SURTSEY RESEARCH PROGRESS REPORT
VIII

THE SURTSEY RESEARCH SOCIETY ● REYKJAVÍK, 1978

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VIII

1971 — 1976 FIELD SEASONS

THE SURTSEY RESEARCH SOCIETY
REYKJAVÍK, 1978

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Introduction

The Surtsey Research Society was formed in the winter of 1963—1964, shortly after the Surtsey eruption started. It is a private non-profit scientific society. The objective of the Society is to strengthen scientific work on Surtsey or related to development there. Members of the Society are Icelandic scientists. Associate members are foreign scientists, who have worked on Surtsey or taken interest in the scientific work there.

Much of the work on Surtsey has been sponsored by the Surtsey Research Society. In addition several institutions and individual scientists have done work there. In such cases the Society has coordinated the scientific work. Emphasis has been placed on collection of as many scientific progress reports as possible for the Society's biannual publication, the Surtsey Research Progress Reports. Thus a unique and most thorough account of the development of Surtsey and of life on the island is to be found in the eight Surtsey Research Progress Reports. Numerous Icelandic scientists have in collaboration with foreign colleagues contributed to that important record.

This report is the eighth in the series of Surtsey Research Progress Reports. In charge of this publication has been the following editing committee:

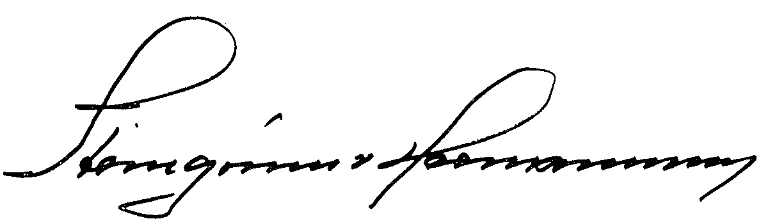
Adalsteinn Sigurdsson, marine biologist
Eythor Einarsson, botanist
Sveinn Jakobsson, geologist

This report covers primarily work on Surtsey from 1974 to 1976.

The scientific work on Surtsey has as previously received support from several sources. The Icelandic government and research institutions have given support either with financial appropriations, scientific personnel or facilities. Financial support has also been received from foreign sources especially in recent years from the U.S. Energy Research and Development Administration. This is highly appreciated. Last but not least the scientific work on Surtsey would not have been possible if it were not for the unselfish work of several scientists from Iceland and from abroad.

The isle of Surtsey was created in November 1963 in a violent oceanic eruption 20 miles off the south coast of Iceland. Its evolution has been studied ever since. Although emphasis has changed somewhat from the geosciences to biology, there are still on Surtsey many interesting phenomena to be studied in both fields. Therefore the scientific work on Surtsey must continue. In order to make that possible, Surtsey has been declared a national reserve and is protected for scientific purposes. It seems to me timely to sit down and review the scientific work that has been carried out on Surtsey to date, determine what fields are of greatest interest in the near future and plan how such work shall be done.

On behalf of the Surtsey Research Society,



Steingrimur Hermannsson
Chairman

BIOLOGY

Vascular plants on Surtsey

1971—1976

by

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Keldnaholti, 110 Reykjavík, Iceland

INTRODUCTION:

The vascular flora of Surtsey has been investigated ever since the first higher plant was observed growing on the island in June 1965. An account of this study has been given in previous Surtsey Research Progress Reports, which cover a six year period including 1970. (Fridriksson et al. 1972). The investigation during the following three years, i.e., 1971, 1972 and 1973, has been reported on in a book on the development of life on Surtsey (Fridriksson 1975). However, in order to keep continuity of reports of this investigation in the Surtsey Research Society's records, the description of annual variation and development of higher plant life on the island in the period 1971 to 1976, (incl.) will be covered here.

METHODS OF RESEARCH:

The methods used in this study have been described previously (Fridriksson 1970). Every year during the summer months trips were taken to the island. In the early summer all overwintering plants were counted and marked on a map. The map bore a grid so that the location of the plant could be given by a coordinate system with plotted out quadrats of 100 m square each. These were marked numerically and alphabetically. Aerial photographs were used to obtain a more precise location of the plants within the quadrat.

In the latter part of summer any new plants that started growth were marked with a stake. Plants that had become at least one year old were given a serial number. A description was given of the stage of growth of individual plants; indicating length and number of branches, number of leaves, flowering and development of fruits. Photographs were also taken of individual plants to document their appearance.

DESCRIPTION OF DISTRIBUTION AND POPULATION SIZE:

An unusually large percentage of vascular plants survived the winter of 1970 to 1971, or 40 of 101 (40%) compared with 18 of 63 (29%) in the previous summer. The corresponding percentages of overwintering plants in the previous winters had been 20% in 1968—69 and 35% in 1969—70. There are doubtless many reasons for this high number of overwintering plants in 1971. One is, that in the summer of 1970 no plants grew in the northernmost part of the island (in quadrats A, B, and C), which is flooded by the sea in winter. Moreover, the winter and spring were unusually mild, much milder than the previous year.

Altogether 85 individual vascular plants were found, belonging to five species: 52 *Honckenya peploides* (syn. *Minuartia peploides*), 21 *Cochlearia officinalis,* 3 *Elymus arenarius,* 3 *Cystopteris fragilis,* 2 *Stellaria media,* and four unidentified individuals. The number of species and individuals of other vascular plants found in Surtsey during that year and in various other years are listed in Table I.

The distribution of plants in 1971 was considerably greater than in the previous year (see map Fig. 1).

In the summer of 1969 plants grew in 17 quadrats, in 1970 in 22 quadrats, and in 1971 in 36 quadrats. The biggest increase, however, was in individual plants scattered throughout the lava, the main growing areas being the same as before, i.e., the hollows between Bólfell and the western cinder cone in Svartagil and between the lava and the eastern cinder cone.

In extensive areas of lava, the tuff had drifted in from the tephra mounds. At first this drifting was mainly in the old lava to the west, and consisted largely of tephra from the small volcanic island Jólnir. After the new lava had flowed to the east,

TABLE I.
Palnts in Surtsey 1968—1976

SPECIES	68	69	70	71	72	73	74	75	76
Cakile edentula ssp. islandica	0	2	0	0	1	33	3	5	0
Elymus arenarius	6	5	4	3	0	66	26	12	10
Mertensia maritima	4	0	0	0	15	25	44	11	6
Honckenya peploides	103	52	63	52	71	548	857	428	500
Cochlearia officinalis		4	30	21	98	586	372	863	501
Stellaria media			4	2	2	1	0	0	0
Cystopteris fragilis				3	4	3	3	2	2
Carex maritima					1	1	1	3	2
Tripleurospermum maritimum ssp. phaeocephalum					1	5	2	1	2
Puccinellia retroflexa					2	1	9	9	8
Angelica archangelica					2	2	0	0	0
Festuca rubra						1	1	2	1
Cerastium fontanum ssp. scandicum								106	99
Equisetum arvense								2	0
Sagina sp.								1	0
Silene vulgaris ssp. maritima								1	0
Juncus sp.								1	0
Unidentified plants	1	0	0	4	2	1	1	2	1
TOTAL	114	63	101	85	199	1273	1319	1449	1132

the drifting of tuff from the mounds to the northern part of the lava continued and sandstorms were frequent, resulting in sand and dust blowing over the surface of the lava and especially in its hollows. It was not until 1971 that most of the lava had become covered with a loose substrate and this explains, to some extent, the increased distribution of plants.

Of the 85 vascular plants that grew on the island in 1971, only 49 individuals survived the winter of 1971—72 or 58%. This was, so far, the highest percentage of surviving individuals recorded on Surtsey. The majority of the plants grew in relatively secure sites of the lava, with fewer individuals growing on the ness than in previous years. This latter location was often flooded during winter storms, which are quite hazardous for the overwintering of plants.

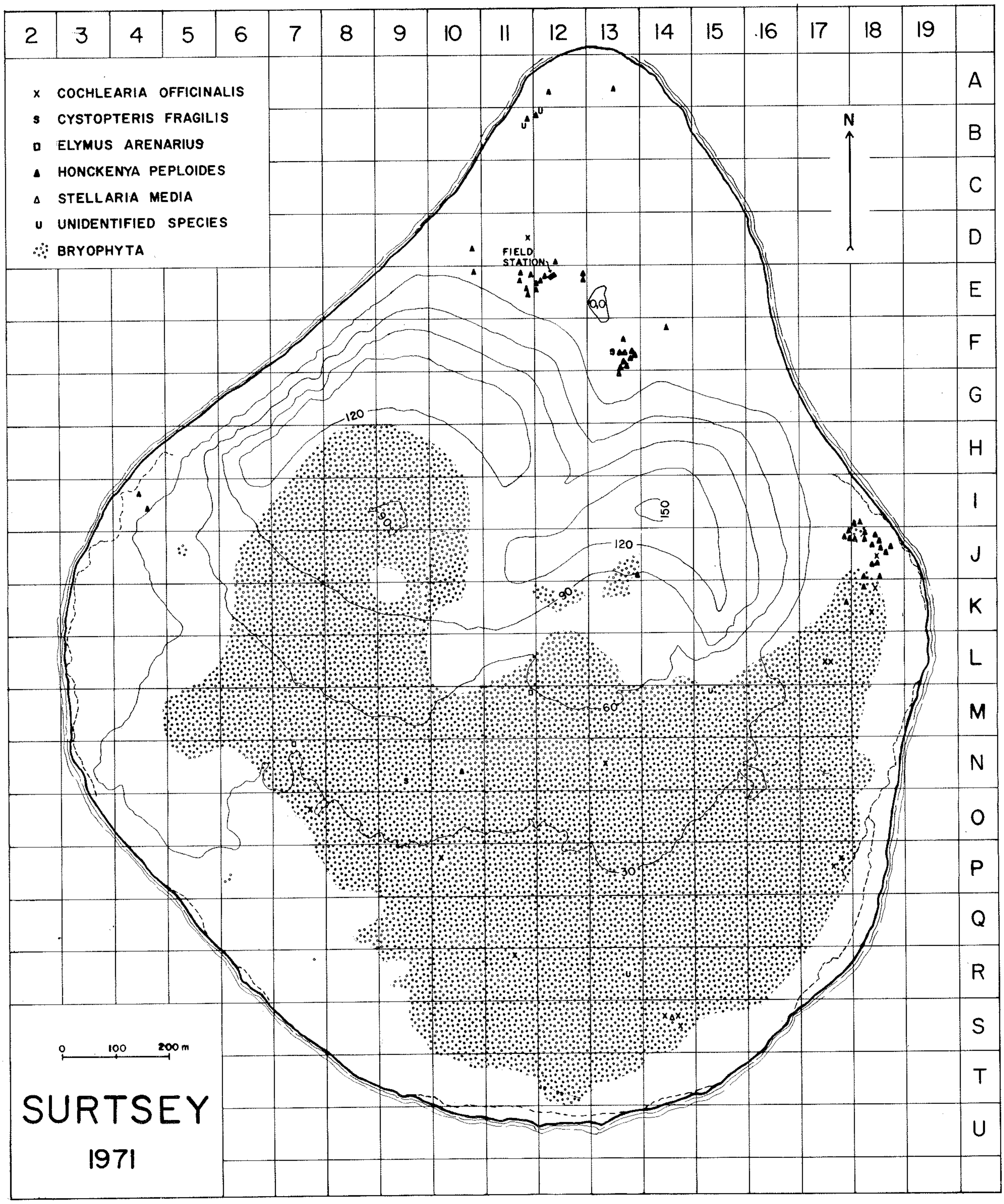
During the previous years *Honckenya peploides* was the most abundant plant in Surtsey, but in the summer 1972 the individuals of *Cochlearia officinalis* outnumbered all others. This was mostly due to the fertility of one plant (No. 38) which produced a number of offspring in 1972.

The main location of the vascular plants during the summer 1972 was in general the same as in previous years, east of the eastern cone in quadrats J-17 and 18, near the hut in quadrats E-12 and 13 and in the Svartagil quadrats F-13 and G-13. The fourth location was on the northern ness, occupied by 40 plants all of which were new colonizers (Fig. 2).

The fifth location was in quadrat S-14 on the southern part of the lava where 91 plants were found occupying an area of 80—100 sq.m.

During the summer 1972 four new species colonized Surtsey for the first time. These species are commonly found on the other islands of the Westman Islands or on lava fields of the mainland, Table I.

The distribution of plants increased heavily in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x COCHLEARIA OFFICINALIS
s CYSTOPTERIS FRAGILIS
ELYMUS ARENARIUS
HONCKENYA PEPLOIDES
STELLARIA MEDIA
u UNIDENTIFIED SPECIES
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FIELD STATION
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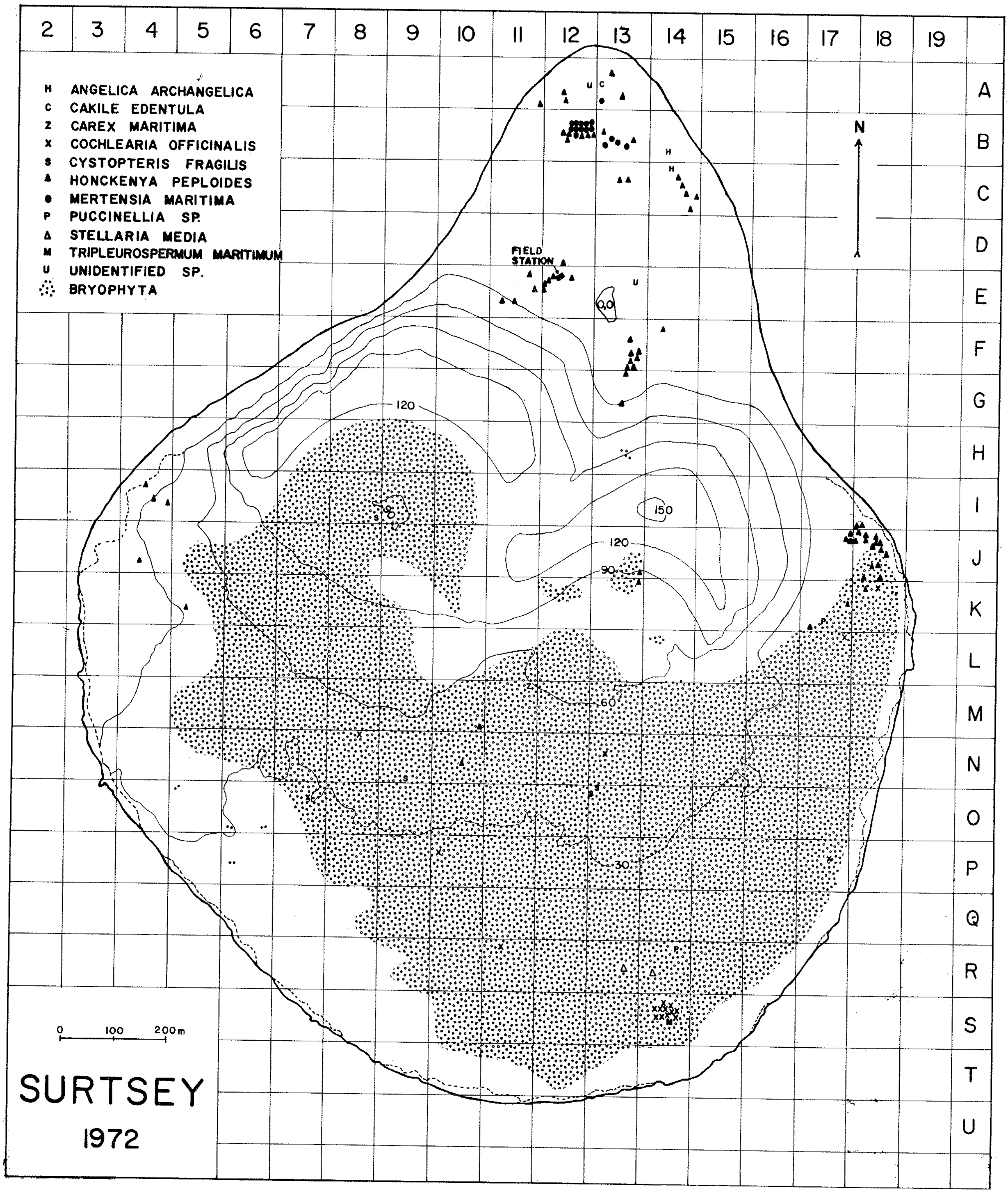
200 m
SURTSEY
1971

Fig. 1



H ANGELICA ARCHANGELICA
C CAKILE EDENTULA
Z CAREX MARITIMA
X COCHLEARIA OFFICINALIS
S CYSTOPTERIS FRAGILIS
▲ HONCKENYA PEPLOIDES
● MERTENSIA MARITIMA
P PUCCINELLIA SP.
Δ STELLARIA MEDIA
M TRIPLEUROSPERMUM MARITIMUM
U UNIDENTIFIED SP.
BRYOPHYTA
FIELD STATION
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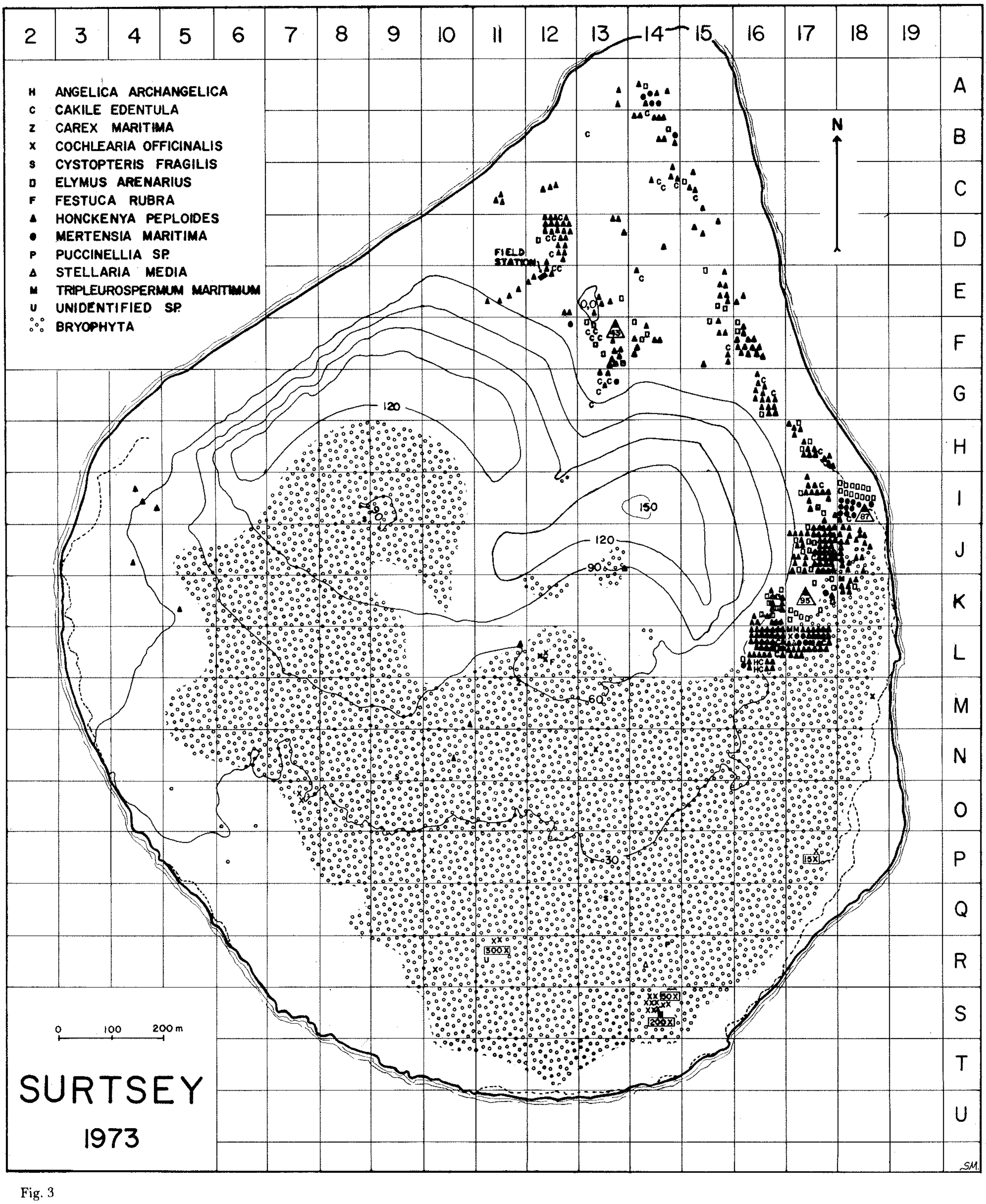
SURTSEY
1972

Fig. 2



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C CAKILE EDENTULA
Z CAREX MARITIMA
X COCHLEARIA OFFICINALIS
S CYSTOPTERIS FRAGILIS
D ELYMUS ARENARIUS
F FESTUCA RUBRA
▲ HONCKENYA PEPLOIDES
● MERTENSIA MARITIMA
P PUCCINELLIA SP.
Δ STELLARIA MEDIA
M TRIPLEUROSPERMUM MARITIMUM
U UNIDENTIFIED SP.
BRYOPHYTA
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SURTSEY
1973
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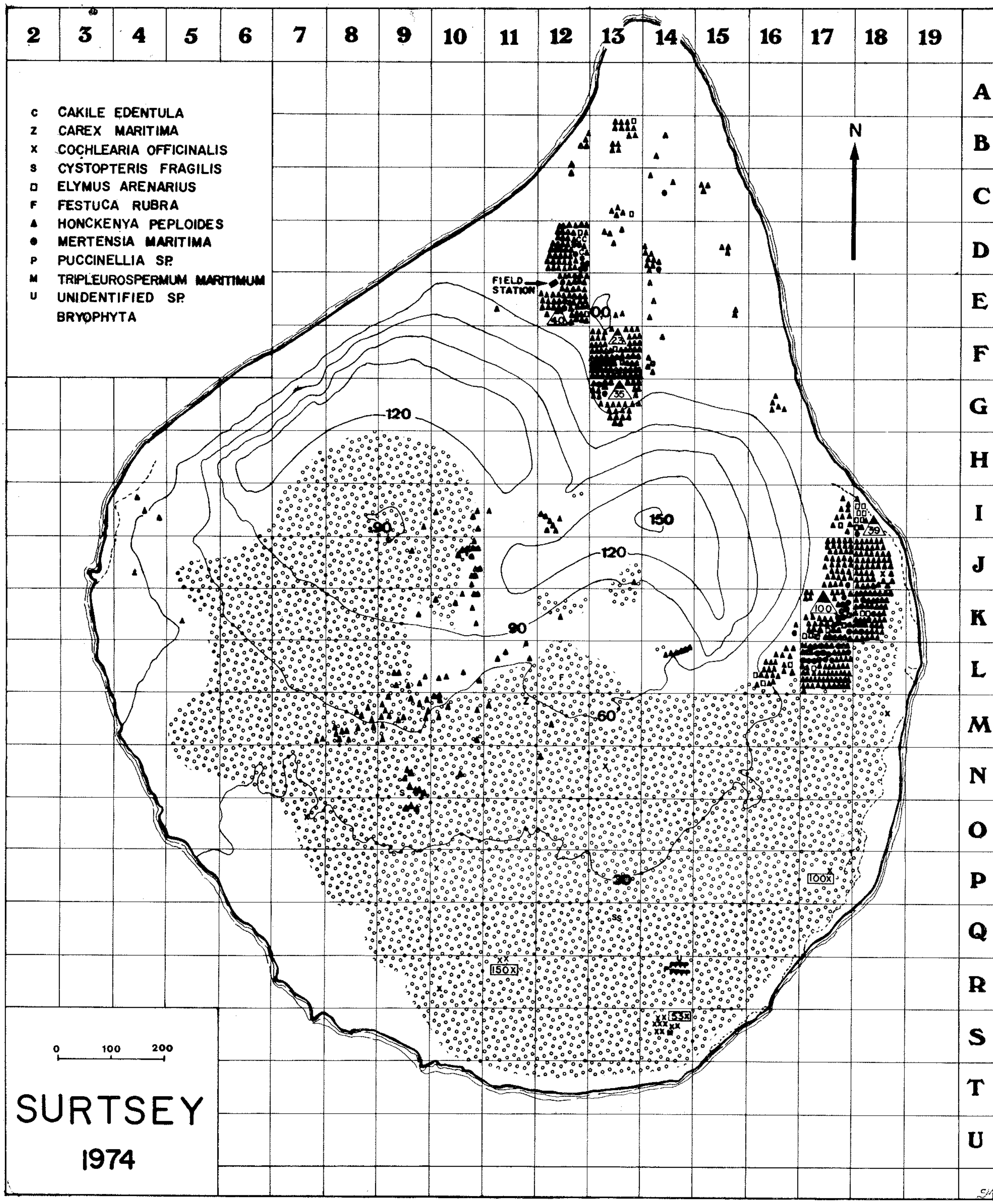
Fig. 3



