström.)	..	..	x	x	..	x	..	..	..	..	..	..	..	..	..	..	..
Omalogyra atomeus (Phil.)	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	x	..
Lacuna pallidula (Da Costa)	..	..	..	..	..	..	..	..	..	..	..	..	..	x	x	x	..
Lacuna divaricata (Fabr.)	x	..	x	x	x	..	..	..	..	x	x	..	..	x	x	x	..
NUDIBRANCHIATA:																	
Adlaria proxima (Alder & Hancock)	..	..	..	x	..	x	..	..	..	..	x	..	..	..	x	..	..
Doto coronata (Gmelin)	x	..	x	x	..	..	..	..	..	x	x	..	..	..	..	..	..
Dendronotus frondosus (Ascanius)	..	..	..	..	..	..	..	..	..	x	..	..	..	..	..	..	..
Aeolidia papilosa (L.)	..	..	..	..	..	..	..	..	..	x	..	..	..	..	x	..	..
Eubranchus sp.	..	..	..	..	..	..	..	..	..	x	..	..	..	..	..	..	..
Catriona aurantia (Alder & Hancock)	..	..	..	..	..	x	..	..	..	..	..	..	..	..	..	..	..
LAMELLIBRANCHIATA:																	
Heteranomia squamula (L.)	..	..	x	x	x	..	..	..	x	x	x	..	..	..	..	..	..
Hiatella arctica (L.)	x	..	..	x	x	x	..	x	..	x	x	x	x	x	x	..	x
Cardium fasciatum (Mont.)	..	..	x	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Modiola phaseolina (Phil.)	..	..	..	x	..	..	..	..	..	x	..	..	..	..	..	..	..
Mytilus edulis (L.)	x	..	..	x	x	x	x	x	..	x	x	x	x	x	x	x	x
Modiolaria discors (L.)	..	..	..	..	x	x	..	..	..	..	..	..	..	..	..	..	..
Chlamys islandicus (Müller)	..	..	..	x	..	..	..	..	..	..	..	..	..	..	..	..	..
CIRRIPEDIA:																	
Balanus balanus (L.)	x	..	x	x	x	x	..	..	..	x	x	x	..	..	x	x	x
Balanus balanoides (L.)	..	..	..	..	..	..	..	..	..	..	..	..	x	..	x	..	..
Verruca stroemia (O.Fr. Müller)	x	..	x	x	..	..	..	..	..	..	..	x	..	..	x	..	..
ISOPODA:																	
Janiropsis breviremis Sars	x	..	x	x	..	..	..	x	..	x	..	x	..	x	..	..	x
Idotea granulosa Rathke	..	..	..	..	..	..	..	..	..	x	..	..	..	..	..	..	..
DECAPODA:																	
Galathea nexa Embleton	..	..	..	x	..	..	..	..	..	..	..	..	..	..	..	..	..
Hyas coarctatus Leach	..	..	x	x	x	..	..	..	..	x	x	x	..	..	..	x	x
ASTERIOIDEA:																	
Asterias rubens L.	x	..	x	x	x	..	..	..	..	x	x	x	..	..	x	x	x
OPHIUROIDEA:																	
Ophiopholis acuelata (O. Fr. Müller)	..	..	x	x	..	..	..	..	..	x	x	..	..	..	x	..	x
ECHINOIDEA:																	
Echinus esculentus L.	x	..	..	..	..	..	..	..	..	..	..	..	..	..	..	x	..
Strongylocentrotus droebachiensis (O.Fr. Müller)	..	..	..	..	..	x	..	..	..	..	..	..	..	..	..	..	x
HOLOTHUROIDEA:																	
Cucumaria frondósa (Gunnerus)	..	..	..	..	..	..	..	..	..	..	..	..	..	x	..	..	..
ASCIDIACEA:																	
Styela rustica L.	..	..	x	x	..	..	..	..	..	..	..	x	..	..	x	..	..
Halocynthia pyriformis (Rathke)	..	..	..	x	..	..	..	..	..	x	..	..	..	..	x	..	..
PISCES:																	
Liparis montagui (Donovan)	..	..	x	x	..	x	..	..	..	..	..	..	..	..	..	..	x

er conspicuous and easily noticed by divers.

Omalogyra atomus (Phil.), occurred the first time in 1987. This is the smallest gastropod in Iceland, and it is therefore not strange that it was not found at Surtsey at first, because it may easily be overlooked by the divers collecting and the personnel sorting the samples.

Nudibranchia

The nudibranchs found at Surtsey are not fully identified. Some specimens are still without given species names. Nudibranchs were one of the first animals to be found at Surtsey (Sigurdsson 1974). The following species have been found there:

Aeolidia papilosa (L.),
Acanthodoris pilosa (Müller),
Adlaria proxima (Alder & Hancock),
Catriona aurantia (Alder & Hancock),
Coryphella sp.,
Dendronotus frondosus (Ascanius),
Doto coronata (Gmelin),
Eubranchus sp.,
Tergipes tergipes (Forskål).

Because nudibranch specimens have not been identified to species from all the collecting years, they are not included in the further analysis of data in faunistic sense.

Lamellibranchiata

Heteranomia squamula (L.), was the first animal to be found on the new bottom at Surtsey. As early as 1965 it was recovered in a dredge sent down to 85 meters depth (Sigurdsson 1974). *H. squamula* has occurred in the samples since and is quite common at depths greater than 10 meters.

Hiatella arctica (L.), occurred in the samples quite early on. It was first found in 1967 and has occurred since. It is very common at Surtsey, and is found at every depth, the only lamellibranch outnumbering it being *M. edulis*.

Mytilus edulis (L.), was also first found at Surtsey in the year 1967, and has occurred since. It is now the most common bivalve at Surtsey, found at every depth, and forming extensive colonies which cover the bottom in many places in the sublittoral zone (see Fig. 2).

Modiola phaesolina (Phil.), was found first in the samples in 1980, at 20–40 meters depths on the west coast. It has not been found every year, so it is probably rare on Surtsey. However its small size may make it inconspicuous and cause the divers to miss it.

Chlamys pusio (da Costa), was collected first in the year 1968, and has occurred since, with the exception of 1984 and 1987. It is not very common occurring as solitary specimens on stones, at the 15–30 meters depth. It has been found at most of the transects, so its distribution is wide although it may be rather rare.

Modiolaria discors (L.), is rare on Surtsey and seems to be a recent inhabitant, because it was first found in 1987, on the east coast at 25 to 30 meters depth.

Chlamys islandicus (Müller), is rare on Surtsey. It was first found in 1987, at 20 meters depth on the east coast.

Cardium fasciatum (Mont.), was first collected in 1968, but has not been found in every year of sampling. It is therefore probably rare. In 1987 it was found at 15 meters depth on the east coast.

Cirripedia

Verruca stromia O. Fr. Müller, was collected as early as 1967 and has occurred since. It is sporadically abundant, being most often found on *Laminaria* stipes and stones. It has been found at most depths and transects.

Balanus balanoides (L.), was the first barnacle to be found on rocks at Surtsey, as early as 1968. This is the most common littoral barnacle in Iceland, but at Surtsey it was found in the sublittoral, as well as littoral zone. One reason for it's occurrence in "deep waters" of Surtsey could be that stones and cliffs, which *B. balanoides* has settled on are broken down by wave action and carried out to deeper waters with the surf. *B. balanoides* could also be using the opportunity and settling deeper on the bare and more stable rocks found there. Since 1980 it has only be found in 1987 on the west coast, at 5 and 15 meters depth. In the littoral zone it settles regularly each year on rocks at the tidal level, but most of the barnacles are destroyed and killed in the heavy surf which hammers the western and southern parts of the island during the autumn and winter, breaking away great parts of the coast each year.

Balanus balanus Da Costa, is the most common barnacle in the Sublittoral zone of Surtsey, as well as elsewhere on the coast of Iceland. It was found as early as in 1968, and every year since. It is found on stones and *Mytilus* shells, at all depths and transects.

Balanus hammeri (Ascanius), was first found in 1968. It is found at from 15 to 30 meters depth, on the south coast. It has not been found since 1980, and is probably not very common on Surtsey.

Ispoda

Janiropsis breviremis Sars, occurred first in the samples in 1974, and has been found regularly since. It is quite common occurring at almost every depth from 5 to 30 meters.

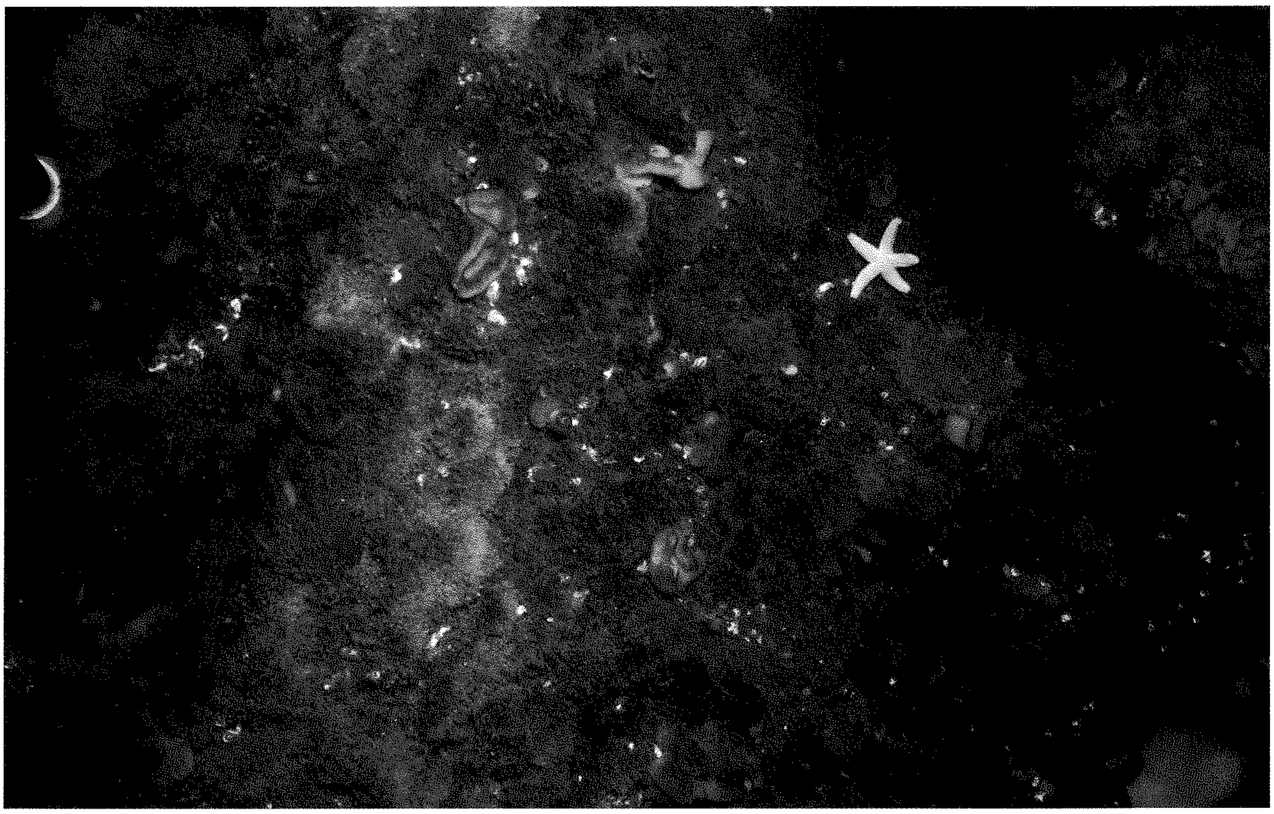

Fig. 1. Underwater photograph showing *Laminaria sp.* on hard rocks with epifauna. Animal species noticable on the photograph are: the star fish *Asterias rubens*, the poriferan *Grantia sp.*, the keelworms *Pomatoceros sp.* and *Hydroides sp.*, hydrozoans most noticeable *Tubularia sp.* and bryozonas (Photogr. Erlingur Hauksson).

Munna kröyeri Goodsir, was first found in 1974 and has most often been found in the years since then. It has been found at depths of 15–30 meters and is usually collected accidentally with other bigger benthic organisms.

Idotea granulosa Rathke, has only been found once on the south coast at 20 meters depth, in 1987. This is a very peculiar depth of occurrence, because *I. granulosa* is a very common intertidal idoteid on Icelandic shores, but does not occur sublittorally elsewhere on the coast.

Decapoda

Eualus (= Spirantocaris) pusiolus (Kröyer), was found as early as 1967. It has occurred in the samples more or less up until 1980 and is found sporadically at most depths.

Hyas coarctatus Leach, was found first in 1967 and has occurred since. It is the most common crab on Surtsey being found everywhere at all diving depths. It is often covered with commensal species of hydroids, bryozoans and algae.

Macropipus (= Portunus) holsatus (Fabricius). Individuals of this species were found in 1964 at 70 meters depth (Sigurdsson 1965) and from 1967 to 1969, but not since then. This may be because *M. holsatus* is a swimming crab and is not strongly tied to the bottom.

Galathea nexa Embleton, occurred first in 1969 and has been found since. This anomura crab is quite common on Surtsey in the depth range 20–40 meters.

Pandalus montaqui Leach, has only been found in 1964 at 70 meters depth on the west coast (Sigurdsson 1965), and in 1974 on the south coast at 40 meters depth. This is however a very common shrimp in shallow waters on the coast of Iceland on various substrata. It is possibly not found more often on Surtsey, because it is an agile animal and readily escapees capture.

Eupagurus bernhardus (L.). This hermit-crab occurred in 1980 samples from Surtsey. It was found at several depths on the west and east coast. On later sampling occasions it has not been found, suggesting that it is probably still scarce at Surtsey. It is however a very common hermit-crab in shallow waters on the Icelandic coasts.

Asterioidea

The only star fish found at Surtsey so far is *Asterias rubens*. L. It was found as early as 1968

Fig. 2. Underwater photograph showing *Mytilus edulis* colonies with associated epifauna. Animals to be noticed on the picture are: the star fish *Asterias rubens* preying on *M. edulis,* hydrozoans and the lamellibranch *Hiatella arctica* (Photogr. Erlingur Hauksson).

and has occurred since. It is quite common being found at almost every depth all around the island. It is especially abundant in association with the common mussel (*M. edulis*), and preys upon it (see Fig. 2).

Ophiuroidea

Ophiopholis acuelata (O.Fr. Müller), is the only brittle star which is very common on Surtsey. It occurred first in 1974, and is now found almost everywhere at most depths.

Ophiura sp. One juvenile was found in 1974, at 40 meters depth on the south coast. A handful of Ophiura species are common on sand- and clay-bottom conditions around the Icelandic coast. *Ophiura affinis* Lütken, has been previously found by W. Nicolaisen (Nicolaisen 1970), making this the most likely species.

Echinioidea

The edible sea-urchin, *Echinus esculentus* L., was the first sea-urchin to be found on Surtsey. It was found in 1980, at almost every depth on the west coast.

Strongylocentrotus droebachiensis Lam., was found first in 1980. It is now quite common around Surtsey at various depths.

Holothuroidea

The only holothurian found at Surtsey so far is *Cucumaria frondosa* (Gunnerus) which was first found in 1987, at 10 meters depth on the west coast.

TABLE 5

Number of species of benthic invertebrates, of the following animal groups, which have been found around Surtsey, since the beginning of investigations: Coelenterata, Gastropoda, Lamellibranchiata, Cirripedia, Isopoda, Decapoda, Echinodermata and Tunicata

Year	Number of species	Number of new species since last investigated	Number of species not recurring since last collection
1965	1	0	0
1967	8	7	0
1968	16	9	1
1969	19	5	2
1974	22	7	4
1980	29	11	4
1983	17	1	13
1984	17	5	5
1987	28	14	3

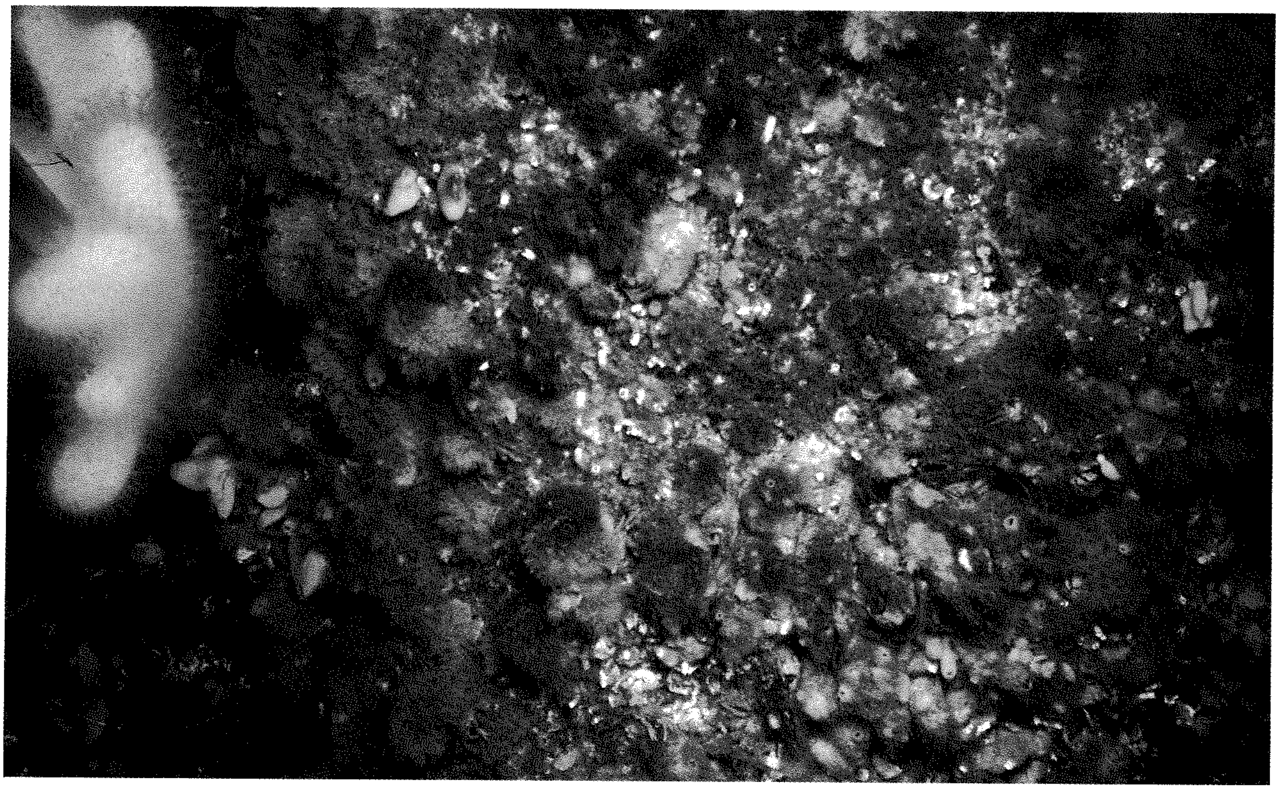

Fig. 3. Underwater photograph showing the *Alcyonium digitatum* epifaunal assemblage. Animals to be noticed on the picture are: *A. digitatum*, the poriferan *Grantia sp.* the keelworms *Pomatoceros sp.* and *Hydroides sp*, *M. edulis* with the barnacle *B. balanus* on its shell, tunicates, hydrozoans and bryozoans (Photogr. Erlingur Hauksson).

Ascidiacea

Ascidia callosa Stimpson, was the first tunicate to be found on Surtsey, being found in 1968 on the west coast at 17–20 meters depth.

Styela rustica L., is the most common tunicate on Surtsey. It was first found in 1969 and has occurred since being found mostly at depths of more than 15 meters all around the island. It is usually heavily overgrown by commensal bryozoans, hydroids and algae. The gastropod *V. velutina* is also sometimes found on the tunicate.

Halocynthya pyriformis (Rathke), occurred first in 1980 and is now fairly common, especially at depths greater than 15 meters.

FAUNAL CHANGES WITH TIME

Parallel succession in the evolvement of the animal part of the biocoenoses on rocky bottoms around Surtsey has been described by Sigurdur Jónsson & Karl Gunnarsson (1987) for vegetation. Shortly after the cessation of the eruption, in 1964, *Portunus holsatus* and *Pandalus montagui* were found, as the first animal inhabitant. In 1965 *Heteranomia squamula* was found. Two years later *Hiatella arctica, Mytilus edulis, Verruca stromia, Balanus balanoides, Eualus pusiolus* and *Hyas coarctatus,* were found. In 1968 a further handful of species were added to the list, such as *Lacuna divaricata, Chlamys pusio, B. balanus, B. hammeri, Asterias rubens, Acidia callosa, Apporhais pes-pelicani* and *Cardium faciatum.* During 1969 a further number of species were added to the list (Table 5). They are *Alcyonium digitatum, Odostomia unidentata, Galathea nexa, Styela rustica,* and the fishes *Cyclopterus lumpus* and *Liparis montagui.* In 1974 a few species not previously found were added to the fauna, they are: *Buccinum undatum, Velutina velutina, Janiropsis breviremis, Munna kröyeri, Pandalus montaqui, Ophiopholis acuelata* and *Ophiura sp.* Now (1987) it seems that the rate of increase of new species, has slowed down a little. A search for new species in 1987 only revealed a few, the most noticeable being *Margarites olivaceus, M. helicinus, Acmaea testudinalis, Idotea granulosa, Modiolaria discors, Chlamys islandicus, Tealia fealina* and *Cucumaria frondosa.*

DEVELOPMENT OF THE EPIFAUNAL ASSEMBLAGE

Variation in the intensity of investigations between years can partly affect the results of the faunistic surveys on Surtsey. It could explain why some species of benthic animals are not found in particular years, even though they were found earlier and later. However a lack of species could also be caused by competition with other benthic animals having similar needs. The number of species of benthic animals at Surtsey, seems to have evened out somewhat and the likelihood of finding new species is much less now than at the beginning of the colonization of the bare rock surrounding the island.

As numbers of species increase on the rocks, the fauna assemblages also increase in diversification. On the *Laminaria* stipes and fronds, a rather diverse epifaunal assemblage has evolved. Hydrozoans, bryozoans, *Verruca stromia* and *Lacuna divaricata,* are the most dominant animals (Fig. 1). *Mytilus edulis* has formed an epifaunal matt covering the stones, and provides a substrata for epifauna of *Balanus balanus, Verruca stromia,* hydrozoans and bryozoans (Fig. 2). *Alcyonium digitatum* also covers the rocks contagiously (Fig. 3). On *Styela rustica* a solitary tunicate epifauna has developed on its own, formed of bryozoans and hydroids.

There is evidence of interactions between animals, other than cooperation and commensalism, which at first play the major role in development of the epifauna. This includes predation of the star fish *Asterias rubens* on the bivalve *M. edulis,* the grazing of *Lacuna divaricata* on the microscopical epiphytes on the *Laminaria* blades and the predation of fish such as *Myoxocephalus scorpius scorpius* (L.), *Liparis montagui* (Donovan) and *Cyclopterus lumpus* (L.), on many benthic agile animals which probably play an important role in the development of the epifaunal assemblage on Surtsey.

A functional community has evolved, which makes a demand for new methods of investigation, and a revaluation of the objects of study. A change is necessary from qualitative faunal investigations to quantitative assessments of animals and plants of the community of hard surfaces around Surtsey. This type of investigation was commenced in 1980 and has continued since then, by the use of underwater photogrammetry.

ACKNOWLEDGEMENT

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GEOLOGY AND GEOPHYSICS

The Submarine Morphology of Surtsey Volcanic Group

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INTRODUCTION

The volcanic activity in the Surtsey area, Vestmannaeyjar, commenced in November 1963 and ended in June 1967, when the island attained its maximum size (Norrman, 1970). On Surtsey, two large craters produced most of the lava that covers the tephra slopes in the southern half of the island. The lava not only covered the supra-aquatic slopes, but also advanced into the sea, thereby considerably enlarging the island (Thorarinsson 1966, Norrman 1980). This lava plateau, with a height of 20 to 100 m a.s.l., rests on tephra and lava breccia below sea-level (cf. Norrman 1980, Fig. 3). The present degree of consolidation of these covered deposits is imperfectly known, but has been estimated by Jakobsson and Moore (1982, Fig. 9). Two more volcanoes, Surtla and Syrtlingur, were formed ENE of Surtsey, and another, Jólnir, to the WSW. Before the eruptions, the depth of the fairly level sea bed varied between 125–135 m.

At the site of Surtla a submarine eruption was noticed on December 28, 1963. A volcanic cone was built up, but did not reach the sea surface. Syrtlingur was seen above sea level on May 28, 1965, and had disappeared by abrasion on October 24 the same year. Jólnir reached sea level for the first time on December 28, 1965, and finally disappeared in October 1966. In these islands no lava was observed. The Surtsey events offer a unique opportunity to study the early stages of a submarine geomorphological cycle.

MARINE ABRASION

Abrasion in bedrock caused by wave action is generally thought to produce shallow, almost horizontal platforms. The gradient of the "bench" is normally very slight and from existing observations seems to be no more than 0.05% (Zenkovich 1967, p. 155). Summarizing her review of The Marine Cycle, King (1972, p. 558) states: "Waves cannot erode rocks below surf-base, which is about 10 m depth."

The depths at which unconsolidated sediments can be set in motion by waves are far larger as is easily demonstrated by wave dynamics formulae (Komar 1976), and also witnessed from field observations. "On the basis of all information available, it is permissible to assume that the base of the submarine beach slope in an open ocean may lie at a depth of more than 100 m" (Zenkovich 1967, p. 163).

In many treatments of the transport of unconsolidated sediments on open coasts, only one wave height and period is considered, the so-called significant wave characteristics. However, the full spectra of wave characteristics has to be considered, since different waves have different rates of damping with depth. The effect of this is illustrated in Norrman (1964, Fig. 56). It has been demonstrated by calculations that the "significant wave height", in a real environment where there are also currents to consider, varies with depth (Erlingsson 1990, Fig. 74).

Furthermore, the morphologically significant property to monitor is not the critical erosion velocity but the actual sediment transport. This varies with depth according to the wave spectra, the grain size, and the current spectra, as illustrated in Erlingsson (1990, Figs. 72 and 75). His calculations showed that with a specific wave and current spectrum, the transport of coarse sand and gravel will decrease rapidly with depth. The transport of medium and fine sand will decrease less rapidly with depth, actually crossing the former curve at a certain depth. Under certain conditions, there will be a mixture of two or even three grain sizes in the same bottom area.

In a situation where sediment is being transported down a slope with decreasing transport capacity, there will be a depth at which the rate of input is greater than the rate of output. Erlingsson (1990, p. 131) suggested the term *wave-base deposit* for the resulting sediment accumulation, thus abandoning the disputed and poorly defined term "wave built terrace" (as suggested also by Moore and Curray 1964). Thus, the depth of the "wave-base deposit" depends on the sediment input, as well as on the wave and current regime.

THE ABRASION OF THE SURTSEY VOLCANIC GROUP

There are no published wave records for Vestmannaeyjar. Wind and wave exposure at Surtsey have been calculated from meteorological statistics by Norrman (1970) and by Bruun and Viggósson (1972). Waves of morphological importance are mainly generated by cyclonic depressions moving from the WSW and the SW. Wind from the southern semicircle dominate within the moving fetches of the depressions. Bruun and Viggósson found 250 nautical miles (1 n.m.=1.852 km) to be a representative length of fetch for winds from the W and the SW, and 135 n.m. to be representative for winds from the S and the E. Within a sector from the NW to the ENE the fetch is limited by the Icelandic mainland, and most strongly so in the sector from the N to the NE where it is only 16–27 n.m. The northern tephra coast of Surtsey is thus far less exposed to wave attack than the southern lava coast.

From the southern coast of mainland Iceland, Viggósson and Tryggvason (1985) have recorded the largest significant waves at Dyrholaey (80 km east of Surtsey) to be H_0=8.1 m and T=13.0 s, and at Thorlákshöfn (60 km NW of Surtsey) to be H_0=10.1 m and T=15.5 s.

The shape of the coastline of Surtsey reflects extremely well the distribution of wave force: The strong erosion of the southern lava cliff coast – the north directed littoral transport along the eastern, and western coasts (where the steep tephra cliff has been consolidated into tuff) – and the deposition that forms the northern ness, which slightly shifts position with alternate storm attacks from the east and the west.

Because of the large depths close to the island, there is little wave refraction, with one possible exception: The greatest erosion of the lava cliff is observed on the side facing Jólnir. If the abrasional platform had protected the cliff by absorbing some of the energy, that part of the cliff would have been less eroded. Instead it appears as if the waves from the dominating SW direction are refracted over Jólnir so that the energy that reaches Surtsey from that direction is reinforced.

Through several expedition to Surtsey by various parties it has been possible to monitor the coastal and submarine development from the last stage of volcanic activity in 1966/67 to the present. Numerous "Surtsey Reports" were summarized by Norrman (1980). The use of photogrammetric surveys carried out by Landmaelingar Íslands, has meant that observations of coastal and inland changes are far more frequent than observations of submarine change.