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Z CAREX MARITIMA
X COCHLEARIA OFFICINALIS
S CYSTOPTERIS FRAGILIS
D ELYMUS ARENARIUS
F FESTUCA RUBRA
▲ HONCKENYA PEPLOIDES
● MERTENSIA MARITIMA
P PUCCINELLIA SP.
M TRIPLEUROSPERMUM MARITIMUM
U UNIDENTIFIED SP.
BRYOPHYTA
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FIELD STATION
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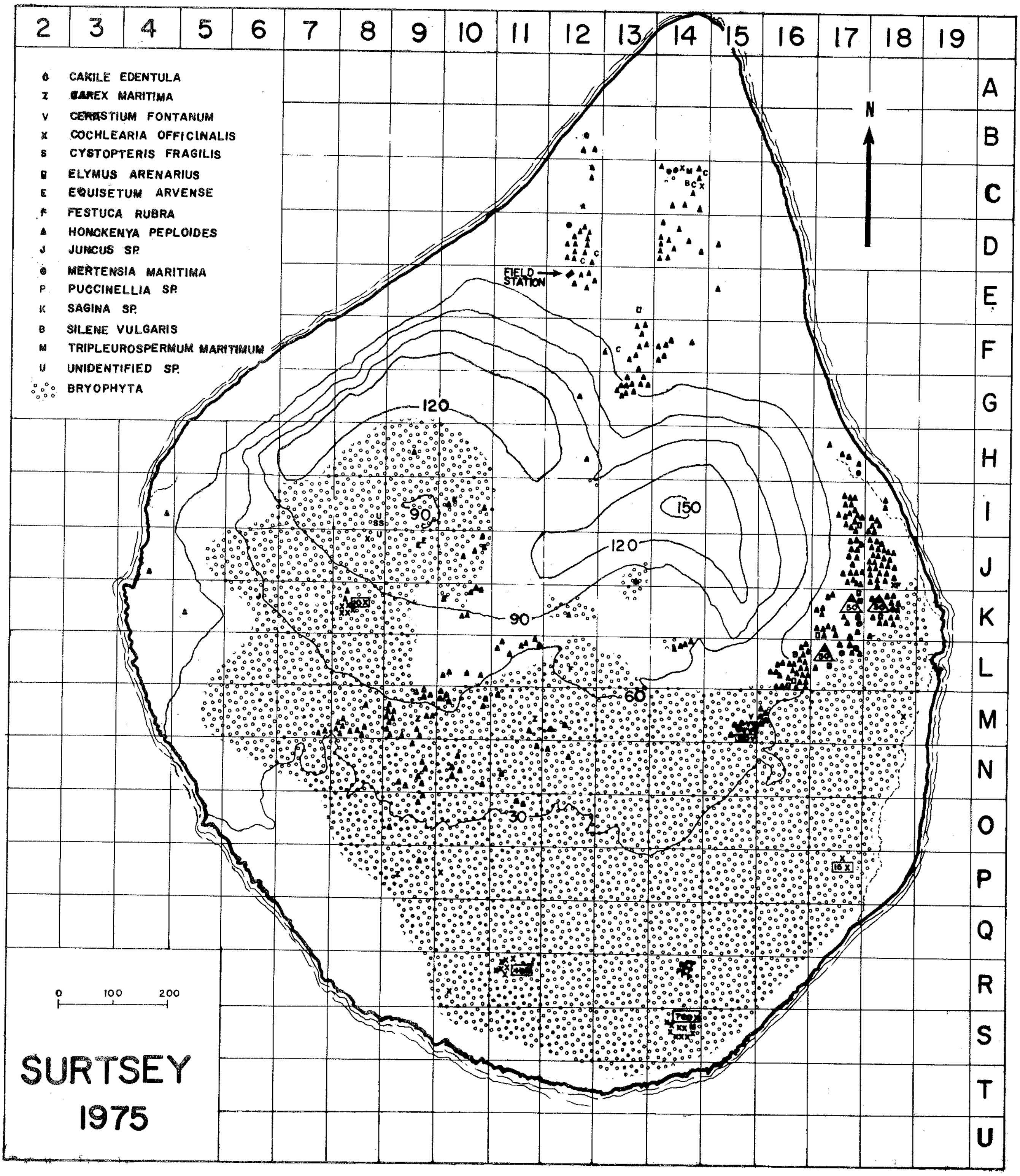
SURTSEY
1974

Fig. 4


CAKILE EDENTULA
CAREX MARITIMA
CERASTIUM FONTANUM
COCHLEARIA OFFICINALIS
CYSTOPTERIS FRAGILIS
ELYMUS ARENARIUS
EQUISETUM ARVENSE
FESTUCA RUBRA
HONCKENYA PEPLOIDES
JUNCUS SP.
MERTENSIA MARITIMA
PUCCINELLIA SP.
SAGINA SP.
SILENE VULGARIS
TRIPLEUROSPERMUM MARITIMUM
UNIDENTIFIED SP.
BRYOPHYTA
FIELD STATION
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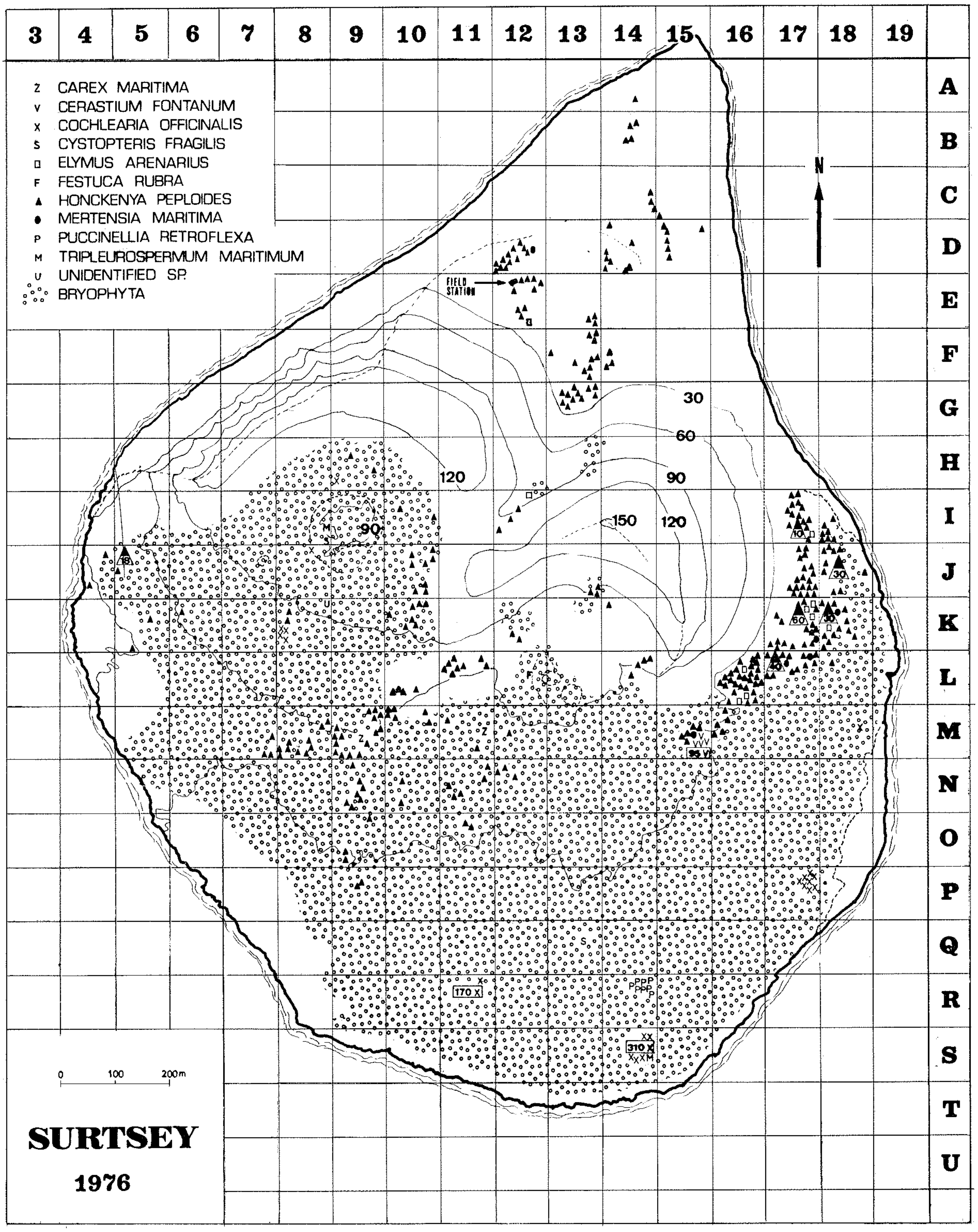
SURTSEY
1975

Fig. 5



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S CYSTOPTERIS FRAGILIS
ELYMUS ARENARIUS
F FESTUCA RUBRA
HONCKENYA PEPLOIDES
MERTENSIA MARITIMA
P PUCCINELLIA RETROFLEXA
M TRIPLEUROSPERMUM MARITIMUM
U UNIDENTIFIED SP.
BRYOPHYTA
FIELD STATION
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120
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SURTSEY
1976

Fig. 6

1973. The number of individual plants jumped to 1273, and these occupied 58 quadrats. The main location of these plants was along the northern ness, extending into the lava on the eastern side, Fig. 3. Of the 1273 plants from 1973 only 537 overwintered but 782 new plants started growth so the total plant number for the year 1974 was 1319. The map in Figure 4 shows locations of the various vascular plants in 1974, however, only 446 of these plants were found in 1975, but as 1003 new plants were recorded the total number of plants was thus increased by about 130, principally due to a large number of new seedlings of *Cochlearia officinalis.* The chief changes in distribution were that new plants were found in quadrats M-15, M-16, N-11, O-11, and P-9, where *Honckenya peoploides* plants had not previously been observed, so that it appeared to the extending its distribution towards the south of the island, Fig. 5.

The total number of species were 15, in addition to two unidentified plants.

Only ten of these species were found again in the summer of 1976. One additional species was discovered but could not be identified. Thus, altogether 11 species of vascular plants grew in Surtsey in 1976.

Species not found in 1976, but grew there the previous year, were: *Cakile edentula* ssp. *islandica Equisetum arvense, Juncus* sp., *Sagina* sp., and *Silene vulgaris* ssp. *maritima.*

Of 1449 individual plants growing on Surtsey in 1975, 502 were found in the spring of 1976. The new additions numbered 630 plants. The total number of plants found in 1976 was thus 1132 individuals, or 317 indiviudal plants fewer than in 1975, Fig. 6. The main reason for the decrease was the smaller number of scurvy grass seedlings compared with the previous year. Apart from seedlings of scurvy-grass and *Cerastium fontanum* ssp. *scandicum* the number of plants was 680, and the mature plants had therefore increased by 175 (Table I). The high mortality of plants was due to a severe winter but other casualities also took place. A pair of great black-backed gulls that nested in quadrat N-10 used, for instance, *Festuca rubra* No. 73—370, *Carex maritima* No. 70—72, and 20 sea sandwort plants for their nest. The birds were particularly fond of the *Festuca rubra* and the *Carex maritima.* For overwintering of plants see Fig. 10.

THE INDIVIDUAL PLANT SPECIES:

Cakile edentula (Bigel) Hooker ssp. *islandica* (Gand.) Á. & D. Löve (syn. *Cakile maritima*):

The first vascular plant on Surtsey found in 1965 was of the species (Fridriksson 1965, 1975). Since then the sea rocket has been observed now and then but it has never been a permanent settler. In 1967 there were 21 individuals growing on the island, of which 15 flowered. It was thus the first higher plant species to flower on Surtsey. During the years 1968, 1970 and 1971 no plants of this species grew on the island. In 1969 there were two plants and in 1972 one individual was discovered, i.e., plant No.95 in quadrat A-13. It was small and situated on the northern ness. In 1973 there were 33 plants recorded on the ness and in 1974 only three were discovered at the high tide line in quadrat D-12. In 1975 five plants were found and three of these managed to flower and bear seed. Plant No.75—89 in C-14 was particularly vigorous and produced 100 mature seeds. This species was not rediscovered on Surtsey 1976.

Elymus arenarius L:

This species was first discovered in 1966 and was the second attempt made by higher plants to invade Surtsey (Fridriksson 1966). In 1968 there were six plants found but these decreased in number to only three plants in 1971 and none was found in 1972. In 1973 there appears to have been a great invasion of seed and 66 seedlings of lyme grass were discovered during that summer, but there were only 26 plants left in 1974. Eleven of these plants survived the following winter and only one new plant was found during 1975. The

Fig. 7. The lyme-grass, *Elymus arenarius.*

number of plants had, therefore, decreased considerably. Nine lyme-grass plants over-lived the next winter and one additional new plant was found in 1976 making a total of ten plants of this species on the island. The largest plant was from 1974, No. 74—51 in K-18. It had 6 culms and 28 leaves, covered an area of 12×3 cm, and was about 45 cm. in height. Other lyme-grass plants were smaller, most having 1—2 culms and 3—8 leaves. None of the plants has managed to flower yet. (Fig. 7).

Mertensia maritima (L.) S.F.Gray:
In 1967 the northern shore-wort was first discovered on Surtsey and four seedlings were found in 1968. During the following three years no individuals of this species were observed growing on the island but it reappeared in 1972 with 15 plants and increased to 25 plants in 1973 and to 44 in 1974 but since then their number has decreased.

Of 11 *Mertensia maritima* plants growing on the island in 1975, 6 were found alive in 1976. No new specimen was discovered. All these plants were small, with 5—7 leaves, and they did not flower. The poor development of these plants was probably due to the low nitrogen content of the soil. One *Mertensia maritima,* No.75—6 in M-15, had been injured when it was inspected in August 1976, probably cut up by a raven. The species is a perennial and two of the plants growing on Surtsey in 1976 are from 1974 and two from 1975.

Honckenya peploides (L.) Ehrh.:
The sea sandwort, a common perennial on the southern shore of Iceland, was first discovered on Surtsey in 1967. It has grown on the island ever since. In 1968 there were 103 plants but the number had dropped to 52 in 1971. Five of these plants flowered and one matured seed. The following summer 71 plants were observed of wich 38 had overwintered. After the large invasion of seed in 1973 there were 548 sea sandwort plants found on the island and this number still increased to 857 in 1974 (Fig. 8).

The new colonists of 1974 were mostly found on the eastern and central parts of the island as well as on the northern ness. Many were offsprings of earlier colonizers. In one instance, in quadrat K-17, a *Honckenya* plant, No.68—56, had 50 offsprings that formed a colony in the same quadrat and in the adjacent one, J-17. The number of plants of *Honckenya peploides* decreased drastically after 1974, principally, because such a small part of the 1974 crop survived to the following year. The reduction was greatest in quadrats D-12, E-12 and F-13, and similarly in the main plant area on the eastern part of the island. Relativly few new plants were found, or about 167, which is much fewer than in the previous two years. In 1975 there were discovered 428 plants. Of these 337 survived the winter, and as there were altogether 163 new plants the total became 500 in 1976. There was thus comparatively little loss, most having been in

Fig. 8 The sea sandwort, *Honckenya peploides,* in 1971.

quadrats B-12, C-12, and G-14, over which the sea flows in the winter. For overwintering of this species see Fig. 9.

By far, the most losses occur in the first year, often being due to drifting sand. If the new seedling is not submerged during the first winter, it will most likely continue to survive, if it is in a fairly favouruable habitat, or not in the drifting sand where it may be washed away. In its second year, the plant already attains a considerable size, and may cover an area of about 30—50 cm^2. Most of the sea sandworts cover about 50—100 cm^2 and have 5—10 culms. Some of the largest are No.-70—39 (90×90 cm) in quadrat G-13, No.58—83 (100×80 cm) in F-13. The largest sea-sandwort plants from 1968 and 1969 now cover an area of 8000 cm^2, and are the most conspicuous plants on the island.

These permanent flat tufts are gradually increasing in size and productivity and are annually pruducing flowers and pods. In 1976 plant No. 58—56 in quadrat K-18 produced the greatest number of pods, or about 1000, and a total of 73 sea-sandwort plants flowered during 1976. But the propagation of single plants may sometimes be slowed down by the blowing sand or even by injuries caused by birds. The pair of great black-backed gulls that nested in quadrat N-10 in 1976, for example, disturbed 20 sea sandwort plants when building their nest, but these partly recovered during the summer. The distribution of the species, however, increases steadily and surprisingly evenly as may be seen on the map. Sea-sandwort was found in 50 quadrats in 1976 so that the species has gradually colonized new areas and spread to four new quadrats since 1975. However, up to now, the sea sandwort cover on Surtsey is relatively small in the vast open fields of lava and sand, but then other plants have even less cover.

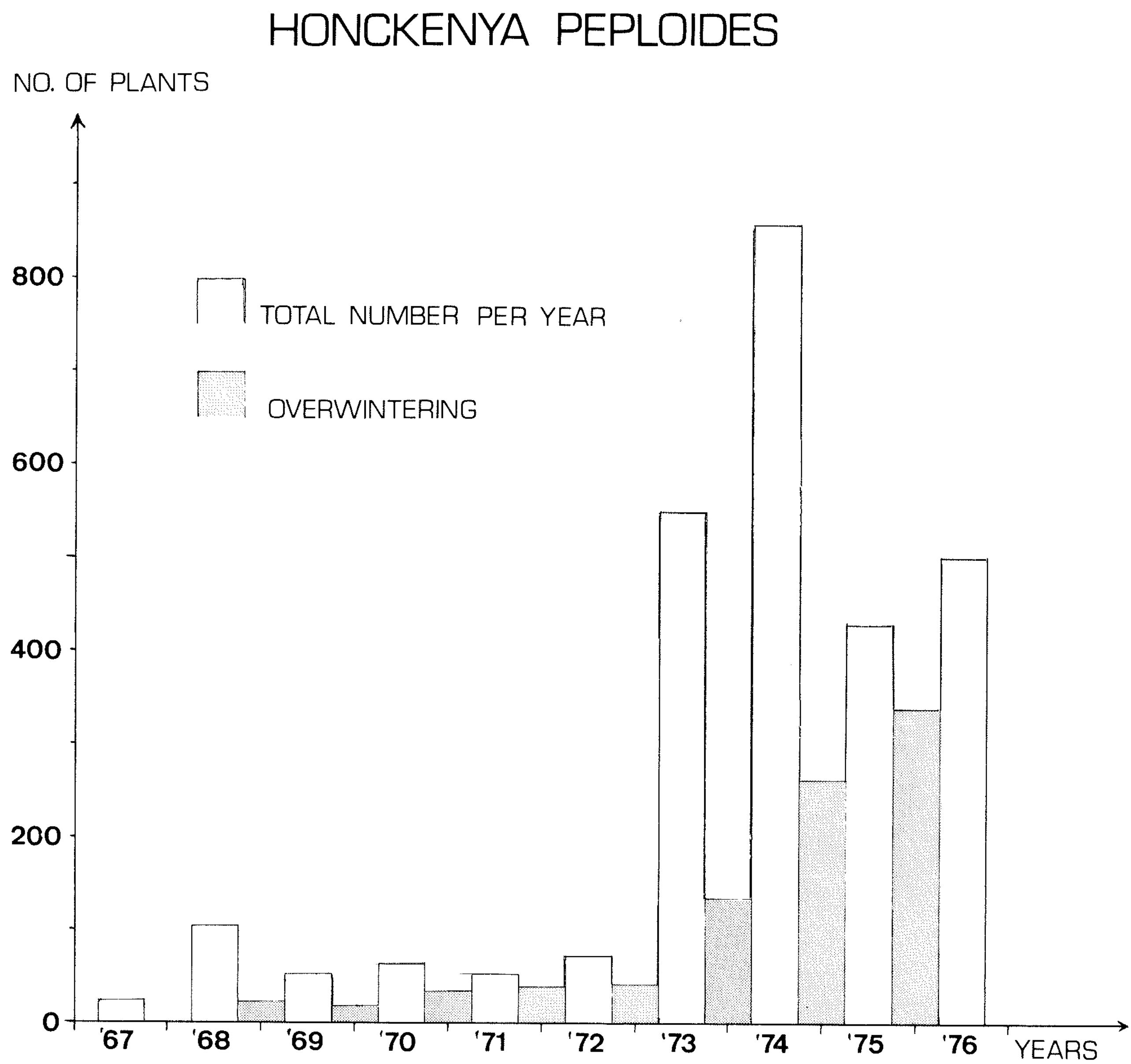

Fig. 9. The total number and overwintering *Honckenya* plants per year on Surtsey.

Cochlearia officinalis L.:

In 1969 the scurvy grass was added to the flora of Surtsey when four plants of this species were discovered in the lava on the eastern side of the island, and this species has since become a permanent resident. In 1970 there were 30 plants found growing at the same location and in 1971 the population amounted to 21 plants. The plants varied greatly in size, or from 1.5 to 30 cm. in diameter. The biggest one was plant No.38 in quadrat S-14 from 1970. It flowered early and siliculae had already formed in June. Observations made in late August, revealed 8 seedlings that had grown up from its seeds, and more seeds were germinating. Similarly many other scurvy grass plants flowered and dehisced seed that same summer. During these years many of the plants were found near a water container and had obviously been dispersed by birds, that had been attracted by the drinking water.

The other plants of the species that were found growing in Surtsey had probably all been dispersed by birds. In some cases the plants have grown up out of bird droppings or bird carcasses, though in other cases no definite assertion can be made. *Cochlearia* is widely distributed over the island, much more so than *Honckenya,* which tends to support the abovementioned theory of the dispersal route.

In 1972 the scurvy grass became the most abundant species on Surtsey with 98 individuals and it has outnumbered all others ever since except in 1974 when the sea-sandwort took the lead. Most of the scurvy grass in 1972 were seedlings, the

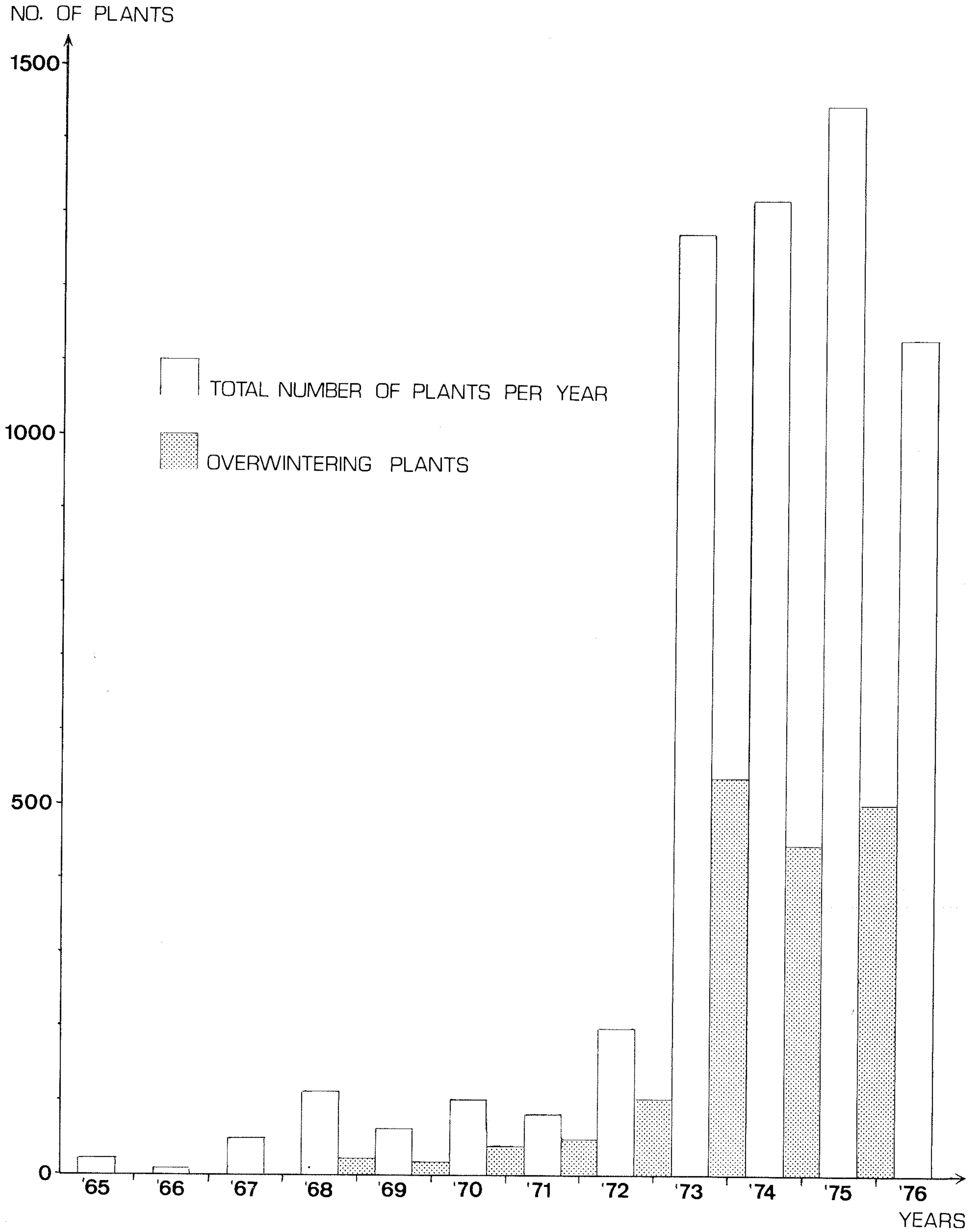

Fig. 10. The total number of vascular plants per year ond overwintering plants on Surtsey.

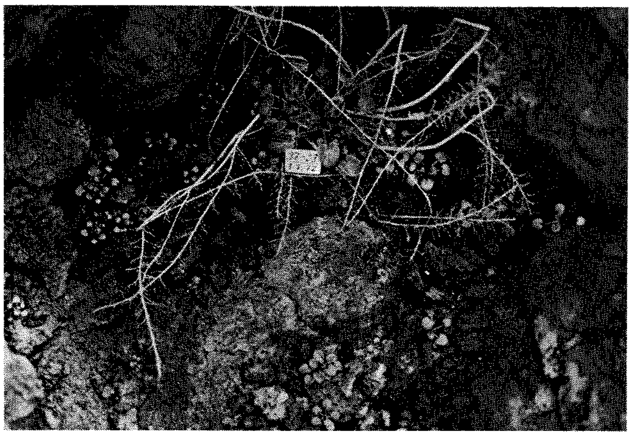

Fig.11 The scurvy grass, *Chochlearia officinalis*, a mature plant and a colony of seedlings in 1972.

Photo: Skúli Magnússon

descendants of plant. No.38. They occupied an area within a 50 cm distance from the mother plant. Over 80 seeds germinated in 1972 but at least 10 seedlings failed to mature due to crowding and various other reasons. In quadrat S-14 there were seven additional plants of the same species which were very likely also the descendants of the same mother plant and had only dispersed farther away. Plant No.30 in quadrat K-18 also matured seed during that same summer but none of these developed.

The only *Cochlearia* to flower during the summer 1972 was plant No.36 in quadrat O-7. It matured seed in August and shortly after the seed dispersed and started to germinate. In the autumn of 1972 a few seedlings were seen growing beside the mother plant. Nine of the *Cochlearia* plants found that summer had survived in Surtsey since the year before (Fig. 11).

In 1973 there was an enormous increase in scurvy grass plants, when 586 plants were counted. Some of these were, however, only small seedlings and mostly offsprings of two plants on the southern side of the lava in quadrats R-11 and S-14. In 1974 there was a decrease in number of plants to 372 individuals. The number of plants increased again by about 491 in 1975 as a result of the large number of seedlings from local sources that year. About 6 plants flowered in the summer and dropped seeds which sprouted as soon as they reached the earth, with the result that a large number of small seedlings were immediately formed around the mother plant. Plant No. 75—1 in S-14 was the main contributor; about 550 seedlings were counted around that plant alone. *Cochlearia officinalis* plants were now found in two new quadrats, J-8 and K-8.

The number of scurvy-grass plants decreased somewhat in 1976 compared with the previous year, or from 863 down to 501. This decrease was mainly due to a great loss of seedlings, which was unusually high. Most of the scurvy-grass plants did not reach maturity, and only three of them produced seed during 1976. Scurvy-grass vanished from three quadrats during that year, from: J-18, P-10 and R-10, but a new plant was discovered in quadrat H-9. Scurvy-grass thus existed in altogether 7 quadrats and usually formed a colony of 10—20 plants, if seedlings were not included. Scurvy grass is not as conspicuous as the sea sandwort but it is a good seed producer and capable of occupying crevices in the lava which it colonizes readily.

Stellaria media (L.)Vill.:

The common chickweed became the new addition to the island's flora in 1970. It was apparent that it had grown up from bird droppings, as four plants were growing together among fragments of shells. That same summer two of these plants bore 12 fruits and a number of seeds. Two plants grew up from those in 1971. During the final observation that summer they were still only seedlings and had not developed much. In 1972 there were two plants of that species still growing on the island. In 1973 only one plant was left, and since it perished in 1974, the species has not been rediscovered.

Cystopteris fragilis (L.)Bernh.:

During a thorough search in the lava in 1971, three specimens of brittle bladder-fern were found growing down from a cave roof in quadrat N-9. The plants were 2 to 3 cm. long and about 0.5 cm broad. They grew above a sand heap deposited under the lava shelf (Fig. 12)

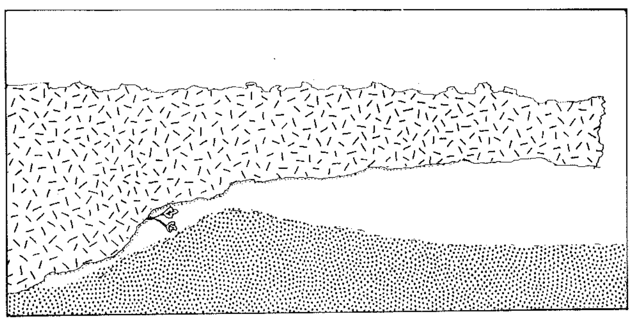

Fig. 12. Schematic drawing of the cave with *Cystopteris fragilis* growing down from its roof.

One of these plants survived the winter, being well protected under the protruding lava. In addition to this plant three new ferns were discovered during 1972. Two of these were found in shallow lava hollows in quadrat 0—13, i.e., No. 117 and 118. The third plant was discovered in the lava crater in quadrat I-8. The conditions were the most favourable for this individual as it grew at the bottom of a crack in the lava, where it was shaded and enjoyed both heat and moisture from hot vapour emitting through the fissure. The development of this plant was accordingly better than that of the three other members of the species. Three plants survived in 1973 and 1974. Only one of the plants from 1974 survived the winter of 1975, No.72—113 in I-8 but a new plant, No.75—62, was found in the same hollow. Both plants were very small, the older having only two leaves, the larger of which was 7 cm in length. Neither of the plants was fertile, but both were alive in 1976, had three blades each but neither produced any spores during the year.

Angelica archangelica L.:

In 1972 two plants of this species were discovered on the north-eastern shore of Surtsey in quadrats B and C-14. This was the first time members of this species colonized the island although its seed had previously been found on the shores of Surtsey. The two plants were only small seedlings with cotyledons and the seed coat attached. They were found growing at the high-tide mark, which indicates that the plants developed from seed which had drifted to Surtsey by the ocean. One of the plants, No.120, died already during the summer 1972 and the other was lost the following winter.

In 1973 the species was again represented. This time by two small seedlings growing at the edge of the lava in quadrat L-16. Their fate was the same as the previous ones and the species has not been rediscovered since.

Carex maritima Gunn.:

A small grasslike plant had been growing up on the lava in quadrat M-11 since 1970. It had previously been incorrectly recorded as lyme-grass but was in 1972 identified and listed as the sedge *Carex maritima.* It did not produce flower stalks but increased in size by stolons and propagated vegetatively so that a colony of several plants was formed. This plant developed until 1975, when it had 86 culms and 8 panicles, but in 1976 it was badly damaged, because the pair of great black-backed gulls, that were nesting in quadrat N-10, tore at it and used it for building material in their nest. It was nearly annihilated, but later that summer it was showing some recovery and had again formed two culms and eight leaves (Fig. 13).

Two additional *Carex maritima* were found in 1975. One was in quadrat P-9 and did not survive the winter, but the other in quadrat M-9 produced

Fig. 13. The curved sedge, *Carex maritima,* plant No. 70—72 showing vegetative propagation.

Photo: Skúli Magnússon.

one leaf in June which had disappeared by August. No new plant was found in 1976. *Carex maritima* thus suffered much loss during that year.

Puccinellia retroflexa (Curt.) Holmb.:

In 1972 two small plants, No.90 in quadrat R-14 and No.110 in quadrat K-17, were identified as of the genus *Puccinellia.* They were both growing near the sites where the water containers had been placed. It is thus very likely that these plants developed from seed dispersed to this area by birds. It was first believed that they were of the species *maritima* but it may now be considered certain that they belong to the species *retroflexa.* The plant in quadrat R-14 flowered and developed seed in 1973.

In 1974 there were eight offspring of that plant growing in quadrat R-14. Four of these second generation plants flowered in the summer of 1975 and bore seed. One unidentified plant, No.74—89 in quadrat R-14 from 1974, proved also to be *Pucinellia* so the total number of plants in that year became ten. In 1976 there were, however, only eight plants found at this spot. Two of them grew in a fissure, the others up on the lava table. The plants growing in the fissure were considerably larger than those on the lava. One of those, No.74—89, produced three panicles, and this was the only *Puccinellia retroflexa* to flower that year. Two of the panicles that emerged in August produced mature seed and one emerged at the end of the season but did not develop further.

Tripleurospermum maritumum, (L.) Koch ssp. *phaeocephalum* (Rupr.) Hämet-Ahti (syn. *Matricaria maritima*):

One scentless mayweed, No. 40, grew in quadrat S-14 in 1972. Its habitat was a sand covered lava hollow, and the plant grew there among the *C.officinalis* individuals that occupied the same hollow.

There is no indication as to how this plant may have been dispersed to this place, but it could have been brought in by birds like the *C.officinalis* plants. The plant is common on the neighbouring islands and various plant parts had previously been found in the drifted material on Surtsey's shores.

In 1973 four more individuals were discovered on the lava on the easternside of the island in quadrats K-18 and L-17. These may very well have developed from seaborne seeds. In 1974 there were only two plants left and the year after only one plant remained in quadrat S-14. It had not grown any larger nor flowered, which was probably due to the soil's infertility. The plant was still very small in 1976. It had only two leaves, each of which was about 1 cm in length.

Another specimen of scentless mayweed was found in the lower part of the lava crater in quadrat I-18. It was given the number 76—171. This plant was much larger than the old one. It produced 20 leaves, had a diameter of 7 cm, but did not flower. It is almost certain that its seeds were carried by a bird for the plant is too far from the sea to have been brought that way. Sheltered by the crater the future of this plant would seem to be fairly secure.

Festuca rubra L.:

The red fescue is the most common grass species on the Westman Islands and it was reasonable to expect it to become a colonizer on Surtsey. In 1967 this species was found growing in sand in quadrat F-15 (Einarsson, 1967) but the specimen was washed away by the sea the following winter. In 1973 a seedling of the red fescue was found on a sandy ridge in quadrat L-12. It continued to develop in 1974.

There were two specimens of *Festuca rubra* on the island in 1975. One was a new colonizer that year, growing in a hollow, together with scurvy-grass, in quadrat J-18 and it is safe to conclude that a bird must have brought the seeds to this spot at the same time but that the scurvy-grass seed germinated first. When inspected in June, 1976 the hollow had filled with sand and the plant had therefore been covered up.

The other *Festuca rubra,* in quadrat L-12, had grown on the island since 1973. It gradually increased in size until 1975, when it had 90 culms. In 1975, the pair of great black-backed gulls that nested in in quadrat N-10 used it for material in nest building. All the surface part of the plant had been thus removed. In August this red fescue plant had formed one culm with three leaves, however the plant's future is now very undertain.

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

A whole colony of *Cerastium fontanum* ssp. *scandicum* plants was found in quadrat M-15. These may have developed from a single plant, which was not deteced in 1974. On June 24, 1975, the colony consisted of seven plants, of which four were in flower. By August 15, 1975, the plants had increased to eight, all had flowered and dropped seed. About 98 minute seedlings had also formed around them by that time.

The following summer of 1976, there were 38 plants growing at the same site in a plot of about 10 m^2. Many of these plants matured during the summer, 16 plants flowered andwhen inspected on August 12th there were 250 flowers and 250 pods with seeds. At the end of the summer there were 99 plants including seedlings in the colony.

Cerastium fontanum ssp. *scandicum* is a common dryland plant throughout Iceland, including Heimaey. It is not easy to say how it was carried to Surtsey, though it is not likely that the seed was brought by sea, since the plant grows quite a distance inland on the island. It is most likely that the seed was brought by a bird. Conditions on the island seem to suit the plant very well; it grows in sand which has blown onto the lava and settled in depressions. The future of this species would seem to be fairly secure on the island, and its propagation area is likely to increase in the next few years.

Equisetum arvense L.:

Two *Equisetum arvense* plants, No.75—74 and No. 75—75, were found in 1975 in quadrat J-9 by the lava crater Surtur II. They were growing on the same patch on the bare lava beside a heat vent. The plants were both very small with traces of three stems on each, all less than 2 cm long, but they were growing up out of the prothallium. About 12 additional prothallia were found in the neighbourhood which had not formed stems.

Equisetum arvense is the most common species of the Equisetaceae in Iceland and grows, amongst other things, on sand and pumice. It has been very prominent on Heimaey since the eruption there in 1973 and the accompanying fall of ash.

The plant was no doubt brought to Surtsey through windborne spores, but it is not easy to say when, since it is not known for certain how long the gametophyte takes to mature after the spore sprouts. Conditions ought to be very favourable for the plant on Surtsey and it will probably hold its own there although it was not found again in 1976.

Sagina sp.

A very small plant, No. 75—78, of the genus *Sagina* was found in 1975 in quadrat No. I-10, probably *S. saginoides* or *S. procumbens,* but because of its small size and absence of flowers it was not possible to reach a conclusion. Both these species are very common all over Iceland and grow in similar conditions.

It is most likely that the seed was brought to the island by a bird, though it is not out of the question that it may have been carried by the wind, since the seed is small and light. It can hardly have come by sea, since the plant is growing far away from the shore at an altitude of about 90 meters above sea level.

Silene vulgaris (Moench) Garcke ssp. *maritima* (With.) Á.&D. Löve:

A small plant of *Silene vulgaris* ssp. *maritima* No. 75—94, was found in C-14; it was without flowers and not very mature. This species is very common in sandy soil throughout the country and thrives well by the sea. It is very common on Heimaey. The seed was without doubt carried to Surtsey by sea. It is very unlikely that the plant will survive in this spot since it is covered by the sea in the wintertime.

Juncus sp.

A small plant, No. 75—64, was found in 1975 in quadrad K-6. It had 11 needle-shaped leaves, but no flower. It seemed safe to assume that this plant was of *Juncus* sp. and probably *Juncus trifidus,* a common moorland plant throughout Iceland, which also thrives well in sandy soil. Judging from its location, there can be little doubt that the seed was carried to Surtsey by a bird. Transport by the sea is out of the question, and the seed is too large to be carried by the wind. The plant was vigorous and its future on the island looked promising, but the plant was not rediscovered in 1976.

Unidentified Plants:

During the course of this study a small number of unidentified plants have been recorded every year. These have been small seedlings, too underdeveloped to be identified with any certainty. Sometimes these plants have lived long enough to obtain proper names on the records, in other cases they have died out the following winter and been lost.

Two unidentified plants were, for example, found in quadrat J-8 in 1975. These were minute seedlings and thought to be of the family *Caryophyllaceae.* Similarly, a plant, which has not yet been identified and is probably a new species on the island was found in quadrat K-8 in 1976.

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The morphological variability of a *Synechococcus* clone from postvolcanic substrate on the island of Surtsey (Iceland)

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Morphological variation can be studied only with a clone to assure genetically homogenous material. Such studies are particularly difficult with *Cyanophyceae* because of their small size and the poor morphological differentiation of their cells. The genera *Synechococcus* and *Synechocystis* were until now considered to show little morphological variability in contrast to e.g. some *Stigonemataceae* and *Rivulariaceae*. This was tested with material from the new volcanic island of Surtsey (Schwabe 1972 a,b, 1973, Schwabe & Behre, 1971, 1972).

A large-celled *Synechococcus* species which can be attributed to *S. aeruginosus* Näg. was found in one locality on Surtsey in the course of intensive investigations in respect to *Cyanophyceae* by the first author. The study of cell variability and growth characteristics of this species seemed rewarding because of its relatively large cells as well as of the rare occasion of earliest stages of ecogenesis found on that island. Here other species tend to thrive than in older biotopes.

The localities south of Lýsuhóll, the most recent lava bed of the big crater Surtur I, where *Synechococcus* was sampled is a favourite resting site for birds. Thus it can be assumed that *Synechococcus* was brought to the island by birds, a similar case might be with the accompanying species *Oscillatoria fracta*. Since the first sampling date of *Synechococcus* in summer 1972 the species has spread considerably in the vicinity during the following two years.

From a sample of wind-swept tephra (sampling date: 31 July 1974, start of culture: 27 August 1974) the *Synechococcus* clone was isolated in an nitrogen-poor modification of Zehnder medium. Contrary to other *Synechococcus* species (Syn.: *Anacystis*) this clone could not be cultivated on agar. During the first weeks *Synechococcus* sp. showed a relatively uniform and typical morphological appearance (Fig. 1) with a cell size of 5.5—7.5 × 11—24 μm. Only few larger cells (7—8 × 20—45 μm) were found. From 24 October 1974 the clone remained in the same medium until 24 August 1975. After 60 days the clone stopped growing, then covering only ca. 25% of the bottom of the culturing flask, where it mostly formed a single cell layer. The colour changed from bright blue-green in the beginning to dirty green towards the end of the growing period, which ceased long before nutrient depletion. Thus a resting phase, typical for many *Cyanophyceae,* was reached, conserving viability while resting almost at zero growth rate (Schwabe, 1966).

270 days after the start of the culturing experiment a surprising variety of cell forms was found (Fig. 3). Cells were mostly longer than wide (diameter 4.5—17 μm), rarely spherical, never shorter, which means that they divided rectangular to their long axis. Long cells were thinner (4.5—15 μm) than short ones (15—17 μm). Cell lengths varied between 10 and 90 μm, with exception 170 μm. The longest cells after 90 days measured 45 μm after 130 days 95 μm and 270 days 170 μm. Morphological variability was lower in the center of the colony than at the edges with fewer cells. Typical cell forms were relatively sparse in the senescent culture. Increasing cell length and disturbance of cell division were most frequently recorded. Plasma structure and cell colour indicated that the morphologically abnormal cells were possibly of reduced viability, yet no distinct limit between normal cells and cells with teratism could be found. Cell walls proved to be exceptionally thick; cell wall thickness might serve as a taxonomical criterion in *Synechococcus.*

It is essential to realize that the morphological variability of *Synechococcus* as demonstrated in Fig. 2,3 included the known typical morphological

Fig. 1: Raw culture of *Synechococcus* with *Oscillatoria fracta* and *Schizothrix lardacea.*

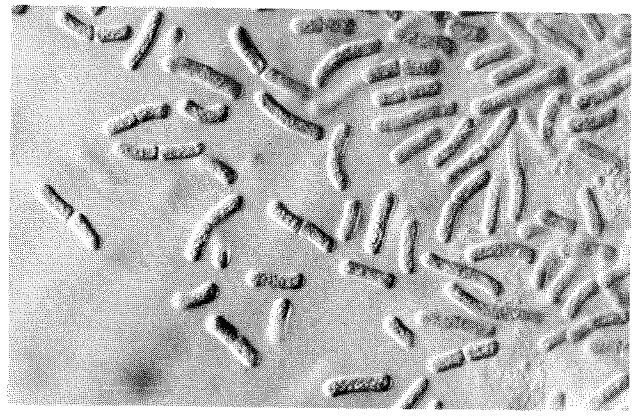

Fig. 2: Clonal culture of *Synechococcus* partly showing elongated cells.

Fig. 3: Same culture as in figure 2, showing more pronounced 'involutionary forms.'

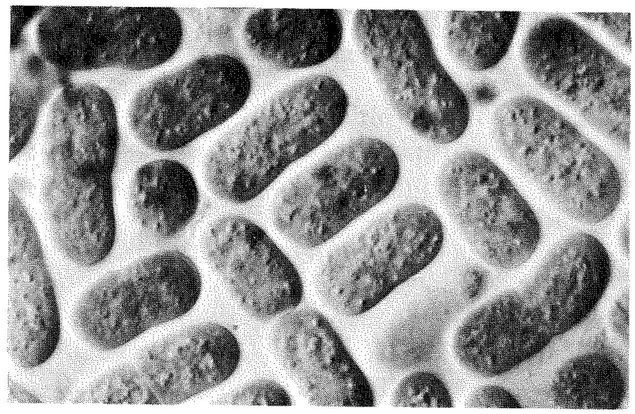

Fig. 4: Typical aggregation of *Synechococcus* in clonal culture.

variety of several species of the genera *Synechococcus* and *Synechocystis.* Taxonomical differentiation of *Synechocystis* from *Synechococcus* by cell morphology thus seems doubtful. However, morphological variability in a natural biotope under favourable growth conditions as well as in the beginning in cultures is much less pronounced (Fig. 1,4). No oblique dividing cell walls and inflated cells are then found except in extreme biotopes like thermal waters (Emoto & Hirose 1940 a,b).

Pure *Synechococcus* populations are rare under natural conditions, being rather found in small colonies in between other algae. Only in biotopes with running water (humid or coarse-grained soils, sprinkling water) they can be more abundant. This lack of larger populations of *Synechococcus* might be explained by the fact of an early growth stop before nutrient exhaustion (which is observed also in cultures of *Oscillatoria fracta*). It is obvious that the *Synechococcus* under discussion could tolerate the extreme physicochemical environmental conditions of Surtsey lava fields. On the other hand, it proves sensitive to competition with other algae.

Both *Synechococcus sp.* and *Oscillatoria fracta* can be considered as fugitive species (Hutchinson, 1951), which grow mainly on sites without competitors, typical for Surtsey at the early stage of ecogenesis. These pioneer species will disappear in the course of further succession, or become rare as on the mainland of Iceland (where *Osscillatoria fracta* does not occur at all).

The genus *Synechococcus* Näg. has been found on Iceland several times (Petersen, 1928, Schwabe, unpublished data). *S. aeruginosus* has been cultivated from a soil sample of Iceland by Møholm--Hansen (Petersen, 1928). The same species was found by Schwabe on crude soil of Iceland in the southern part of Hallormstadir forest (cell size 5.3 — 7×9.5 — 12.5 μm) in between *Plectonema* as well as on weathered lava between Reykjahlid and Grimstadir/Mývatn (cell size 6.8 — 9×13 — 20 μm) together with many other algae. *Synechococcus* found in Laugarvatnsheidi can be attributed to *S.maior* Schroeter (cell size 6.5 — 23×12.5 — 47 μm) according to the taxonomy of Geitler (1932). *Synechococcus* species of small cell size (6.5×12.5 μm) were rarely found in between *S.maior* stands together with *Tolypothrix* and some colonies of *Pleurocapsa minor.* Hansg. However, such frequent *Synechococcus* populations as described from Surtsey have not been detected on Iceland. The rare occurrence of *Synechococcus* in apparently favourable biotopes on Iceland is in contrast to the abundant occurence in other thermal biotopes (Castenholz, 1969). The same is the case with the thermal alga *Cyanidium caldarium*.

In culture experiments Pringsheim (1968) and Komarek (1970) showed that a similar variability in morphological characteristics could be induced by different factors such as temperature (>20°C), medium nutrient content and length of cultivation period. This seems to be the case only with certain genera or clones.