At the end of July 1966 the submarine slopes of Surtsey were echosounded to produce a map with 5 m contour intervals (Rist 1967, Fig. 1). In this map the submarine morphology is characterized by a sloping platform around the island with a width of 100–200 m, a slope of 1:7 and a depth at its outer margin of 25–30 m. Off this platform the slope steepens sharply to about 1:2 to 1:3. The steep slope gradually flattens below a depth of 60 to 100 m. Lack of good positioning makes this map very difficult to compare with later soundings.

The first complete sounding of the area was made in 1967 (Norrman 1968). It was followed up by diving operations in 1968 in order to study active processes and morphology (Norrman 1970). The area was again sounded in 1973 (Norrman 1980), by Sjómaelingar Íslands in 1985, and in 1989 (see below).

The most spectacular phenomena on the map based on the soundings of 1967 are the table-like sea mounts produced by abrasion of the tephra cones of Surtla, Syrtlingur and Jól-

Fig. 1. The survey vessel in front of Surtla I. Surveys can be made at a speed of up to 12 knots; top speed in transit is 30 knots.

nir. From diving observations the plateaux of these shoals were found to be covered with rippled tephra and lava fragments, mainly of coarse sand and granule size. No trace of solid lava beds was found.

Diving and echosounding at the northern ness of Surtsey showed a sharp transition from the platform to the steep slope at a depth of 12 m. This slope was at the frictional angle of repose (30°–34°) down to about 70 m, and below that gradually levelled off. Boulders were deposited at the top of the slope, and others that had moved down the slope formed boulder streams. Touching the slope caused widespread avalanching (Norrman 1970, Fig. 7).

Off the lava cliff on the southern coast, the platform was found to be covered by large boulders. At the top of the steep submarine slope, 150 m from the shore and at a depth of 20 m, giant blocks, some with a diameter of 5 m, were loosely piled on top of each other. Further down, the blocks were smaller and coarse sand started to fill up the space between the boulders at a depth of 30–40 m. The sand below 40 m was deposited at its frictional angle of repose, which was less than the boulder slope.

When the depths of the abrasion surfaces at Surtla, Syrtlingur and Jólnir from 1967, 1968 and 1973 were plotted versus time since the islands disappeared below sea level (Norrman 1980, Fig. 7; see also Jakobsson 1982, Fig. 2), it was found that the shoals had been lowered rapidly down to about 20 m b.s.l. (ca. 1.5 yrs). Thereafter the abrasion slowed down most markedly at the rather sheltered Syrtlingur, far less at the freely exposed Surtla (down to 40 m), and intermediately at Jólnir (down to 30 m).

In a recent paper by T. Sunamura (1990), these data (excluding Syrtlingur) have been used to verify his model for describing submarine bedrock erosion, considering the wave-induced shear stress as the primary force causing abrasive bedrock lowering. The "design wave" is represented by a mean of the maximum wave records from Dyrholaey and Thorlákshöfn: H_0=9 m and T=14 s. Sunamura finds the wave base below which abrasion is insignificant to be 54 m, and 95% of this abrasion is reached within 10.7 yrs.

FIELD SURVEY

The 1989 expedition was focused on studying the submarine morphology and processes.

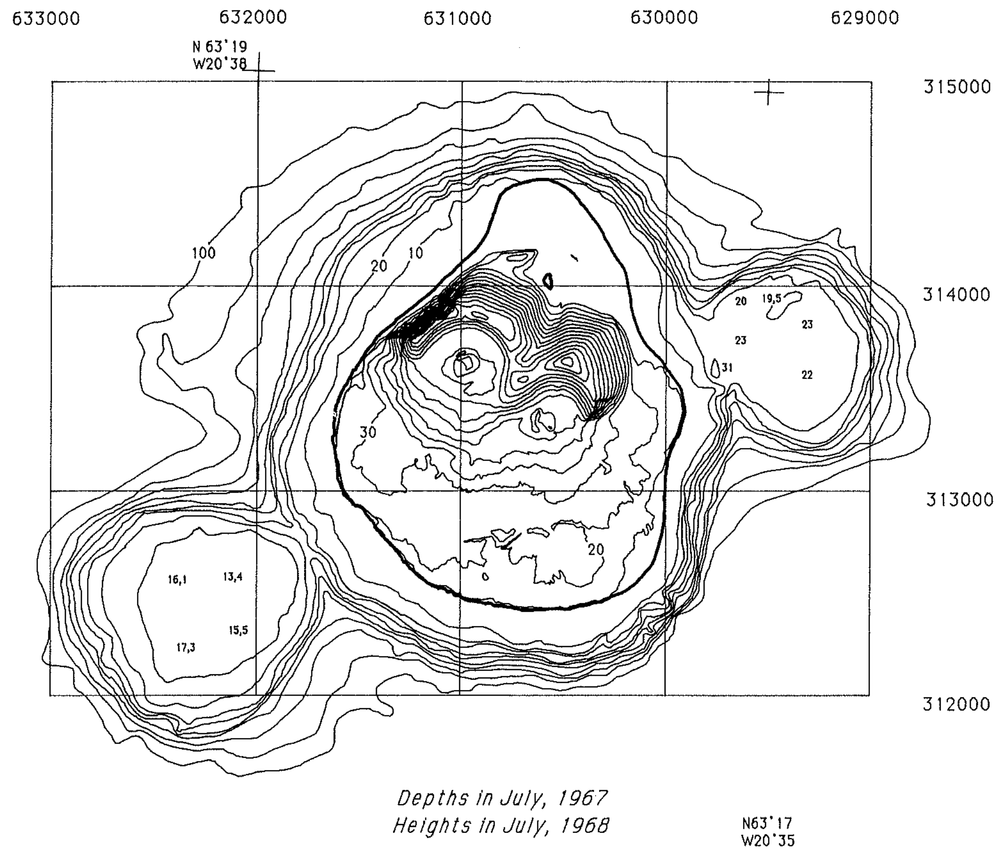


Fig. 2. Topographical map based on soundings from 1967 and air photos taken in 1968. The contour intervals is 10 m, with the coastline emphasised. Jólnir is the volcano to the west of Surtsey, and Syrtlingur on the east of it. Surtla is outside the map in the direction ENE (cf. Fig. 5).

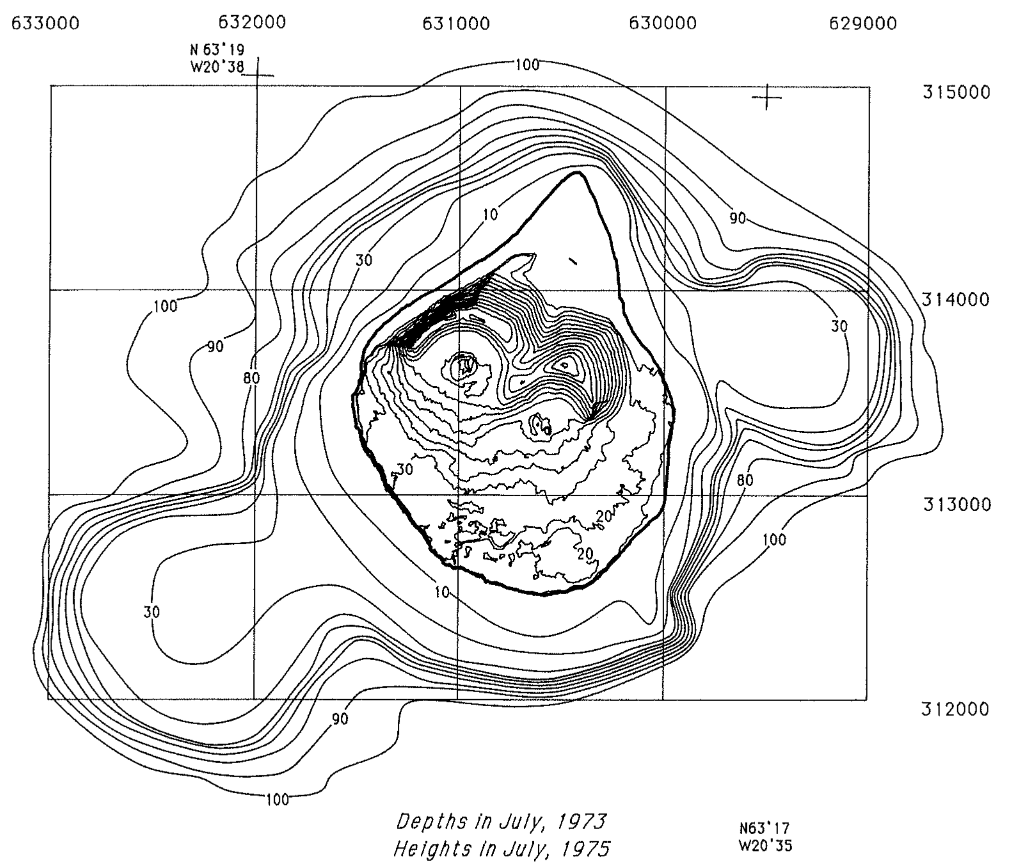


Fig. 3. Topographical map from 1973/1975 (cf. Fig. 2).

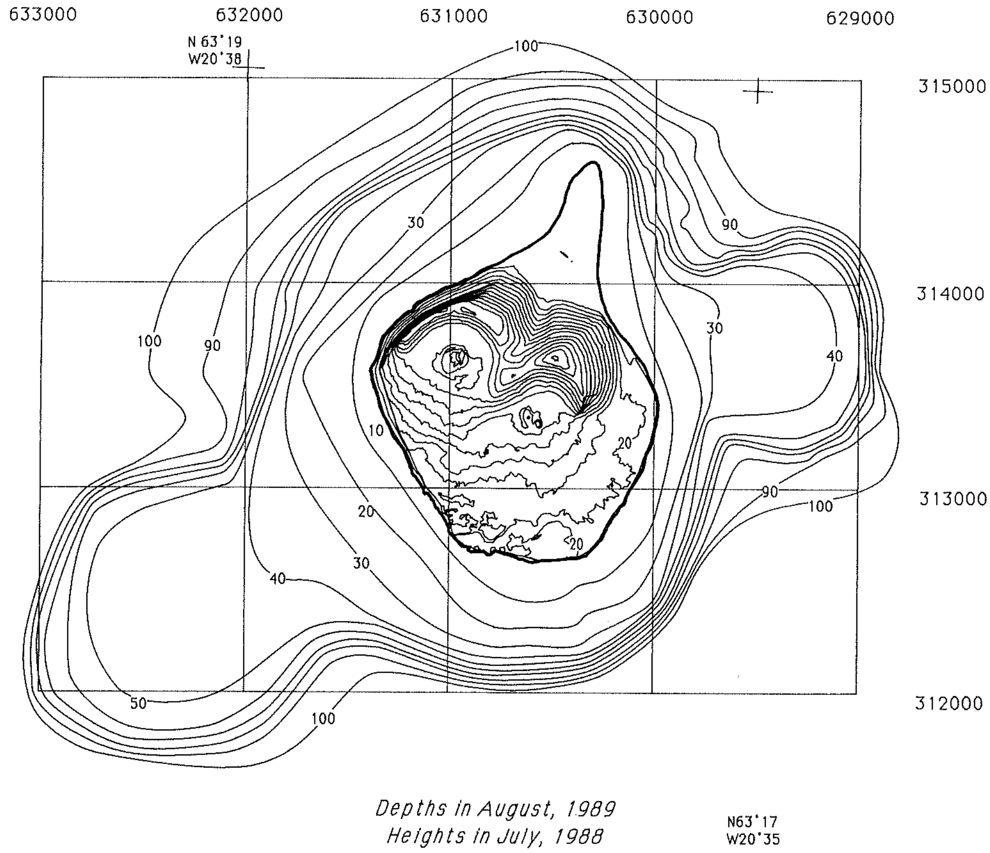
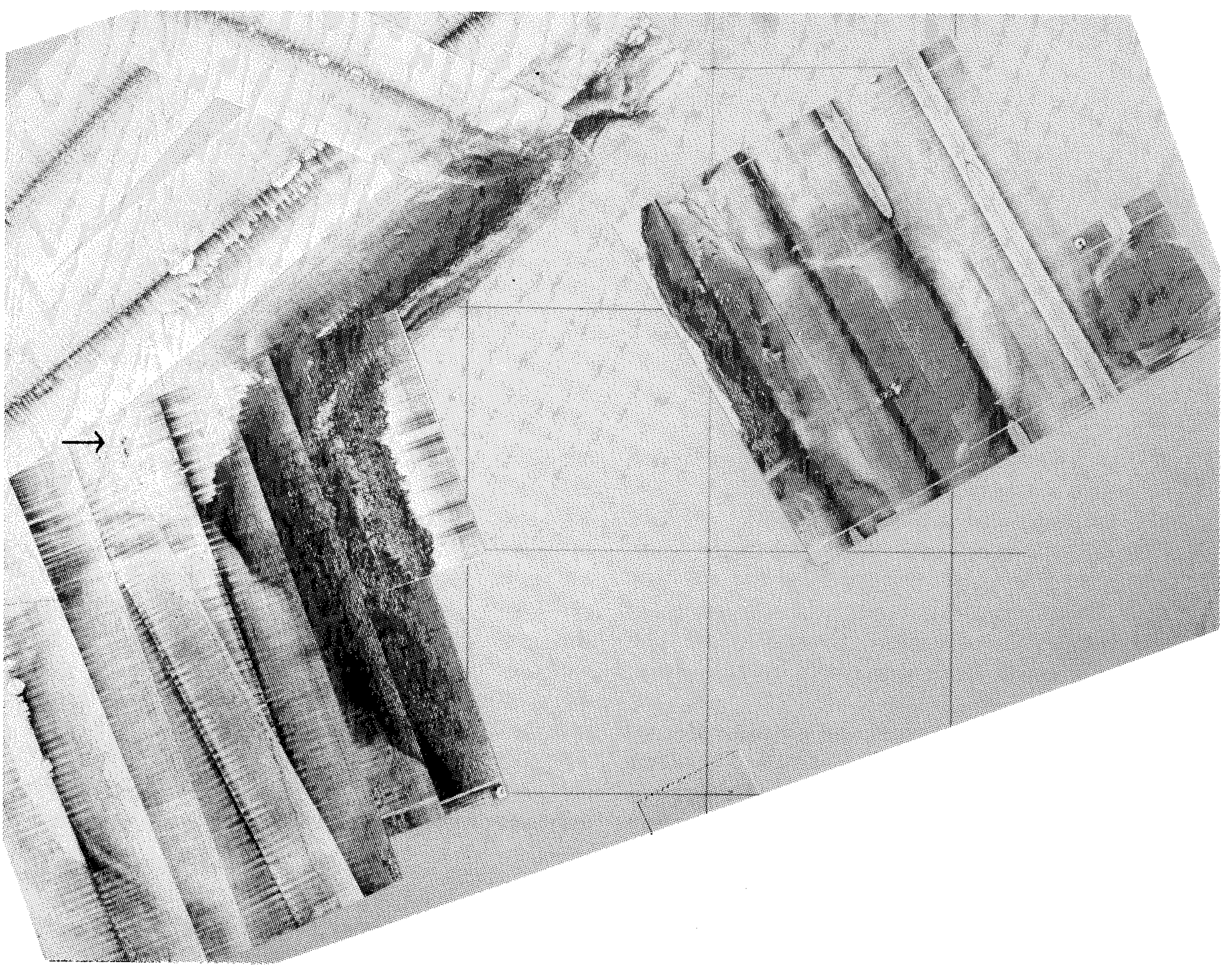


Fig. 4. Topographical map from 1988/1989 (cf. Fig. 2).

Fig. 5. Side-scan sonar mosaic of the bottom around Surtsey (the island occupies the empty space in the centre). Surtla can be seen to the far right. The background lines mark a 1 km² grid (cf. Figs. 2–4), and the arrow points to three volcanic plugs at 110 m depth (see text). The former position of the western coastline of Surtsey can be seen as the border between large blocks on the bottom (speckled area) and the lava breccia sand (uniform dark tone). See also Fig. 6.



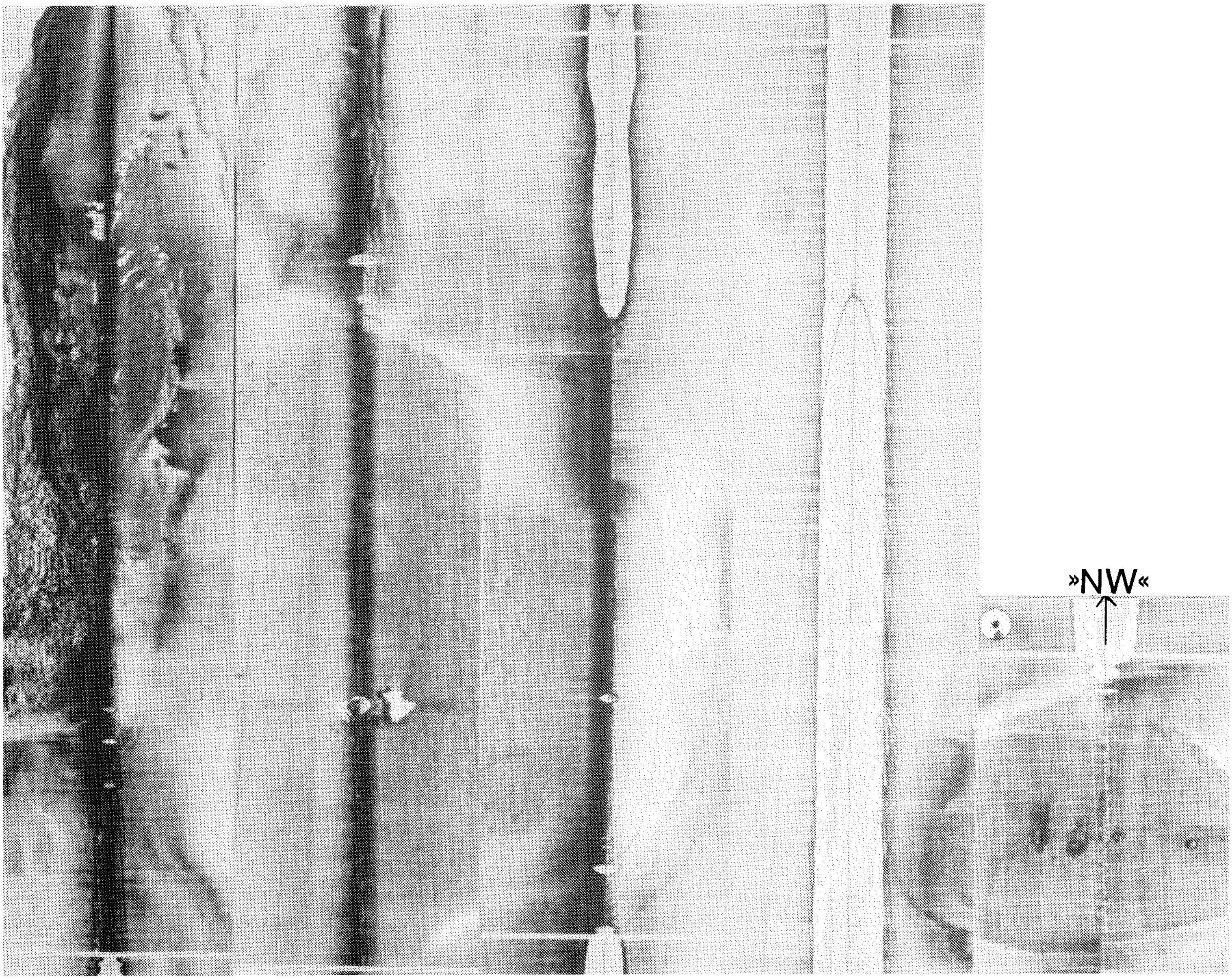


Fig. 6. Side-scan sonar mosaic over Syrtlingur (left) and Surtla (right). Scale 1:10,000. The white stripe between them, and N and SE of Syrtlingur, is caused by the water depth being too great for the instrument set-up. The two volcanic plugs on Syrtlingur, and the four on Surtla, are seen as dark objects – the former are so high that they also throw a considerable white shadow. The arrow at Surtla marks the direction of the survey line, from which the sub-bottom profile in Fig. 14 is taken. To the far left, Surtsey can be seen in white (no echoes are obtained from land).

A survey vessel, Akusta (Fig. 1), equipped with side-scan sonar (EG&G Mod 260 with 100/500 kHz towfish) and sub-bottom profiler (O.R.E. Geopulse Pinger with four 3.5 kHz hull-mounted transducers) were used for the surveys. Positioning was made with the use of a Geodimeter "total-station" from Surtsey. The equipment has been described by Erlingsson (1990, pp. 41–46).

Based on these surveys, and air photos from 1988, a topographical map with 10 m contour interval has been constructed (Fig. 4). Maps in the same style have also been made based on earlier maps from 1967/68 and 1973/75 (Figs. 2 and 3).

A side-scan sonar mosaic (Fig. 5) could be made over most of the bottom around Surtsey, the main uncovered part being the southern slope. Tephra areas have a light gray shade, as seen on Surtla, Syrtlingur and Jólnir. Samples taken on Syrtlingur in 1989 gave a mean size of ca. 1.2 mm, and a flume test showed the critical erosion velocity to be ca. 48 cm/s at 1 m above the bed (which is in line with the "Sundborg diagram" for this relatively light material; cf. Sundborg 1967). The west-

Fig. 7. The base on the northwest side of the western volcanic plug on Syrtlingur (depth 34 m). The bottom material is tephra in sand and granule size (mean≈1.3 mm), with some small boulders. There is an abundance of fish that blurs the sonographs, which makes it difficult to measure the exact size of these features.

ern slope off Surtsey is speckled with blocks from the lava cliff, whereas the NW slope has an even dark colour, suggesting lava breccia in sand or granule size. The lightest shade, indicative of medium or fine sand, is found on the bottom to the north and east of the northern ness of Surtsey (which is the area of maximum accumulation).

During a submarine volcanic eruption, the outflowing lava will be chilled rapidly and form pillow lava, unless the gas pressure in the lava is so great that it explodes to form tephra. At what depth this will occur has been discussed by Thórarinsson (1966) and Kjartansson (1966), on theoretical grounds, but no field data was available at the time. A later drilling project on Surtsey did not encounter any pillow lava (Jakobsson and Moore, 1982), but a dredge haul at 85–95 m depth at the base of Jólnir, did (Jakobsson, 1982; see also Thors and Jakobsson, 1982).

On the side-scan sonar mosaic in Figure 6, two "volcanic plugs" can be seen on Syrtlingur (top level ca. −25 m), and four on Surtla (top level ca. −45 m). On Jólnir no volcanic plug was found, but it may be present below the tephra. A group of volcanic plugs was also found at one location at ca. 110 m depth, north of Jólnir and west of Surtsey (Fig. 5). This group, situated on a low elevation of the old sea-bed, may possibly be a remnant of a tephra island formed by an earlier eruption.

The more western of the volcanic plugs on Syrtlingur was visited by diving. It protrudes ca. 10 m above the surrounding bottom (34 m), and it is narrower at the base than at the top (Fig. 7). The diameter at the top is ca. 25 m. The entire volcanic plug is cleaved by a ca. 0.2 m wide crevasse running in ENE-WSW (Fig. 8). A rock sample taken at the crevasse, at the top of the volcanic plug, was identified as tuff (pers. comm., Sveinn Jakobsson). The upper surface is fairly flat (Fig. 8), the relief being generally less than 1.5 m, but at several places up to 1 m high structures protrude. As can be seen on Figure 9 these may be cleaved by the crevasse (the rock sample mentioned was taken close to this point).

A dive was also made on the east side of the northern ness, where the sand on the slope below the knee at 25 m depth was found to lie at the angle of repose, and avalanches started

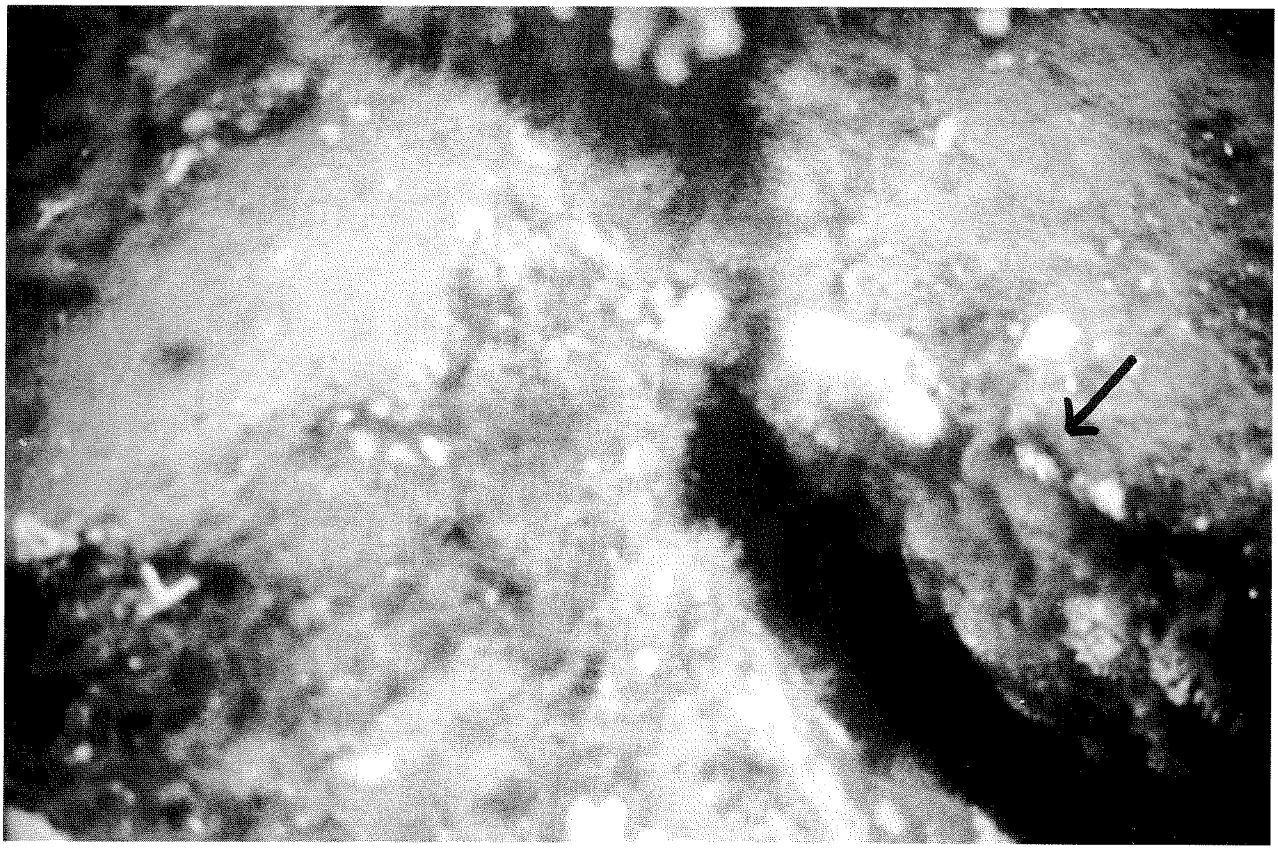


Fig. 8. The top surface of the volcanic plug in Figure 7, showing the crevasse where the sample was taken (depth 24 m).

if it was touched. On the southeastern slope, the bottom between 25 and 30 m depth was found to be covered by rippled coarse sand in patches, and boulders in the size range 0.3 to 0.8 m. Below the knee at 30 m, only boulders were found (in the same size range). These were sparsely overgrown, and it appeared that only some of the larger ones had been at rest since the previous summer, thus achieving a more flourishing vegetation. In contrast, the lava rock on Syrtlingur was densely covered by soft corals, etc. (Fig. 9).

MORPHOLOGICAL EVOLUTION OF THE VOLCANIC GROUP

The evolution of the Surtsey volcanic group, as shown by the hypsographic curves in Figure 10, is one of constructing a "shelf" by a combination of cliff erosion and the accumulation of a "wave-base deposit". As mentioned, the depth at which this accumulates depends on the sediment input rate, and since the

Fig. 9. Horizontal view through the crevasse at the top of the volcanic plug in Fig. 7 (depth 24 m). The width of the crevasse is ca. 0.2 m. Note the dense "vegetation" cover that indicates stable geomorphological conditions – a similar vegetation cover is not found on the blocks on the submarine slopes off Surtsey.