In our experiment the small morphological variability ended towards the end of the growing phase. The maximal variability was observed at the bottom of the culturing 100 ml-flask under uniform environmental conditions for all cells. Yet a non-uniform variation in cell forms was observed, the greater variation being at the edges of the colony. Thus it is obvious that some sort of biotic factor may influence the morphological variability of *Synechococcus*.

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The Bacteria Azotobacter, Beggiatoa, and Desulfovibrio in the Surtsey soil

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INTRODUCTION

The soil of Surtsey contains only extremely low amounts of organic matter and very low quantities of available nitrogen. Therefore, it was not surprising to find that the first colonizers of importance were certain blue-green algae and mosses, since both of them are photoautotrophic with low nitrogen requirements. Chemoautotrophic bacteria may also act as pioneers in this type of soil and can be of importance for further development of plant associations. For instance, bacteria of nitrification together with denitrifiers were commonly occurring in the first stage of colonization. It is also of interest to study other groups of bacteria linked to the nitrogen cycle of Surtsey and characterized by ability to live under severe conditions.

The occurrence of the following bacteria are studied in this paper: *Azotobacter, Beggiatoa,* and *Desulfovibrio,* which all have the power to fix nitrogen. Schwartz & Schwartz (1972a, 1972b) have made similar investigations in the same area.

This investigation is a continuation of our Surtsey studies which started in 1970 (Henriksson *et al.,* 1972, Henriksson & Henriksson 1974a, 1974b, Henriksson & Rodgers, 1978).

SOIL SAMPLING AND ENRICHMENT CULTURES

The soil sampling was performed in the same way as earlier described (Henriksson & Henriksson 1974a). The soil samples were collected from the soil surface only, which means the upper 1 cm layer. The localities studied are described and plotted on maps by Henriksson & Rodgers (1978, Tables 1—2, Figures 1—2), and the samples from 1976 have also been studied by Hedin (1978) investigating the terrestrial microfauna. They correspond to those of 1974. The sites were choosen on the basis of being an interesting object of study, and therefore are not quite typical for the islands as a whole. The days of sampling were July 29—31 and Aug. 1—3 1974 and Aug. 7—10 1976.

About 1 g of soil from each locality, divided into two parallels, was used for the enrichment cultures of each of the three types of microorganisms studied.

The medium for the enrichment of *Azotobacter* was the same as earlier used (Henriksson & Henriksson 1974a). The *Azotobacter* growth was determined by studies of the film developed on the medium surface.

For the enrichment cultures of *Beggiatoa* the medium recommended by Aaronson (1970) was used and was prepared as follows: Dried hay was extracted 3 times at 100°C in large volumes of water. The extracted hay was then drained and dried at 37°C. A suspension of 0.8 g hay/ 100 ml of water was used as medium after autoclaving. The growth of *Beggiatoa* was determined by studies of the surface of the medium. For that purpose a microscope with phase contrast equipment was used.

The enrichment medium used for *Desulfovibrio* was as follows (Parkinson *et al.* 1971): K_2HPO_4 0.5 g, NH_4Cl 1.0 g, Na_2SO_4 1.0 g, $CaCl_26H_2O$ 0.1 g, $MgSO_47H_2O$ 2.0 g, sodium lactate (70% solution) 3.5 g, yeast extract 1 g, $FeSO_47H_2O$ 0.002 g, water 900 ml (pH 7.5), and sodium thioglycollate 0.1 g, ferrous ammonium sulphate 0.1 g, water 100 ml (pH 7.4$\pm$0.3). The two solutions were separately autoclaved. The bottles were completely filled. The blackening of this medium indicates presence of sulfate reducing bacteria.

All cultures were incubated at 20°C for 12 weeks.

In the cases where the bacteria studied were found in at least one-third of the enrichment cultures, the bacteria have been recorded as present in the Surtsey soil; and if never found as not being present.

RESULTS AND DISCUSSION

The presence of the bacteria *Azotobacter, Beggiatoa,* and *Desulfovibrio* in soil samples from Surtsey is presented in Table 1.

Table 1

Nitrogen fixing organisms studied in enrichment cultures originating from about 1 g of soil. The table includes about 15 localities each year, "+" signifies that the bacterium is found in at least one-third of the enrichment cultures, "−" signifies that the bacterium is never found.

	1974	1976
Azotobacter	−	+
Beggiatoa	+	+
Desulfovibrio	−	−

It is of interest to find that in 1976 *Azotobacter* is a part of the microbial life on Surtsey. Since *Azotobacter* grows heterotrophically, the bacterium is of very little importance as a nitrogen fixer in the upper soil layer of Surtsey in comparison to the blue-green algae. However, when growing in the rhizosphere of the emigrated phanerogams, *Azotobacter* may play an important role as supplier of nitrogen to the associated plants, since the roots are able to give off organic matter to the surroundings in more or less degrees.

Beggiatoa is facultative chemoautotrophic and is able to use hydrogen sulfide as an energy source. This bacterium occurs in fresh water and marine environments containing hydrogen sulfide and is common in mud. It therefore seems surprising to find *Beggiatoa* species around the crater borders of Surtsey belonging to the first emigrants. The soil analyses of the Surtsey soil show very low content of sulfur (Henriksson & Henriksson 1974a). However, hydrogen sulfide in soil disappears easily at sampling, and therefore is not included in these actual analyses, but the smell of hydrogen sulfide on the island indicates its presence.

From an ecological point of view *Beggiatoa* is probably not an important link in the nitrogen cycle nor in the sulfur cycle of Surtsey.

Sulfate-reducing bacteria (such as *Desulfovibrio*) have not yet been found on Surtsey. Enrichment cultures from soil sampled in 1974 near the airport of Heimaey, showed, however, that they did occur there. Our analyses indicates that the microbial sulfur cycle of Surtsey is still not quite complete.

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ABSTRACT

Enrichment cultures from soil samples collected from different localities in 1974 and 1976 showed that *Azotobacter* was not found in the 1974 samples but was common two years later. On the contrary, *Beggiatoa* species were found both years but *Desulfovibrio* has not yet been recorded. The ecological importance of these bacteria for the microbial development of the Surtsey soil is mentioned.

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Further studies in the nitrogen cycle of Surtsey, 1974—1976

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INTRODUCTION

The volcanic island of Surtsey was formed by a series of eruptions during 1963—68. Since the eruptions ceased, colonization of the island by algae (Behre and Schwabe, 1970, Schwabe, 1972, 1974), bacteria and fungi (Henriksson and Henriksson, 1974a), lichens (Kristinsson, 1974), mosses (Magnusson and Fridriksson, 1974) and angiosperms (Fridriksson, 1975) is proceeding rapidly. A primary factor limiting the settlement and dispersal of the organisms may be the lack of utilizable nitrogen. Unfortunately there are few data on the initial mineral nitrogen contents of Surtsey soils. However, Ponnamperuma et al. (1966) determined the NH_4—N content of soil as 0—5 ppm soil and NO_3—N as 0—30 ppm soil. In 1972 Henriksson and Henriksson (1974b) determined NH_4—N as 60—70 ppm soil and NO_3—N as 0—10 ppm soil.

Various mechanisms could be responsible for the input of combined nitrogen to the island. Henriksson and Henriksson (1974b) have shown that organic nitrogen can enter Surtsey soil via the fixation of atmospheric nitrogen by blue-green algae and the mean value of 150 samples determined *in situ* in August 1972 was 13.74 ng nitrogen fixed per cm^2 and hour. The sea, rain, wind and animals may also transport organic nitrogenous material, either living or dead, to the island. Inorganic combined nitrogen may be deposited on Surtsey as NH_4 or NO_3 dissolved or suspended in rainwater. Also dry deposition of particulate ammonium or gaseous ammonia from the atmosphere may occur (Söderlund and Svensson, 1976). This deposited ammonia may be augmented by ammonia released from numerous steam vents on the island as volcanic activity has been suggested as an important source of atmospheric ammonia.

The aim of our present investigation was twofold: *First,* to compose and evaluate the various processes by which combined nitrogen may be added to Surtsey soils. *Second,* to obtain baseline--data on NH_4—N, NO_3—N and total N contents of soils from sites on the island, where different mechanisms of combined nitrogen input are operative, so that future studies can determine the importance of activities of the mechanisms involved in the nitrogen balance of Surtsey soil.

In 1974 (July 29 — Aug. 3) one of us (Henriksson) and in 1976 (Aug. 6—11) both of us visited Surtsey for field works and the following study is based on our results from these investigations.

MATERIAL AND METHODS

The methods and techniques used for collecting, analysing and cultivating the samples, according to the data recorded in Tables 1 and 2, are published by Henriksson and Henriksson (1974b). The acetylene reduction technique was used for the *in situ* determinations of the biological nitrogen fixation in the soil surface layers, and also potential bacterial nitrogen fixation was taken into consideration (Henriksson and Henriksson, 1978). However, the medium for *Thiobacillus denitrificans* was according to Postgate (1966) and as follows: NH_4Cl 0.5 g, $MgCl_2 \cdot 6H_2O$ 0.5 g, KH_2PO_4 2 g, $Na_2S_2O_5 \cdot 5H_2O$. 5 g, KNO_3 2 g, $NaHCO_3$ 1 g, $FeSO_4 \cdot 7H_2O$ 10 mg, tap water up to 1 l (pH 7.0).

Material from the localities in 1976 (Table 2 and Figure 2) has also been analysed in regard to the terrestrial microfauna by Hedin (1978).

The data recorded in Table 3 and 4 were based on the following methods. Soils were collected and stored in polythene bags prior to analysis. NH_4—N, NO_3—N and total N contents of soil were determined by the extraction and distillation

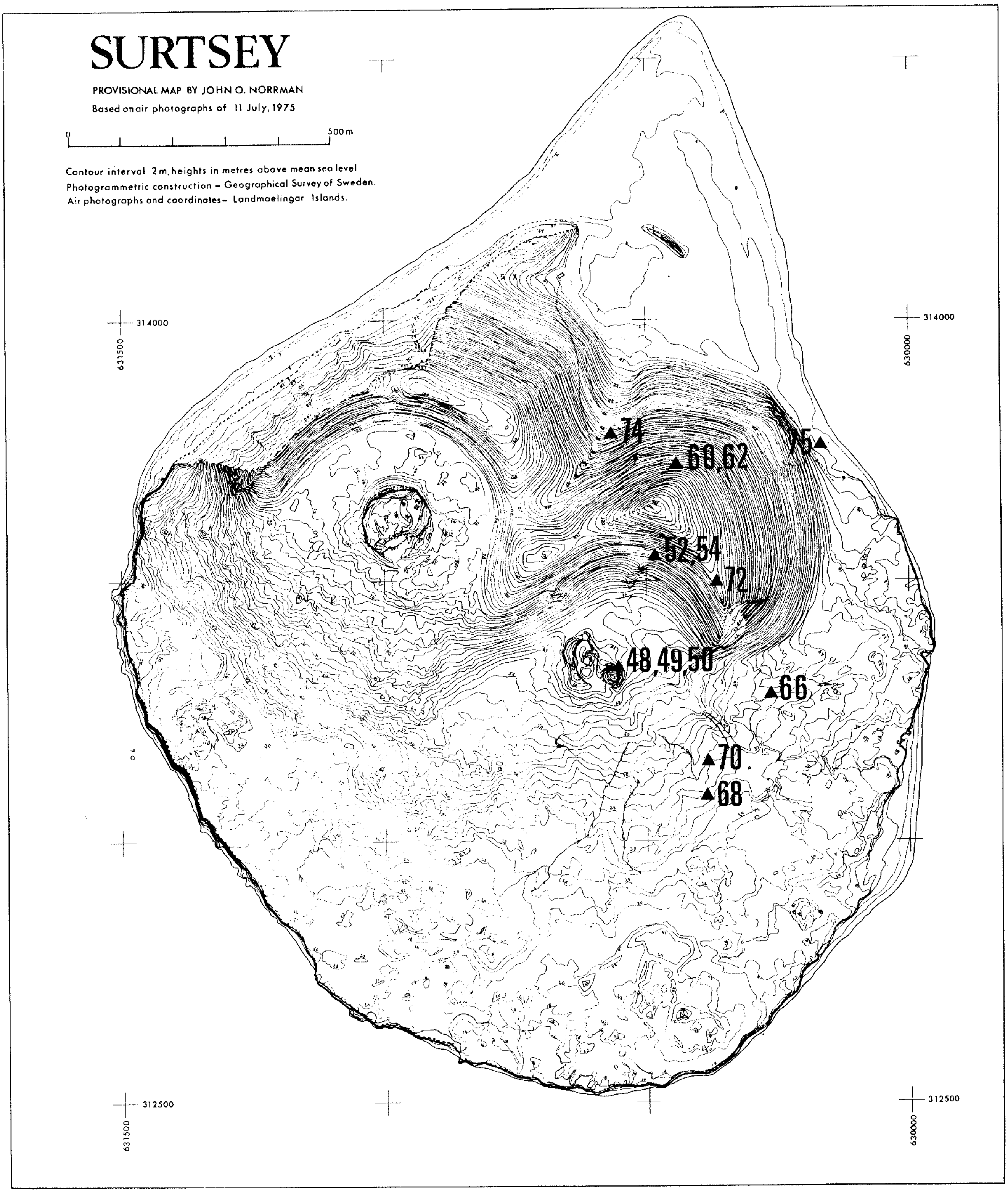
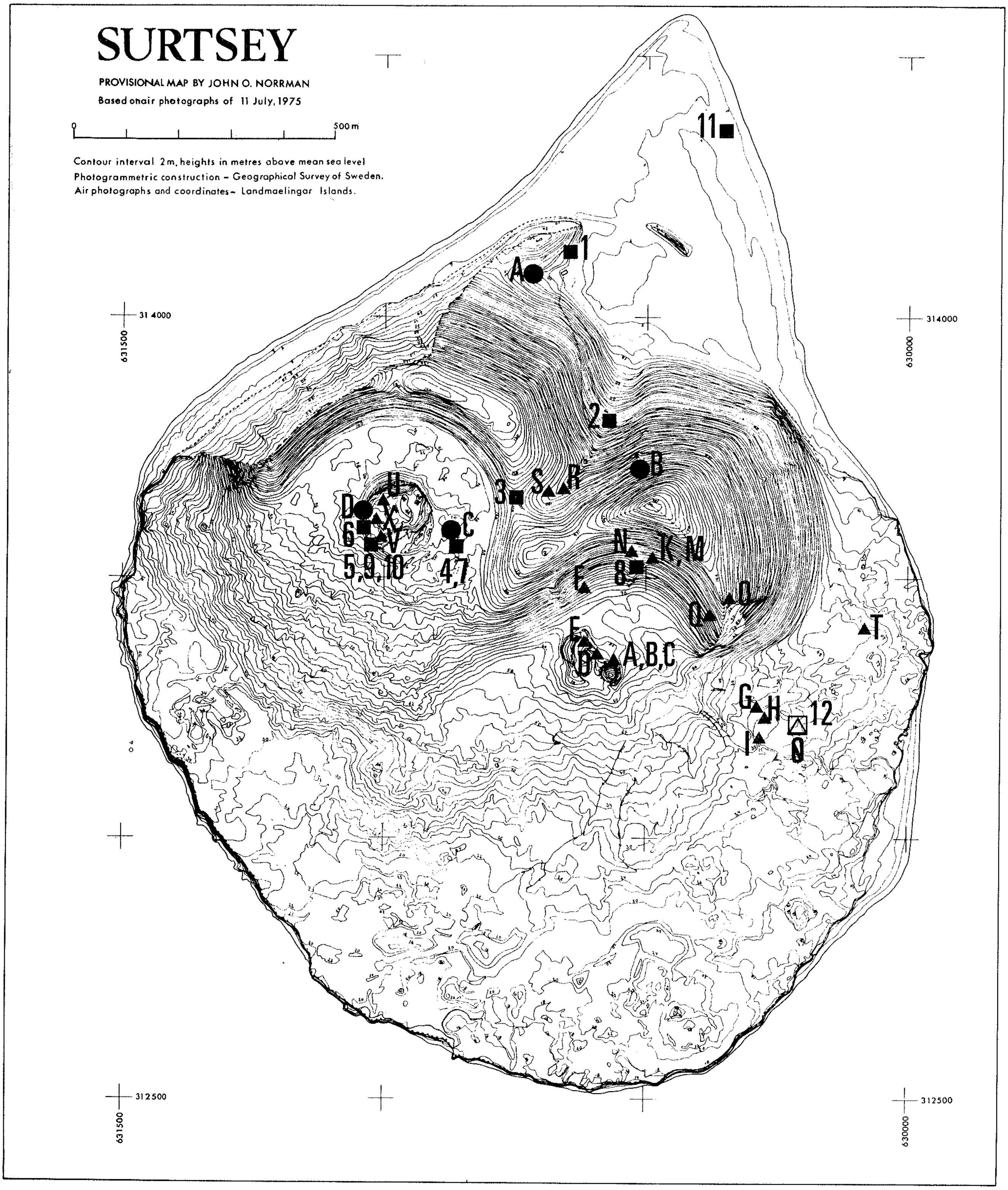


Figure 1. The symbols show the locations for samplings and the nitrogen fixing determinations *in situ* in 1974 and refer to Table 1. — Map of Surtsey by John Norrman, Uppsala.



Fugure 2. The locations for the samplings and analyses in 1976. The symbols ▲, ■, ● refer to Tables 2, 3, and 4, respectively. — Map of Surtsey by John Norrman, Uppsala.

procedures of Bremner (1965). Ammonia distillates were collected in 5% boric acid and analysed for ammonium by the indophenol technique of Rommers and Visser (1969).

Dry deposition of ammonia was calculated by exposing 12.5 cm diameter Whatman No. 41 filter papers to the air at various sites (Table 4). The papers were clamped in perspex frames and only one side was exposed to the air. After exposure the papers were stored in sealed polythene bags until return to the laboratory. The papers were dissolved in 5 ml 18M H_2SO_4 and the solution deluted to 30 ml with H_2O, then steam distilled for 3 minutes in a Markham distillation apparatus with 50% NaOH. The distillate was collected in 5% boric acid and analysed for NH_4—N.

Rainwater was collected in a rain gauge but the amounts collected during the field work period in 1976 were too small for analysis. Therefore figures for the nitrogen content of rain were taken from those of Miller (1913) for Vifilsstadir (Heimaey, Westman Islands) during 1911—1912. These figures may be underestimates due to increases in general atmospheric pollution since they were taken.

The distribution of lava and tephra areas on the island is analysed by Norrman et al. (1974), and their results have been taken into consideration.

RESULTS

The analytical results from the field seasons 1974 and 1976 are recorded in Tables 1—5 together with short descriptions and actual data of the localities investigated. The presence of the investigated microorganisms involved in the nitrogen cycle is also reported in Table 2 and the sites are plotted out in Figures 1 and 2 respectively.

The biological nitrogen fixation

All localities investigated *in situ* in 1974 and 1976 showed biological nitrogen fixation which could be referred to the activities of the frequent presence of the blue-green algae *Nostoc muscorum* Ag. and *Anabaena variabilis* Kütz. (Tables 1 and 2).

Table 1. The results of the nitrogen fixing determinations *in situ* in 1974 and the total—N content, pH and spec, conductance of the soil and a description of the localities studied. Location Nos refer to Fig. 1.

Table 1.

Sample location No.	ng N_2 fixed $cm^{-2}h^{-1}$ Mean of 9 samples	Total N mg/100 g dried soil	pH	Spec. conductance 20°C —10^{-4}	Description of the locations and temperature and light conditions at time of sampling and during the *in situ* experiments
48/74	4.6 ± 1.7	14.0	—	—	The south outside of the crater, 4 m from border. Light green lava. Water vapour. Soil temp. 38°C. 110.000 Lux.
49/74	2.8 ± 1.4	16.0	—	—	Crater border. Moist. Sparse young mosses. Soil temp. 29°C. 110.000 Lux.
50/74	12.2 ± 2.1	19.0	—	—	2 m from site 49, near steam vent. Soil temp. 48°C. 110.000 Lux.
52/74	6.0 ± 1.9	30.0	6.8	0.3	1.5 m from opening of the "Bell"-cave (according to G.H. Schwabe). Moist. Sparse moss cover. Soil temp. 22°C. 110.000 Lux.
54/76	5.3 ± 1.7	4.0	5.6	0.9	Right interior wall of the "Bell". Very moist. Moss-covered. Soil temp. 32°C. 450 Lux.
60/74	12.9 ± 2.5	10.0	7.9	0.3	Northern lateral crater of Surtur I. Moist. Green surface. Soil temp. 22°C. 68.000 Lux.
62/74	10.7 ± 1.4	11.0	7.9	0.3	East-side of lateral crater site 60. Slightly green lava soil. Soil temp. 22°C. 91.000 Lux.
66/74	12.7 ± 1.8	14.0	—	—	East-side of island about 30 m above sea level. Moist. Brown-yellow tephra. Soil temp. 17°C. 62.000 Lux.
68/74	7.5 ± 1.6	16.0	—	—	Lava field, south of Surtur I, 35 m above sea level. Moist. Brown--yellow tephra. Soil temp. 19°C. 59.000 Lux.
70/74	31.6 ± 1.9	16.0	—	—	About 50 m north site 68. Moist, brown-grey tephra. Soil temp. 19°C. 59.000 Lux.
72/74	13.5 ± 2.0	11.0	8.5	1.0	South-eastern slope of Surtur I, 120 m sea level. Moist, grey-brown lava. Soil temp. 22°C. 130.000 Lux.
74/74	27.5 ± 3.7	38.0	7.6	0.4	Pass between Surtur I and II. Moist. Soil temp. 16.5°C. 78.000 Lux.
75/74	17.4 ± 2.4	6.0	7.4	63.0	North-eastern slope-base of Surtur I, 10 m above sea level. Moist. Soil temp. 27°C. 110.000 Lux. Obviously contaminated by the sea.

Sample location No.	ng N_2 fixed $cm^{-2}h^{-1}$ Mean of 9 samples	Occurrence of					mg/1
		nitrogen fixing blue-green algae	*Azoto-bacter*	nitrifying organisms	denitrifying organisms	*Thiobacillus denitrificans*	NH
A/76	10.7 ± 1.1	*Anab. variabilis*	+	+	+	+	2.3
B/76	10.8 ± 3.5	*Nost. muscorum*	+	+	+	+	1.8
C/76	5.1 ± 1.8	*Nost. muscorum*	+	+	+	+	0.2
D/76	10.2 ± 1.7	Akinetes.	+	+	+	+	1.0
E/76	0.6 ± 0.2	*Anab. variabilis* *Nost. muscorum*	+	+	+	+	0.8
F/76	8.6 ± 2.0	*Nost. muscorum* Oscillarieae (*Schizothrix sp.?*)	+	+	+	0	5.3
G/76	6.0 ± 0.4	*Anab. variabilis*	+	+	+	+	0.5
H/76	12.4 ± 4.1	—	+	+	+	+	0.2
I/76	15.7 ± 1.8	*Nost. muscorum*	+	+	+	+	1.2
K/76	9.4 ± 0.8	*Nost. muscorum*	+	+	0	0	2.2
M/76	10.2 ± 1.1	*Nost. muscorum*	+	+	+	(+)	0.8
N/76	3.7 ± 0.5	—	+	+	+	0	2.6
O/76	0.9 ± 0.1	*Nost. muscorum*	+	+	+	0	1.5
R/76	1.3 ± 0.1	*Nost. muscorum*	+	+	+	(+)	2.9
S/76	0.2 ± 0.	*Nost. muscorum*	+	+	+	(+)	1.2
T/76	0.3 ± 0.1	—	+	+	+	+	1.6
U/76	44.8 ± 6.1	*Anab. variabilis*	+	+	+	+	1.2
V/76	56.9 ± 5.7	*Anab. variabilis*	+	+	+	+	0.
X/76	81.9 ± 12.8	*Anab. variabilis* *Nost. muscorum*	+	+	+	+	1.4
Ø/76	4.3 ± 1.1	*Nost. muscorum*	+	+	+	+	1.2

Table 2. The occurrence of some different types of microorganisms involved in the nitrogen cycle of Surtsey, the results of the nitrogen fixing a description of the localities studied in 1976. Location Nos refer to Fig. 2. and symbols ▲. Organisms present +, absent O.

Table 2

g dried soil					
NO_3-N	Total-N	pH	Spec. conductance, 20°C ·10^{-4}	Humidity % above soil surface	Description of the locations and temperature and light conditions at time of sampling and during the *in situ* experiments
< 1	6.0	7.5	0.1	90.5	Crater border Surtur I. Sparse moss protonemata. Moist. Soil temp. 10°C. 50.000 Lux.
< 1	10.0	7.6	0.2	90.5	4 m from site A/76. Sparse moss protonemata. Moist. Soil temp. 11.5°C. 48.000 Lux.
< 1	10.0	7.6	0.2	90.5	12 m from site A/76 on outside slope. New moss protonemata. Soil temp. 16°C. 40.000 Lux.
< 1	13.0	7.2	0.1	101.0	Interior south-eastern slope Surtur I. 8 m from crater border. Surface blue-green. Some moss protonemata. Soil temp. 26°C. 26.000 Lux.
< 1	21.0	7.5	0.2	101.0	Next to site D/76 and of the same appearance. Soil temp. 33°C. 32.000 Lux.
7.2	15.0	6.1	0.7	100.0	The rocky knoll between the "Bell" (the cave according to G.H. Schwabe) and the southern lateral crater. Blue-green algal masses on the vertical, steaming site. Soil temp. 40—45°C. 20.000 Lux. (The highest soil temp. for Surtsey this visit was recorded here, 72°C).
< 1	16.0	7.5	0.1	92.0	Eastern lava field. *Elymus arenarius* area (Surtsey No. 74/75). Samples from surface close to the plants. Soil temp. 12°C. 55.000 Lux.
< 1	6.0	7.4	0.1	96.0	About 15 m from site G/76. Continous tuft of *Honkenya peploides* (Surtsey No. 73/440). Surface samples just under the plants. Soil temp. 11°C. 30.000 Lux.
< 1	9.0	7.8	0.1	94.5	About 50 m south site G/76 nest to lava blocks. 1—1.5 m^2 of soil with young species of the lichen *Stereocaulon* (rather common). Soil temp. 12°C. 38.000 Lux.
< 1	28.0	6.8	0.2	98.0	The "Bell", the interior left wall of the cave, 4 m from the entrance. Water leaking out. Wall greenish and occasionally mosses. Soil temp. 12°C. 8.000 Lux.
1.3	10.0	7.1	0.3	98.0	At the right side of the entrance of the "Bell". Soil greenish. Very moist. Soil temp. 16°C. 50.000 Lux.
3.8	16.0	7.9	0.7	100.0	About 15 m from the entrance of the "Bell" and about 10 m from a bigger steaming vent. Greenish soil and occasionally mosses. Soil temp. 18°C. 38.000 Lux.
< 1	10.0	8.2	0.2	90.0	South-eastern slope of Surtur I, about 100 m above the sea level. Signs of erosion, greenish surface. Soil temp. 16°C. 40.000 Lux.
< 1	10.0	7.6	0.2	97.0	The upper part of the passage between the head craters. Soil grey. Moist. Soil temp. 11°C. 32.000 Lux.
< 1	7.0	7.4	0.2	97.0	About 3 m from site R/76. Blackish soil. Soil temp. 11°C. 30.000 Lux.
< 1	8.0	7.2	0.3	93.5	The shore plateau at the eastern slope of Surtur I, about 20 m above sea level. The blueish lava sand contaminated by the sea. Colony of *Rissa tridactyla* L. (more than 200 kittywakes). Soil temp. 10°C. 36.000 Lux.
< 1	15.0	7.0	0.5	92.0	The southern part of the crater bottom of Surtur II. Continuous well-developed areas with mosses. Moist. Soil temp. 13°C. 39.000 Lux.
< 1	13.0	7.2	0.1	88.5	About 15 m from site U/76 and similar. Moist. Soil temp. 16.5°C. 45.000 Lux.
< 1	17.0	7.2	0.2	84.5	Southern part of the crater bottom next to sites U/76 and V/76 and similar. Soil temp. 14.5°C. 40.000 Lux.
< 1	7.0	7.2	0.3	89.5	The investigation square (6×6 m), marked out by the Swedish Bio-Geo-Group, Uppsala Aug. 8, 1976. (Ref. map point 1:4 p. 611, John Norrman, Uppsala).

terminations *in situ*, and the chemical analyses of the soil, and

The total number of the *in situ* determinations from Surtsey 1972 (Henriksson and Henriksson, 1974b), 1974 and 1976 are collated in Table 5 and the average values from the different seasons indicate that the biological nitrogen fixation seems to be of the same order during this time.

These data from Surtsey and those of Henriksson et al. (1972b) and Henriksson and Henriksson (1974b) correspond well to the results published by Englund (1976, 1978). Thus she reports about the same values from the new lava fields on Heimaey in 1974 and 1976. Crittenden (1975) has also obtained results of interest in regard to nitrogen fixation by lichens on glacial drift at Sólheimajökull, Iceland.

The most striking observation will be the low nitrogen fixing capacities for the Icelandic virgin soils, both on Surtsey and on Heimaey and on the main island as well in comparison to e.g. many Swedish soils (Henriksson, 1971, Henriksson et al., 1972a, 1975 and Granhall, 1975). In the Swedish soils a biological, ecological balance is already established and this balance is still missing in the new Icelandic soils.

However, at present the nitrogen fixing activities of the blue-green algae must be of major importance for the nitrogen input and economy on Surtsey as even a small input of nitrogen to an ecosystem characterized as nitrogen deficient must be of hithest importance. This fact is of fundamental significance for the primary stages of soil formation (Schwabe, 1963, Harley, 1970, Shtina and Nekrasova, 1971, Vlassak, 1972).

The heterotrophic bacterium *Azotobacter* was registered for the first time on Surtsey in 1976 and was frequent occurring (Table 2) and also the chemoautotrophic bacterium *Beggiatoa* was found in about one third of the localities investigated (Henriksson and Henriksson, 1978). Any nitrogen fixing activities in the Surtsey soil by these organisms has, however, not yet been observed.

Nitrification and denitrification organisms in Surtsey in 1976

The occurrence of nitrifying and denitrifying organisms on Surtsey was demonstrated in 1972 by Henriksson and Henriksson (1974b). Further studies were continued in 1976 (Table 2) and the results showed the frequent occurrence of organisms representing these significant activities in the nitrogen cycle. In 1976, however, the chemoautotrophic bacterium *Thiobacillus denitrificans* was also registered in most localities investigated.

As far as can be judged from the observations and results recorded nitrification may be assumed to occur on Surtsey and, although bacteria ca-

Table 3

Sample location No.	mg / 100 g dried soil			Soil type	Description of the locations
	NH_4—N	NO_3—N	Total-N		
1/76	0.32	0.03	1.06	Tephra	Soil under *Honkenya peploides* (L.) Ehrh. colony.
2/76	0.27	0.06	0.75	Tephra	On bare hillside 100 m above sea level.
3/76	0.35	0.03	0.45	Tephra	Top of slope 125 m above sea level.
4/76	0.13	0.04	0.25	Lava	Steam vent, near the opening.
5/76	0.37	0.03	0.52	Lava	Soil with mosses near Surtur II.
6/76	0.20	0.05	0.44	Lava	Soil without mosses near Surtur II.
7/76	0.27	< 0.01	2.53	Lava	Steam vent with visible blue-green algae.
8/76	0.33	0.34	3.44	Tephra	Soil from the "Bell"-cave with blue- green algae.
9/76	0.38	0.04	0.89	Lava	Surface (1—2 cm) soil near Surtur II.
10/76	0.24	0.04	0.42	Lava	Soil at 20—25 cm near Surtur II.
11/76	6.10	0.18	14.40	Lava	Soil from boulder zone on shore with bird excreta.
12/76	0.20	0.06	0.68	Lava	The investigation square, marked out by the Swedish Bio-Geo-Group, Uppsala, Aug. 1976. (Ref. map point 1:4 p. 611, John Norrman, Uppsala).

Table 3. Analyses of NH_4—N, NO_3—N, and total-N, and a description of the localities studied in 1976. Location Nos refer to Fig. 2 and symbols ■.

Table 4

Site and description	Height above sea level (m)	Time papers exposed (h)	Deposition ng $cm^{-2}h^{-1}$	Deposition kg ha^{-1} ann^{-1}
A. On clifftop.	10	73	2.91	2.6
B. On the north-eastern slope.	100	72	3.30	2.9
C. At a fumarole opening.	100	19.8	16.45	14.4
D. At Surtur II, near steam vent.	100	19.3	59.74	53.3

Table 4. NH_4/NH_3 dry deposition at different sites on Surtsey in 1976. Location characters refer to Fig. 2 and symbols ●.

pable of denitrification are present, it is doubtful if denitrification can generally occur due to the absence of organic carbon or reduced sulphur compounds necessary for energy formation and growth, and also the well-drained nature of Surtsey soil.

The chemical soil analysis and the air-borne nitrogen deposition on Surtsey

The chemical soil analyses both from 1974 and 1976 indicate an increasing total nitrogen content of the Surtsey soils in comparison to earlier available data (Ponnamperuma et al., 1967, Henriksson and Henriksson, 1974b). Increasing values were specially recorded in respect to NH_4—N and organic nitrogen (Tables 2 and 3).

In respect to the in 1976 registered and calculated air-borne NH_4/NO_3 depositions on Surtsey (Table 4) the nitrogen contributions to the soil will be between 2.9—59.7 ng N $cm^{-2}h^{-1}$. This actual nitrogen deposition on Surtsey must however be divided into two main sources: one generally occurring (A and B in Table 4) and one greatly enlarged just in the vicinity of the fumaroles and steam vents (C and D in Table 4) on the island.

The determinations of the specific conductance (Table 1 and 2) indicate an increased inclusion of inorganic matter in all localities investigated (cp. Henriksson and Henriksson, 1974b). This contribution in the upper layers of the soil has obviously come from the sea.

The pH-values of the soils investigated in 1974 and 1976 represent neutrality or small divergences from that (Tables 1 and 2). However the results show a clear tendency of the soils becoming more alkaline in comparison to the earlier available data from 1965 pH 4.5—6.8 (Ponnamperuma et al., 1967), 1970 pH 5.7—7.0 (Schwartz and Schwartz, 1972), 1972 pH 6.6—6.8 (Henriksson and Henriksson, 1974b).

During dry weather in 1974 and 1976 several restricted areas (up to 1—2 m^2) were covered with noticeable and rather thick surface layers of crystals. These spots were especially noticeable on the slopes of Surtur I and II. Analyses have shown, that these crystals were principally built up by chlorides of sodium, magnesium and potassium but sulphates were not found (Location Ø/76, Figure 2). It seems possible that these crystal spots are the result of leaching processes.

Some observations about the water conditions on Surtsey and the water and temperature factors according the biological nitrogen fixation of the blue-green algae

Any annual mean values of the precipitation and temperature on Surtsey are not recorded. However, from the seasonal data and calculations by Sigtryggsson (1968) an annual mean value of the precipitation can be estimated to about 1000 mm from the basis of the annual long-term values from Stórhöfdi Meterological Station, Westman Islands (Vedráttan, 1944—76). The precipitation variability may be less than 10% of the longterm average (Morales, 1977) and the long-term records from Stórhöfdi also indicate a rather uniform distribution of the precipitation during the year.

The annual mean temperature is recorded at Stórhöfdi to be +5.4°C for the period 1931—1960 (cp. +5.7°C for Uppsala) and there will probably be small differences between Stórhöfdi and Surtsey.

In regard to temperature conditions it has been demonstrated that the blue-green algae have a remarkable nitrogen fixing capacity at low and at sub-zero temperatures (Kallio et al., 1972, Englund and Meyerson, 1974).

During the period Aug. 6—11, 1976 the recorded precipitation on Surtsey was 24 mm. The air humidity values just over the soil surface varied during the same time between 84.8—101.0% and the supersaturated values could be related to effects from steaming vents. The air temperature during daytime was for the same time 10.5—15.0°C, however two shorter periods of 18.0 and 15.5°c respectively were observed.

Shtina (1972) reported that the soil moisture was one of the main conditions that determined the distribution and degree of nitrogen fixation by blue-green algae, and optimum activities were observed at 80—100% of humidity.

In laboratory experiments under controlled conditions it was shown, that the effect of soil humidities lower than 40% reduced the nitrogen fixation by *Nostoc sp.* and *Anabaena sp.* in an obvious way even though the air humidity in the experimental flasks was more or less saturated, and at 30% soil humidity the nitrogen fixation was only one third of that at 40% humidity. These results (unpublished) and the data above, however emphasize favourable water conditions for algal nitrogen fixing activities on Surtsey.

DISCUSSION

Due to the very low content of organic matter in Surtsey soils the decomposition rate must be very low and in such environments the biological nitrogen fixation must be of especial importance. Besides nitrogen fixation the atmospheric fallout represent the second major nitrogen input to the island. This is in accordance with the opinion of Alexander (1975), who found nitrogen fixation and rain being the two major nitrogen inputs to the soil in polar and subpolar regions.

Even in developed and cultivated soils the mineral factor of the solid phase dominates and only a smaller part of the total mass represents organic matter. The fertility of a soil is increased by an increase in organic matter content due to its water holding capacity, structure-building function and absorbing properties (Pearson, 1967), and the latter fact is specially true in respect to NH_4—N. In that way the fertility of the Surtsey soil generally seen will therefore be low on account of its extremely low content of organic matter, which means a more or less absence of the ability to absorb and store NH_4—N.

The NO_3—N is known to leach out rapidly in soils (Overrein, 1969) and in the sandy soils of Surtsey the leaching effect may be total.

The annual wet deposition of nitrate and ammonia compounds can be calculated as 0.1 g NO_3—N $m^{-2}ann^{-1}$ and 0.1 g NH_4—N $m^{-2}ann^{-1}$ maximum respectively in the Icelandic regions (Söderlund, 1977). However, if influences of man's activities are left out on account, the background value of the total nitrogen fallout can be estimated to be about 0.1 g N $m^{-2}ann^{-1}$.

Owing to the above facts and the abundant rainfall on Surtsey a very low accumulation of nitrogen might be referred to the atmospheric fallout. Anyhow some parts of this particular nitrogen delivery can be assimilated by the present plants or transferred in the nitrification and denitrification processes on the island.

The nitrogen analyses from the period 1965—1976 indicate a distinct sign of enrichment of organic and NH_4—N in the lava soil of Surtsey. The determinations of the biological nitrogen fixation *in situ* on the island indicate that this activity is of fundamental, ecological importance for the nitrogen economy of the island. The average values of the total number of determinations *in situ* of the nitrogen fixation from Surtsey in 1972, 1974 and 1976 respectively are estimated and recorded in Table 5 and they indicate, that the biological nitrogen fixation on Surtsey can be regarded as a constant nitrogen deliverer to the lava soil. The favourable external factors as humidity, annual mean temperature and pH existing on Surtsey for the activities of the present nitrogen fixing blue-green algae emphasize these observations.

Englund (1977, 1978) has reported the same experiences from the new lava fields on Heimaey (Westman Islands) formed in 1973. However her average value from 1976 was about half those from Surtsey, which may be referred to differences in ages of the soils.

The biological nitrogen fixation on Surtsey is known to be due to the frequent occurrence of blue-green algae (Schwabe, 1974, Henriksson et al., 1972, Henriksson and Henriksson, 1974b). These algal pioneers frequently exist free-living, in symbiosis with lichens and in associations with mosses on the island. Of special interest is the moss association, a connection known for a long-

Table 5. Mean values of the determinations *in situ* of the nitrogen fixation by blue-green algae on Surtsey in 1972, 1974 and 1976. The data in 1972 from Henriksson and Henriksson (1974b).

Table 5

Field season	Number of locations	Number of analyses	Biological N-fixation, ng N_2 cm $^{-2}$h^{-1}	
			Range	Mean value
1972	13	150	0.2—64.5	13.7 ± 1.9
1974	13	150	2.8—31.6	12.8 ± 2.8
1976	20	200	0.2—81.9	14.7 ± 1.2

time (e.g. Richter, 1907) which has been brought to the fore again on Surtsey and Heimaey by Schwabe (1974), Rodgers and Henriksson (1976) and Englund (1977a,b) and this association can explain the very early colonization and rapid distribution of moss plants on these new lava territories.

The pH of the Surtsey soils have gradually become more alkaline, which indicates a stimulation both in growth and nitrogen fixing activity of the blue-green algae, as the optimum ranges are pH 7.0—8.5 and pH. 7.0—7.5 respectively (Fogg et al., 1973). More acid conditions inhibit both growth and the nitrogenase activity. This is also of especial interest in the case of *Azotobacter,* as this organism is principially only found and established in soils at pH 6.5 or more.

The frequent occurence of *Azotobacter* in the Surtsey soil, recorded for the first time in 1976, will give new impetus to the nitrogen fixing processes since associated growth of *Azotobacter* with other organisms, including blue-green algae and protozoa, stimulates the nitrogen fixation (Bjälfve, 1963, Jensen and Holm, 1975, Henriksson, 1977).

The nitrogen deficiency in Surtsey soils for the development of higher plants has initially been demonstrated by Henriksson (1976) in laboratory experiments. However, this nitrogen deficiency on Surtsey might perhaps be eliminated by nitrogen fixation in the rhizosphere of the plants by e.g. *Azotobacter* or *Spirillum sp.* (Döbereiner, 1975, 1977, Smith et al., 1976).

Nitrification processes are nowadays generally occurring on Surtsey. Nitrifying organisms, including *Nitrosomonas* and *Nitrobacter,* are found everywhere on the island. The denitrifier *Thiobacillus denitrificans* is frequently observed in the lava soil in 1976. Stationary organisms on the island are species of bacteria, algae, actinomycetes, terrestrial fungi, mosses, lichens, higher plants, protozoa and insects. These facts indicate, that a representative part of the nitrogen cycle is already functioning on Surtsey. The different parts of the cycle may however still be suppressed (e.g. denitrification) in respect to the virgin conditions and the hitherto limiting biological development on the island. In that way genuine humus protein is still lacking, which in a common soil is of great importance for the nitrogen economy and balance of the biotype.

Further studies will determine whether or not the soil NH_4—N and NO_3—N levels will increase further with time or if they have reached an equilibrium. The organic levels in Surtsey soils are very low, e.g. compared with soil at Rothamsted (England), which has been under grass for 200 years, where the organic nitrogen content is 2800 ppm organic nitrogen. However, there is already a distinct increased level of organic nitrogen on localities containing blue-green algae and again further studies will establish the amounts of organic nitrogen they contribute to the soil and allow comparisons to be made with estimated nitrogen fixing rates.

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ABSTRACT

The relevant components of the nitrogen cycle of Surtsey are described and evaluated, due to the importance of combined nitrogen in the continued development of the island's soil and it's biology. The biological nitrogen fixation by the frequently present blue-green algae, determined *in situ* by using the acetylene reduction technique, is found to be of major importance for the nitrogen input to the Surtsey soil. In addition, NH_4—N and NO_3—N, washed from the atmosphere by rain augment soil nitrogen, as well as dry atmospheric deposition of NH_4—N, determined in higher concentrations around the fumaroles in certain localities on the island. Much of the inorganic nitrogen may be lost due to the presence of nitrifying bacteria and the welldrained soil from which NO_3—N can easily leach. It is unlikely, at yet, that denitrification generally occurs, though organisms involved in this part of the nitrogen cycle are frequently identified on Surtsey, as soils are well aerated and still lack utilizable reserves of organic carbon. However, in 1976 the chemoautotrophic bacterium *Thiobacillus denitrificans* was found to be frequently occurring in the Surtsey soil.

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The development of the land-arthropod fauna on Surtsey, Iceland, during 1971—1976 with notes on terrestrial Oligochaeta

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INTRODUCTION

In 1973 Lindroth et al. published the results of their terrestrial invertebrate survey on Surtsey and in its adjacent areas. The publication deals with the Surtsey collections from 1964—1970, which consist of 5742 specimens. Only a few species from 1971 and 1972 were included in the discussions.

THE FIELD-WORK 1971—1976

In 1971 the author stayed on the island from June 12 to August 24, and Mr. H. Björnsson from October 10—28. Mr. J. Eldon stayed there from June 6 to August 23, 1972, and from June 24 to August 21, 1973. However only seven collecting days have been noted in 1973. In 1972 (July 4—8) the island was also visited by Dr. C.H. Lindroth, Dr. H. Bödvarsson, Mr. S.H. Richter and Dr. P. Douwes. In 1974—1976 no regular collecting took place on Surtsey. In 1974 and 1976 the island was visited by Dr. H. Bödvarsson and the author on July 30 to August 3 and August 7—12 respectively. No collecting took place in 1975, and because of unfavourable weather during the visit in 1976 the capture was very poor that year, especially regarding the flying insects.

In 1971 no traps were in use as all the available traps had been damanged the previous summer. In 1972 two new screen-traps (see Lindroth et al., 1973, p. 148) were set up in the northern part of the island and kept running from June 8 to August 15. However trap collecting was not continuous, as it was often disturbed by unfavourable weather and other events. On August 20, 1973, insects were unusually common around the hut. Then 409 flies were caught in a water-filled bowl outside the hut.

THE MATERIAL FROM 1971—1976

In this paper unpublished data collected by Dr. H. Bödvarsson are not included, so all numbers given are data from other collectors.

The material consists of 4064 specimens. Most of the groups have been identified to species. The important group Acari (918 specimens) has only partly been treated by a specialist, but the author has not yet received the results. Most of the Hymenoptera (9 specimens) are still in the hands of a specialist. Diptera Sciaridae and some of the Chironomidae have not been identified.

Dr. Å. Holm, Uppsala, has been very helpful and has identified the Araneae (10 ex.), Dr. S.L. Tuxen, Copenhagen, identified the single Protura found on the island and Mr. K.J. Hedqvist, Stockholm, the single Chalcidoidea (Hymenoptera). Dr. H. Bödvarsson identified the Collembola, and the author is responsible for the identification of the remaining groups.

This material consists of at least 122 species of which 33 are new to Surtsey and one is new to the Icelandic fauna.

ADDITIONS TO THE SURTSEY LIST OF TERRESTRIAL ARTHROPODS.

DIPTERA

Fam. Bibionidae
Bibio nigriventris Hal. 17. VI.72, 1 ex. (J.E.).
Fam. Chironomidae
Cricotopus ? sylvestris Fabr. 3.—5. VII. 72, 6 ex.; 1. VII. 73, 1 ex (J.E.).
Diamesa aberrata Lundb. 11.VI.72, 1 ex.; 15.VIII.72, 1 ex. (J.E.).
Fam. Ceratopogonidae
Gen. sp. 3.VIII.74, 1 ex. (E.O.).
Fam. Simuliidae
Eusimulium aureum Fries 31. VII. 74, 1 ex. (E.O.).
Fam. Tipulidae
Tipula rufina Meig. 4.VII.72, 1 ex. (J.E.).
Fam. Dolichopodidae
Hydrophorus viridis Meig. 23.X.71, 1 ex. (H.B.).
Fam Syrphidae
Platycheirus manicatus Meig. 1.VII.72, 1 ex. (J.E.).
P. peltatus Meig. 30.VII.72, one dead ex. in drift on the shore; 4.VII.72, 1 ex.; 5.VII.72, 1 ex. (J.E.).

Syrphus torvus O.-Sack. 19.VI.72, 1 ex. (J.E.).
Fam. Muscidae
Spilogona baltica Ringd. (see Lindroth et al., 1973, p. 51, *Spilogona sp.* A and *sp.* B) 16.VI.71, 1 ex. (E.O.); 27.VI.72, 1 ex. (J.E.).

HYMENOPTERA

Chalcidoidea
Eupteromalus fucicola Walk. 21.VII.71, 1 ♀ hatched from a pupa of *Coelopa frigida* F. collected in drift on the N shore (E.O.).

COLEOPTERA

Fam. Carabidae
Nebria gyllenhali Schnh. 26.VI.72, 1 ex. dead and badly damanged in drift on the N shore.