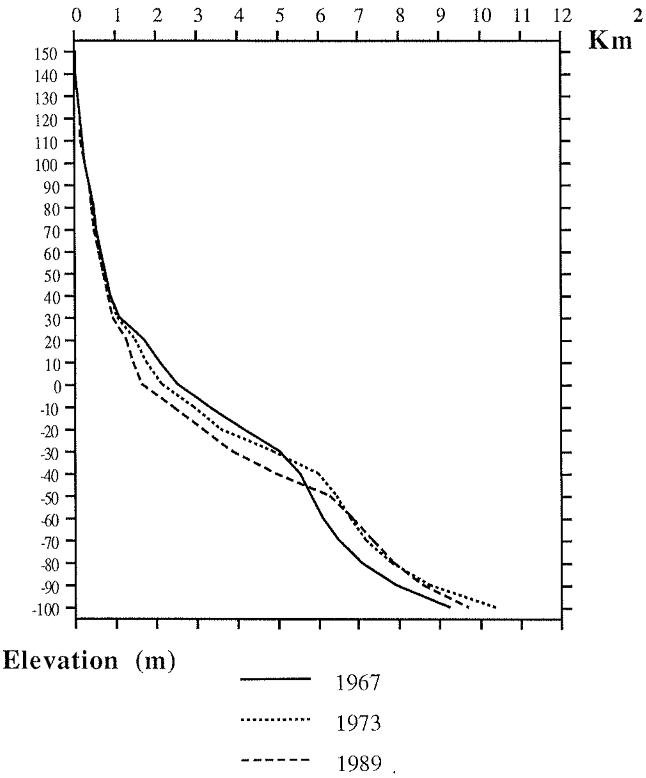


Fig. 10. Hypsographic curves based on the maps in Figs. 2–4.

eruption has ceased there is a steadily diminishing amount of material available for sediment transport. The effect can be seen on the hypsographic curves: The (local) "shelf break" moves down, from −30 m in 1967, to −40 m in 1973, and to −50 m in 1989. At the same time the coastline has moved back through cliff erosion – thus creating a situation very similar that envisaged in many early concepts for the evolution of a continental shelf, although on a smaller scale. The future for the tephra areas is that the "shelf break" will move down until it merges into the surrounding, insular (continental) shelf level at ca. 110 m depth. Surtla, Syrtlingur and Jólnir will be reduced to volcanic plugs on the shelf floor, similar to many other shoals in the area.

Using the 1989 soundings along with the older ones, the rates of abrasion of the former tephra islands were calculated. The data were fitted to an equation of the form

$$d=K+e^{(At^{q})} \qquad \text{Eq. 1}$$

where d=depth over the tephra plateaux, t=time in years since the plateaux disappeared from the surface, K=−1, a constant needed to obtain the depth 0 at time 0, and A and q are the variables. The first depth measurement on Jólnir is at t=0.9 yrs, for Syrtlingur at t=1.75 yrs. After such a short period the variations in the weather around the long-term average can be expected to give unreliable results in the calculations, so the same

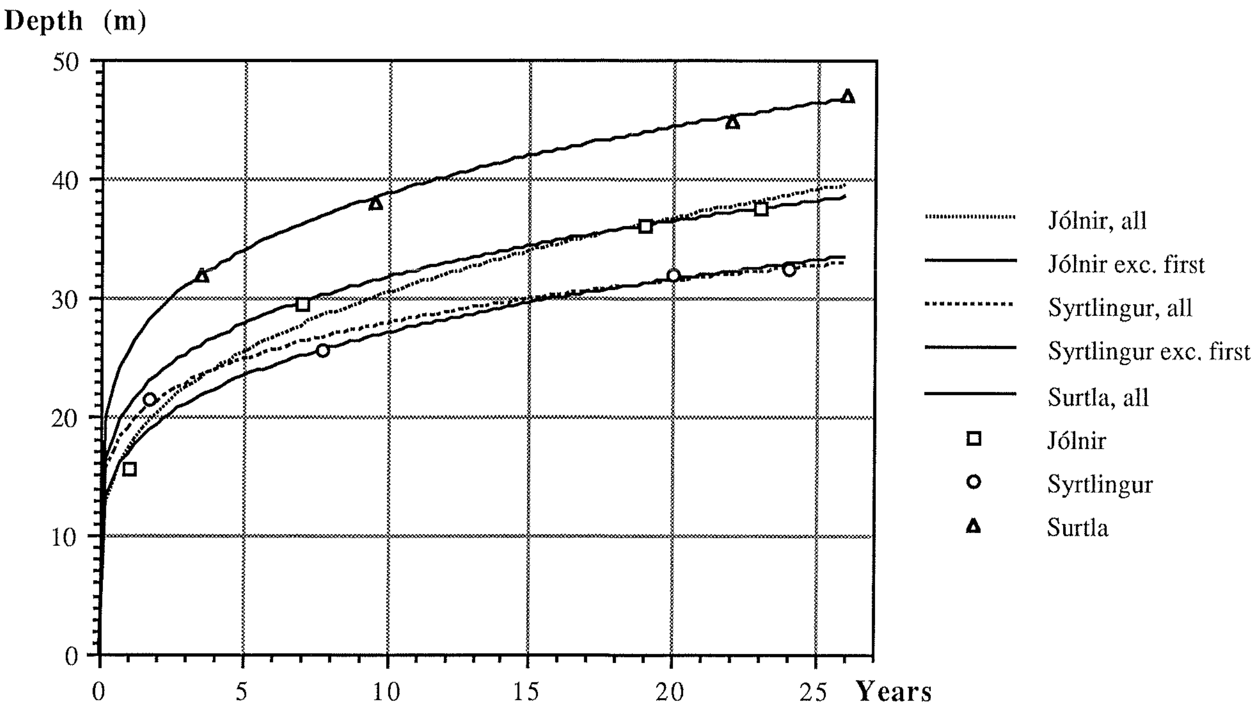


Fig. 11. Data points and fitted curves for the abrasion of the tephra plateaux of Surtla, Syrtlingur and Jólnir. The origin is when they disappeared from the sea surface. The dashed lines are the curves resulting when the first data point (after the origin) of Jólnir and Syrtlingur are included. That first point is not reliable, since it depends on whether a major storm appeared or not during the first winter.

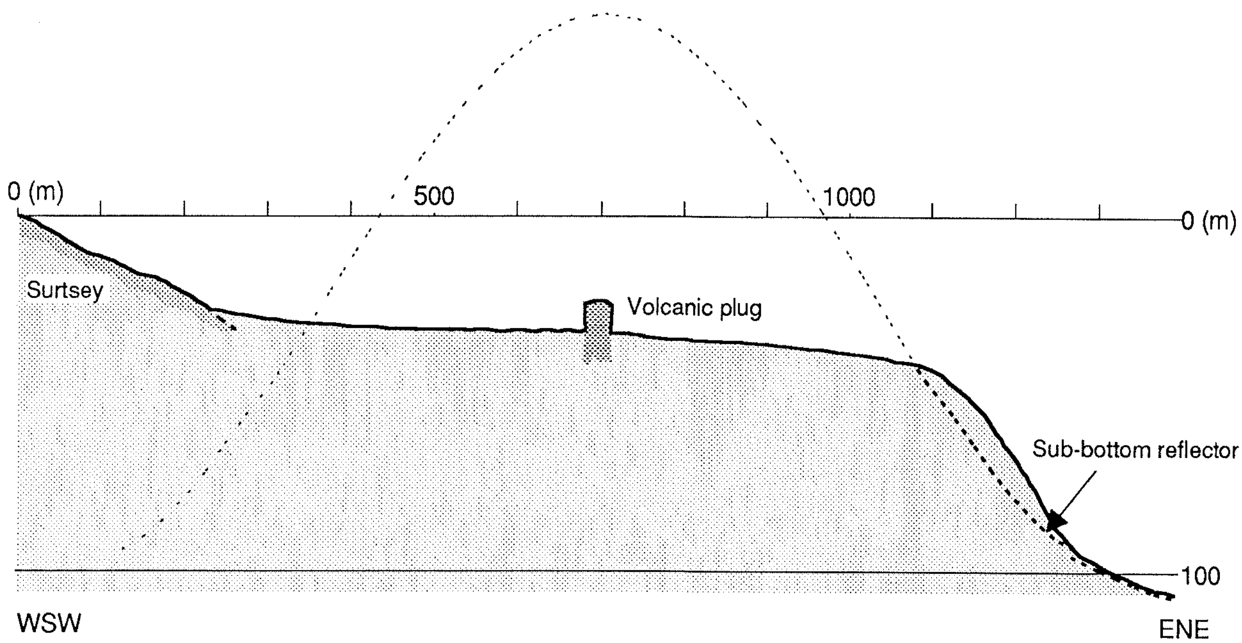


Fig. 13. Profile from WSW to ENE from Surtsey over Syrtlingur with one of its volcanic plugs. The dashed lines are internal reflectors, indicating the position of the sea-bed at an earlier time. The dotted line suggests a profile of the former island Syrtlingur, consistent with the dashed line on the plateau slope. (Interpreted from a 3.5 kHz sub-bottom profile).

curve fit was tried without these two data points. The result can be seen in Figure 11. The solid lines are fairly parallel and all agree well with the data points (with the exceptions mentioned). The dashed curves represent the fit with those two points. The values of A and q are listed in Table 1. Note that the predictions are only valid for the tephra – the volcanic plugs will last much longer.

The maps of Figures 2 to 4 were imported into a GIS-program (Map II) using 10 m spatial resolution and 10 m contour intervals, from +150 m to −100 m. All bottoms beyond that were given the value −110 m, which is a fair approximation, and relevant for the purpose. By subtracting an older map from a newer, pixel by pixel, a map is obtained showing the net mass balance. It turned out that the change from 1967/68 to 1973/75 was positive, instead of negative as one would expect. This and other indications, like the regional distribution of the areas of positive and negative mass balance, make it clear that the depth map from 1973 displays such major errors due to unsatisfactory positioning that it does not deserve a comprehensive treatment. The change from 1967/68 to 1988/89 is shown in Figure 12. (The 1985 map from Sjómaelingar Íslands was not digitized, since the differences to 1989 were within what can be expected to be the error margin.)

The depth of the conceptual "wave-base deposit", i.e., where there is a change from erosion to accumulation, can be seen to vary from 50 m on the southwestern slope of Jólnir, to sea-level at the northern ness. This image reflects a long-term average, meaning that there is probably erosion today at many places where the map shows a net accumulation.

TABLE 1

The values of the variables A and q were derived by fitting the data points in Fig. 11 to Equation 1 (the corresponding curves are plotted in the same figure). t_{100} is the time (in years) required to abrade the plateaux to a depth of 100 m, under the unrealistic assumption that they consist of nothing but unconsolidated tephra. The first two columns (Jólnir and Syrtlingur) give the values that resulted when the first data point (after depth=0 at time=0) was not included in the calculations. These values are more realistic than those in the last two columns, where all points were considered.

	Jólnir	Syrtlingur	Surtla all	Jólnir all	Syrtlingur all
A:	3.08	2.88	3.27	2.90	3.00
q:	0.0546	0.0629	0.0510	0.0746	0.0493
t_{100}	1685	1761	841	500	6128

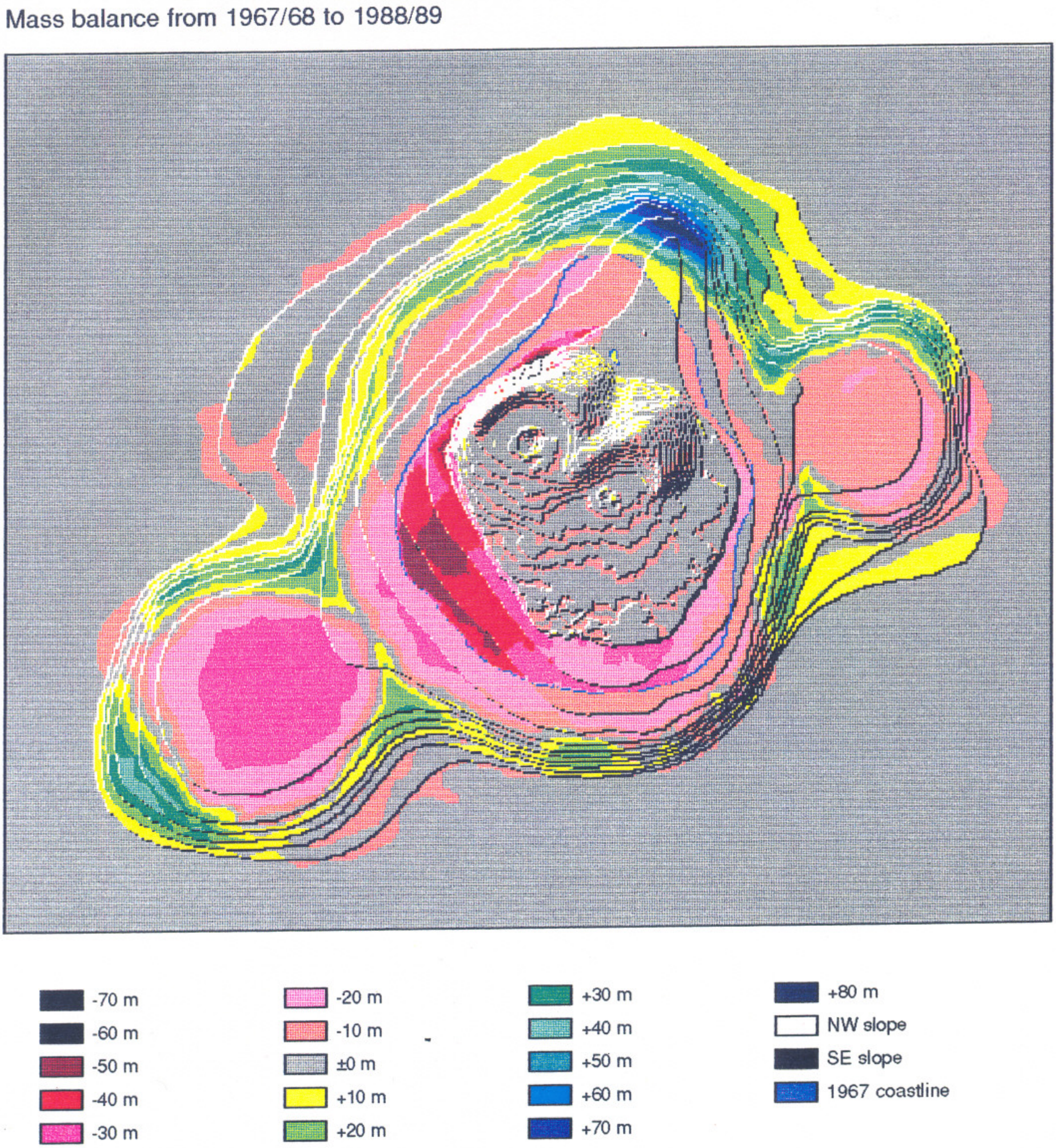


Fig. 12. Mass balance of the Surtsey volcanic group (except Surtla), obtained by subtracting the map in Fig. 2 from the map in Fig. 4. The values of the zones show the height difference thus obtained in each 10×10 m pixel. The contour lines from 1988/89 have been added, as has the 1967 coastline.

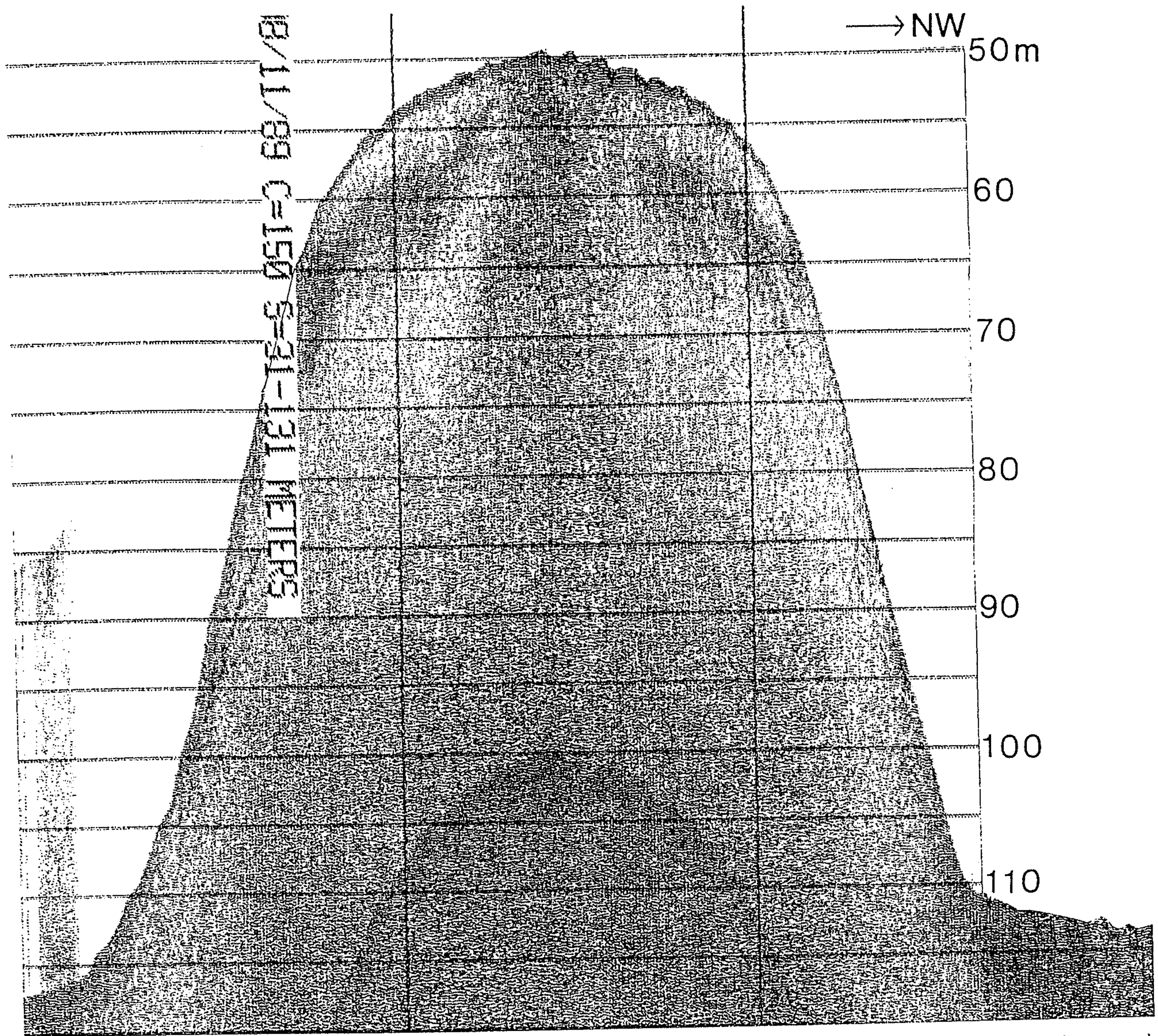


Fig. 14. Sub-bottom profile from Surtla (for position cf. Fig. 6). Some internal reflectors can be seen on the slopes of the plateau and on the bottom of the NW of it, indicative of post-volcanic deposition of tephra. The most prominent reflector on Surtla, however, is the prolonged echo at 5 to 10 m below the plateau surface. In the very centre of Surtla, where the profile passes the volcanic plugs, this reflector disappears. Instead, a long dark echo appears, obviously related to the volcanic plugs.

Nevertheless, the geographical distribution of the wave energy is clearly reflected by the net mass balance as shown by Figure 12.

The sub-bottom profiles were compared to this map, and it is obvious that the net accumulation on the slopes is a real feature. The dashed lines in Figure 13 reveal that there is a small accumulation on the NE slope of Syrtlingur, and an accumulation between Syrtlingur and Surtsey. It also shows one of the volcanic plugs. Profiles from around the northern ness reveal the presence of mass movement down the slopes, and profiles from the south slope of Surtsey and from the western and northern part of Jólnir also show the accumulation of material on the slopes.

In the central parts of the tephra plateaux of Surtla and Jólnir, a reflector (with a prolonged echo) is generally seen at 5 to 10 m below the surface. The best example is from Surtla (Fig. 14), where one also can see the stronger echoes obtained when passing over the volcanic plugs. The subsurface reflector bears a resemblance to reflections caused by gas in the sediments. But if there was gas (notably steam), the high temperatures would palagonitize the tephra and furthermore, there is no impermeable surface that prevents the gas from rising to the sea bottom. Instead, one may hypothesize that the reflection is caused by a steep temperature gradient, from the temperature of the ambient sea water, to 50–

100° (cf. the temperature log from Surtsey; Jakobsson and Moore, 1982, Fig. 7). When the tephra was deposited during the eruption it was chilled by the sea water, so the heat must be a secondary feature. The abrasion that lowers the platforms every year could explain why such high temperatures may be present so close to the cold surface.

CONCLUSION

In the future the lava cliff of Surtsey will probably become entirely eroded, unless it is resting on palagonitized tephra. Because of the decreasing transport of material towards the north, the northern ness will gradually become eroded while shifting position during storm events. The part of the island that will remain for probably thousands of years is the core of palagonite around the craters, very much like the other small islands and skerries in the Vestmannaeyjar archipelago.

The tephra plateaux of Surtla, Syrtlingur and Jólnir are still being abraded at a slowly decreasing rate. If they are not consolidated into palagonite, they will be abraded to the level of the surrounding bottom within 2000 yrs or less. The sub-bottom profiles of Surtla and Jólnir could indicate the presence of heat at a depth of less than 10 m below the tephra surface. If this heat causes the formation of palagonite, the plateaux will remain as sea mounts, with steep sides and a flat surface.

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Remote sensing studies of the geomorphology of Surtsey, 1987–1991

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INTRODUCTION AND BACKGROUND

The volcanic island of *Surtsey*, formed by explosive submarine and effusive subaerial eruptions between November 1963 and June 1967, consists of a complex combination of primary and redeposited tephra and alkaline olivine basalt lava flows in a 2.5 km^2 area (Thorarinsson, 1967; Thorarinsson et al., 1964; Fridriksson, 1975). During the past 24 years, wave and wind erosion of this subaerial mid-ocean ridge (MOR) vent complex have modified Surtsey's coastal morphology, including the deposition of a 0.5 km-long northern peninsula (*ness*) composed of tephra and rounded lava fragments derived from the southern half of the island. Detailed geomorphologic and sedimentologic mapping of the various surface units now present on Surtsey has been accomplished throughout the history of the evolving island, most recently by Calles et al. (1980) and Ingolfsson (1980). On the basis of these studies, an effort to quantify the topographic characteristics of the primary geomorphic units on the island was initiated by the *National Aeronautics and Space Administration* (NASA) and the *United States Geological Survey* (USGS) in 1987. The objective has been to directly measure the microtopographic properties of the widest range of surface types possible, with special emphasis on the pristine or dynamic types. While large-scale topographic maps of Surtsey were prepared in 1968 and 1975 (Norrman, 1980; Norrman and Erlingsson, 1991; Calles et al, 1980), and geodetic levelling surveys have been carried out (Moore, 1980), there have been no recent attempts to geodetically determine the local topography of the island. Because of the rapid rates of geomorphic processes, such as erosion and deposition, on a small, geologically isolated volcanic island such as Surtsey, it is desirable to determine the meter-scale topographic character of its surface units and landforms, and later a remeasurement of the same surfaces to further quantify volumetric change, subsidence, and process rates. In addition, precise measurements of sub-meter-scale topography of pristine geologic surfaces provides necessary data for the investigation of whether various geologic processes demonstrate fractal or self-affine behavior at a range of length-scales within the interval 0.1 m to 1 km. Thus Surtsey offers a unique opportunity to apply new remote sensing techniques to the measurement of the evolving surface "roughness" characteristics of pristine geologic surfaces within an historically well-monitored environment.

In 1987, NASA and USGS scientists and engineers initiated a multi-year project with the aim of measuring geodetically controlled topographic cross-sections of Surtsey on a biannual basis using aircraft laser altimeters. With the availability of the Global Positioning System (GPS) geodetic surveying techniques, it has become possible to position high spatial and vertical resolution topographic profiles determined by means of airborne laser altimetry (ALA) to within 10 cm (Bufton et al., 1991). GPS-tracking of aircraft, however, for the purpose of correcting for the vertical and horizontal positioning errors is in its infancy, and as the technique matures, our expectation is that annual surveys of the topography of rapidly evolving volcanic islands such as Surtsey could become routinely possible. In May of 1987, however, GPS tracking of aircraft motion was relatively untried, and this approach was attempted in parallel with previously proven methods that employed aircraft inertial navigation systems (INS), roll and pitch gyros, and vertical accelerometers. One of our colleagues, W. Krabill (NASA), has facilitated the application of GPS techniques to the problem of multi-temporal topographic monitoring of surfaces on Surtsey and elsewhere, and the new GPS-tracked ALA dataset acquired in September of 1991 provides 10–15 cm positional control on the basis of analyses conducted in the field (i.e., surveys of airfield runways).

The intent of this report is to summarize the ALA-based topographic data collected during our 1987, 1989, and 1991 remote sensing campaigns, and to highlight the preliminary results of our geologic analyses of these new forms of geomorphic data. In addition, we describe the initial results of a brief microtopographic field experiment conducted on Surtsey on 25 September 1991, as well as ancillary remote sensing data that has been acquired for the island since 1987 (Garvin and Williams, 1988). Once the 1991 ALA dataset is fully reduced and analyzed, justification for conducting future, geodetically controlled ALA overflights on a regular basis will be demonstrated.

A final objective in our topographic remote sensing studies concerns the morphometry of the vent craters, especially in comparison with craters associated with other Icelandic volcanoes. The morphometry of pristine volcanic craterforms is of interest to NASA, in part because of the commonplace occurrence of such features at various scales on all of the terrestrial planets (Venus, Mars, and the Moon). Indeed, NASA's *Magellan* mission to the planet Venus has revealed millions of volcanic edifices, many of which display summit craters reminiscent of those on Surtsey and elsewhere in Iceland (Garvin and Williams, 1990).

The format of this report is centered around examples of the data collected and a discussion of new methods for quantifying landscapes at very high spatial and vertical resolutions (i.e., finer than 1 meter in most cases). Details about the aircraft remote sensing instruments beyond those summarized in this report can be found in Bufton et al. (1991), and in Garvin and Williams (1990).

DATA ACQUIRED

In May of 1987, a NASA P-3 aircraft equipped with an airborne laser altimeter known as the *Airborne Oceanographic Lidar* (AOL) was deployed to acquire high-spatial resolution topographic cross-sections of Surtsey with sub-meter vertical control. The AOL was operated in a terrain mapping mode in this case at an altitude of 300 to 400 m above sea level (asl). The instrument utilizes a nitrogen laser transmitter together with a telescope and receiver electronics to acquire 400 pulses per second sampling of the topography along the P-3 aircraft's nadir track on the surface. The relative vertical resolution of each observation is better than 5 cm, and at an overflight altitude of 400 m the surface footprint (laser spot size on the ground) is approximately 40 cm in diameter. Thus, the topography is highly oversampled along the ground-track, because a typical P-3 aircraft velocity is 90–100 meters per second. Figure 1 illustrates four of the ALA profiles acquired on 28 May 1987 using the AOL in the NASA P-3 aircraft. GPS-tracking of the P-3 was attempted, but only the profile designated "GV305" (lowermost in Fig. 1) utilized the full benefits of GPS for vertical aircraft motion removal. The remaining three cross-sections were corrected using traditional vertical accelerometry, roll and pitch gyro, and INS techniques, and have an approximate vertical precison of better than 1 m.