LEPIDOPTERA

Fam. Tortricidae
Eana osseana Scop. 30.VII.74, 33 ex. dead in drift on the N shore; 2.VIII.74, 4 ex; 3.VIII.74, 1 ex. (E.O.).
Fam. Nymphalidae
Vanessa atalanta L. 26.X.71, 1 ex. (H.B.).
Fam. Geometridae
Cidaria (Xanthorhoe) designata Hufn. 23.VI.71, 2 ex. (E.O.).
C. (Epirhoe) alternata Müll. 16.VI.71, 1 ex. (E.O.).
Fam. Noctuidae
Euxoa islandica Staud. 10. VIII.72, 1 ex. (J.E.).
Noctua pronuba L. 27.VII.72, 1 ex.; 25.VI.73, 1 ex. (J.E.).
Peridroma saucia Hübn. 16.VII. 71, 1 ex. (E.O.).
Diarsia mendica Fabr. 3.VII.72, 1 ex. (J.E.).
Cerapteryx graminis L. 30.VII.74, 9 live and 2 dead ex. in drift on the N shore; 1.VIII.74, 1 ex. newly dead in the lava-slope of Surtur II (E.O.).
Phlogophora meticulosa L. 27.X.71, 1 ex. (H.B.).

TRICHOPTERA

Fam. Limnephilidae
Limnephilus elegans Curt. 1971, 1 ex. dead on the NE shore (E.Ó.).
L. griseus L. 5.VII.72, 1 ex. (J.E.).

HEMIPTERA

Coccina
Arctorthezia cataphracta Olafs. 1.VIII.74, 9 live and 10 dead ex. in a tuft of grass that was washed ashore (E.O.).

PROTURA

Protentomon thienemanni Strenzke 1. VIII.74, one live ex. in a tuft of grass that was washed ashore (E.O.). New to Iceland.

COLLEMBOLA

Three new species (*Friesea mirabilis* Tullb., *Onychiurus armatus* Tullb. and *Folsomia quadrioculata* Tullb.) will be treated by H. Bödvarsson in a later publication

ARANEAE

Fam. Linyphiidae
Erigone atra Bl. 18.X.71, 1 ♀ (H.B.).
Erigone arctica maritima Kulc. (previously recorded with doubt) 9.VIII.76, 1 ♂ 1 ♀ (E.O.)
E. tirolensis L. 12.VIII.72, 1 ♂ (J.E.).
Islandiana princeps Braend. 29.VII.71, 1 ♀ with an egg cocoon (E.O.).

Of these 33 new species only four can possibly be regarded as permanent settlers on the island, i.e. the spiders and perhaps the collembole *Onychiurus armatus.* The ten new Diptera, ten Lepidoptera and the two Trichoptera are all casual visitors, and the remaining species were carried to the island in a tuft of grass, that was washed ashore.

EXAMPLES OF HYDROCHOROUS TRANSPORT OF LAND-INVERTEBRATES TO SURTSEY

It was pointed out by Lindroth et al. (1973), that hydrochorous dispersal of land-invertebrates to Surtsey is of great importance. Animals have been carried to the island both by floating objects and simply by floating on the surface of the sea.

Puparia of three species of seashore flies (*Coelopa frigida* Fabr., *Thoracochaeta zosterae* Hal. and *Fucellia fucorum* Fall.) have been found washed ashore and at least the two latter species have hatched afterwards.

On July 21, 1971, six puparia belonging to the above mentioned Diptera species (three, two and one specimens respectively) were collected in drift on the north beach. One of the *C. frigida* puparia hatched a few days later producing the parasitic wasp *Eupteromalus fucicola* Walk. (Chalcidoidea), which in Iceland is only known from the Westman Islands (Lindroth et al., 1973). The host was unknown. Most likely the pupa became infected outside Surtsey, and the inhabiting wasp managed to survive during the hydrochorous transport.

Apparently floating tussocks are going to be of great importance for the establishment of soil fauna on Surtsey. On July 8, 1972, a small tuft of grass (dry weight 52 g) was found washed ashore on the northeast beach. It contained two life specimens of Collembola and ca. 30 specimens of Acari. The origin of the tuft could not be traced. (Lindroth et al., 1973, p. 255). On August 1, 1974, a new floating tussock was washed ashore, this time a large one. It was cylindrical, 90 cm long and 10—20 cm wide. About one half of it (dry weight 884 g) was sampled and isolated in plastic bags. The other half was left on the beach. A few days later the sample was treated in Berlese funnels. Altogether 653 terrestrial invertebrates were extracted through the funnels. Afterwards the dry sample was thoroughly examined, and the search for dead animals resulted in 10 specimens of *Arctorthezia cataphracta.* The invertebrates found in the tussock are listed in table 1.

Various skilled botanists have studied the plant remains in the tussock, but they have not been able to give a definite identification. The tussock could possibly consist of the remains of *Poa sp.*

To trace the origin of the tussock both pollen analysis and geological studies were performed. The pollen analysis, performed by Miss M. Hallsdóttir, Dept. of Quarternary Geology in Lund, showed a marked predominance of grasses (Gramineae). The results are given in table 2. These results do not give any proof of the origin of the tussock, but undeniably it has got the character of the bird cliffs or the puffin grounds of the Westman Islands, which are often characterized by grasses, *Festuca rubra* and *Poa pratensis,* the composit *Tripleurospermum matitimum* and caryophyllaceous plants like *Stellaria media* (Fridriksson et al., 1972).

Mr. S. Jakobsson at the Natural History Museum in Reykjavík kindly studied grit sampled from the tussock. The grit proved to be quite palagonitizated tuff. Phenocrysts of plagioclase and olivine were common, and zeolites were quite common in holes. This type of tuff resembles that of the Westman Islands, especially in the northernmost part of Heimaey (the Heimaklettur area), where the palagonitization of the old tuff is advanced (Jakobsson, 1968). Thus the tussock could originate from that area, but no proof has been obtained.

FURTHER NOTES ON THE LAND-INVERTEBRATE GROUPS FOUND ON SURTSEY

Diptera

At least 114 species of Diptera have been caught on Surtsey, but the actual number might exceed 120, as the identity of some species is still uncertain, especially within the families Chironomidae and Sciaridae.

As could be expected, the different species have been collected on Surtsey in varying quantities. In figure 1 the 114 species of Diptera are divided into ten groups to illustrate this further. The first group includes species, that have been caught only once or twice, the second group species, of which 3—5 specimens have been caught and so on. Of only one species the number caught has exceeded 1000 specimens. In table 3 the nine most common species are listed. In 1964—1976 these nine species made up 80.6% of the total Diptera capture, so the remaining 105 species (plus some unidentified species) totalled only 19.4%. During the period 1964—1970 these same species constituted 83.8% of the total Diptera capture as compared with 76.5% during 1971—1976. Even though these numbers are fairly alike some changes in abundance of individual species are noted. Most notable is the decreasing number of *Heleomyza borealis* and *H. serrata.* During the very first years of Surtsey's existence the conditions were ideal for saprophagous insects like the *Heleomyza* species since carcasses, that were washed ashore, could lie there for a long time. From 1970 onwards, the beach became a very popular resting place for immature gulls, so all carcasses were quickly devoured. This has no doubt greatly affected the species *H. borealis,* which was previously known to reproduce on the island (Lindroth et al., 1973).

The increase of *Scatophaga stercoraria* in the material is due to the great capture on August 20, 1973, when 381 specimens were caught in a water-filled bowl outside the hut. In 1973 443 Diptera were caught, so *S. stercoraria* makes up 86% of that years capture.

Another biotope, that previously favoured at least two species, i.e. *Chironomus lububris* Zett. and *Scatella tenuicosta* Coll., has also disappeared. These two species had reproduced in the artificial freshwater "pools" erected by Dr. Maguire in 1967. In 1971 his plastic tubs were removed, so no freshwater resourses were available on the island after that, except for condensing vapour around the fumaroles. In such places where algal vegetation is usually luxuriant, the *Scatella* species can easily reproduce, but they have been observed in great numbers in identical places in the new lava on Heimaey. However no *Scatella* flies have been caught on Surtsey after 1970.

No new species of Diptera have been proved to have settled permanently on Surtsey after 1970. *Cricotopus variabilis* (Chironomidae) no doubt reproduces regularly in the salt water rock-pools and 21 larvae were collected in 1972. In 1974 many Calliphoridae larvae were observed in a dead kittiwake in the lava slope of Surtur II. However *Cricotopus variabilis* is the only Diptera species suspected to have a permanent population on the island.

Hymenoptera

During 1964—1970 21 specimens of Hymenoptera were collected (Lindroth et al., 1973). They belong to eight species. Ten specimens were collected 1971—1976. One of them has been identified, i.e. *Eupteromalus fucicola* Walk. (Chalcidoidea), that hatched from a pupa of the seashore fly *Coelopa frigida* Fabr., found in drift on the north shore (21. VII.71). The other specimens are at present being treated by a specialist.

Coleoptera

Only four species of Coleoptera have been found alive on Surtsey, 108 specimens altogether.

Additional six species have been found dead in drift on the shore, in some cases only parts of the animal (10 ex.).

The capture of 66 specimens during 1971—1976 gave no new species, except for the drifted and badly damanged *Nebria gyllenhali* Schnh. Three of the old species were rediscovered. *Enicmus minutus* L. is still regularly found inside the hut. Seven new specimens of *Atheta atramentaria* Gyll. have been collected, all caught flying on sunny days. Then *Amara quenseli* Schnh. was rediscovered when a single beetle was found running on the ground in crater Surtur I on August 15, 1972 (leg. J.E.). The specimen was macropterous like the one previously captured. *Otiorrhynchus arcticus* O. Fabr. has not been found after 1969.

Lepidoptera

Altogether 19 species (124 ex.) of Lepidoptera have been found on Surtsey. Nine species (31 ex.) were captured in 1964—1970 (Lindroth et al., 1973). During 1971—1976 ten new species were captured and four of the old species were rediscovered, i.e. *Plutella maculipennis* Curt. (5 ex. in 1972), *P. senilella* Zett. (4 ex. in 1972 and 1 ex. in 1974), *Agrotis ipsilon* Hufn. (1 ex. 25. IX.1976, leg. S. Jakobsson) and *Autographa gamma* L. (22 ex. in 1971). The last species invaded the island on October 19—27, 1971. That event is discussed by Lindroth et al., 1973 (pp. 216—219).

On July 30, 1974, 11 specimens of *Cerapteryx graminis* L. were found in drift on the north shore. Nine of them were alive but wet and unable to fly. At the same time 33 specimens of *Eana osseana* Scop. were collected in the drift, but all of them were dead. On August 1 yet another specimen of *C. graminis* was found newly dead (soft and undamanged) in the lavaslope of Surtur II. Then on August 2—3 five specimens of *E. osseana* were found alive. These first days of August, 1974, the island was invaded by a variety of flying insects. Only one or two specimens were caught of the remaining 8 new species of Lepidoptera.

Neuroptera

The single Icelandic species, *Boriomyia nervosa* Fabr., was first collected on Surtsey in 1966 (1 ex.) (Lindroth et al., 1973). A second specimen was captured on June 14, 1971.

Trichoptera

The first Trichoptera were found on Surtsey in 1970, when three specimens of *Limnephilus fenestratus* Zett. were captured. The same year a single *L. affinis* Curt. was found dead in drift on the shore (Lindroth et al., 1973).

In 1971 a single specimen of *L. elegans* Curt. was found dead on the northeast shore. The specimen was in a good condition. The date of this finding is unfortunately not available at the time of writing. A new species, *L. griseus* L., was caught flying on July 5, 1972.

Hemiptera

Two aphid species had previously been found on Surtsey. Now the coccid species *Arctorthezia cataphracta* Olafs. has reached the island, transported by a floating tussock (see above). The species is very common all over Iceland.

Three dead specimens of *Arctocorisa carinata* C.R. Sahlb. were found in drift on the shore in 1969. Still one specimen was found drifted ashore on July 30, 1974.

Protura

Only two species of this order had previously been found in Iceland, both of them being extremely rare. It was therefore surprising when the third species appeared in the tussock, that was washed ashore on Surtsey in 1974 (see above). This species, *Protentomon thienemanni* Strenzke, was previously known from West-Germany (Tuxen, 1964).

Collembola

Lindroth et al. (1973) partly includes the material collected by Dr. H. Bödvarsson in 1972. Eight species were recorded from Surtsey.

The material collected by other collectors during 1971—1976 consists of 691 specimens, belonging to 10—11 species. Three of them had not been recorded, i.e. *Friesea mirabilis* Tullb., *Folsomia quadrioculata* Tullb. and *Onychiurus armatus* Tullb. These species were collected from the floating tussock found in 1974. The last species has also been found on the island on other occations, under pieces of driftwood. Altogether 243 collemboles were extracted from the above mentioned tussock. They belong to five species (table 1). This group of insects will be treated more thoroughly by Dr. H. Bödvarsson in a later publication.

Araneae

In 1964—1970 11 spiders belonging to five species were found on Surtsey (Lindroth et al., 1973). During 1971—1976 ten specimens were found, giving three new species to the Surtsey list. One species, *Erigone arctica maritima* Kulcz., previously identified with doubt, was rediscovered.

The first spiders were found on Surtsey in 1967, i.e. *Lepthyphantes mengei* Kulcz. (2 ex.) and *Meioneta nigripes* Sim. (2 ex.) (Lindroth et al., 1973). In 1968 and 1969 no spiders were found, but from 1970 onwards spiders have been found every year. In 1976 silky threads produced by spiders were observed all over the lava fields, especially in sheltered and damp holes and caves. Therefore spiders are obviously becoming quite common. Three specimens were found that year, *Erigone arctica maritima*, 1 ♂ and 1 ♀ in a cave on the east part of the island, and *Meioneta nigripes*, 1 ♀ on a big trunk of wood on the boulder beach on the southeast part of the island (leg. S. Nilsson). The latter has become the most frequent species on Surtsey, collected in 1967, 1970, 1971, 1973, 1974 and 1976.

One species has been found with eggs, i.e. *Islandiana princeps* Braend., collected on July 29, 1971, under a piece of driftwood near the airstrip on the northern ness. The egg cocoon was attached to the underside of the wood and was guarded by the mother.

Acari

Acari have been collected in great numbers on Surtsey. The collecting in 1964—1970 gave 1894 specimens and 17 species (Lindroth et al., 1973). In 1971—1976 918 specimens were collected altogether (the collections of Dr. H. Bödvarsson are not included). The material is unfortunately still mostly unidentified due to lack of specialists. However the 398 specimens extracted from the floating tussock have been studied by a specialist, but the results are not yet available.

Oligochaeta

The first representatives of this group of invertebrates were discovered on Surtsey in 1972 when two and nine specimens of Enchytraeidae were found under driftwood on the northern ness on July 7 and 9 respectively. One specimen of the same group was extracted from the floating tussock in 1974, and one was found under driftwood outside the hut on August 10, 1976. No further attempts to identify the species have been made.

FUTURE PLANS

It may be assumed, that good information has been achieved on transport of insects to Surtsey and what species are regularly carried out there and thus are most likely to inhabit the island in the future. As the vegetation on the island is now rapidly progressing, an increase in permanently settled land-invertebrates should be expected in the near future. Thus the most important task for the future is to follow the development of the biotopes on the island and see how they will be invaded by animals. Active collecting of flying insects will be of minor importance. The island should be visited every second year.

ACKNOWLEDGEMENTS

This work was sponsored by the Surtsey Research Society with grants from the U.S. Atomic Energy Commission, Environmental Branch, and by the Swedish Natural Science Board.

The author is greatly indebted to the specialists mentioned in this paper for their help with identification of the collections and to Dr. C.H. Lindroth and Dr. H. Andersson, Lund, for their help and stimulating interest in this work.

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Tuxen, S.L. 1964: The Protura. Paris.

Table 1. Terrestrial invertebrates found in a tussock, that was washed ashore on Surtsey, 1. VIII.1974.	No. of specimens
Acari	398
Collembola	
Onychiurus armatus Tullb.	214
Archisotoma besselsi Pack.	18
Friesea mirabilis Tullb.	7
Hypogastrura sp.	3
Folsomia quadrioculata Tullb.	1
Hemiptera	
Arctorthezia cataphracta Olafs.	9 (+ 10 dead)
Protura	
Protentomon thienemanni Str.	1
Diptera	
Chironomidae larva	1
Oligochaeta	
Enchytraeidae	1
Total	653 (+ 10)

Table 2. Results of pollen analysis performed on the tussock mentioned in table 1.	No. of pollen	%
Gramineae	776	92.60
Compositae		
Tubuliflorae	31	3.70
Caryophyllaceae	28	3.34
Chenopodiaceae	1	0.12
Rumex acetosa type	1	0.12
Alnus	1	0.12
Total	838	100.00

Table 3. The most frequent Diptera species on Surtsey	1964—1970		1971—1976		1964—1976	
	No. of specimens	% of Diptera	No. of specimens	% of Diptera	No. of specimens	% of Diptera
Cricotopus variabilis Staeg.	756	24.2	693	30.8	1449	26.9
Heleomyza borealis Boh.	659	21.1	163	7.3	822	15.3
Scatophaga stercoraria L.	317	10.1	430	19.1	747	13.9
Coelopa frigida F.	425	13.6	176	7.8	601	11.2
Diamesa zernyi Edw./*bohemani* Goet.	93	3.0	143	6.4	236	4.4
Heleomyza serrata L.	173	5.5	12	0.5	185	3.4
Copromyza similis Coll.	43	1.4	65	2.9	108	2.0
Scatophaga furcata Say	83	2.7	14	0.6	97	1.8
Fucellia fucorum Fall.	70	2.2	24	1.1	94	1.7
Total	2619	83.8	1720	76.5	4339	80.6

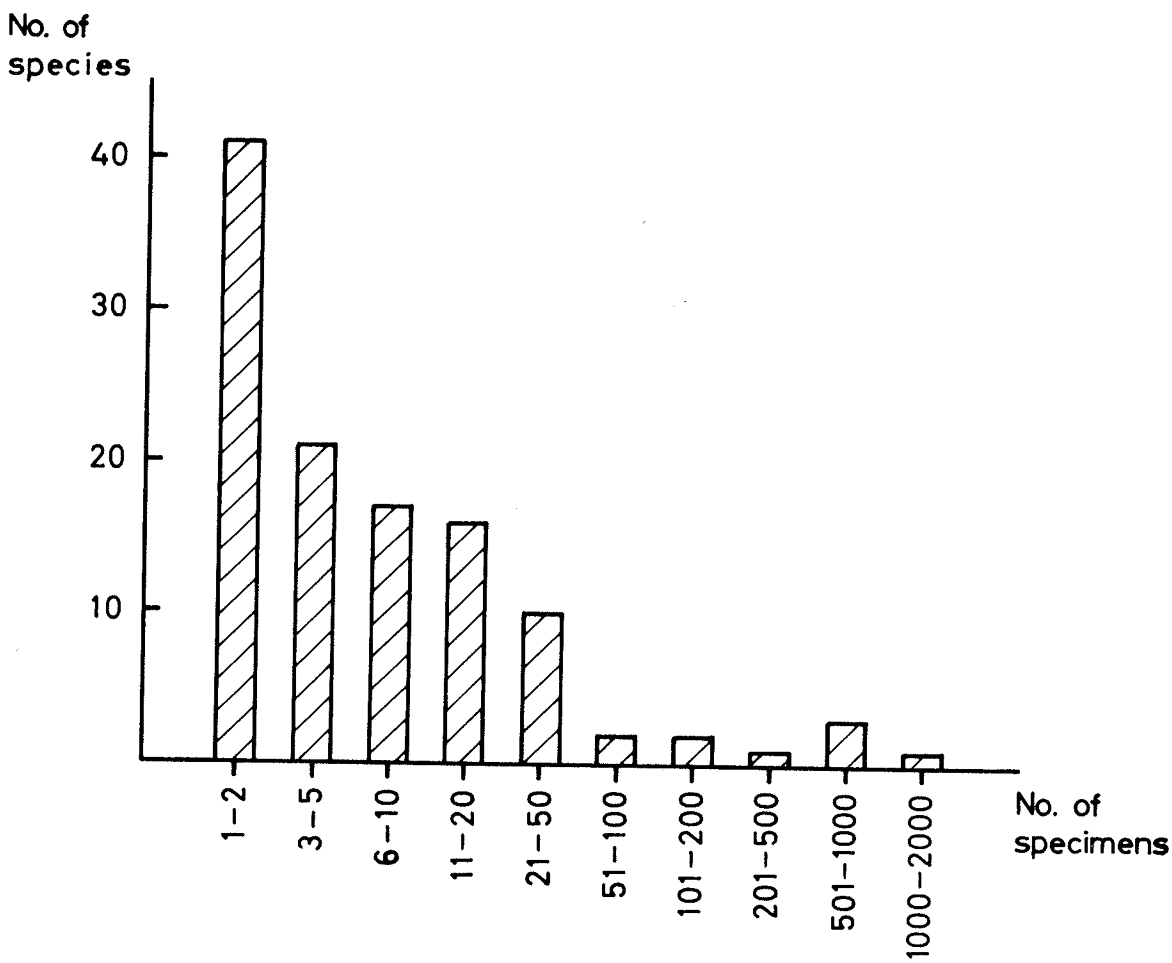

Figure 1. Relation between no. of species and no. of specimens of 114 species of Diptera caught on Surtsey 1964—1976.

On the terrestrial microfauna of Surtsey during the summer of 1976 with special reference to the Ciliates

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ABSTRACT

The number of ciliate species on Surtsey has increased considerably during recent years. In this study 11 species, belonging to 2 orders and 3 suborders, were observed in cultures on material collected on Surtsey in August 1976. The most frequent genus was *Holosticha.* The other components of the terrestrial microfauna were amoebae, rotifers and nematodes. No predators were found and the ecological pyramid therefore still consists of only the two first levels.

INTRODUCTION

The Surtsey eruption ceased in June 1967, after having continued for more than three and a half years. Among the first pioneers on the island were bacteria (Kolbeinsson and Fridriksson 1968), blue-green algae (Behre and Schwabe 1970, Schwabe 1974) and flagellates (Smith 1968). In earlier studies of the terrestrial microfauna, Holmberg and Pejler (1972, 1974) mainly dealt with the rhizopods and rotifers. Only one species of ciliate, *Cyclidium citrullus,* was identified. A few species of nematodes were reported by Sohlenius (1972, 1974).

A new expedition to Surtsey took place in August 1976. As regards the microfauna, the investigations this time were principally focused on the ciliates.

METHODS

The soil samples were stored in sterilized plastic capsules (Cerbo, Sweden, No. 18010) of 20 ml volume equipped with sample spoons inside the screwcaps. On arrival at Uppsala they were inoculated either to agar substrates (localities A, F, U, V and X) or to a liquid nutrient solution (localities A, B, C, E, F, G. I. K, M, N, O, R, S, T, U, V and X). The composition of this medium is described in Henriksson et al. (1972). The positions of the localities are shown in Fig. 1. Descriptions of the sampling locations are given in Henriksson et al. (1978). The cultures were kept under controlled conditions at +20°C and approximately 3000 Lux with the humidity balanced in order to avoid exsiccation. The prevalent standards when working with sterilized material were followed.

As pointed out by Fenchel (1969), fully satisfactory identifications are often difficult to obtain when working with microfauna. Many groups still lack sufficient taxonomic treatment. In this study the ciliates were mainly determined according to Kahl (1930—35), the amoebae to Hoogenraad and de Groot (1940), Harnisch (1960) and Grospietsch (1965) and the rotifers according to Donner (1965). The nematodes were determined by Dr. B. Sohlenius.