Figure 1 displays four different azimuthal cross-sections of Surtsey. The profile designated "GV205" extends from west to east across the m-shaped pair of tephra rings. For each profile in this figure, four generalized topo-

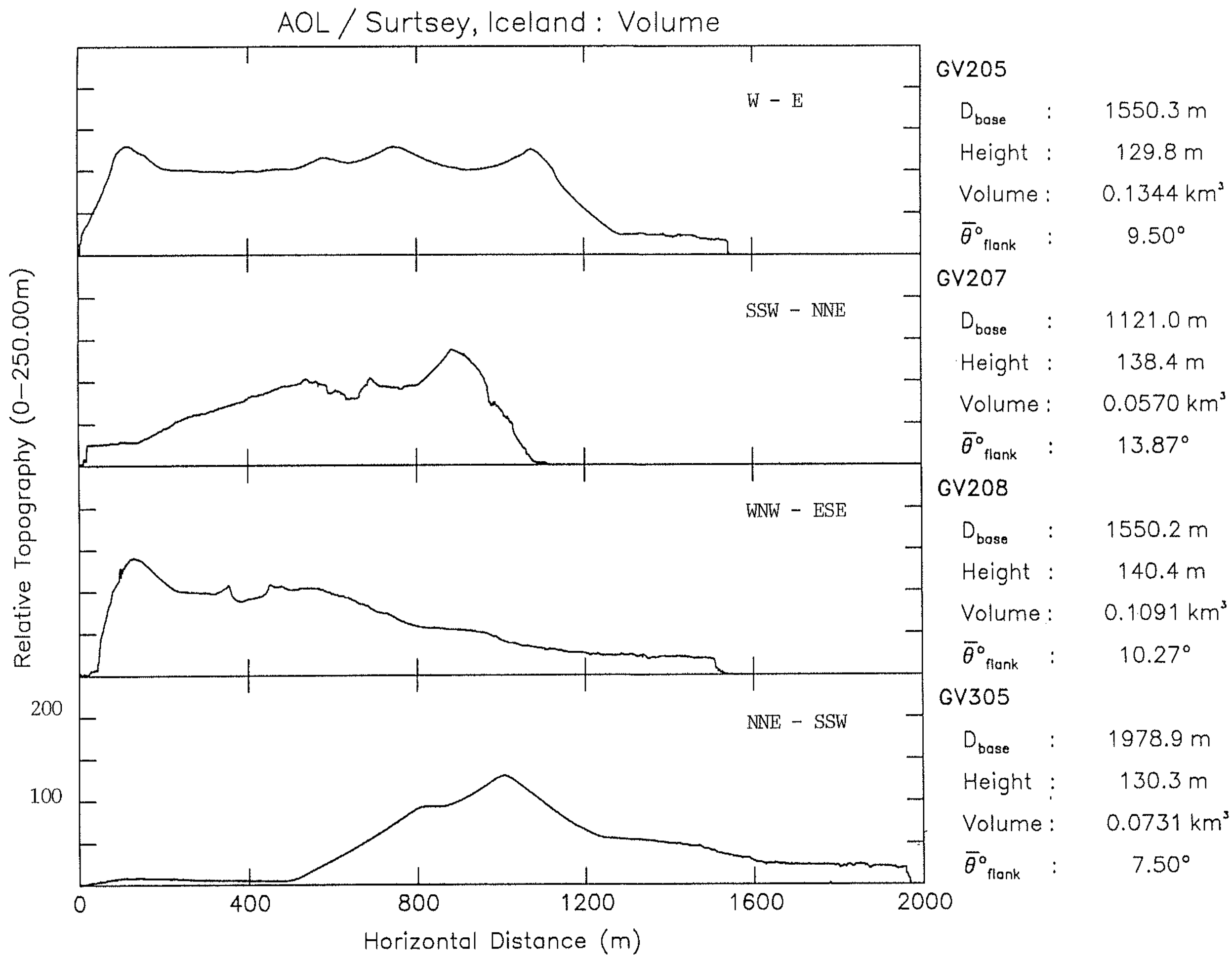

Fig. 1. Representative airborne laser altimeter topographic cross-sections of Surtsey acquired in 1987 using the AOL instrument. Spatial resolution is ~ 0.33 m, with vertical control at sub-meter levels (resolution is 5 cm point-to-point). Profile *GV205* is oriented from W to E, profile *GV207* extends from SSW to NNE across Surtur II crater, profile *GV208* traverses the island from WNW to ESE, and profile *GV305* bisects the island from NNE to SSW. Simple morphometric parameters are listed to the right of the topographic profiles. See text for details and figure 5 for location of the flight lines.

graphic parameters are given. The total length of the subaerial expression of the island is listed as *Dbase*, while the maximum height is listed under "*Height*". The above-water land volume of Surtsey is computed by numerical integration of each cross-section and listed under "*Volume*", and the average local slope of the entire cross-section is described by *∅°flank*. These parameters provide a framework for comparison of the different topographic profiles. The profile designated "GV207" extends across the Surtur II vent from SSW to NNE; profile "GV208" traverses Surtur II from from WNW to ESE; and profile "GV305" crosses the central region of the northern ness and the middle of the island from NNE to SSW. We have used these data to estimate the above water volume of materials exposed on Surtsey circa 1987 (i.e., *Volume* parameter at right of Fig. 1), and to compare these values with those for other small volcanoes within Iceland (Fig. 2). The numerical integration algorithm used in estimating the land volume from topographic profiles utilizes a straightforward "volumes of revolution" method, and as such assumes circular symmetry. As Surtsey does not display a circular perimeter, the computed volume estimates are best used as reasonable lower and upper bounds to the actual land volume.

Thorarinsson (1967), Calles et al. (1980), Jakobsson and Moore (1980), and Norrman and Erlingsson (1991) describe the apparent volume of the entire Surtsey system (submarine plus subaerial) as 1.1 to 1.2 km^3, with 60 to 70% of this volume manifested as tephra. A weighted average of the subaerial volume of Surtsey computed on the basis of the four

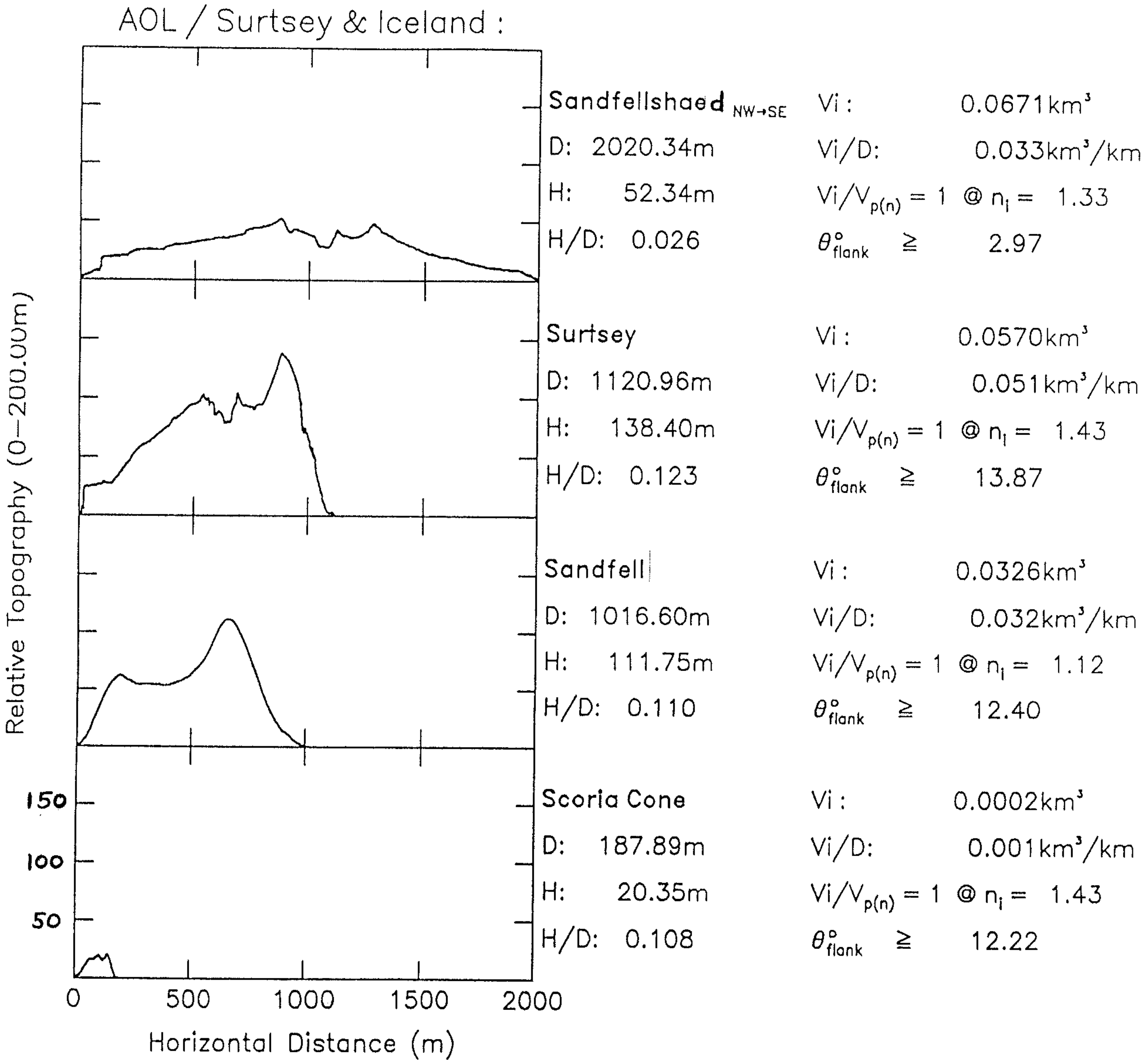

Fig. 2. Airborne laser altimeter topographic cross-sections of a representative suite of Icelandic mid-ocean-ridge volcanic landforms, including a SSW to NNE transect of Surtsey (GV207; see Fig. 1). All profiles except that for Surtsey have ~ 15 cm vertical control on the basis of GPS-tracking. All data are from the AOL instrument with 0.33 m horizontal spacing along track. Data for the Sandfellshaed lava shield, the Sandfell hyaloclastite ridge, and the Reykjanesskagi scoria cone were acquired in May of 1989, while that for Surtsey is from the May 1987 survey. Morphometric parameters listed to the right of the profiles are discussed in the text.

ALA profiles shown in Fig. 1 is 0.11 km^3 (similar to that of profile GV208 in Fig. 1), which is only ~ 10% of that computed for the entire edifice. In order to derive this estimate, we have measured the coastal outline of the island from 1989 aerial photographs (see Fig. 5) and then we have computed the fraction of the outline that is best represented by one of our ALA-based topographic cross-sections (Fig. 1). A simple weighted average of the volumes computed from the profiles using the weightings estimated from the coastal outline yields a volume of 0.11 km^3 to within 10%. This is consistent with the classification of Surtsey as a composite submarine volcano not unlike the subglacial table mountains of the Iceland mainland (Williams et al., 1983). Therefore, only 0.033 km^3 of effusive lava materials apparently cover the tephra core of the island in the form of a carapace of geologically more resistant materials. This lava volume is within a factor of two of that typical of the smaller Icelandic lava shields (Garvin and Williams, 1990; c.f., Fig. 2); hence we suggest that it is a reasonable estimate, at least for the subaerial inventory. Furthermore erupted lava volumes in the 0.01 to 0.10 km^3 range are apparently typical of limited-duration subaerial eruptions within all of Iceland (Garvin and Williams, 1990) and at other locales on the Mid-Atlantic Ridge (e.g., the Azores), and may be related to fundamental limits on the sizes of near-surface magma storage zones in MOR geologic settings.

COMPARISON WITH TYPICAL ICELANDIC VOLCANIC LANDFORMS

It is instructive to compare representative topographic cross-sections of typical subaerial MOR volcanic landforms with Surtsey. To facilitate such comparisons, we conducted an aircraft ALA remote sensing campaign in May 1989 using the AOL sensor together with a differential GPS tracking system. As part of our remote sensing experiment, we obtained geodetic topographic profiles of a Holocene lava shield within the western part of the Reykjanes peninsula known as *Sandfellshaed*, as well as cross-sections of the *Sandfell* hyaloclastite ridge just to the NE of Sandfellshaed, and of a small scoria cone near the *Eldvarpahraun* lava flow field (Fig. 2). In Fig. 2, we compare the 1987 SSW to NNE Surtsey cross-section (designated GV207 in Fig. 1) with a NW to SE profile of the Sandfellshaed lava shield, a NW to SE (orthogonal to the long axis) profile of the Sandfell hyaloclastite ridge, and a S to N transect of a small basaltic scoria cone. From these topographic data, we have computed the aspect ratios of the volcanoes (*H*/*D*), the total edifice volume (*Vi*), a polynomial shape parameter $\boldsymbol{n}$ (where $\boldsymbol{n} = 1$ represents a cone, $\boldsymbol{n} = 2$ a paraboloid etc.), and the average flank slope *∅°flank*. It is clear that Surtsey demonstrates an aspect ratio that strongly reflects its construction by means of tephra accumulation as a result of hydromagmatism; the subglacial Sandfell volcano illustrates a similar aspect ratio, while that of the monogenetic lava shield Sandfellshaed is a factor of 4 to 5 lower, reflecting its origin by purely effusive activity. All four of the volcanoes illustrated in Fig. 2 are predominantly conical in cross-section, although only the orthogonal profile across the Sandfell hyaloclastite ridge is purely conical ($\boldsymbol{n} = 1.12$). There is a tendency to develop a slightly concave (down) cross-section in almost all eruptions from a central vent, so that the polynomial shape factor $\boldsymbol{n}$ tends to values such as 1.5 to 2.0 (Garvin and Williams, 1990). While Surtsey and Sandfellshaed display similar edifice volumes (*Vi*) on the basis of the ALA profiles illustrated in Fig. 2, when one compares their volume productivities, here defined as the ratio of *Vi* to a typical basal diameter *D* (*Vi*/*D*), Surtsey is clearly the more volumetrically productive per unit length than simple effusive lava shield volcanoes such as Sandfellshaed. Indeed, because of its volumetrically dominant core of explosive tephra, Surtsey demonstrates a relatively large *Vi*/*D* ratio in comparison with most small basaltic volcanoes in general.

PRIMARY VENT CRATER SURTUR II

The most developed vent crater on Surtsey is *Surtur II*, the westernmost of the primary craters on the island (Figs. 3 and 5). Surtur II is the summit crater associated with the subaerial lava shield that built the pahoehoe lava carapace over most of the western third of the island. Figure 3 is a vertical aerial photograph of Surtur II acquired using a 70 mm *Hasselblad* camera system which was operated synchronously with the acquisition of our 1991 geodetic ALA topographic profiles. This view of the crater illustrates its relatively complex formation history. The general morphology of Surtur II suggests that the crater has undergone widespread interior collapse of its onetime continuous lava lake floor, yet its rim region reflects a stage in which lavas and scoria spilled over the edge to construct a lava ridge, perhaps analagous to the lava ring features observed on the mainland of Iceland (i.e., Eldborg; see Williams et al., 1983). Smooth appearing lava terraces within Surtur II apparently represent pre-existing lava lake levels, before the drainback processes that were established once flank eruptions became more dominant in the construction of the lava shield in southwestern Surtsey.

It is apparently useful to compare the detailed topography of various end-member volcanic craters in order to investigate whether there are systematic variations in their morphometries perhaps reflective of specific growth histories or of the mechanics of formation.

Fig. 4 illustrates three simple volcanic craters, including a 1987 SSW to NNE transect of Surtur II, a typical ALA cross-section of the summit crater at Sandfellshaed, and that of the SP Mountain basaltic-andesite scoria cone in northern Arizona, USA. We display the SP Cone pit crater because it is the most canonical example of a pit within a scoria cone for which we have GPS-tracked laser altimetry data. The source of the data for the Surtsey and Sand-

Fig. 3. 70 mm *Hasselblad* vertical aerial photograph acquired on 24 May 1991 from an altitude of ~ 460 m from a NASA P-3 aircraft. The image illustrates the morphology of the Surtur II vent crater, which has an average diameter of ~ 150 m and a typical depth of 25 m.

fellshaed profiles in Fig. 4 is the AOL sensor previously described, while that for SP Cone is NASA's *Airborne Terrain Laser Altimeter System* (ATLAS) which acquired topographic profiles of Northern Arizona volcanoes in October of 1989. The spatial resolution of ATLAS is 1.5–2 m depending on sensor altitude, and the vertical resolution is 15 cm (Bufton et al., 1991).

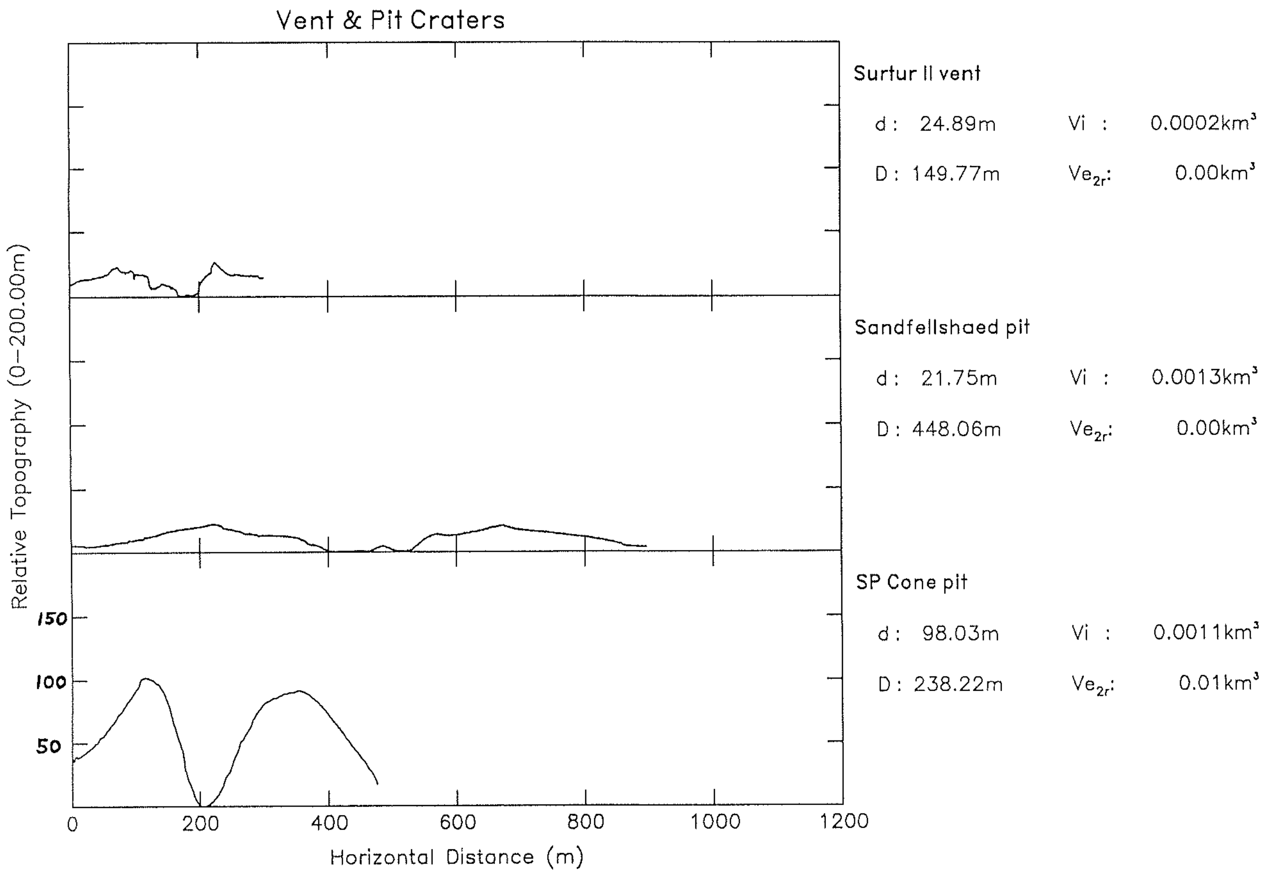

Fig. 4. Airborne laser altimeter topographic cross-sections of three volcano summit craters, including the 1987 SSW to NNE profile of Surtur II on Surtsey (top), the SW to NE profile of the Sandfellshaed lava shield summit crater acquired in 1989, and a 1989 *Airborne Terrain Laser Altimeter System* (ATLAS) profile of the *SP Mountain* basaltic-andesite scoria cone in northern Arizona, USA (with 2 m diameter footprints in contrast to the 0.33 m diameter footprints for the AOL data). All profiles display sub-meter vertical control. Simple depth *d*, basal diameter *D*, edifice volume *Vi*, and exterior volume *Ve* (within one diameter of the rim crest) geomorphic parameters are listed to the right of the profiles.

Figure 4 clearly shows the difference in appearance of the three craters. To quantify the crater shape differences, we can analyze the hypsometric properties of each crater by constructing a cumulative height frequency distribution and then computing the best-fitting power-law relationship to the height-frequency data. If N_z represents the cumulative percentage of heights greater than some height z, then we can find the parameters k and β so that:

$$N_z = k\, z^{\beta},$$

where the exponent β indicates the slope of the hypsometric distribution. If we compute such power law relationships for Sandfellshaed, Surtur II, and the SP Cone pit, we find that:

$$N_z = 267\, z^{-0.96}$$

for Surtur II (i.e., $k = 267$, and $\beta = -0.96$), whereas $k = 171$ and $\beta = -0.80$ for the summit crater of the Sandfellshaed lava shield. For the SP Cone pit crater, $k = 433$ and $\beta = -0.61$. The appreciable differences in the power-law slope values (the β's) for the three craters reflects their formation and degradation histories. The pristine Surtur II vent crater was formed by a combination of collapse (lava-lake foundering due to magma withdrawl) and extensive fire-fountaining and possibly lava spillover, while the apparently simpler Sandfellshaed summit crater was predominantly formed by collapse of a summit source vent lava lake as magma withdrew in anticipation of flank eruptions. Improved geodetic ALA topographic profiles of both Surtur II and the central portion of Surtur I were collected as part of our 1991 aircraft remote sensing campaign to Iceland and will be described later in this report.

NORTHERN NESS

As part of our data acquisition sequence in May of 1989, we acquired W to E cross-sections of the middle and northern portions of

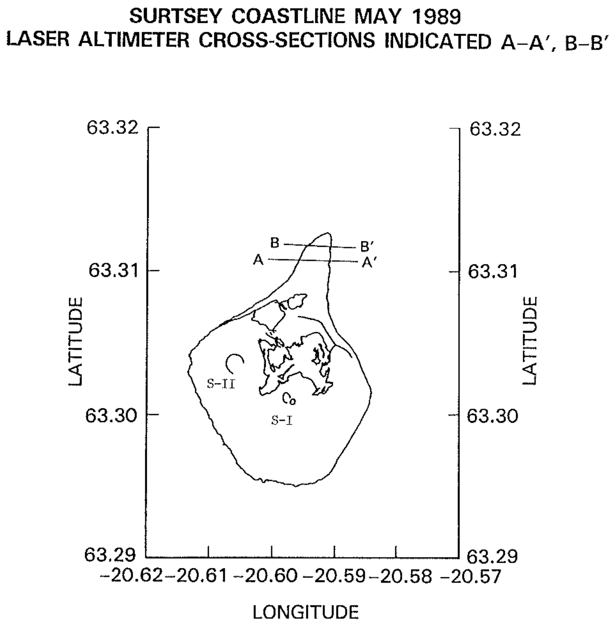

Fig 5. Outline map of Surtsey circa May 1989 illustrating the location of high-resolution topographic profiles of the northern ness acquired with the AOL system, and the other flight lines over the island described in the text.

the northern ness of Surtsey with enhanced spatial resolution. This was accomplished by operating the NASA P-3 aircraft at a flight altitude of 100 m, permitting the 400 pulses per second mode of the AOL instrument to acquire profiles with 20–25 cm horizontal sampling. Figure 5 illustrates the position of our extremely high resolution ALA profiles, acquired on 28 May 1989. In Figure 6, an E to W cross-section of the ness is shown in which the high frequency structure in the profile represents the cross-sections of individual boulders in the sub-meter-size range. In addition, it is possible to observe the nature of the wind-driven wave structure around Surtsey from the ALA data over the ocean adjacent to the island. The subtle concave character of the central, interior portion of the ness is apparent, in part a consequence of the deposition and erosion cycle in this part of the Surtsey system (Norrman, 1980; Moore, 1980; Norrman and Erlingsson, 1991). Our field experiment of 1991 confirmed that the 0.5 to 1.0 m scale berms seen in the ALA topography of the northern ness are wave-transported boulder berms derived from the eroding lava flows of the SW part of Surtsey.

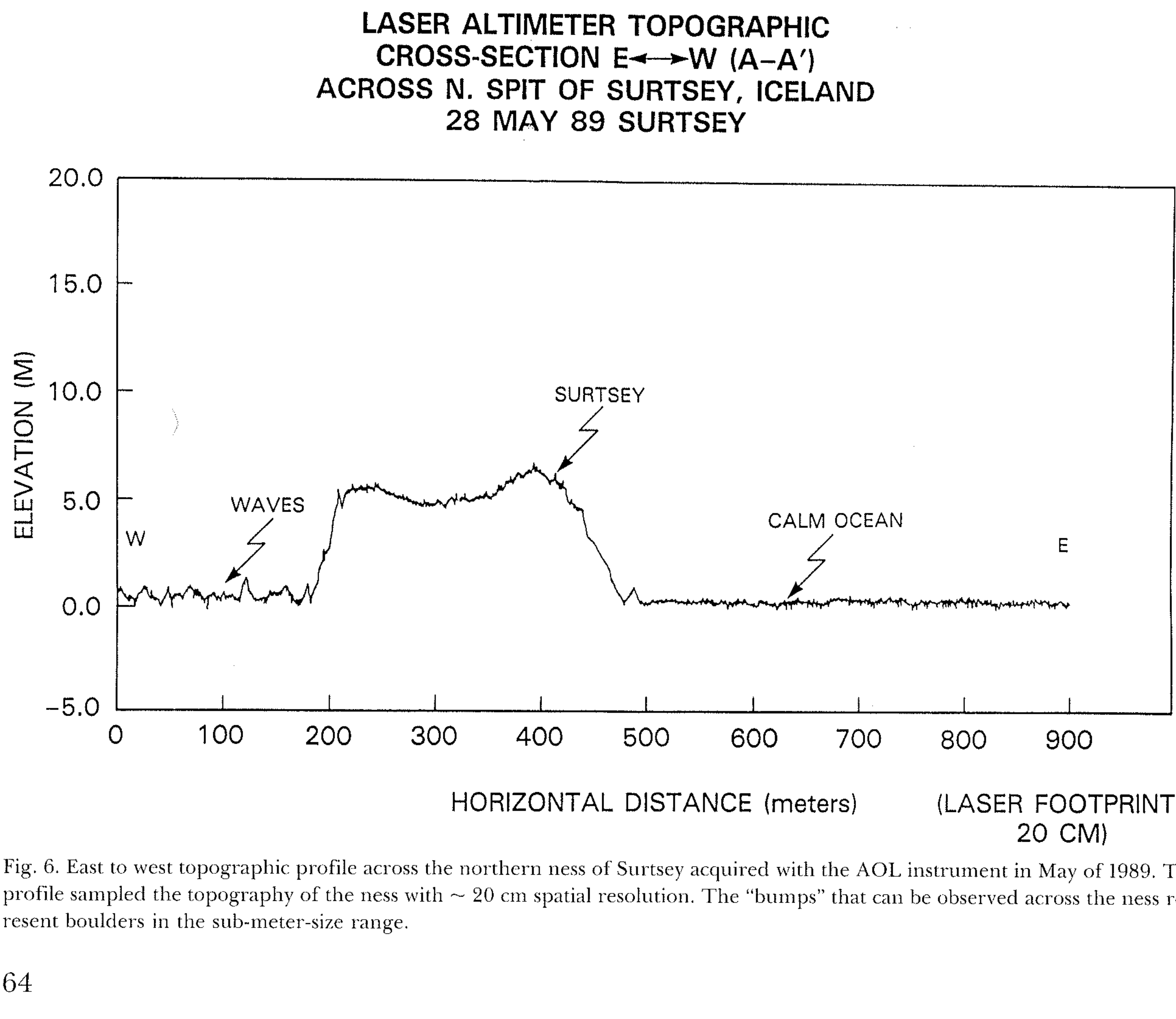

Fig. 6. East to west topographic profile across the northern ness of Surtsey acquired with the AOL instrument in May of 1989. This profile sampled the topography of the ness with ~ 20 cm spatial resolution. The "bumps" that can be observed across the ness represent boulders in the sub-meter-size range.

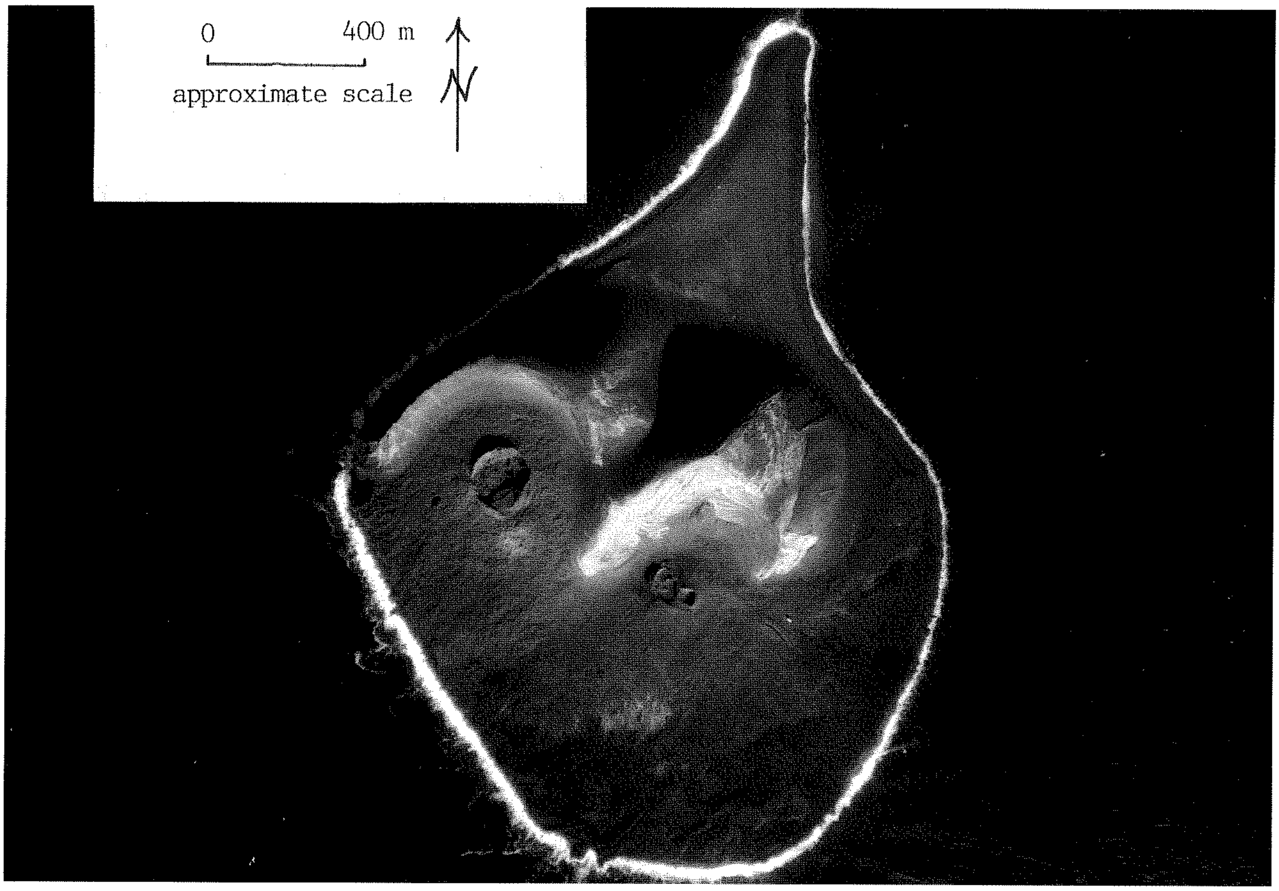

Fig. 7. 70 mm *Hasselblad* vertical aerial photograph of Surtsey acquired on 23 May 1991 from the NASA P-3 aircraft operating at ~ 3.3 km altitude (10,000 feet asl). This image was acquired at 11:30 local time (UT).

The topographic remote sensing data collected in 1987 and 1989 provided us with a mechanism for quantifying the microtopography of the more significant geomorphic units and volcanic features on the island. In 1991, we returned to Iceland to conduct a topographic remote sensing mission in which our objective was to measure the sub-meter scale topography of all the major units on Surtsey, but also to do so in a manner so that repeat overflights in later years can be carried out to quantify microtopographic changes, if any. All of the data collected in the 1991 topographic remote sensing campaign was required to have associated GPS-determined positional information at the 10 cm level. This entailed the use of multiple GPS receivers within the aircraft and GPS control of the autopilot (i.e., to facilitate reflying the same transect to within 10 m on the ground of the initial overpass). Topographic monitoring with geodetic-levels of accuracy for the most dynamic regions of Surtsey is our long-range objective, and the 1991 project was intended to provide baseline data for the purpose of comparisons with future datasets.

1991 FLIGHT AND FIELD MISSION

Figure 7 illustrates Surtsey as seen from a NASA P-3 aircraft on 23 September 1991. The 70 mm *Hasselblad* vertical aerial photograph is one of a series of overlapping frames acquired in order to document our ALA datasets. The photograph illustrated in Fig. 7 was taken by photographic engineer W. Lazenby (NASA) from an altitude of 3300 m asl at approximately 11:30 local time.

Figure 8 illustrates a "raw" laser altimeter profile (from S to N) of the middle region of Surtsey, acquired by the ATLAS sensor with a horizontal sampling resolution of 1.7 m and a vertical resolution of better than 15 cm. All of the profiles displayed in this report from our 1991 mission to Surtsey are not yet corrected for aircraft motion using the simultaneously acquired differential-GPS tracking data, but first-order roll-and-pitch variations have been removed, in some cases. Our calculations suggest that "raw" ATLAS data has a vertical integrity of 1–3 meters over a length scale of ~ 1 km. In Fig. 8, and all other preliminary 1991 ALA datasets, the horizontal axis is in units of

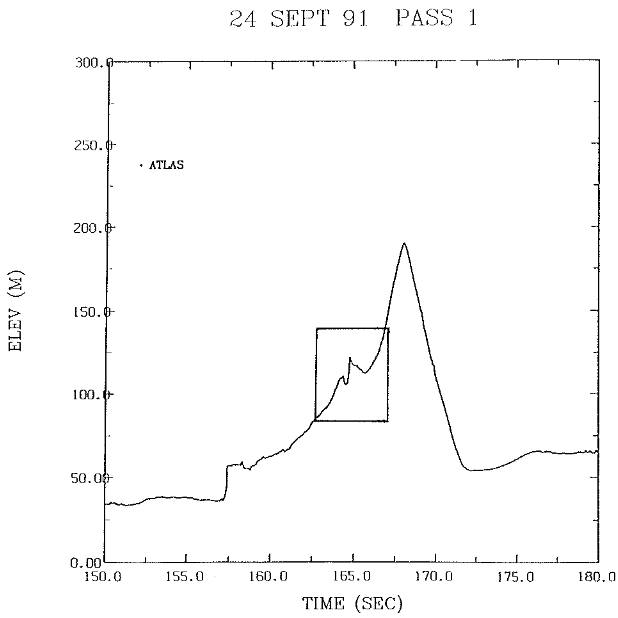

Fig. 8. Uncorrected ATLAS laser altimeter profile across Surtsey from S to N acquired on 24 May 1991 at 330 m elevation. The ATLAS instrument has a spatial resolution of about 1.7 m from this altitude, with a vertical resolution of better than 15 cm. Surtur I can be observed in this profile. Aircraft motion has not been removed from these preliminary data (i.e., GPS trajectories with which to correct the data are still forthcoming for all of our 1991 data). The horizontal axis is in units of time (seconds), and can be converted to horizontal distance using the observation that the NASA P-3 aircraft had an average forward velocity of 90 meters per second (i.e., 1 sec corresponds to 90 m along the ground).

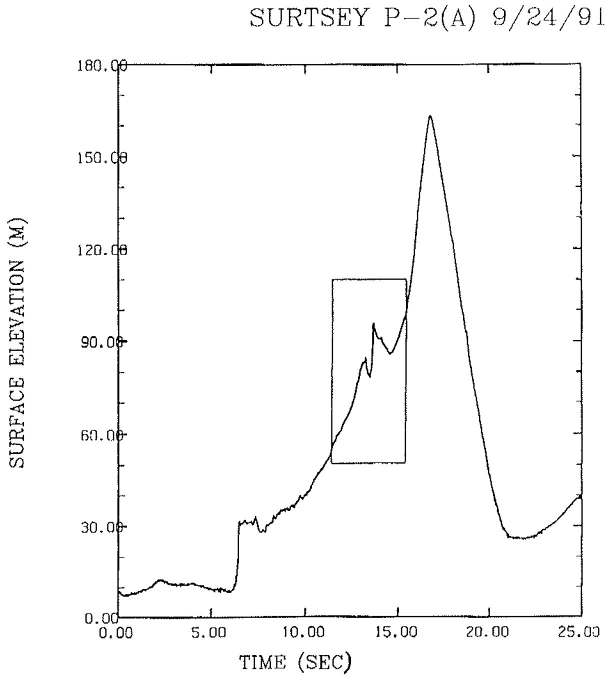

Fig. 10. South to north topographic cross-section of Surtsey acquired with the AOL sensor on 24 May 1991 from an altitude of 330 m. These data are uncorrected for aircraft motion. The AOL sampled the topography of Surtsey at 900 pulses per second in its 1991 configuration, which corresponds to a measurement every 10 cm along the ground-track. The inset box highlights the topography of Surtur I. These data have approximately 15 times greater horizontal sampling resolution than the ATLAS data illustrated in Figs. 8 and 9. The start of the pass was at 11:41:35 UT.

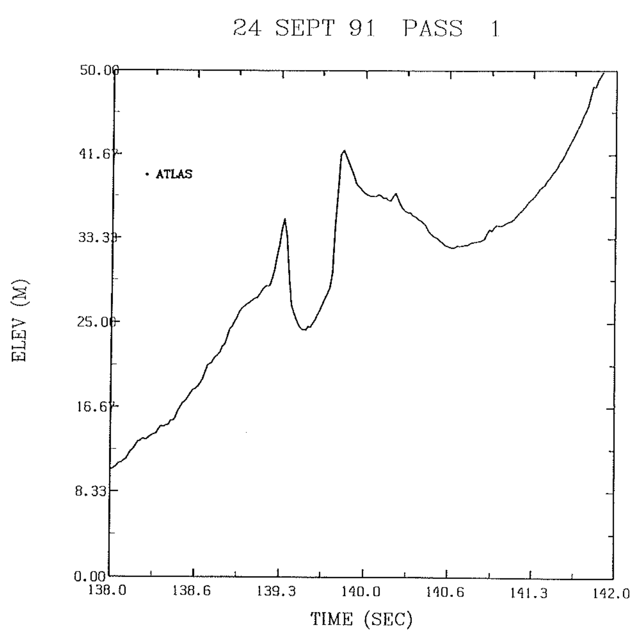

Fig. 9. Enlargement of a section of the topographic cross-section shown in Fig. 8 which illustrates the topographic structure of the *Surtur I* vent crater. One second corresponds to ~ 90 m on the surface in this and all other profiles from the 1991 remote sensing campaign.

time (seconds), where 1 second represents approximately 90 m. Figure 8 demonstrates that Surtsey is dominated by two indurated tephra rings (Jakobsson, 1972) which form a crude m-shaped outline across the middle portion of the island. A closeup ATLAS view of a S to N cross-section of Surtur I is illustrated in fig. 9. The largest crater in Surtur I is apparently more than 10 m deep and only tens of meters in width.

Figure 10 shows the S to N cross-section of Surtsey acquired by means of the AOL instrument operating at 900 pulses per second at 330 m aircraft altitude (i.e., one 30 cm diameter laser footprint spatially positioned every 10 cm along track). An inset box highlights the region around Surtur I, and Figure 11 shows a closeup of the vent crater. The high frequency structure in the floor of Surtur I represents a lava terrace which sits above the eolian drift sand that fills the crater's interior. Contrasting Figures 9 and 11 illustrates the effect of increasing the spatial resolution in topographic profile data by a factor of 10, from ~ 1.7 m

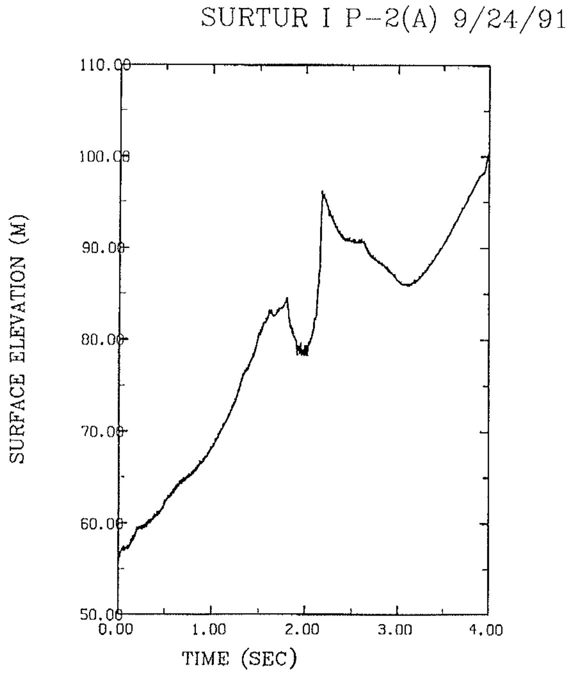

Fig. 11. Enlargement of section of topographic cross-section shown in box in Fig. 10 highlighting the *Surtur I* vent crater at high spatial resolution. Compare with the lower spatial resolution view (1.7 m) from the ATLAS sensor shown in Fig. 9. One second on the horizontal axis corresponds to 90 m. The start of the pass was at 11:41:46.5 UT.

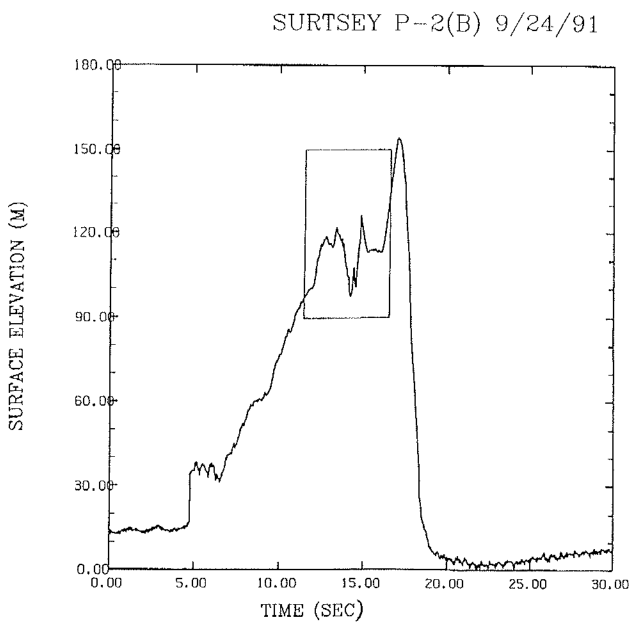

Fig. 12. Topographic cross-section of Surtsey acquired in a SSE to NNW direction using the AOL sensor on 24 May 1991 from an altitude of 330 m. Horizontal resolution is ~ 10 cm. The inset box highlights the Surtur II vent crater. The start of the pass was at 11:57:20 UT.

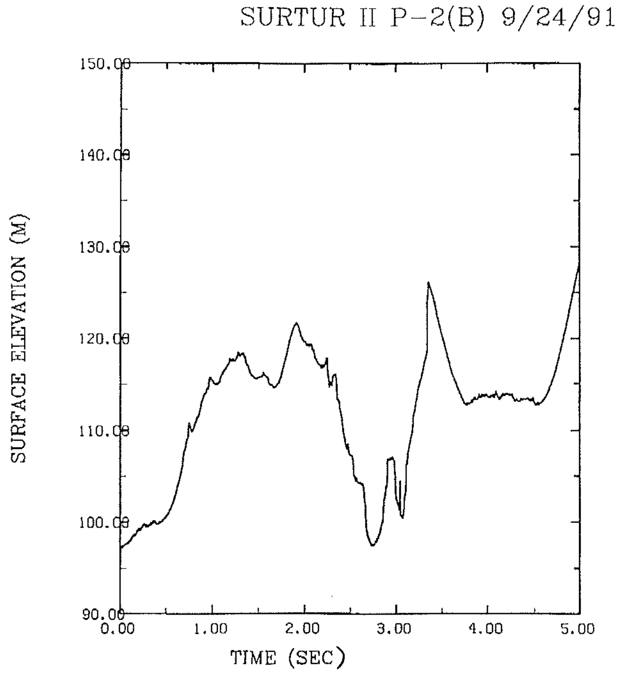

Fig. 13. Enlargement of region shown in the inset in Fig. 12. The clearly-defined depression is the pristine *Surtur II* vent crater. One second represents 90 m on the surface. The start of the pass was at 11:57:31.5 UT.

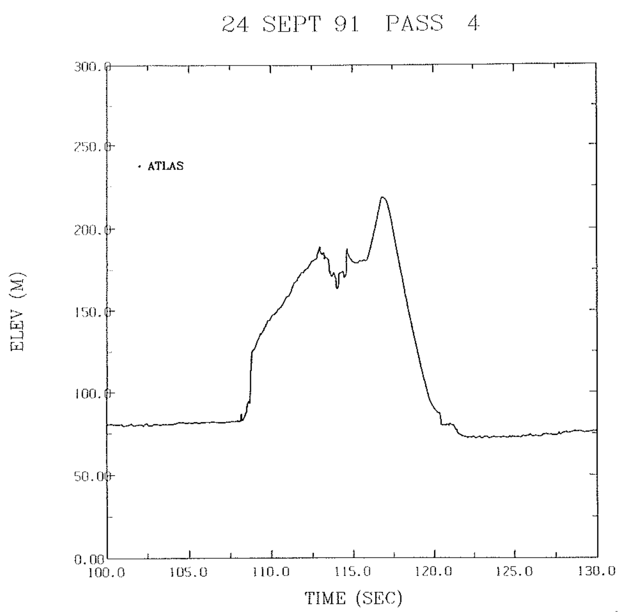

Fig. 14. Topographic cross-section of Surtsey in a SSW to NNE direction acquired on 24 May 1991 using the ATLAS sensor operating at 460 m elevation from a NASA P-3 aircraft. One second corresponds to 90 m along the surface. The ATLAS data have a horizontal resolution of ~ 1.7 m and a vertical resolution of better than 15 cm. Compare with the AOL profile shown in Fig. 12.

(Fig. 9) to ~ 0.10 m (Fig. 11) for the Surtur I vent crater.

As part of our 1991 mission, we acquired data in two different azimuths across the Surtur II vent crater, including that highlighted in Figures 12 and 13. These two Figures illustrate how the AOL sensor measured the detailed topography of the Surtur II vent at a sam-

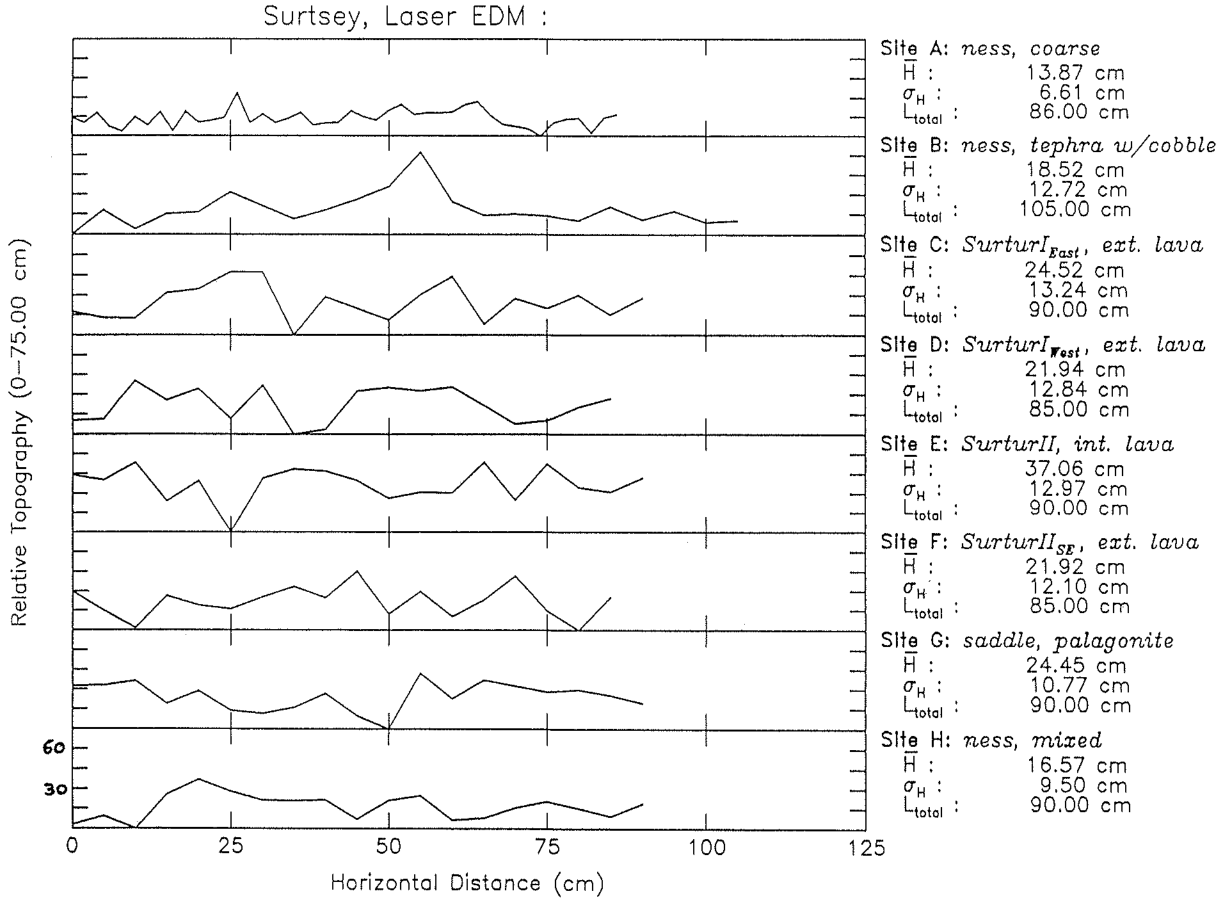

Fig. 15. Field-measured microtopographic profiles acquired on Surtsey using a laser electronic distance measuring device (Cubic Precision „*Red Dot*") with 4 mm vertical precision. Data were collected on 25 May 1991 for 8 sites on Surtsey. See text for further details. Profile at Site A (ness, coarse sand) produced from measurements spaced at 2 cm intervals; measurements for other sites (B through H) were acquired with 5 cm sampling intervals.

pling interval of 10 cm. Indeed, Fig. 13 shows a closeup of the tens of cm scale vertical structure of a 150 m diameter craterform, with a depth in excess of 25 m. Figure 14 illustrates another topographic profile of Surtsey acquired by the ATLAS sensor at 55 pulses per second (i.e., 1.7 m horizontal sampling along track). This profile (Fig. 14) crossed Surtur II from the SSW to NNE. These 1991 data should provide a unique set of ground-control points for features on Surtsey, because each profile has its own associated differential GPS tracking file to permit removal of aircraft vertical motion to 10 cm levels.

1991 SURTSEY FIELD SURVEYS

On 25 September 1991, the senior author and three other individuals (see acknowledgements) visited Surtsey for ~ 6 hours for the purpose of making direct measurements of the 2–5 cm scale microtopography of representative geomorphic surfaces. Our method for making the required measurements in so short a time centered around a hand-held laser distance measurement device known as a "*Red Dot*" (manufactured by Cubic Precision; see acknowledgements), together with a pair of tripods on which we mounted a 1.4 meter-long reference bar. We calibrated the "*Red Dot*" system under several conditions (inside and outside) and found that for smooth surfaces it yielded reproducible results at the 4 mm level. Therefore we decided to translate the "*Red Dot*" instrument either 2 or 5 cm along a graduated and levelled reference bar supported by a pair of tripods in order to construct a profile of the surface microtopography. Our objective was to acquire as many 1 meter long microterrain profiles as possible, with either 2 cm or 5 cm sampling along each meter-long traverse. Due to winds that averaged over 30 knots (~ 15 meters per second), additional sources of error in our "*Red Dot*" measurements are likely, at least at the 1–2 mm level.

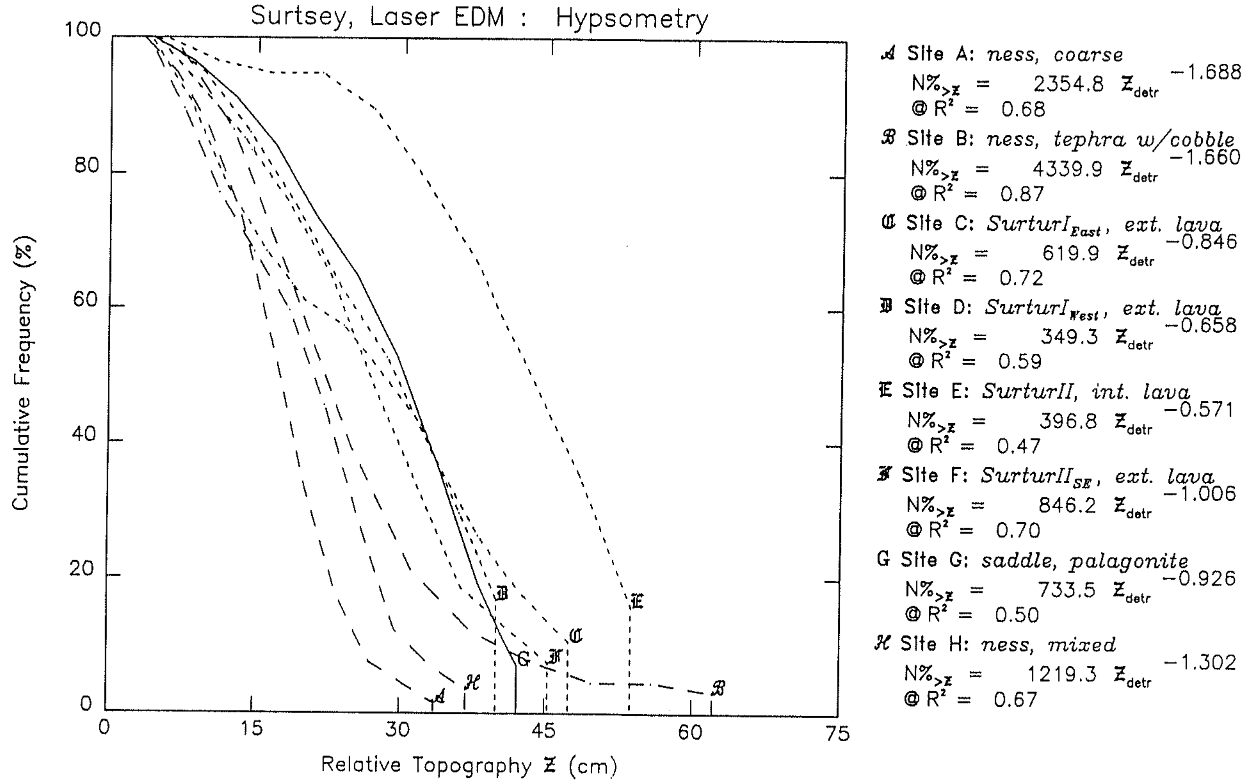

Fig. 16. Hypsometric distributions for the field survey site microtopographic profiles illustrated in Fig. 15. Sites A, B, and H are on the *ness* and are denoted with dashed curves, while sites C–F are lava surfaces and these are denoted with dotted curves. The solid curve (G) represents the one palagonitized tephra site (saddle area of the dual tephra rings). Those power-laws which best fit the actual data plotted in this figure are listed at the right. See text for additional details.

Figure 15 illustrates the 8 microterrain profiles acquired with the "*Red Dot*" sensor on 25 September 1991. The 8 sample sites ranged from poorly-sorted coarse eolian deposited tephra on the ness to various examples of slabby or platey lavas adjacent to and within the two vent craters. The text for sites A through H listed to the right of the actual data in Fig. 15 summarize the mean relative elevation (*H*), the standard deviation of local elevation (*sigma*), and the total length of the profile. Except for the initial site (A) within the poorly consolidated surficial materials of the ness, we used a sampling increment (***dx***) of 5 cm. For site A on the ness, we investigated the merits of a 2 cm ***dx***, but found that instrument stability in the gusty winds made observations difficult for longer than 10 minutes. These field data will serve as the basis for assessing whether our ALA topography data adequately sample the most significant wavelengths of topography necessary to understand the geomorphic evolution of a natural surface. In Figure 16, a family of hypsometric curves derived from the cumulative distribution of cm-scale elevations which can be computed from the topographic profiles shown in Fig. 15 is illustrated. In this plot, the solid curve represents our one test site (G) in palagonitized tephra (in the saddle region between the two tephra rings), the finely stippled curves denote lava sites, and the dash pattern denotes those sites on the ness. From the data plotted in Fig. 16, it appears that the relict lava lake slab pahoehoe (*helluhraun*) lava surface at site E is anomalous, and the power-law exponent in the fit to the raw hypsometric data is statistically distinct from all the other sites at a 95% level of confidence. To the right of the curves plotted in Fig. 16 is the best-fitting power law to the cumulative height frequency distribution (hypsometric distribution) for each site. These relationships are listed in the form of equations with two free parameters, k and β.

If N_z is the cumulative frequency (%) of local, relative elevations larger than a given elevation z, then the hypsometric power law is given by:

$$N_z = k\, z^{\beta},$$

with a correlation coefficient of R^2. Thus, sites A and B located within the same general vicinity of the ness display very similar power-law statistics. The hypsometric power law exponent values (β's) apparently reflect some degree of formation process control on cm-scale topography at meter length scales. Thus, β values for the lava flow surfaces range from −0.57 to −1.00, while those for the ness sites vary from −1.3 to −1.7. The indurated palagonite site (saddle site G) appears to statistically resemble the lava flow sites in terms of its β value (−0.93), yet this similarity may be more a function of the mechanical strength or competency of the target. We have not fully interpreted the significance of these field microterrain data for Surtsey, but we did learn that 6 hours on a 2.4 km^2 island is not sufficient time to measure the entire suite of surfaces that exist on the island.

SUMMARY

In this report we have summarized the highlights of an ongoing NASA/USGS investigation of the topographic characteristics of a geomorphically active, yet pristine MOR volcanic island. Geodetic microtopography profiles from aircraft remote sensing data acquisition missions have been acquired in 1987, 1989, and most recently in September of 1991. We have demonstrated the unique morphometries of various terrain types on Surtsey, and are now in the process of reducing and analyzing the hundreds of megabytes of aircraft laser altimeter data (AOL and ATLAS), as well as the associated data from our GPS receivers acquired during our September 1991 aircraft remote sensing campaign. Results of our ALA and *in situ* field topographic surveys of Surtsey attest to the uniqueness of several of its surfaces, including the main vent crater Surtur II and the palagonitized tephra.

From the four directional profiles illustrated in Figure 1, the subaerial expression of the MOR volcanic edifice that represents Surtsey as a whole is best approximated by an asymmetric ridge with a cross-section that approaches a paraboloid in an E-W direction, but is more conical in a N-S orientation, not unlike Hekla (Williams et al., 1983). The surface area of the island as of May 1987, as computed from a weighted numerical integration of the four profiles shown in Fig. 1, is less than 2.43 km^2, and the aspect ratio (Height to basal Diameter ratio, *H/D*) of Surtsey apparently averages 0.09, with a range from 0.066 to 0.12. Mean local slopes are 20° to 24° depending on orientation, with large variances (10°–16°). The normalized mean height of the island is approximately 44 m (± 2 m), on the basis of the mean volume-to-surface area ratio. We believe that these data represent the meter-scale topographic character of Surtsey, and that they serve as the basis for comparison with other MOR volcanoes.