RESULTS

The material investigated was inoculated both to firm substrates (agar) and to liquid nutrient solutions. Microzoa developed in all agar cultures (Table I) and in 8 of the liquid nutrient solution cultures (Table II). Altogether at least 11 species of ciliates, 5 species of amoebae, 2 species of rotifers and 1 species of nematodes were encountered. According to Grell (1973) the ciliates would represent 2 orders, Holotricha and Spirotricha, and 3 suborders, Gymnostomata, Hymenostomata (holotrichs) and Hypotricha (spirotrich). The most frequent genus was *Holosticha,* which was found in cultures from 5 different localities. As for the amoebae, the most common forms were small specimens of *Vahlkampfia,* which were observed in cultures from 4 different localities. The rotifers, which in some cultures developed in masses, were *Philodina acuticornis* and *Habrotrocha constricta.* The nematodes were identified to the genus *Monhystera.*

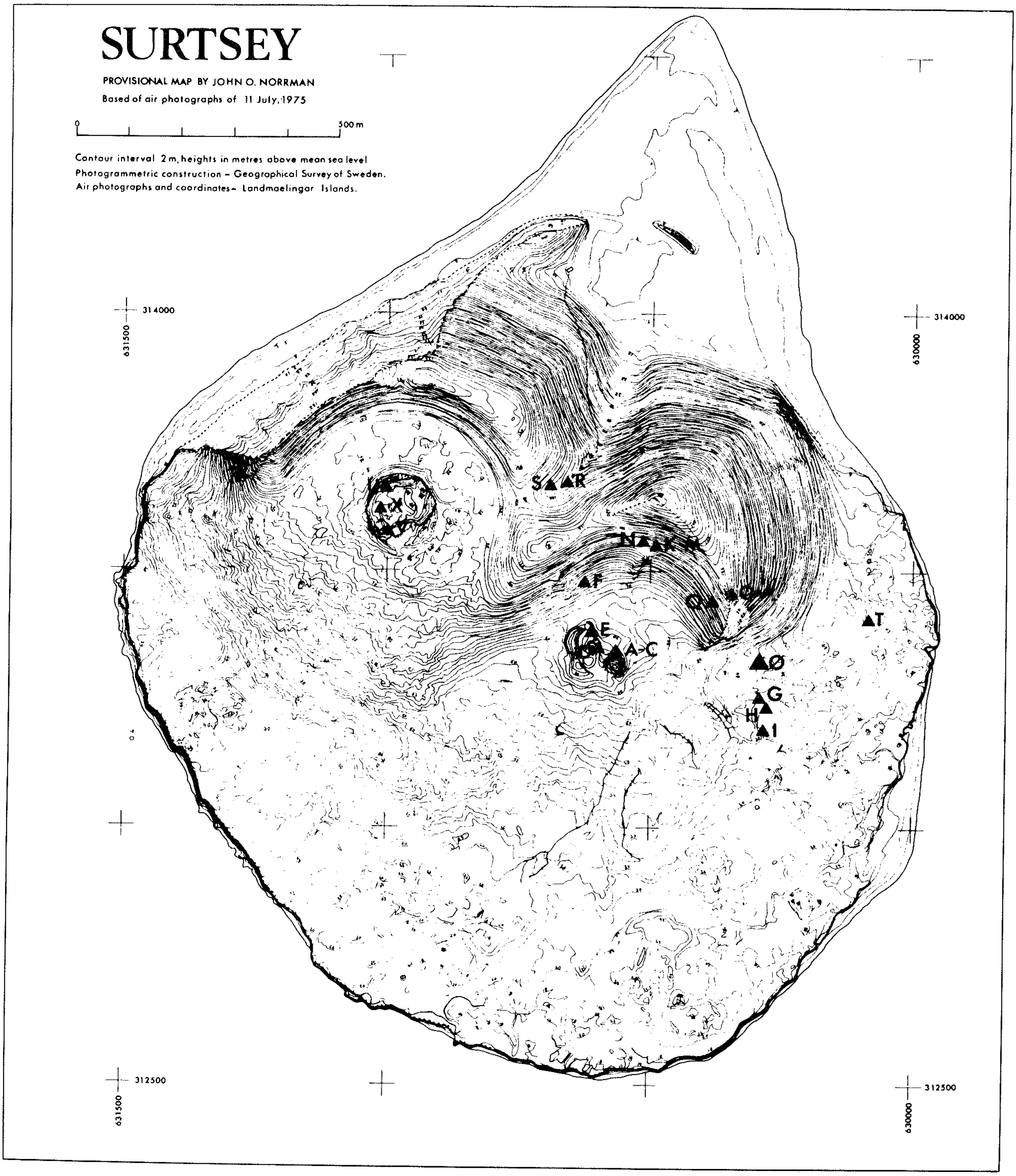

Fig. 1. Sampling locations on Surtsey during the summer of 1976. No samples were collected from the locations D, H, Q and Ø in this study. Map of Surtsey by John O. Norrman, Uppsala.

There were some differences in the species spectrum between the agar cultures and the liquid nutrient solution cultures. However, the ciliates dominated both kinds of cultures.

DISCUSSION

Earlier investigations of the terrestrial microfauna of Surtsey have reported very few ciliates. Smith (1968) found nothing but flagellates, and Holmberg and Pejler (1972, 1974) could only determine 1 species, *Cyclidium citrullus*. According to Holmberg (pers. comm.) there might also have been a further 2 or 3 very infrequent species. Although these studies were not primarily concerned with the ciliates, it is fairly clear that the ciliate fauna has become more diversified in recent years. The number of species had increased considerably, and the abundance of individuals in the cultures was much greater now than during the investigations by Holmberg and Pejler, using the same culturing methods. An indication of this development of ciliates in terrestrial habitats can be discerned already in Maguire Jr (1970), who found numbers of ciliate species in aquatic traps left in the field for 14 months during 1967—68.

Compared with the above reports by Holmberg and Pejler, no increase in the number of species of amoebae and rotifers could be detected. In fact, there seem to be somewhat fewer amoebae now.

All the forms observed are widespread and with the ability to reproduce asexually or parthenogenetically. No predators were found and the ecological pyramid is probably still formed by only two trophic levels, the photoautotrophs and those microzoa feeding on algae and bacteria/detritus.

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TABLE I
Occurrence of microzoa in the different localities during the summer of 1976. Agar cultures.

Locality	A	F	U	V	X
RHIZOPODA, AMOEBINA					
Vahlkampfia	x		x		
RHIZOPODA, TESTACEA					
Euglypha	x				x
CILIATA, HOLOTRICHA					
Gymnostomata					
Chilodonella		x			
Hymenostomata					
Glaucoma	x				
Paramecium				x	
CILIATA, SPIROTRICHA					
Hypotricha					
Holosticha	x		x	x	x
hypotrich I			x		
hypotrich II				x	
ROTATORIA, BDELLOIDEA					
Habrotrocha constricta Dujardin			x		
NEMATODA					
Monhystera				x	x

TABLE II
Occurence of microzoa in the different localities during the summer of 1976. Liquid nutrient solution cultures.

Locality	B	E	K	M	N	U	V	X
RHIZOPODA, AMOEBINA								
"Astramoeba" x)			x					
Thecamoeba	x							
Vahlkampfia	x		x					
Vexillifera			x					
CILIATA, HOLOTRICHA								
Gymnostomata								
Chilodonella				x			x	
Nassula								x
Hymenostomata								
Cyclidium citrullus Cohn			x					
Cinetochilum margaritaceum Perty			x					
CILIATA, SPIROTRICHA								
Hypotricha								
Stylonychia curvata Kahl				x				
Euplotes				x				
Holosticha				x				
ROTATORIA, BDELLOIDEA								
Philodina acuticornis odiosa Milne		x						
Habrotrocha constricta Dujardin								x
NEMATODA								
Monhystera			x		x			x

x) The genus *Astramoeba* has been shown to constitute merely a form which can appear in many groups of Amoebina under certain environmental conditions.

GEOLOGY AND GEOPHYSICS

Coastal changes in Surtsey Island, 1972—75

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During the active volcanic phase (1963—67) the coastal configuration of Surtsey Island abruptly changed when lava flows reached the shore. At the same time rapid erosion of the tephra deposits seemed to threaten the very existence of the island. Following the volcanic phase which came to an end in the spring of 1967, shoreline changes have not been especially dramatic, although erosion by wave action has been unusually rapid by comparison with most other coastal areas. This can be explained by the extremely frequent, high wave energy events in the North Atlantic Ocean, the exposed position of the island at the outer margin of the Icelandic shelf, and the physcical properties of the volcanic material.

TOPOGRAPHIC MAPPING

In 1970 a topographic map at a scale of 1:5,000 based on air photographs of 5th July 1968 was printed and also published at the reduced scale of 1:10,000 (Norrman 1970). As there are only a few copies of this map now available and the island has changed considerably since, a new map has been constructed based on air photograps of 11th July 1975, here published as Fig. 2. Separate maps at 1:5,000 scale can be obtained from the Surtsey Research Society or from the author.

The contour interval over most of the map is 2 metres but in areas of very sharp relief such as the steep tephra wall of the north-western coast and part of the eastern tephra cone, only a 10 metre interval is shown. Heights are related to mean sea level determined from observations in a well excavated in the shore deposits of a former lagoon 150 m east of the research station.

The roughness of the terrain in the lava areas south of the craters is clearly demonstrated by the contour irregularity which contrasts markedly to the smooth curves of the tephra slopes facing the interior of the craters and the northern ness. Thus, although the lava area has not been delimited on the map it is nevertheless easily detectable and clearly picked out by comparing with the photograph on Fig. 1.

COASTLINE CHANGES

From vertical air photographs taken almost every year it has been possible to follow the coastal changes by photogrammetrically processed models. Aerial survey in each case was undertaken during summer and the photographs thus depict the net effects on the beaches of the high energy

Fig. 1. Aerial photograph of Surtsey Island, 11th July 1975. Photograph by Landmaelingar Islands.

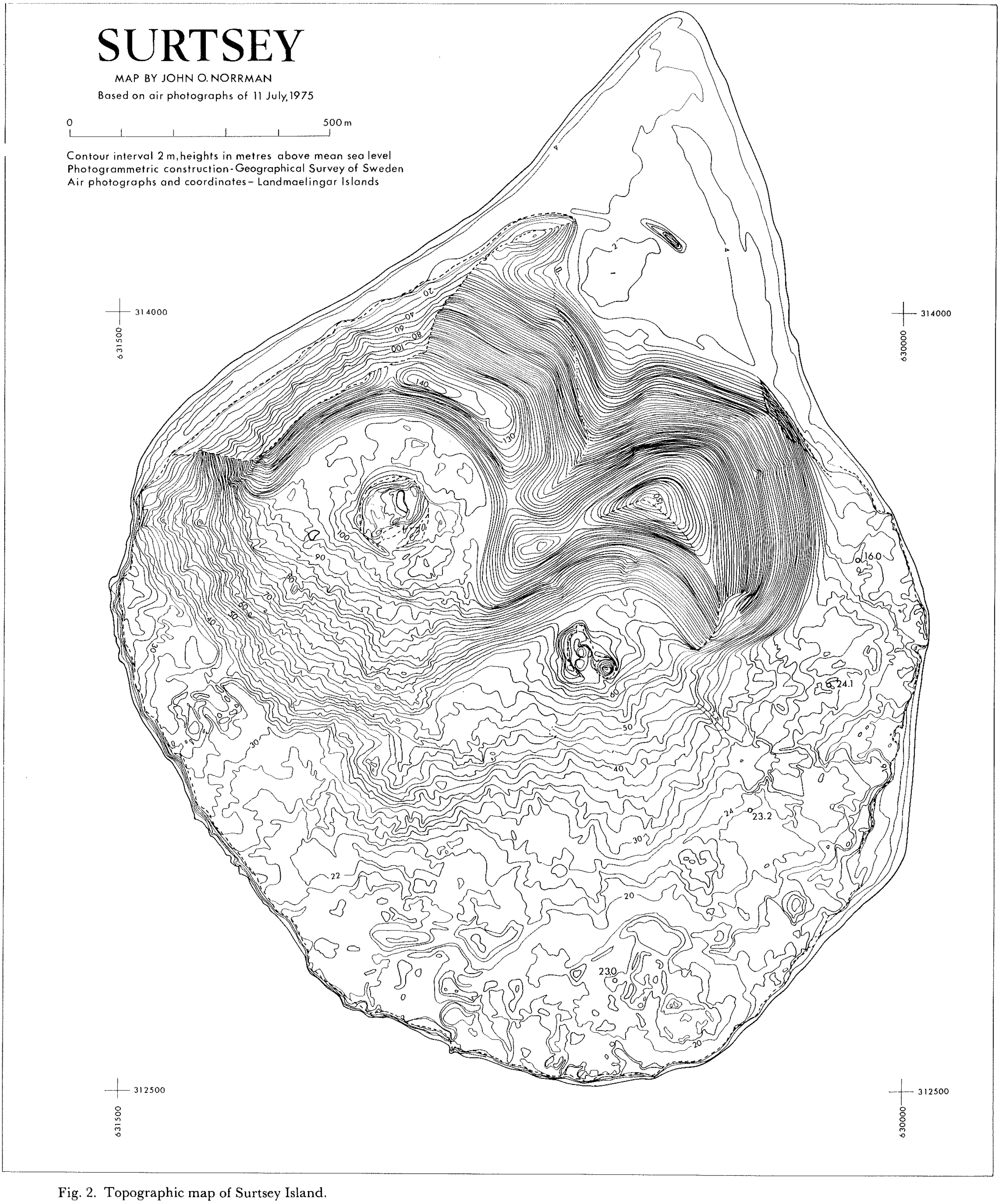

Fig. 2. Topographic map of Surtsey Island.

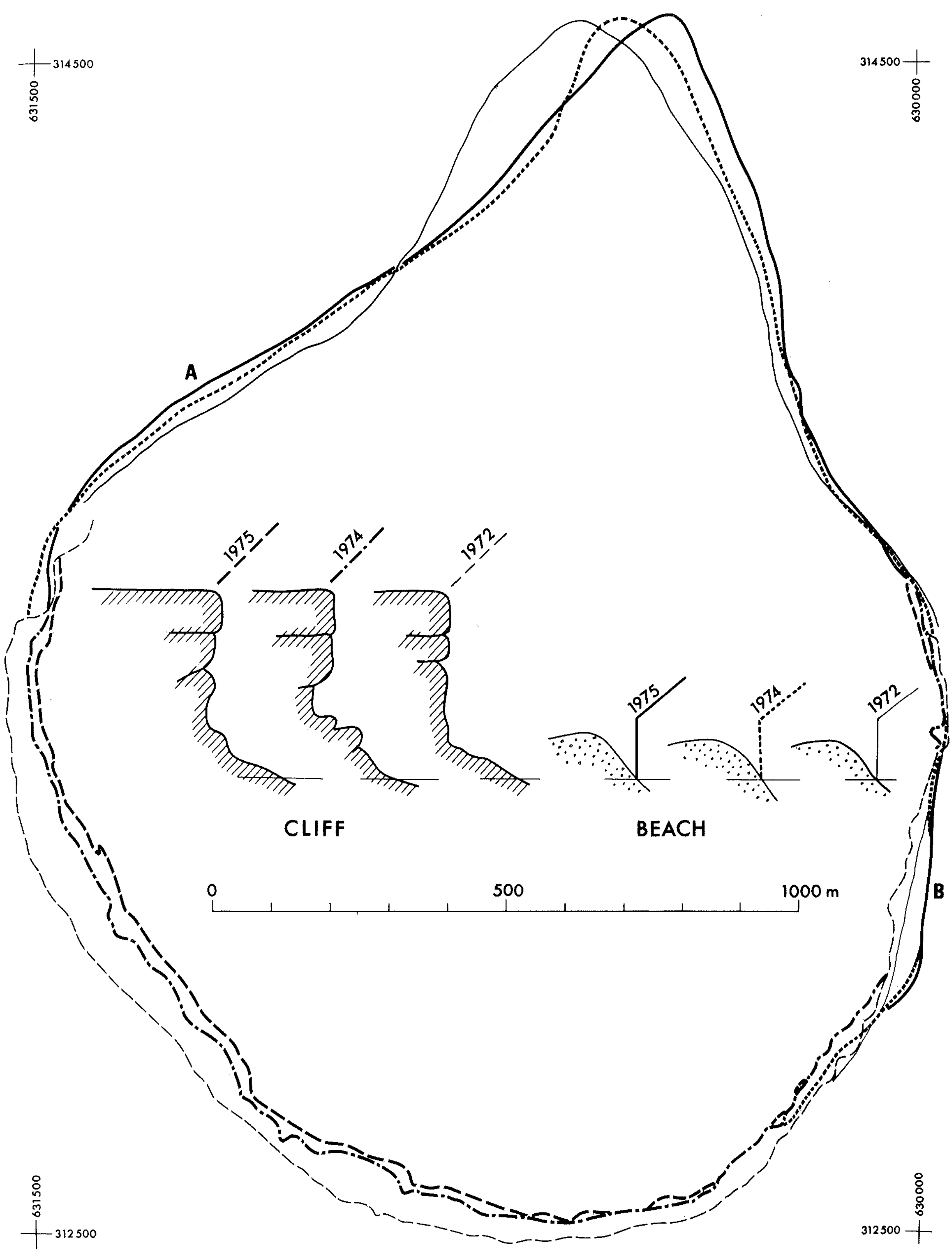

Fig. 3. Cliffline and shoreline on 7th August 1972, 16th July 1974, and 11th July 1975. A: Western boulder terrace, B: Eastern boulder terrace. Photogrammetric constructions by the Department of Physical Geography, Uppsala University and the Geographical Survey of Sweden. Ground control by the author and Mr. B. Calles.

conditions of the preceding winter season and the amount of erosion of the lava cliffs since the previous photograph was taken.

During the period 1972—75 the northern ness appears to have shifted gradually eastwards (Fig. 3), but it may occasionally have tended towards the opposite direction in response to easterly storms. According to our records, the 1975 position of the eastern shore of the ness is further to the east than at any time before. Movement from the 1974 to the 1975 position, which encompasses an area of 2.0 hectares, would require a transfer of about 1.6×10^{6} m^{3} of beach material to infill along the submarine slope which stands at the frictional angle of repose (Norrman 1970, pp. 107—112). As can be seen from Fig. 3 the shift of the ness only affected the western part of the ness proper by erosion and not the western boulder terrace below the high tephra wall (Fig. 4). On the contrary this terrace was broadened during both periods and its width was almost doubled from 1972 to 1975 (A in Fig. 3). The coarse boulders were brought by swash action from the strongly abraded lava cliffs of the south-western coast.

In 1972 the eastern boulder terrace (B in Fig. 3) was very narrow and merely consisted of a steep foreshore below the indented lava cliff (Fig. 5, a). In 1969 it was also very narrow following a period of intense erosion of the south-eastern coast during the preceding winter (Norrman 1972a, Fig. 8), but was built up again during the following year (Norrman 1972b, Fig. 2). Half of its width was lost in 1971 and almost all the next winter (Norrman, Calles, and Larsson 1974, Fig. 10). Heavy accretion of material from the lava cliffs south of the terrace in 1972—74 and a small amount of deposition the next year made the terrace about as wide in 1975 as it was in 1970, but because of erosion of the south-eastern cliff cape, it moved 250 m towards the north.

In 1974 the top surface of the winter berm was very flat and showed no specific morphological forms, but in the foreshore some erosive downslope furrows were to be found on the southern part of the terrace (Fig. 5, b). The photograph of 11th July 1975 shows the foreshore and the 6-m winter storm berm to be covered with boulder ridges which have a predominant east-west orientation (Fig. 5, c and d). This pattern demonstrates that southerly storm waves had swept over the terrace without any significaant offshore refraction, indicating that no submarine abrasion platform had been cut in the lava off the present shoreline although there has been a 170-m retreat of the lava cliff since 1967.

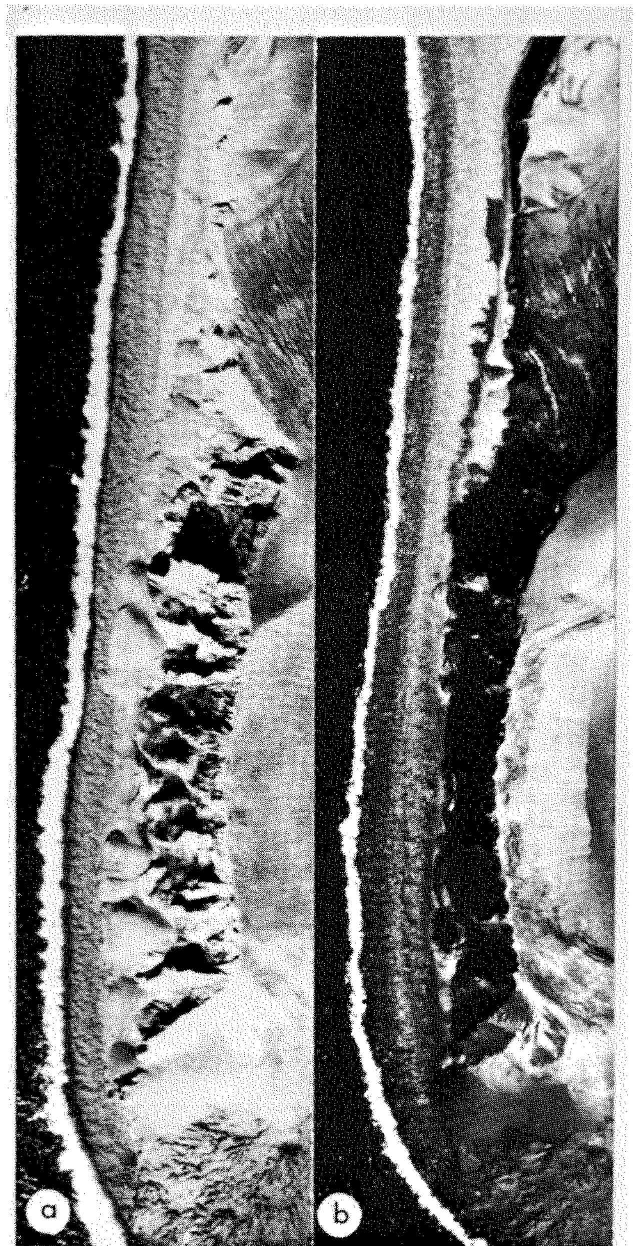

Fig. 4. The western boulder terrace and the tephra cliff of Surtur Junior in 1974 (a) and 1975 (b). In the 1974 photo the well developed funnels and sandy tephra cones of the 140 m high tephra wall are readily visible. The coarse boulders of the terrace form irregular ridges at an angle of ca. 70° to the shoreline The ridges are best visible in the southern part of the terrace. — In the 1975 photo the sculpture of the tephra wall is shadowed, but it can be seen that the terrace has been broadened by erosion of the talus cones as well as by swash accretion on the foreshore. Photographs by Landmaelingar Islands.

From 1972 to 1974 the high lava cliff of the south-western coast suffered intensive erosion with a maximum yearly average retreat of 40 m. In this area the vertical cliff stands 34 m above sea level. The retreat of the southern cliff was about 20 m/year, and along the eastern cliff north of the boulder terrace it was less than 10 m. In 1974—75 the tendency was the same but the rate was lower (cf. Fig. 3).

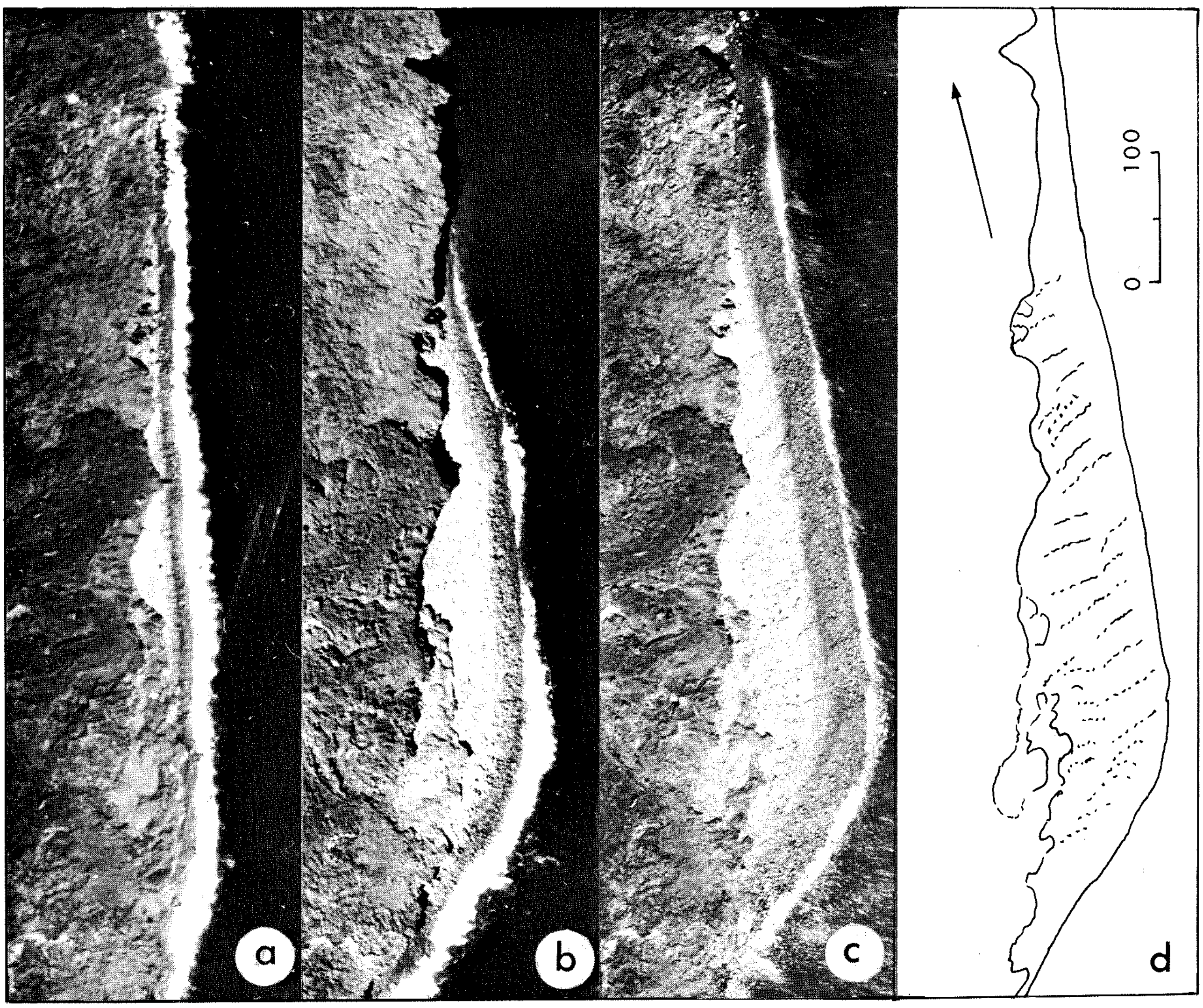

Fig. 5. The eastern boulder terrace in 1972 (a), 1974 (b), and 1975 (c). The 1975 pattern of boulder ridges according to stereoscopic interpretation (d). Photographs by Landmaelingar Islands.