Ground surveys of the cm-scale topography of small segments (100 cm) of typical surfaces clearly demonstrate that differences in local topography reflect formation and degradational histories. Our objective is to return to Surtsey for additional field surveys, perhaps utilizing differential GPS surveying techniques for measuring extremely local topography (< 10 cm scale). The ALA topographic data collected for Surtsey can be used to assist scientists who will be investigating newly acquired (June 1991) airborne imaging radar (SAR) and multispectral imaging spectroscopy data; these uniques datasets were collected for Surtsey in June of 1991, but await reduction at the time of this writing.

ACKNOWLEDGEMENTS

The authors are especially grateful to Prof. Sveinn P. Jakobsson for promptly issuing us a research permit to visit Surtsey. In addition, all of the ALA topographic data displayed in this report was made possible by the efforts of a team of NASA-affiliated scientists, engineers, and technicians, including William B. Krabill (GPS, terrain science), Jack L. Bufton (laser altimetry), J. Bryan Blair (software engineering), Robert N. Swift (sensor operations), David J. Harding (topographic science), William O. Lazenby (photography), Earl B. Frederick (GPS and data analysis), Dave L. Pierce (Mission operations and logistics), James K. Yungel (AOL operations), pilots Virgil E. Rabine, George W. Postell, and John T. Riley, and to data analyst/programmer Melanie A. Taylor. Finally, we wish to thank our dynamic friend *Surtsey* itself, Lt. Susan N. Greer, USN (Naval Oceanography Command Facility, Keflavik Air Station) for expert data logging in the field on Surtsey, Commander Frederick C. Zeile, USN (NOCF) for helping us secure helicopter support for our Surtsey field experiment, Jósef Hólmjárn, Icelandic National Energy Authority, and William O. Lazenby, NASA Photographic Engineer, for their assistance in the field on Surtsey, and Cynthia J. Slater for motivation throughout all of this. Mr. Lucian Caycee of Cubic Precision, Inc.

(Tennessee, USA) kindly loaned us his prototype "Red Dot" laser ranging device for use in the field on Surtsey. We would like to especially thank Dr. Miriam Baltuck and colleagues at NASA's Code SEP project office for funding RTOP 465-44-03 (Ridge Volcanism Project) to support these activities over the past several years.

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Encrustations from Lava Caves in Surtsey, Iceland. A Preliminary Report

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INTRODUCTION

During the Surtsey eruption off the south coast of Iceland (Thorarinsson 1967), abundant volcanogenic encrustations formed at the lava craters of Surtsey, especially at the large western lava crater (Fig.1). Nine samples of high-temperature encrustations, which were collected from the surface of lava in Surtsey during the eruptions in 1963-1967, were analysed in detail by Óskarsson (1981). He recognized four minerals in these encrustations, sulfur, galeite, thenardite and aphthitalite, the two last-named being most abundant. Torssander (1988) determined the sulfur isotope ratios in some of these samples. Jakobsson & Moore (1986) further identified gypsum and halite as common low-temperature encrustations.

Since the cessation of the eruptions in 1967, samples of encrustations have been collected during the many trips to the island, mainly from lava caves, since surface encrustations quickly started to decompose. The present report is a preliminary account of the encrustation samples from Surtsey which are kept in the mineral collection of the Icelandic Museum of Natural History in Reykjavík. The samples were collected during the years 1967-1990.

LAVA CAVES IN SURTSEY

The Surtsey lavas are of alkali basaltic composition and because of their low viscosity they tended to flow in tubes and closed trenches, especially from the western lava crater (Fig. 1), where the lavas formed a 100 m thick shield. Although lava caves were discovered by visitors at least as early as 1966, the speleology of Surtsey did not really attract the attention of scientists until recently, when two members of the Icelandic Speleological Society visited Surtsey to investigate the lava caves (Jónsson & Hróarsson 1990 & 1991). In addition to two lava caves recorded by Ólafsson (1982), eight new lava caves were investigated. Most of the caves are emptied sub-horizontal lava tubes, others are emptied near vertical lava feeder-channels in the eastern lava craters. The location of the largest lava caves in Surtsey along with a few profiles is shown in Jónsson & Hróarsson (1990) and some of the caves are described by Hróarsson (1990). Encrustations presumably formed in most of these caves, at least during the initial cooling period of the la-

TABLE I

Encrustations from lava caves and caverns in Surtsey, collected 1967-1990. Minerals are listed in estimated order of abundance for each sample. Localities are shown on Fig. 1.

IMNH 1092. Stalactite, length 9,5 cm, from a lava cave somewhere on the south shore. Collected on January 3, 1967; no temperature data.
HALITE, yellow, stalactitic.
CARNALLITE, brownish, powdery coating.
Unidentified species.

IMNH 1027. Powdery crust, up to 1 cm thick, from a lava cave at the western lava crater. Locality 1 in Fig. 1. Collected in Sept. 1969; no temperature data.
THENARDITE, white, powdery.
GYPSUM (trace), white.

IMNH 1962. Solid crust, up to 3,5 cm thick, from the floor of „Grillid", the entrance to the lava cave S-4, 80 m SE of the western lava crater. Locality 1 in Fig. 1. Collected on July 9, 1971; temperature ≥70°C.
HALITE, colorless, massive.
ANHYDRITE, white.
KAINITE, colorless.
GLAUBERITE, white.
$Na_2Ca_5(S0_4)_6 \cdot 3H_20$ (JCPDS no. 35-137).
Unidentified species.

IMNH 7484. Stalacites, length up to 45 cm, from „Grillid", the entrance to the lava cave S-4, 80 m SE of the western lava crater, cf. IMNH 1962. Locality 1 in Fig. 1. Collected on July 9, 1971; temperature ≥70°C.
HALITE, colorless, stalactitic
LOEWEITE, colorless.
Unidentified species.

IMNH 1963. Stalactites, length up to 25 cm, from „Grillid", the entrance to the lava cave S-4, 80 m SE of the western lava crater. Locality 1 in Fig. 1. Collected on June 13, 1972; temperature 65°C.
HALITE, colorless, stalactitic.
BLOEDITE, colorless.
THENARDITE, white.
GLAUBERITE, white.
Unidentified species.

IMNH 1964. Stalactites, length up to 10 cm, from „Grillid", the entrance to the lava cave S-4, 80 m SE of the western lava crater, cf. IMNH 1963. Locality 1 in Fig. 1. Collected on June 13, 1972; temperature 65°C.
HALITE, colorless, stalactitic.
KAINITE, colorless.
KIESERITE, white, botryoidal.
LOEWEITE, white, massive.
Unidentified species.

IMNH 1965. Powdery crust, up to 1,5 cm thick, from a cavern in the southwestern wall of the western lava crater. Locality 2 in Fig. 1. Collected on June 13, 1972; ambient temperatures.
THENARDITE, white, powdery.
GYPSUM, white.

IMNH 6382. Crust, up to 3 mm thick, on lava from a lava cave at the western lava crater. Locality 1 in Fig. 1. Collected on Sept. 7, 1973; no temperature data.
GYPSUM, white, prismatic.
ANHYDRITE, white.
HALITE, white.
Unidentified species.

IMNH 7459. Grayish crust (impregnated with basalt tephra), botryoidal on surface, 1-3 mm thick, from a vertical feeder-channel to the easternmost Ágústgígar. Locality 3 in Fig. 1. Collected on August 17, 1979; ambient temperatures.
GYPSUM, colorless, massive.

IMNH 12382. Powdery crust, up to 2 mm thick, from the roof of lava cave S-1 on the east shore. Locality 4 in Fig. 1. Collected on August 10, 1988; ambient temperatures.
HALITE, white, powdery.
CALCITE, white, powdery.
GYPSUM (trace), white.

IMNH 12383. Massive crust, up to 2 mm thick, on the under side of a lava slab, at the entrance to lava cave S-1 on the east shore, cf. IMNH 12382. Locality 4 in Fig. 1. Collected on August 10, 1988; ambient temperatures.
SULPHUR, light yellow, massive.

IMNH 12387. Crust, up to 1-2 mm thick, on the under side of a lava slab, at lava craters from Dec. 1966. Locality 5 in Fig. 1. Collected on August 10, 1988; temperatures 63°-67°C.
CALCITE, white, crusty.
OPAL-A, white, massive.

IMNH 15100. Crust, up to 2-3 mm thick, of minute crystals from the floor of cave S-3 on the western side. Locality 6 in Fig. 1. Collected on July 12, 1990; ambient temperatures.
GYPSUM, grayish-white, diamond-shaped.

IMNH 15101. Powdery crust, up to 3 cm thick, from the floor of cave S-3 on the western side, cf. IMNH 15100. Locality 6 on Fig. 1. Collected on July 12, 1990; ambient temperatures.
THENARDITE, white, powdery or platy
GYPSUM (trace), white.

IMNH 15102. Crust of crystals, up to 3 mm thick, from a shelf in cave S-4 on the western side. Locality 7 in Fig. 1. Collected on July 12, 1990; temperatures 35°-40°C.
GYPSUM, colorless-white, prismatic crystals
FLUORITE, white.
Unidentified species.

IMNH 15103. Layered crust, up to 2 cm thick, from a shelf in cave S-4 on the western side, cf. IMNH 15102. Locality 7 in Fig. 1. Collected on July 12, 1990; temperatures 35°-40°C
GYPSUM, white, prismatic crystals.
FLUORITE, white, powdery.
OPAL-A, white.

IMNH 15104. Efflorescence, up to 2 mm thick, from the wall in cave S-4 on the western side, cf. above. Locality 7 in Fig. 1. Collected on July 12, 1990; temperatures 35°-40°C.
FLUORITE, white, fibrous or platy.
OPAL-A, white.

IMNH 15105. Layered crust, up to 5 mm thick, from a shelf in cave S-4 on the western side, cf. above Locality 7 in Fig. 1. Collected on July 12, 1990; temperatures 35°-40°C.
GYPSUM, white, prismatic to tabular crystals.

IMNH 15106. Layered crust, up to 1 cm thick, from the floor in cave S-4 on the western side, cf. above. Locality 7 in Fig. 1. Collected on July 12, 1990; temperatures 35°-40°C.
GYPSUM, white, prismatic to tabular crystals.

IMNH 15107. Crust, about 1-2 mm thick, from a shelf in cave S-4 on the western side, cf. above. Locality 7 in Fig. 1. Collected on July 12, 1990; temperatures 35°-40°C.
OPAL-A, white.
FLUORITE, white.
RALSTONITE, yellow-brown.

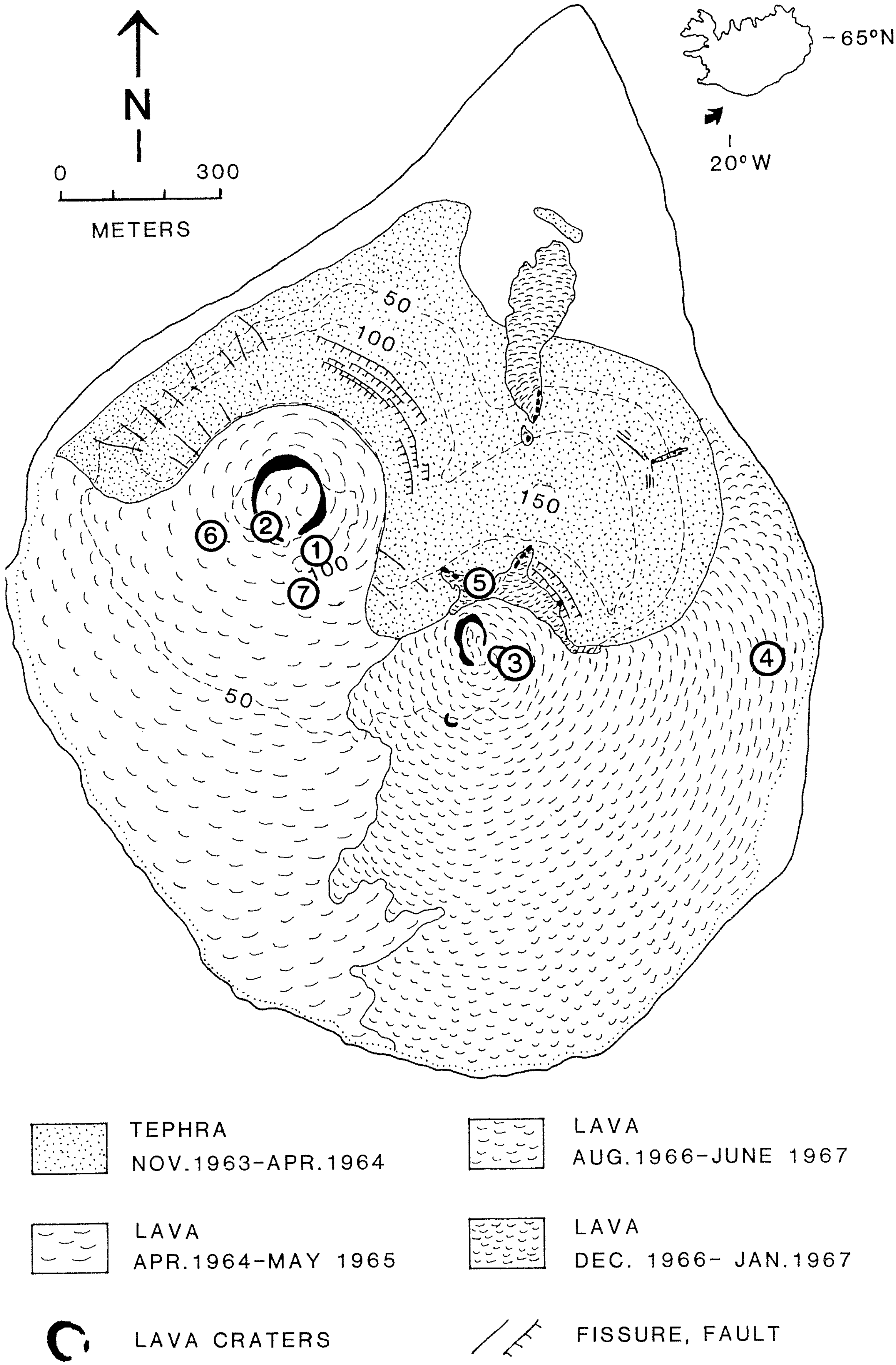

Fig. 1. Geologic map of Surtsey. Elevation contours are in meters. After Jakobsson & Moore (1986). Sample localities mentioned in TABLE I are marked with numbers.

vas. In 1990 abundant encrustations were still to be found in three of the caves, designated S-2, S-3 and S-4, while traces were found in one, S-1. Emptied lava tubes appear to be exceptionally common on Surtsey and in addition there are numerous caverns and voids in the Surtsey lavas where volcanogenic encrustations were deposited during cooling of the lavas.

MINERALOGY OF THE ENCRUSTATIONS

Twenty samples of encrustations from the caves were examined, the samples being described in TABLE I and the localities given in Fig. 1. Each sample was examined under the binocular microscope and all discernible phases separated by hand-picking. The determination of the mineral phases was performed at the Department of Mineralogy, University of Copenhagen, with a Philips vertical powder diffractometer, using CuKα radiation. A few small samples were identified with the Gandolfi camera. The identifications were performed with aid of the JCPDS standard diffraction file, sets 1-39, CD-ROM edition.

Altogether 16 minerals could be determined leaving several species undetermined. The minerals are listed under each sample in Table I in estimated order of abundance. Halite, thenardite and gypsum proved to be abundant in the samples, although unevenly distributed. Opal-A (cf. Jones & Segnit 1971), fluorite, calcite and anhydrite are rarer and are found in much smaller amounts. Glauberite, kainite and loeweite are only found in small amounts and kieserite and bloedite in trace amounts in stalactites which mainly consist of halite. Carnallite, ralstonite and a mineral, corresponding to the synthetic compound Na_2 Ca_5 $(SO_4)_6 \cdot 3H_2O$ (JCPDS No. 35-137) are very rare, and sulfur was found at one locality. There appear to be at least five unidentified species. Seven of the above-mentioned minerals, glauberite, kainite, loeweite, kieserite, bloedite, carnallite and ralstonite, apparently have not been described from Iceland previously.

ENVIRONMENTAL FACTORS

Several of the encrustations appear to have been sampled at the time of deposition. Of special interest is „Grillid" the entrance to the lava cave S-4, which was visited in July 1971 (cf. TABLE I, samples IMNH 1962 and 7484) and again in June 1972 (samples IMNH 1963 and 1964). In 1971, stalactites of halite with anhydrite, kainite, glauberite and loeweite were sampled at ≥70°C and in 1972 halite, bloedite, thenardite, glauberite, kainite, kieserite and loeweite were sampled at 65°C. In these samples only thenardite and possibly halite appear to be decomposing. Since kainite, glauberite and loeweite could be sampled again in 1972 without signs of dissolution, it appears probable that these minerals were in equilibrium with the surroundings in „Grillid" in 1971 and 1972. The temperatures in 1971 may have been somewhat higher than 70°C (the thermometer was still rising when the geologists had to retreat to the surface because of the heat), and in places possibly as high as 90°-100°C. During the following years temperatures declined in „Grillid". In August 1979 temperatures of approx. 25°-35°C were prevalent and no traces of encrustations could be found. In August 1988 only ambient temperatures (10°-12°C) could be measured. It is tentatively suggested that kainite, glauberite, loeweite, bloedite, kieserite and probably halite were being deposited in the stalactites mainly at 65°-100°C. The lower limit of deposition of these minerals cannot be determined, it is, however, well above 35°C. It appears possible that thenardite, anhydrite, carnallite and $Na_2Ca_5(SO_4)_6 \cdot 3H_2O$ also were formed in the above-mentioned temperature range.

Most of the minerals identified in the stalactites are common in oceanic salt deposits. Deuterium measurements of steam condensates collected in 1971 in fissures in the Surtsey lavas (Jakobsson 1978) indicated a sea water origin where the steam emanation was vigorous, the steam being vaporized sea water. Presumably the sea water has been boiling at sea level where it comes into contact with hot intrusions inside Surtsey. Another possibility is that the stalactites originated in downseeping precipitation containing a high amount of ocean spray. Either way the stalactitic minerals probably are evaporitic.

In sample IMNH 12387 (TABLE I), collected in 1988, calcite and opal-A were identified. The encrustation appears fresh and temperatures at the time of sampling were measured at 63°-67°C. However, during 1979-1982 temperatures at this locality were measured at 80°-100°C. It appears certain that calcite and opal-A formed somewhere in the temperature range of 60°-100°C at this locality.

When samples were collected in the lava cave S-4 in July 1990 (IMNH 15102-15107), temperatures were measured at approximately 35°-40°C. Gypsum is abundant in this cave and appears to be very fresh. Aeolian sand which has fallen through a crack to the floor of the cave, forms a linear ridge and is covered with an extensive crust of fresh gypsum. This indicates that this mineral formed at a late stage. The fact that gypsum has not been identified in samples collected at temperatures above 63°C, see TABLE I, may indicate that it forms mainly in the temperature interval 35°-60°C in these lava caves. According to Posnjak (1938) the temperature of transition of gypsum to anhydrite is 42°C in pure water. Fluorite, ralstonite and sulfur, which were only found in small amounts, most probably formed at high temperatures, cf. Stoiber & Rose (1974).

It appears that the encrustations collected in the lava caves and caverns of Surtsey during 1967-1990 are mostly low-temperature encrustations, crystallizing from fumarolic gases. The encrustations are volcanogenic and evaporitic in origin (cf. Shopov 1989). The present survey does not permit any speculation on the paragenesis of the encrustation minerals. Table II gives a summary of secondary minerals identified in Surtsey, including alteration products of tephra at low temperatures.

TABLE II

Secondary minerals identified in Surtsey. Ideal mineral compositions after Fleischer & Mandarino (1991).

I. Formed as encrustations on lava and scoria, both on the surface and at depth, during cooling and degassing of magma.

A. At high temperatures (Óskarsson 1981 and this study).

sulfur S
aphthitalite $(K,Na)_3Na(SO_3)_2$
thenardite Na_2SO_4
galeite $Na_{15}(SO_4)_5F_4Cl$
fluorite CaF_2
ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$

B. At temperatures between approx. 35°-100°C (this study).

halite NaCl
thenardite Na_2SO_4
gypsum $CaSO_4 \cdot 2H_2O$
opal-A $SiO_2 \cdot nH_2O$
calcite $CaCO_3$
anhydrite $CaSO_4$
glauberite $Na_2Ca(SO_4)_2$
kainite $MgSO_4 \cdot KCl \cdot 3H_2O$
loeweite $Na_{12}Mg_7(SO_4)_{13} \cdot 15H_2O$
kieserite $MgSO_4 \cdot H_2O$
bloedite $Na_2\ Mg(SO_4)_2 \cdot 4H_2O$
carnallite $KMgCl_3 \cdot 6H_2O$
$Na_2Ca_5(SO_4)_6 \cdot 3H_2O$ (JCPDS no. 35-137)

II. Formed as alteration products of basalt tephra within a hydrothermal system, both above and below sea level; at temperatures between 25°-150°C (Jakobsson & Moore 1986). Minerals listed in estimated order of abundance.

smectite (nontronite) Ca,Na,K; Al,Mg,Fe-silicate
analcime $NaAlSi_2O_6 \cdot H_2O$
phillipsite $(K,Na,Ca)_{1-2}(Si,Al)_8O_{16} \cdot 6H_2O$
tobermorite $Ca_9Si_{12}O_{30}(OH)_6 \cdot 4H_2O$
calcite $CaCO_3$
anhydrite $CaSO_4$
chabazite $CaAl_2Si_4O_{12} \cdot 6H_2O$
opal-A $SiO_2 \cdot nH_2O$
gypsum $CaSO_4 \cdot 2H_2O$
xonotlite $Ca_6Si_6O_{17} \cdot (OH)_2$

CONCLUSIONS

The encrustations from the lava caves and caverns of Surtsey collected in 1967-1990 are mainly low-temperature encrustations, crystallizing from fumarolic gases in cooling lavas. They are volcanogenic and evaporitic in origin.

Altogether sixteen mineral species were identified, leaving several species unidentified. Most abundant are halite, thenardite and gypsum. Seven of the minerals apparently have not been described from Iceland previously.

It is suggested that kainite, glauberite, loeweite, bloedite, kieserite and possibly halite were deposited mainly at 65°-100°C. Possibly all the stalactitic minerals were formed in this temperature interval. At another locality calcite and opal-A apparently were deposited somewhere in the range 60°-100°C. Gypsum may have formed mainly at 35°-60°C.

ACKNOWLEDGEMENTS

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Shallow Structures beneath Heimaey and Surtsey from Local Gravity Data

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ABSTRACT

In July and August 1989, local gravity surveys of the islands and Heimaey and Surtsey were conducted. Networks of 42 points on Heimaey and 41 points on Surtsey were surveyed for height and measured using a LaCoste and Romberg gravimeter. The data were reduced in the conventional way to obtain Bouguer anomaly maps of the islands. The average density of the material above sea level was 2250 kg/m^3 for Heimaey and 2000 kg/m^3 for Surtsey. This indicates that Surtsey is composed of material with a higher percentage of hyaloclastites than Heimaey.

On Heimaey, negative anomalies associated with Eldfell, Helgafell and Sæfell indicate that their summit conduits evacuated most of their lava at the end of their last eruptions and are now filled with low density ash and tephra. The relatively high densities on the flanks indicate increased percentage of lava flows there. A gravity high over Stórhöfdi indicates that this summit conduit was filled with magma at the end of its last eruption, which froze in the pipe to form a massive, high density core. The relatively low density flanking material indicates material with a higher percentage of hyaloclastites than the core.

On Surtsey, gravity lows associated with the tuff hills north of the eruptive vents Surtur I and Surtur II suggest that these hills have cores of low density tephra accumulations containing large cavities. Higher density bodies underly Surtur I and Surtur II which indicates that these vents are plugged with more massive material.

INTRODUCTION

The Westmann Islands are a 30 km long volcanic archipelago that is the continuation of the southwards propagating Eastern Volcanic Zone of Iceland. Heimaey is the largest, and contains rocks at least 5400 years old (Jakobsson, 1968). Surtsey is the youngest, and erupted out of the sea during the period 1963 to 1967 (Jakobsson and Moore, 1982).

In July and August 1989 local gravity surveys were made of these, the two largest islands. Since there had been no previous detailed gravity surveys there, it was necessary to also establish a network of geodetic stations at which the gravity measurements could be made.

The aim was to investigate the near-surface crustal structure with particular reference to the volcanoes og Eldfell and Helgafell on Heimaey, and the tuff hills and eruptive vents (Surtur I and Surtur II) of Surtsey.

FIELD MEASUREMENTS

Surveying

A Pentax Electronic Theodolite and a Sokkisha Red Mini EDM were used to determine the heights of the stations where gravity measurements were to be made.

The method of theodolite tacheometry was employed (Bannister and Raymond, 1984).

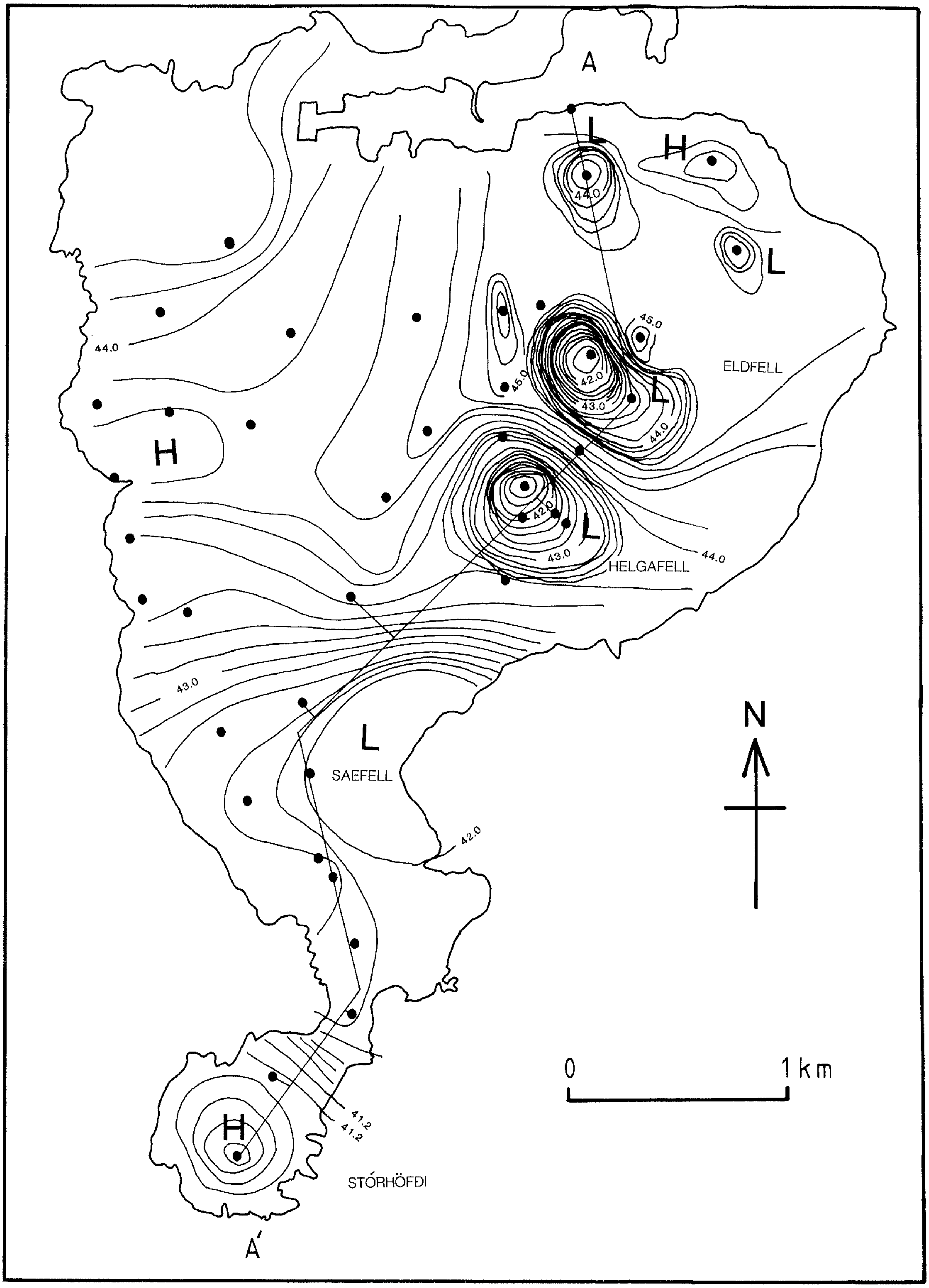

Fig. 1. Bouguer anomaly map of Heimaey. Black dots indicate survey points.

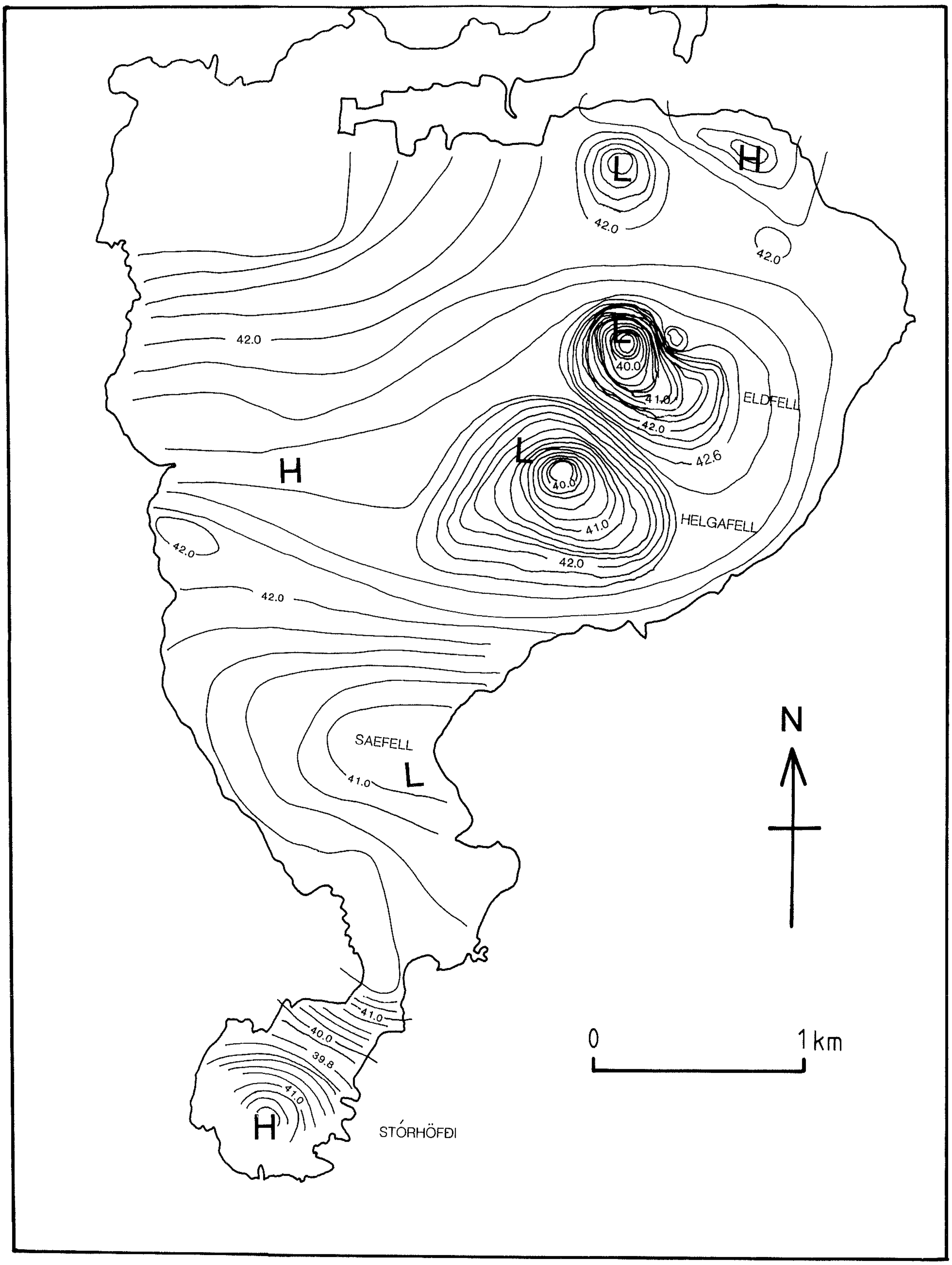

Fig. 2. Bouguer anomaly map of Heimaey. A regional gradient of 0.5 mgal/km increasing to the north has been removed.

This involves measuring the vertical angle and direct distance between points, and using simple trigonometry to determine the relative heights of the stations. By tying to a point of known height above sea level, the heights of all the survey points above mean sea level

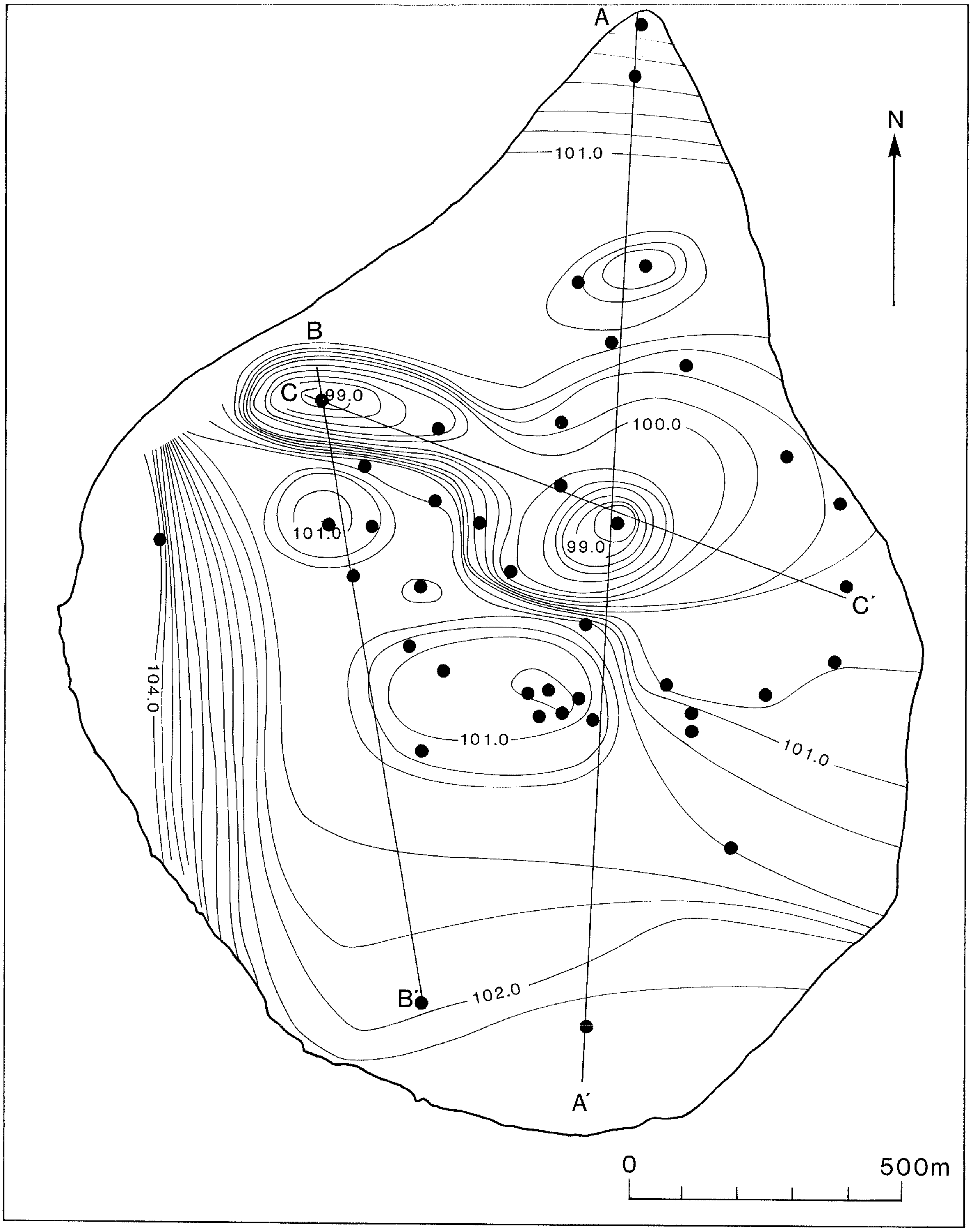

Fig. 3. Bouguer anomaly map of Surtsey. Black dots indicate survey points.

were determined. The latitudes of the points were determined by plotting the stations on large-scale maps, calculating their coordinates in the local coordinate systems of Heimaey (Ólafur Ólafsson, pers. comm.) and Surtsey (Sjómaelingar Íslands, 1985), and converting to geodetic coordinates (Ólafur Ólafsson, pers. comm., Sjómaelingar Íslands, 1985).

A network of 42 points was measured on Heimaey, which was tied to several bench-

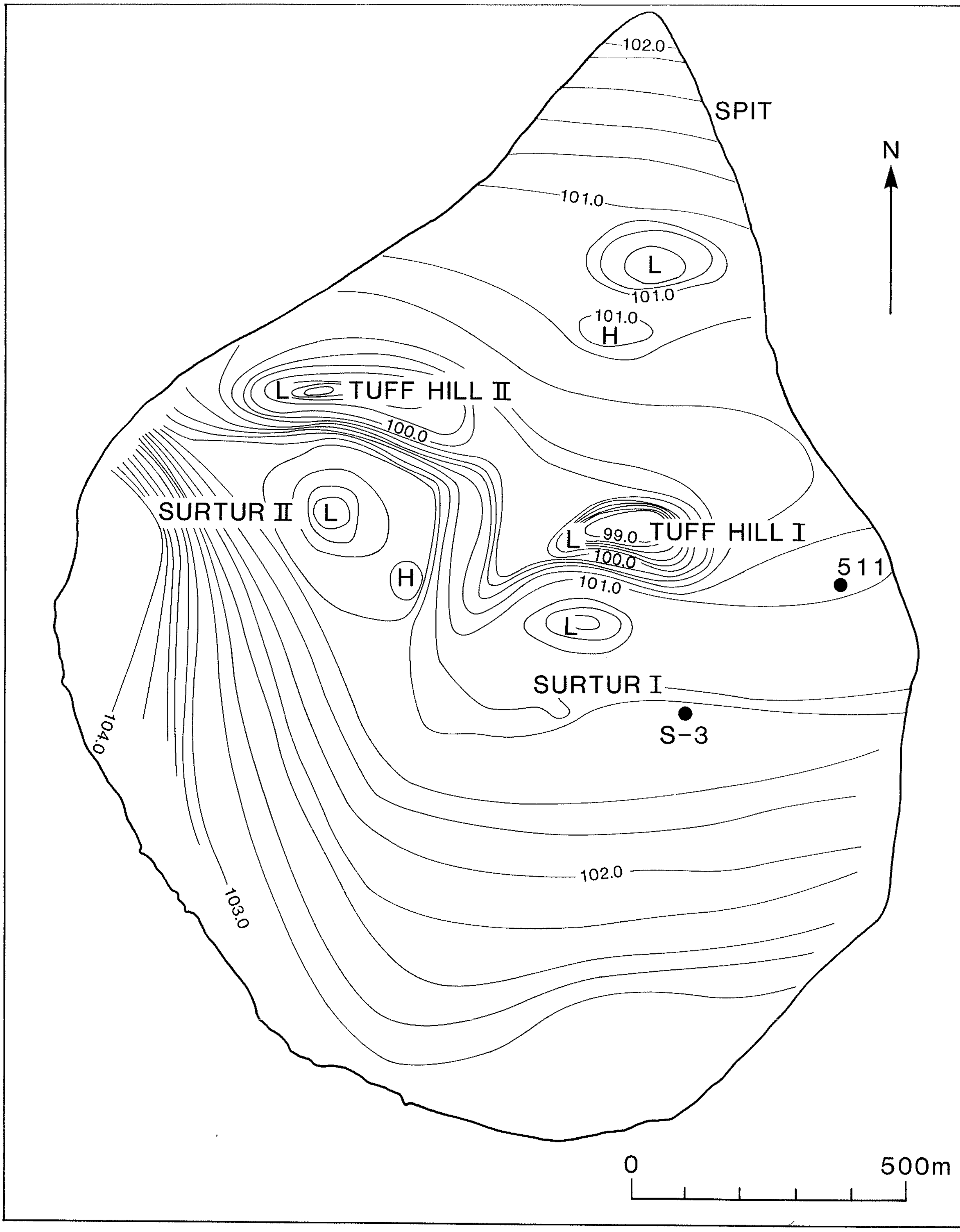

Fig. 4. Bouguer anomaly map of Surtsey. A regional gradient of 0.5 mgal/km decreasing to the north has been removed.

marks in the town (Fig. 1). On Surtsey, a network of 41 points was surveyed (Fig. 3) and tied to point 511 (Moore, 1982). The points were marked by yellow painted crosses and/or nails.

Gravity

A LaCoste and Romberg standard model G Gravimeter was used to measure gravity at the stations. The gravimeter was levelled using a concave levelling plate on top of the station or as close to it as possible. The difference in height (if any) between the station and gravimeter position was measured. Terrain around the stations was estimated for compartments B and C (out to a total of 36 m from the stations). Tie backs to a base station were made at intervals of no more than 2 hours to enable gravimeter drift to be calculated.

It is desriable in surveys of this kind to tie all measurements to a station where absolute gravity is known. There was an absolute gravity station on Heimaey at the old airport terminal building, but unfortunately this was destroyed when the new terminal was built. A new base at the airport control tower was therefore used, and all station readings were made relative to this base, although the absolute value of gravity is not yet known there (Fig. 1).

On the island of Surtsey, no previous gravity measurements had been made, and all readings were made relative to a base at station S-3 (Fig. 4), which is close to the new hut in the west, and at a surveying station of Tryggvason (1972).

REDUCTION OF DATA

The Bouguer anomaly was calculated using the formula:

$$BA = g_{obs} - g_{\varnothing} + FAC - BC + TC$$

where BA is the Bouguer anomaly, g_{obs} is the observed value of gravity after correcting for gravimeter drift, $g_{\varnothing}$ is theoretical gravity at latitude $\varnothing$, FAC is the Free Air correction, BC is the Bouguer correction and TC is the terrain correction. The value of observed gravity was obtained by correcting the raw gravity measurements for drift. Gravimeter drift was typically less than 0.05 mgal/hour. Theoretical gravity was calculated using the IGRF formula:

$$g_{\varnothing} = 9.780318(1+5.3024x10^{-3}\sin^2\varnothing + 5.9.10^{-6}\sin^2 2\varnothing)$$

The equation used to make the Free Air correction was:

$$FAC = 0.3085h$$

where h is the height of the station above mean sea level. The Bouguer correction was made using the formula:

$$BC = 4.188.10^{-5}\rho h$$

where ρ is the average density of the material above sea level.

The terrain correction for each station was assessed by estimating the average height in compartments for zones D to M using available topographic and bathymetric maps, and summing the correction factors given in the Hammer chart (Hammer, 1939) for all zones estimated both in the field and from the map (i.e. zones B to M).

$$TC = \rho \sum_{i=B}^{M} HTF_i$$

HTF is the Hammer terrain factor. In considering the terrain corrections for those segments that were mostly in the sea, the volumes above and below sea level were compensated for separately, and a correction was made for the presence of the sea layer, which was taken to have a density of 1000 kg/m^3.

In order to make the Bouguer and terrain corrections, the value of the average density for the material above sea level is required. Three methods were used to obtain estimates for the average rock density of the islands:

(a) Direct measurement of the volumes and masses of samples of rock, from which the density is calculated. This method has the drawback that the densities obtained may not accurately reflect those of larger rock masses.

(b) Nettleton's Method (Dobrin and Savit, 1988, p 557–558). This involves calculating Bouguer anomaly profiles for a number of stations that traverse a topographical feature, using a series of densities. The density that yields a Bouguer anomaly profile that shows least correlation with the topography is taken to be the average density of the feature. This method may be untrustworthy, in particular in Iceland, because in a young volcanic environment topographic features may be directly attributable to lateral variations in structure and density.

(c) The least squares method. This involves rearranging the Bouguer anomaly equation into density dependent and independent parts to form the equation of a line whose gradient is the density:

$$g_{obs} - g_{\varnothing} + FAC = BA_{ave} + \delta BA + \rho(0.04191h - \sum_{i=B}^{M} HTF_i)$$

BA_{ave} is the average Bouguer anomaly and δBA is the deviation from this for a particular station. A graph may then be drawn, whose gradient is the average density of the material above sea level, and whose intercept is BA_{ave}. This is a robust method of determining average density over a survey area, that has some statistical foundation.

The average Bouguer density used for Heimaey was 2250 kg/m^3. This was decided on the basis of the following density determinations:

i) Direct measurement – 2230 kg/m^3
ii) Nettleton's method – 2350 kg/m^3
iii) Least squares method – 2170 kg/m^3

The average Bouguer density chosen for Surtsey was 2000 kg/m^3. This value was a reasonable mid value of the following determinations:

i) Direct measurements:
   Lava – 2230 kg/m^3
   Basic glomerobreccia – 2160 kg/m^3
   Palagonitised tuff – 1850 kg/m^3
   Sedimentary xenolith – 2420 kg/m^3
ii) Nettleton's method – 2200 kg/m^3
iii) Least squares method – 1880 kg/m^3

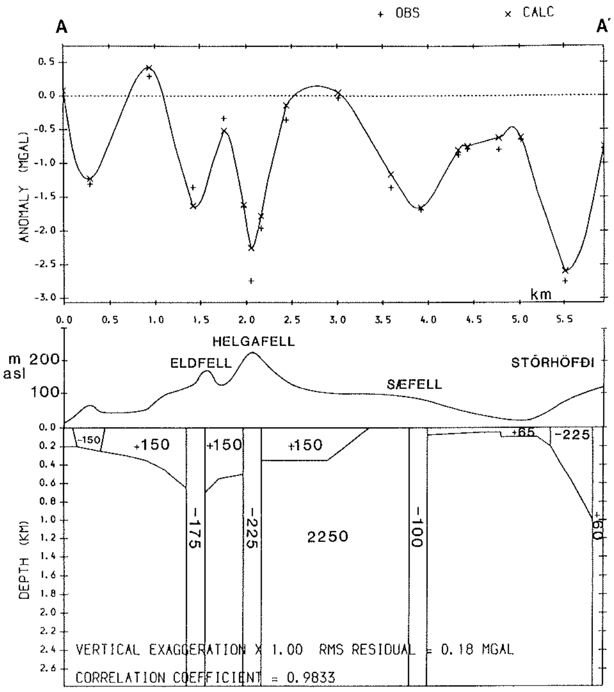

Fig. 5. Profile AA' (c.f. Fig. 1), running NS through Heimaey. Upper part of Figure indicates field (+) and theoretical (×) gravity values. Lower part of Figure illustrates the structure modelled. The densities of the bodies are indicated in kg/m^3. The topography is indicated above the lower part of the Figure.

RESULTS

Bouguer anomaly maps of Heimaey and Surtsey are presented in Figs 1 to 4. The data are tabulated in Tables 1 and 2. An error analysis was performed (Table 3), and the estimated error in the calculated values of the Bouguer anomaly is 0.3 mgal, or about one contour interval in Figs. 1 to 4.

INTERPRETATION

Method

After removing the island-wide gravity trend (the "regional"), the program GRAVN (Bott, 1986) was used to model the gravity profiles along various sections of the Bouguer anomaly maps. Bodies are defined by the coordinates of their corners and their density contrasts with the background material are declared. The program decomposes each body into a set of semiinfinite slabs with sloping ends and calculates and sums the gravity contributions due to each slab and each body. The resultant theoretical profile may be plotted on a graphics computer screen, and the true values obtained by processing the field data superimposed. The model is progressively adjusted until a good fit to the field data points is obtained. When this has been achieved, a candidate interpretation has been established. It should be borne in mind, however, that in theory, an infinite number of structures could be found to fit the observed gravity field. This is known as the ambiguity problem. In the models presented below, effort was made to arrive at geologically reasonable solutions.

Heimaey

The island-wide gradient over Heimaey was found to be 0.5 mgal/km, increasing to the north. This result is in agreement with the results of 4 gravity measurements reported by Einarsson (1954). Such a gradient is in the opposite direction to the regional gravity trend of Iceland which is bowl shaped with a central low in the middle of Iceland. This discrepancy points towards the existence of structure on the scale of 5 km or more, that overprints the regional gradient of Iceland.

A Bouguer gravity map of Heimaey with the regional removed is presented in Fig. 2. This map is dominated by 3 narrow, steep anomalies, with amplitudes of approximately 2 mgal, in the areas of Eldfell, Helgafell and Stórhöfdi. A broader gravity low was detected

TABLE 1
Gravity data from Heimaey.

1	STATION	HEIGHT		LATITUDE		T.C.	BOUGUER ANOMALY
2		m	degs	mins	secs		mgals
3	L1	120.896	63	23	28.3	2.491	41.81743
4	M1	54.967	63	23	40.9	0.8823	41.04887653
5	M2	13.565	63	23	49.94	0.2709	42.34997626
6	M3	38.636	63	24	1.895	0.5201	42.39790172
7	M4	51.168	63	24	11.91	0.6549	42.40622044
8	T1	46.789	63	24	14.82	0.572	42.52087138
9	M6	40.702	63	24	24.83	0.403	42.31037171
10	M7	66.204	63	24	35.49	0.5694	42.44268465
11	Z8	70.496	63	24	54.87	0.4961	43.58199809
12	Z6	67.512	63	24	56.48	0.69	43.75726783
13	Z4	47.945	63	25	6.818	0.505	43.79164077
14	Z2	38.384	63	25	15.22	0.3913	44.40993141
15	s7692	32.155	63	25	41.38	0.4201	44.38804415
16	s7693	25.129	63	25	27.17	0.2931	43.98602443
17	s132	26.461	63	25	52.68	0.9093	43.52337259
18	s7802	57.786	63	26	4.635	0.9188	45.43163004
19	s7804	93.01	63	25	50.75	1.3859	44.36985569
20	s7800	66.656	63	26	3.343	0.7544	43.68686246
21	shore	0	63	26	13.36	0.7906	45.13982822
22	E2	117.032	63	25	34.92	1.4131	41.71446967
23	E4	135.611	63	25	41.38	1.709	43.04403451
24	E5	92.705	63	25	34.92	0.9291	45.20983251
25	V	73.622	63	24	28.38	0.7056	41.90494765
26	F1	81.719	63	24	39.69	0.586	42.44334226
27	F2	98.143	63	24	56.16	0.5721	43.97359006
28	s111	39.319	63	25	25.88	0.3518	44.45849489
29	s103	56.493	63	25	23.94	0.3895	44.30448782
30	s101	47.705	63	25	37.83	0.3594	44.00892489
31	s7606	39.031	63	25	40.41	0.3595	44.4761089
32	s222	35.859	63	25	42.99	0.4254	45.51713908
33	s226	48.773	63	25	41.38	0.545	44.88486342
34	F4	89.85	63	25	11.99	0.5791	44.53597211
35	R14	84.968	63	25	22.65	0.6515	44.72988054
36	R5	72.592	63	25	28.46	0.7901	45.10192845
37	HELGA1	156.573	63	25	21.03	2.8103	43.74596895
38	R7	112.225	63	25	18.12	1.0034	44.06974595
39	HELGA2	138.038	63	25	8.756	1.9183	42.56303017
40	R9	118.23	63	25	6.172	1.0978	42.57261904
41	R11	109.26	63	24	59.07	0.9138	43.64348483
42	HELGA4	175.757	63	25	8.433	3.3343	43.23993761
43	HELGATOP	227.039	63	25	12.31	6.1346	41.45506725
44	OB	108.85	63	25	1.973	0.7906	
45							

around Saefell. In the cases of Eldfell, Helgafell and Saefell, the summits of the mountains are associated with gravity lows. The opposite case was true of Stórhöfdi, where the mountain summit gave a high gravity value when compared with the flanks.

It is to be expected that gravity decreases with height, and the possibility was considered that the negative anomalies observed over Eldfell, Helgafell and Saefell resulted from too high a density having been used to make the Bouguer and terrain corrections. (This is equivalent to testing the hypothesis that the anomalies observed were all due to lateral variations in density in the material above sea level). It was found that densities as low as 1000 kg/m^3 for the material above sea level would be required to account for the observations. It was therefore concluded that density variations exist also in the material below sea level.

A N-S trending profile passing through all the major anomalies was modelled (profile A A′, Fig. 1). The results of this modelling are shown in Fig. 5. The correlation coefficient between the observed and theoretical values was better than 0.98. The anomalies observed over Eldfell, Helgafell and Saefell may be explained by low density pipes extending from the surface down to 3 km depth, flanked by higher density bodies of shallower extent (extending from the surface to 0.5–1.0 km depth). The density contrasts used are shown in Fig. 5. These are typically -100 kg/m^3 between the low density bodies and the background, and $+200$ kg/m^3 between the high density bodies and the background. This corresponds to a density contrast of about 300 kg/m^3 between the high and low density bodies. The anomaly in the Stórhöfdi area was modelled as a relatively high density pipe beneath the centre of the hill and low density bodies on the flanks.

It was a somewhat surprising result that the central cores of Eldfell, Helgafell and Saefell are associated with low density bodies. It is suggested that these bodies represent columns of tephra, and probably contain sizeable cavities also. This may indicate that the summit conduits of Eldfell, Helgafell and Saefell evacuated most of their lava towards the end of their respective eruptions. The higher density flanking bodies may exhibit higher densities because of lava flows, many of which are visible at the surface.

The relatively high density pipe modelled beneath the summit of Stórhöfdi suggests a contrasting eruptive history. The summit conduit of this volcano was not evacuated at the end of the eruption, but filled with magma that later crystallised and solidified in the pipe to form high density core. The relatively low density flanking material probably contains a relatively high proportion of pumice and hyaloclastites.

To the north of Eldfell, the part of the volcano that crumbled away is modelled as a low density slab. This could represent a sector collapse of the volcano with the low density attributed to the fractured and unconsolidated nature of the tephra. The area to the east of Helgafell were the 1.9 km long fissure opened up at the start of the 1973 Eldfell eruption (Jakobsson et al., 1973), is characterised by relatively low density material.

A schematic cross section of Heimaey is presented in Fig. 9, that illustrates the structure along the profile modelled. The relatively large depths to which the structures appear to extend was also surprising. Because of the ambiguity problem in gravity interpretation, there is a trade-off between density contrast and extent, and it is possible that the anomalies may also be interpreted as shallower bodies with greater density contrasts. Drilling on Heimaey shows that at least 1 km of sediments overly the basalt basement (Björnsson, 1967).

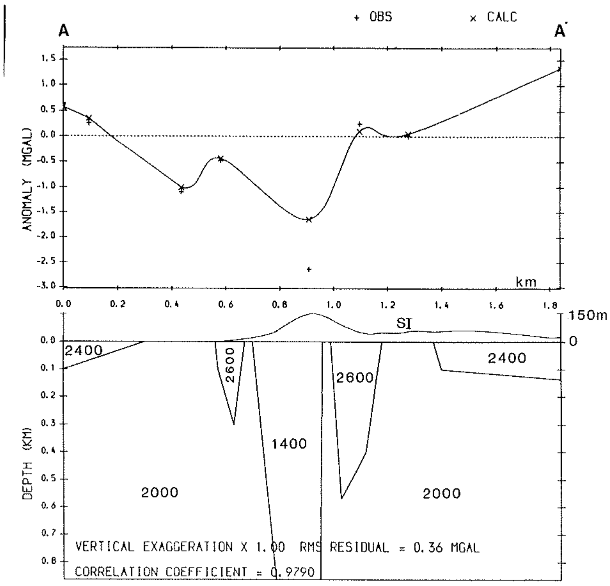

Fig. 6. AA' (c.f. Fig. 2), running NS through Surtur I in Surtsey. Caption as for Fig. 5. SI indicates the position of Surtur I.

Surtsey

An island-wide Bouguer anomaly trend of 0.5 mgal/km, decreasing northwards over the island (1.8 km) was removed. This trend is similar to that of Iceland as a whole (Einarsson, 1954), although opposite to that of Heimaey. Structure on a scale of kilometers is doubtless responsible for the undulatory regional gravity trend along the archipelago.

After the regional is removed (Fig. 4), the gravity map of Surtsey is dominated by a general gravity trough, approximately 2.5 mgal deep, crossing the island from east to west and containing the tuff hills north of their eruptive vents Surtur I and Surtur II. This general low may be subdivided into several narrow anomalies up to approximately 2 mgal in amplitude and 1–200 m in diameter. Two such anomalies are associated with the tuff hills, and another two with Surtur I and Surtur II. A fifth negative anomaly was observed north of the easternmost tuff hill.

As with the Heimaey data, different Bouguer densities were tried, to see whether the anomalies that correlated with topography could be explained by lateral density variations in the material above sea level. It was found that densities of as low as 500 kg/m^3

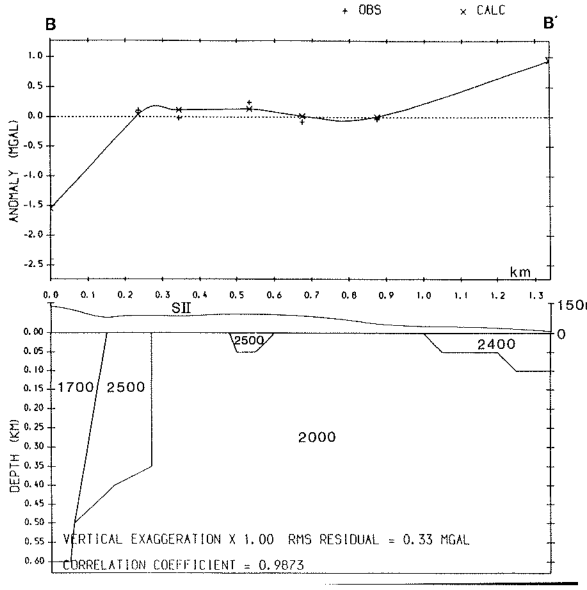

Fig. 7. Profile BB' (c.f. Fig. 2), running NS through Surtur II in Surtsey. Caption as for Fig. 5. SII indicates the position of Surtur II.

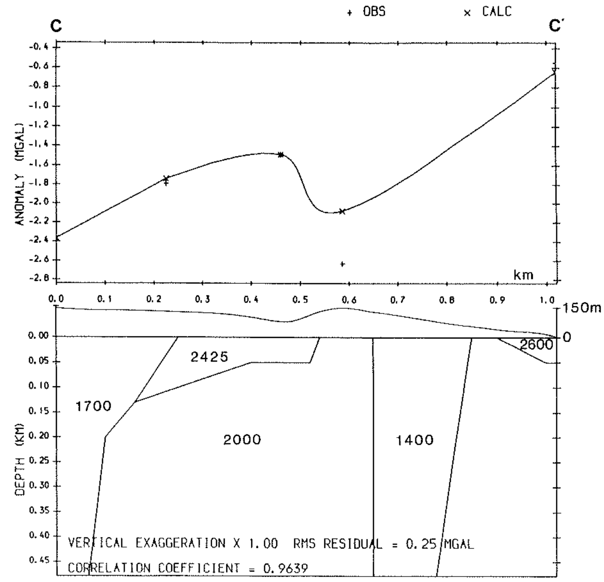

Fig. 8. Profile CC' (c.f. Fig. 2), running EW through the tuff hills in Surtsey. Caption as for Fig. 5.

would be necessary to explain the anomalies by this. These are geologically unreasonable, and it was concluded that density variations extending deeper than sea level were necessary to explain the observations.

Three profiles that sampled the main anomalies were chosen for computer modelling of the subsurface features. Two profiles (AA' and BB', Fig. 3) run approximately N-S through the tuff hills and Surtur I and Surtur II, and a third runs E-W across the tuff hills (CC', Fig. 3). Structures were modelled that fitted the observed data with correlation coefficients better than 0.95.

Profile AA' lies in the east of the island and traverses Surtur I, the tuff hill to the north of it and the negative anomaly to the north of that. Between the three gravity lows, the Bouguer anomaly had rather higher values. This profile was modelled by a structure involving a low density pipe extending from the surface to 1 km depth beneath the tuff hill, with higher density bodies extending from the surface down to 300 and 600 m depth on its flanks (Fig. 6). The body to the south of the tuff hill partially underlies Surtur I. Relatively high density, shallow bodies (up to 150 m in thickness) at the extreme north and south ends of the island were necessary to account for the general increase in Bouguer anomaly away from the central trough.

Alternating high and low density bodies in the vicinity of the tuff hill and Surtur I were necessary to model the steep Bouguer anomaly gradients observed. The low density core of the tuff hill had a density contrast of -600 kg/m^3 with the background material. The high density bodies flanking the tuff hill had contrasts of $+600$ kg/m^3 with the background whereas in the case of the distal bodies it was $+400$ kg/m^3.

Profile BB' traverses Surtur II and its associated tuff hill to the north (Fig. 7). A similar structure was necessary to model this profile, with a vertical low density central pipe extending from the surface to 600 m depth. A flanking high density body extending from the surface to a depth of 4–500 m in the vicinity of Surtur II was necessary to model the steep gravity gradient. The density constrasts of these bodies with the background material were -300 kg/m^3 for the low density pipe, and $+500$ kg/m^3 for the high density body in the vicinity of Surtur II. A shallow (100 m) high density body at the far south of the island was necessary to explain the increase in Bouguer anomaly there.

An east-west profile passing through the tuff hills is shown in Fig. 8, and is reasonably well modelled with the same structure obtained by modelling the two north-south profiles (Figs. 6 and 7).

The low density pipes beneath the summits of the tuff hills probably represent ash accummulations of particularly low density from the phreatic eruptions, and large cavities may also

TABLE 2
Gravity data from Surtsey.

1	STATION	HEIGHT		LATITUDE		T.C.	BOUGUER ANOMALY
2		m	degs	mins	secs		mgals
3	base	41.172	63	18	3.077	0.6455	101.5844579
4	np	2.527	63	18	43.84	0.532	102.1491814
5	n1	6.836	63	18	40.8	0.4405	101.7615594
6	th	4.646	63	18	29.48	0.3815	100.4060145
7	wp	3.661	63	18	28.44	0.6335	100.8141374
8	s7	4.41	63	18	25.31	0.8735	101.0186802
9	n2	5.253	63	18	23.78	0.795	100.6601136
10	du1	5.75	63	18	18.16	0.965	100.5326848
11	du2	8.634	63	18	15.28	0.837	100.7383513
12	sw	15.875	63	18	10.46	0.609	100.95082
13	s607	22.82	63	18	6.127	0.615	101.195306
14	s1	27.122	63	18	4.201	0.4785	101.0562995
15	base	41.172	63	18	3.077	0.6455	101.5853114
16							
17	base						
18	du3	36.636	63	18	2.034	0.5215	101.5373469
19	base						
20							
21	base						
22	sdh1	57.854	63	18	5.003	0.6215	101.1070028
23	du4	67.567	63	18	8.454	1.058	101.74817
24	du5	60.287	63	18	2.917	0.7915	101.4990841
25	j518	68.088	63	18	3.238	0.9365	101.190798
26	c1	63.956	63	18	4.04	0.9185	101.3688503
27	j517	65.604	63	18	4.682	0.9005	101.1285025
28	j519	61.865	63	18	3.077	0.7985	101.2130072
29	c2	65.907	63	18	4.441	0.8415	101.1733849
30	du6	67.073	63	18	5.485	0.921	101.2574288
31	du7	84.577	63	18	6.929	1.152	101.4242362
32	base						
33							
34	base						
35	c3	101.718	63	18	11.26	1.401	101.7513341
36	c4	88.869	63	18	14.23	1.1	101.4771049
37	c5	93.026	63	18	14.31	1.115	101.0816472
38	du8	91.879	63	18	13.35	2.253	104.4483797
39	du10	96.08	63	18	17.84	1.305	101.6136132
40	du9	98.559	63	18	15.92	1.555	101.6983137
41	ws1	102.422	63	18	10.62	1.5175	101.9276631
42	ws2	51.013	63	18	0.67	0.608	101.4767251
43	ws3	21.02	63	17	45.99	0.363	102.4088575
44	base						
45							
46	base						
47	du12	137.236	63	18	21.7	4.2645	99.12217724
48	du11	129.551	63	18	20.09	2.744	99.72203408
49	rf14	111.105	63	18	14.47	1.5555	100.8327949
50	du14	129.556	63	18	11.5	2.8555	100.1085952
51	du15	152.228	63	18	14.39	3.997	98.87237458
52	du16	86.372	63	18	16.72	1.6055	100.0100882
53	vi	40.734	63	18	20.33	1.0935	100.4630428
54	base						
55							
56	base						
57	ws4	22.99	63	17	55.06	0.4455	101.8690912
58	ws5	22.879	63	17	44.63	0.409	102.8393265
59	base						

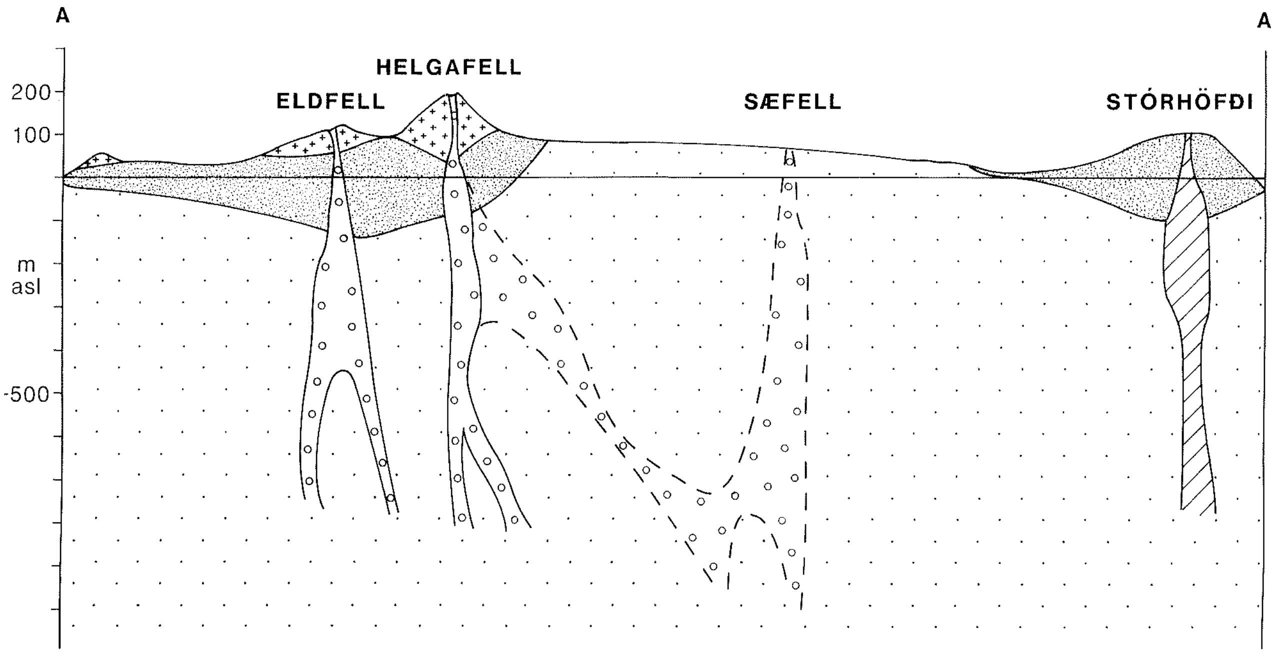

Fig. 9. Schematic cross section of Heimaey illustrating the structure along Profile AA', which traverses Helgafell, Eldfell, Saefell and Stórhöfdi.

be present. The western tuff hill (modelled with a pipe of density contrast -300 kg/m^3) appears to have a slightly higher density than the eastern one (modelled with a pipe of density contrast $+600$ kg/m^3). This may indicate higher density of the eruptive material from Surtur II than Surtur I, and/or fewer cavities. The high density bodies in the vicinity of the Surtur I and Surtur II vents probably represent basaltic material more massive than that comprising the tuff hills. This may be attributable to higher percentage of magma that has solidified in situ, forming a plug-like structure. The minor gravity lows centred on Surtur I and Surtur II may indicate that the high density material is offset to the north of the vents, and slightly lower values of gravity over the vents themselves result from the collapse of near surface material.

This interpretation is consistent with the facts that eruptions occurred from the south flank of the tuff hill north of Surtur I in December 1966 – January 1967 (Jakobsson and Moore, 1982), and the vent of Surtur II has suffered a major collapse in the top part.

The (slightly lesser) high density body modelled in the south of the island corresponds to the lava field there, that was erupted in August 1966 to January 1967 (Jakobsson and Moore, 1982). In the north of the island, the spit is underlain by relatively high density material. This probably represents lava which has been crushed and compacted by the sea to form the spit that exists there now.

A schematic NS cross section is presented in Fig. 10 that illustrates the structure along Profile AA', which traverses Surtur I and it's associated tuff hill.

As in the case of Heimaey, we were surprised at the large depth to which the structures modelled appeared to extend. Models involving larger density contrasts and shallower structures may also fit the data, though densities greatly lower than those modelled here could only be accounted for by large cavities.

CONCLUSIONS

The Bouguer gravity anomaly maps of Heimaey and Surtsey exhibit island-wide trends that increase to the north in the case of Hei-

TABLE 3
Error analysis.

Error source	Error	mgal equivalent
Gravimeter readings	0.02 mgal	0.02
Altitude	0.05 m	0.01
Latitude	1.0	0.02
Density	200 kg/m^3	0.26
Time	1 min	0.0004
	Total	0.31 mgal

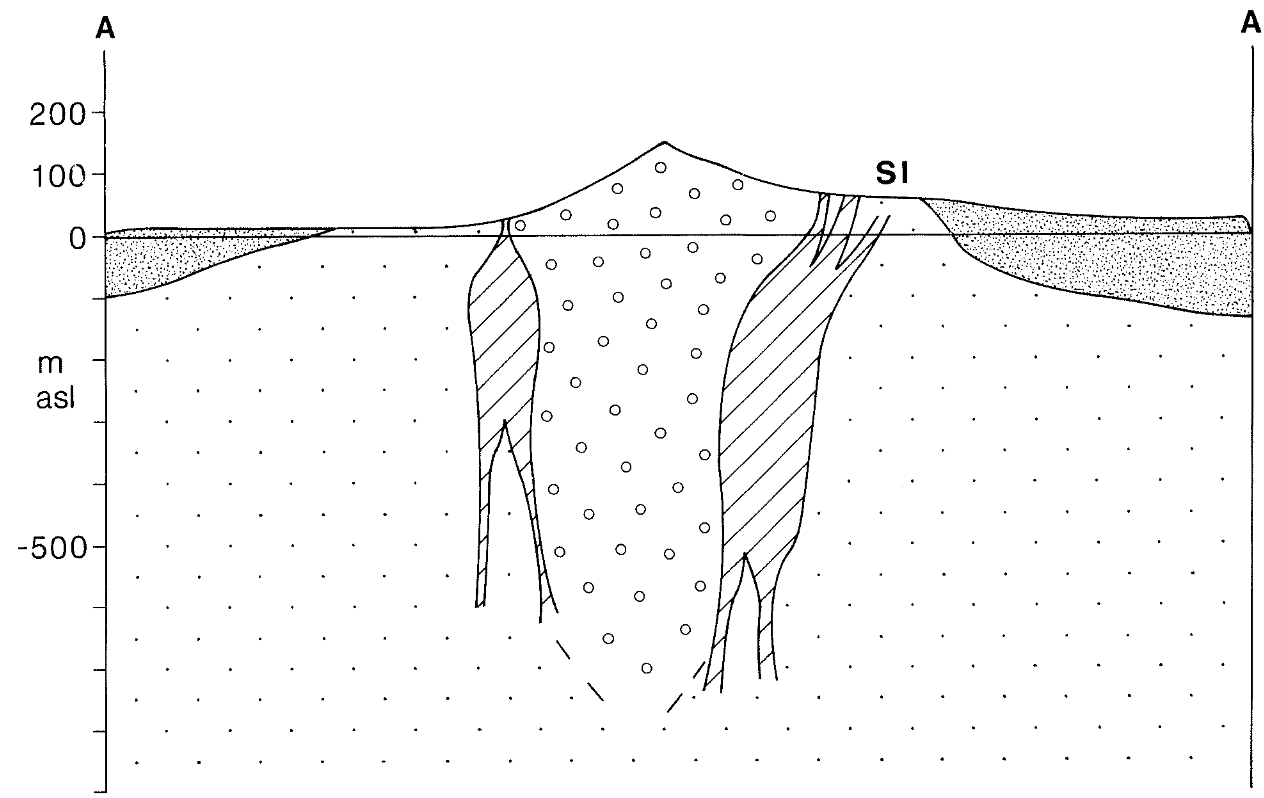

Fig. 10. Schematic cross section of Surtsey illustrating the structure along Profile AA', which traverses Surtur I and it's associated tuff hill.

maey and to the south in the case of Surtsey. These trends reflect variation of structure along the archipelago on a scale of kilometers. The average density to the material above sea level was 2250 kg/m^{-3} for Heimaey and 2000 kg/m^{-3} for Surtsey. Surtsey is on average less dense than Heimaey, probably because Surtsey is younger, less compacted, and composed of material with a higher percentage of hyaloclastites than Heimaey.

On Heimaey, negative anomalies with amplitudes up to approximately 2 mgal, and a few hundred metres in lateral extent associated with Eldfell, Helgafell and Saefell were interpreted as low density pipes extending from the surface down to 3 km depth, flanked by higher density bodies a few hundred metres in thickness. Density contrasts of about -300 kg/m^{-3} were required. These pipes may have formed because the summit conduits evacuated most of their lava at the end of their last eruptions and became filled with low density ash and tephra. Higher densities on the flanks indicate an increased percentage of lava flows. A gravity high over Stórhöfdi was modelled as a relatively high density pipe. This may indicate that the summit conduit did not evacuate at the end of the eruption, but filled with magma that later froze in the pipe to form a massive, high density core. The relatively low density flanking material indicates material with an increased percentage of pumice and hyaloclasties.

A general EW trending gravity trough approximately 2.5 mgal deep traverses Surtsey. Within this are several negative anomalies of up to 2 mgal in amplitude and 1–200 m in diameter. Four of these are associated with Surtur I and Surtur II and their corresponding tuff hills. The data suggest that the tuff hills have very low density cores extending from the surface to 1 km depth, with shallower, higher density bodies on their flanks, in the vicinity of Surtur I and Surtur II. The cores of the tuff hills are probably composed of unusally low density tephra, perhaps containing large cavities. Higher densities associated with Surtur I and Surtur II indicate magma that has solidified in situ, although slight gravity lows centred on the vents themselves suggest that the high density material is offset to the north. The vents themselves may have slightly depressed near surface densities as a result of the collapse of near surface material.

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Earth Science Bibliography of the Surtsey (1963-1967) and Heimaey (1973) Eruptions, and their Eruptive Products.

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INTRODUCTION

Surtsey and Heimaey are the two largest islands of the Vestmannaeyjar archipelago, off the south coast of Iceland. Surtsey was built up in volcanic eruptions during 1963-1967 and Heimaey, the only inhabited island, erupted in 1973 with disastrous effects on the small community. Both these eruptions aroused much interest, as well as sympathy, in the scientific community and with the general public. The result has been a diversity of publications in scientific and popular magazines all over the world, and many books deal entirely or partly with Surtsey or Heimaey.

Many of those who recently have been active in the research on the Surtsey and Heimaey (Eldfell) eruptions have felt the need for a comprehensive bibliography of these eruptions. Two bibliographies have previously been published on Surtsey. The first appeared in 1968 in Surtsey Research Progress Report 4, p. 197-206, under the title „List of publications on Surtsey research and related scientific work", with no author designation. The bibliography lists 82 publications in the fields of biology, geology, geophysics, geochemistry, oceanography and „general". The second bibliography appeared in 1971 in NASA Technical Memorandum, NASA TM X-62,009, p. 125-138. The bibliography is compiled by I. Pubulis and lists 237 publications in the fields „general", biology and physical science.

The present bibliography is a compilation of references in the fields of earth science which contain information on, or discussion of, the eruption history and/or the eruptive products of the Surtsey and Heimaey (Eldfell) eruptions and their effects on the surroundings. The bibliography contains references to articles in magazines, reports and books but not newspaper articles. Extended abstracts of meetings and symposia are included although ordinary short abstracts are omitted. Special maps and posters are also included. In addition available films and videos of the eruptions are listed separately. The publications have been classified in six categories:

1. Eruption history, general descriptions of the volcanoes, abbreviated to ERUPT in the bibliography.
2. Geomorphology, including hydrographic surveys, abbreviated to GEOM.
3. Geology, including marine geology, paleontology, and leveling and thermal measurements, abbreviated to GEOL.
4. Geochemistry, including mineralogy and petrology, abbreviated to GEOCH.
5. Geophysics, including utilization of geothermal heat, abbreviated to GEOPH.
6. Oceanography, abbreviated to OCEAN.

The present bibliography has been in preparation for about 6-7 years. It is based primarily on the reprint collections and the book collection of the library of the Icelandic Museum of Natural History, Reykjavík. The reprint collection of the Surtsey Research Society and the Departmental library in the Geoscience Building of the University of Iceland were also examined. Six individuals who have been active in the research on Surtsey and Heimaey

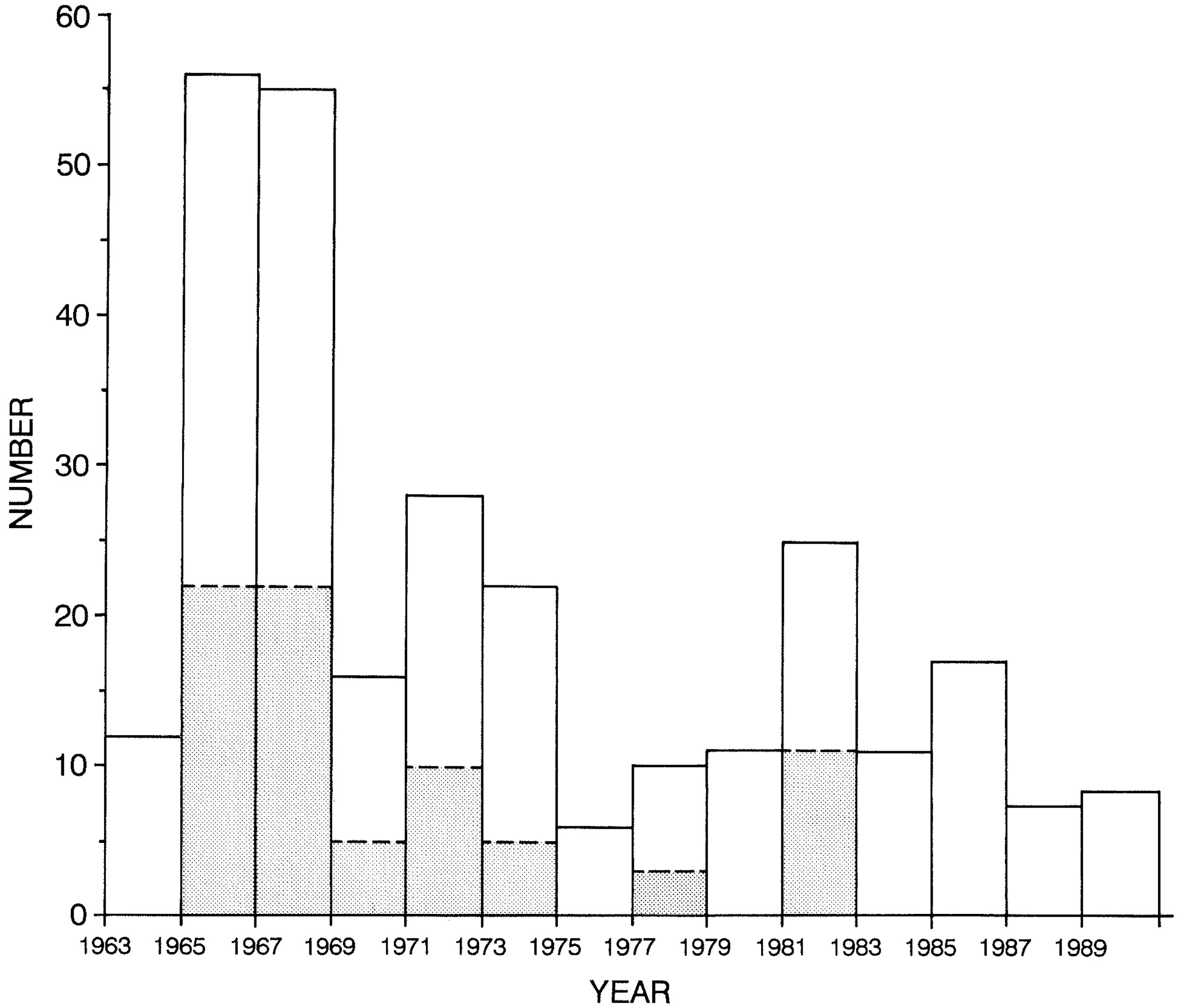

Fig. 1. Distribution of publications which deal with the Surtsey eruptions and Surtsey in the period 1963-1990, inclusive. There are altogether 288 publications, and each bar indicates the number of publications for every two years, starting with 1963. The shaded part of each bar indicates the number of publications (78) which have appeared in the Surtsey Research Progress Reports.

(cf. Acknowledgements), contributed many references. A computer search in the data files of GEOARCHIVE (Copr. Geosystems), GEOREF (Copr. American Geological Institute) and GEOBASE (Copr. Geo-Abstracts Ltd.) through the University Library, Reykjavík, provided additional references. About 46% of the references in the present compilation are found in the above mentioned computer files.

In spite of all the measures which have been taken during the compilation, the present bibliography is obviously not complete. It is hoped, however, that no important references are missing.

The bibliography contains 288 references on Surtsey. Fig. 1 shows how the publications on Surtsey are distributed through the period 1963-1990. The rate of production of publications is by far the greatest during the eruptions, while after 1968 a slow decline in the production can be noticed. Compared to the general output of publications in the fields of mineralogy, petrology and geochemistry of Iceland (Jakobsson & Gautason in prep.) the Surtsey eruptions are the most discussed volcanic eruptions in these fields until now. In summary it can be claimed that the Surtsey eruptions have had a great and lasting influence on the development of earth sciences in Iceland and possibly elsewhere. They are one of the best recorded series of submarine eruptions to date, and many of the data collected during the monitoring of the volcano after cessation of the eruptions have proved to be of unique value.

There are 135 references on the Heimaey

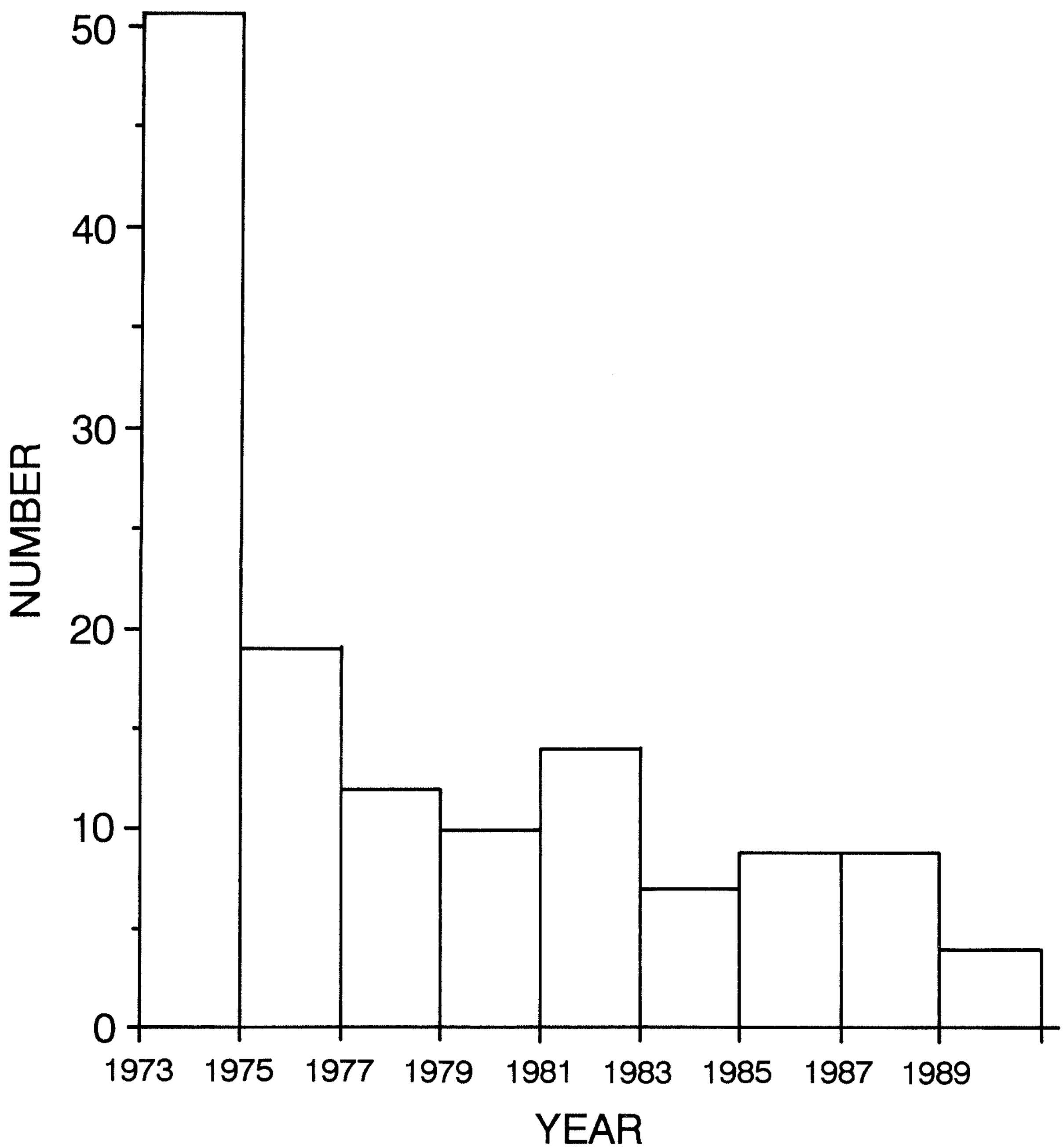

Fig. 2. Distribution of publications which deal with the Heimaey (Eldfell) eruption and its eruption products in the period 1973-1990. There are altogether 135 publications and each bar indicates the number of publications for every two years, starting with 1973.

(Eldfell) eruption. Fig. 2 shows how the publications are distributed through 1973-1990. Comparing Heimaey with Surtsey it appears that Heimaey has had much less influence on the scientific community, although the volcanic drama and the unique utilization of thermal energy from the lava gave birth to many publications.

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