Changes in land area during the period from 1967—75 according to the surveys examined in this paper and previous records are summarized in Table 1.

TABLE 1. AREAL COASTAL CHANGES 1967—75 (hectares)

Period	Cliffs	Beaches	Total
1967—68	− 13	− 2	− 15
1968—69	− 7	− 10	− 17
1969—70	− 7	+ 4	− 3
1970—72(2 yrs)	− 9	− 5	− 14
1972—74 (2 yrs)	− 11	− 1	− 12
1974—75	− 3	+ 4	+ 1
1967—75	− 50	− 10	− 60

The extensive erosion of the lava cliff along the south-western coast is further illustrated by the shape of the island in 1967 as compared to that of 1975 ~~(Fig. 6). The figures~~ for 1974—75 in Table 1 may be interpreted as an indication of a future stage of more stable conditions. However, according to preliminary reports on the 1976 conditions, erosion has again been strong, and these yearly deviations can be attributed to normal variations of storm frequencies.

SUBMARINE MORPHOLOGY

Investigation by diving in 1968—69 indicated that no abrasion platform had formed off the lava cliffs. Immediately off the swash zone, which was covered almost entirely by boulders right up to the cliff notch, there was a continuous submarine slope in the form of a scree often containing huge boulders. Wave action had, however, cut submarine platforms across the remnants of the former tephra volcanoes of Surtla, Syrtlingur and Jolnir; the level of the platform being dependent on the duration of development (Norrman 1970).

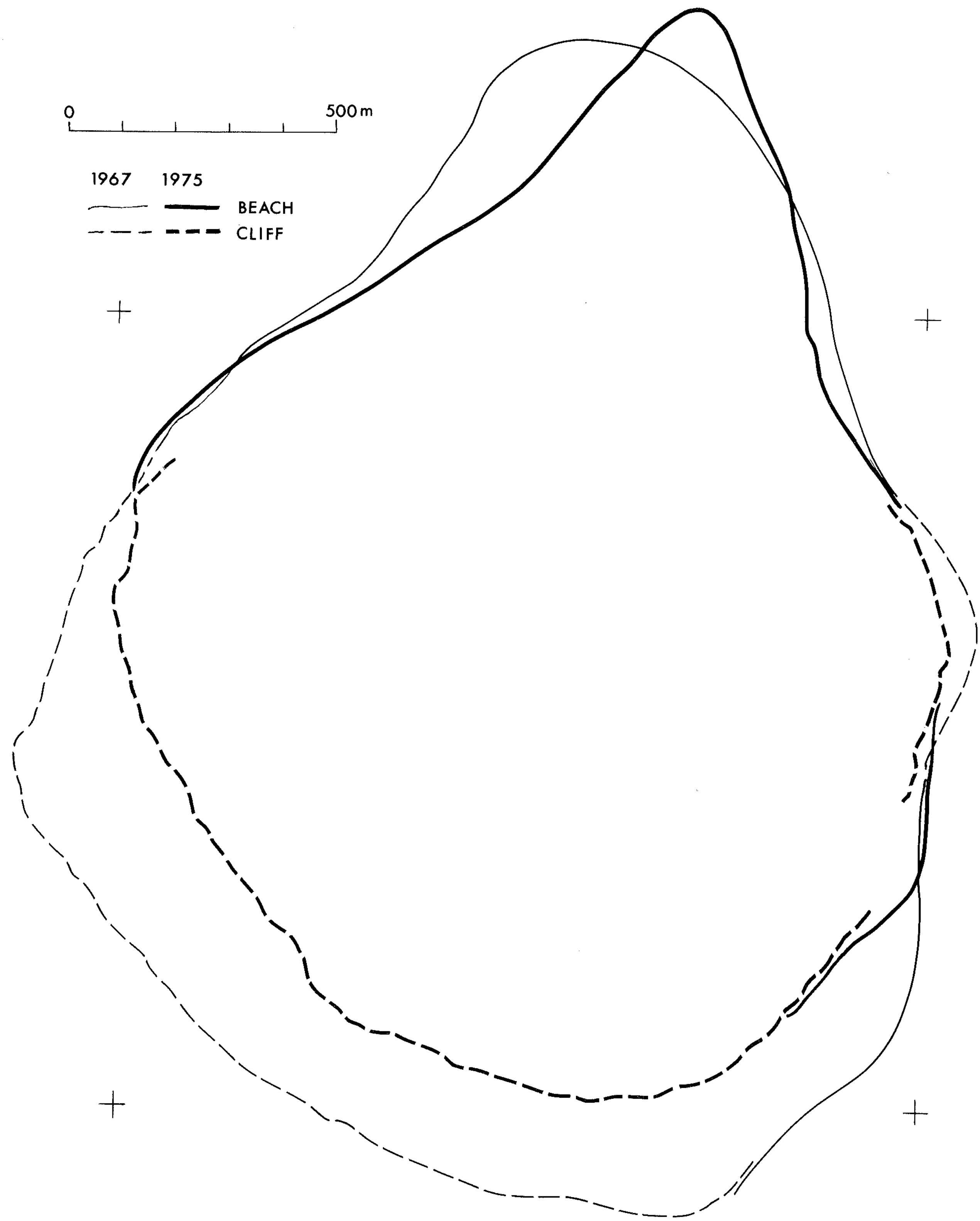

Fig. 6. The coastline of Surtsey Island in 1967 and 1975.

Since 1969 there has been no submarine research carried out around Surtsey. From the 1967 and 1975 coastlines in Fig. 6 a retreat of more than 200 m of the south-western lava cliffs is evident. At the moderate wave conditions of which we have been able to make observations in summertime, there has been no sign of breakers forming over these abraded areas. In addition, as was previously mentioned, the morphology of the eastern boulder terrace does not give any indication of an abrasion platform refraction effect. However, it seems unlikely that no submarine shelf of any type has developed in association with such considerable coastal retreat. It may be very low or steeply sloping. The lowest platform found in 1968 at Surtla was situated at a depth of 40 m.

Information regarding the present submarine conditions is necessary to fully explain the present coastal changes and to prognosticate the future development of the island. This information is also of great general interest as data from abrasive high energy coasts and connected submarine slopes are limited. It is therefore hoped that it should be possible to include the submarine morphology in future surveys.

ACKNOWLEDGEMENTS

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Seasonal means of temperature and salinity in the shelf area in Háfadjúp and across Selvogsbanki in 1971—1975

by
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During the years 1971—1975 relatively comprehensive hydrobiological investigations were carried out in the shelf area southwest of Iceland — "The Háfadjúp-Snæfellsnes project" (Malmberg, 1978 a, b).

The investigations included i.a. temperature (± 0.02°C) and salinity (± 0.003‰ S) observations, carried out at standard stations and depths in various seasons during the years 1971—1975.

At this stage the data have been worked up as

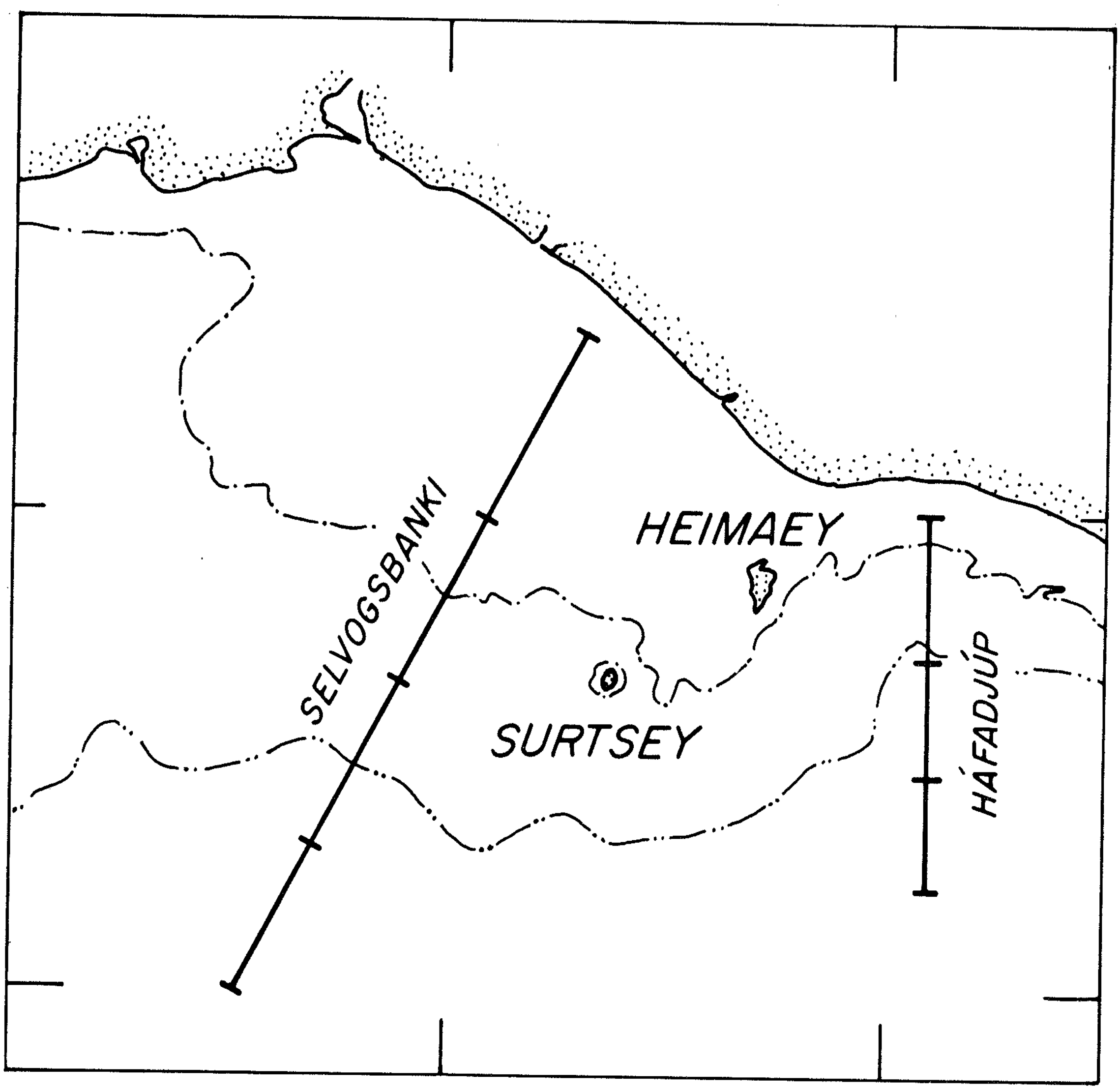

Figure 1. Location of standard hydrographic stations in Háfadjúp and across Selvogsbanki.

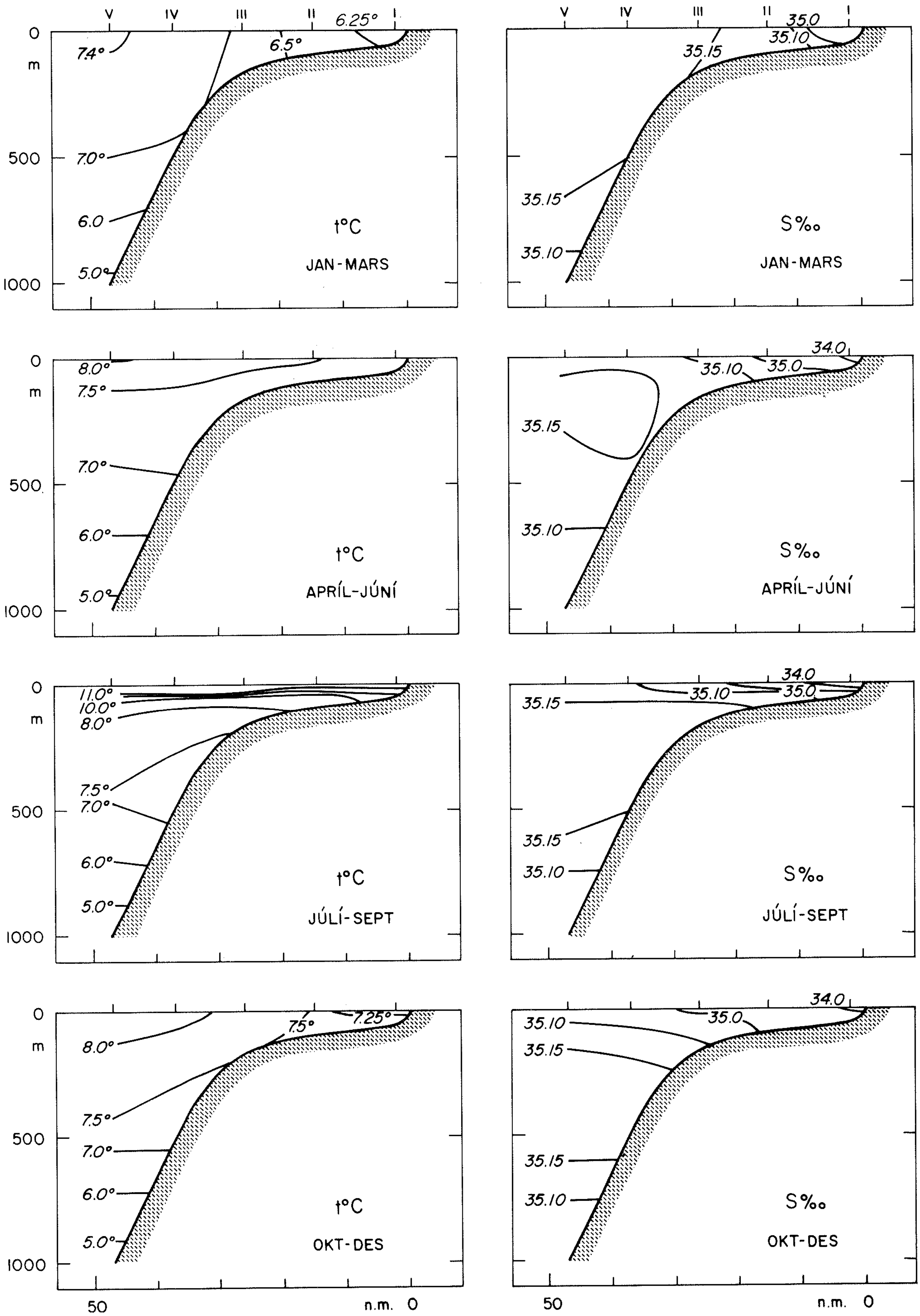

Figure 2. Seasonal means of temperature and salinity on a section across Selvogsbanki (1971—1975).

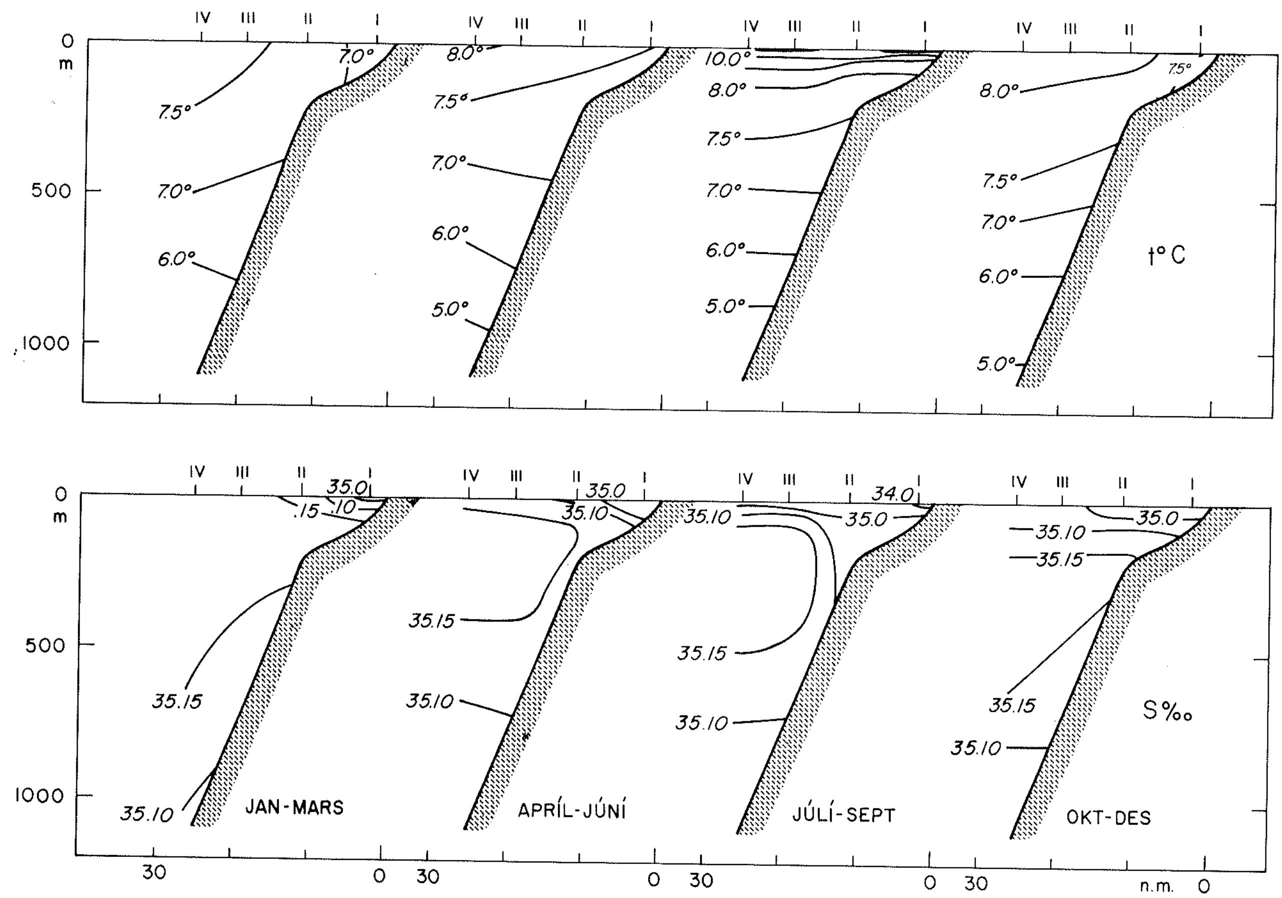

Figure 3. Seasonal means of temperature and salinity on a section in Háfadjúp (1971—1975).

time series and means for different stations and depths per months, seasons and years. The results are available in tables and diagrams at the Marine Research Institute in Reykjavík.

This report presents a few results of two sections, more specifically seasonal means of temperature and salinity for the *Háfadjúp* section consisting of 4 hydrographic stations and a section across *Selvogsbanki* consisting of 5 hydrographic stations (Fig. 1). The stations were worked 28 and 30 times, respectively, in 1971—1975. The mean sections shown in Figures 2 and 3 can be taken as representative for the hydrographic conditions in the waters around Vestmannaeyjar as well as around *Surtsey*. For orientation it should be noted that the volcanic island Surtsey is situated about 20 n.m. off the mainland with a surrounding depth of about 120 m.

Two different water masses, Atlantic water (S‰ > 35.0‰) and Icelandic coastal water (S‰ < 35.0‰), are present in the waters in question. The seasonal variations, both in properties and distribution, are relatively small in the Atlantic water but much greater in the coastal water. In short, seasonal variations of the hydrographic conditions in the study area decrease seawards and with depth down to 200 m.

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Svend Aage Malmberg 1978 a: Háfadjúp — Snæfellsnes 1971—1975. I. Háfadjúp. Hafrannsóknir 13.

Svend Aage Malmberg 1978 b: Háfadjúp — Snæfellsnes 1971—1975. II Selvogsvanki. Hafrannsóknir 15.

The thermal anomaly in Surtsey revisited

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On Sept. 5th 1975 an expedition was taken to Surtsey in the Coast Guard helicopter to map changes in the thermal anomaly formed in the tephra and lava after the eruption 1963—1967. Participants were, apart from the pilot, Karl Sæmundsson, a teacher going on behalf of the Surtsey Society to supervise the hut, Sveinn Jakobsson of the Museum of Natural History, Hörður Johnsen from the Vestmann Islands, Þórður Kristófersson, assistant, and the present author, both employed at the Science Institute, University of Iceland.

The expedition covered most of the island, taking temperature measurements at well over 100 points. The chief aim of the investigation was to map, as accurately as possible, the extent of thermal anomaly, to compare it with previous records, and to measure the temperature in previously investigated areas, noting changes in the heat flow with time. The earlier investigations were made in connection with plans to utilize geothermal heat from domestic heating in the town of Vestmann Islands.

Similar measurements were carried out by the present author in 1970 and the results published in the Surtsey Research Progress Report of 1972 (Vol.VI). Sveinn Jakobsson has also made similar measurements in Surtsey almost every year since the eruption came to an end in June 1967, and although there is a slight difference between his methods of measurement and those of the present author, causing minor divergences in their results, a fairly overall picture of thermal evolution in Surtsey from the very beginning has been obtained. The measurements carried out by the present author were made with a mercury thermometer, whereas those carried out by Sveinn Jakobsson were performed with a thermocouple at 20 cm depth. In the tephra, measurements made by the present author were, almost without exception, taken at a depth of 100 cm, and the limits of the thermal areas are therefore based on the 30°C isotherm at that depth.

The accompanying map of Surtsey (Fig. 1) shows thermal areas as well as the two main hot spots in the lava within the crater wall of Surtur II. Sveinn Jakobsson has kindly allowed me to use some of his results from the last few years, for which I am very grateful.

TEMPERATURE IN THE TEPHRA.

The thermal areas in the tephra have expanded greatly in later years (Surtsey Research Progress Report VI, 1972). All the thermal areas are enlargened to some extent and some of them considerably. In 1970 the tephra in the north-west part of the island was cold, but now the thermal anomaly extends almost to the rim of the tephra ring of Surtur II and new thermal areas have formed in the tephra wall on the NW-shore, reaching down to the beach and probably also up to the highest ridges. The heat has also ascended the northern slopes of the crater Surtur II, extending over the rim on the east side of Bunki, going in a sweep down to Svartagil, somewhat farther down than established in 1970.

On the east and southeast of Strompgígur the limits of the thermal anomaly stretch in a curve across the slope at 60—70 m above sea level, whereupon it slants down to the lava lying at the foot of a nearly vertical tephra wall at the easternmost corner of the tephra ring of Surtur II.

In the areas where heat was first discovered in the Surtsey tephra, hard móberg has long since been formed. Scarcely any surface heat can be detected there now and primitive measuring equipment cannot be forced through hard rock for

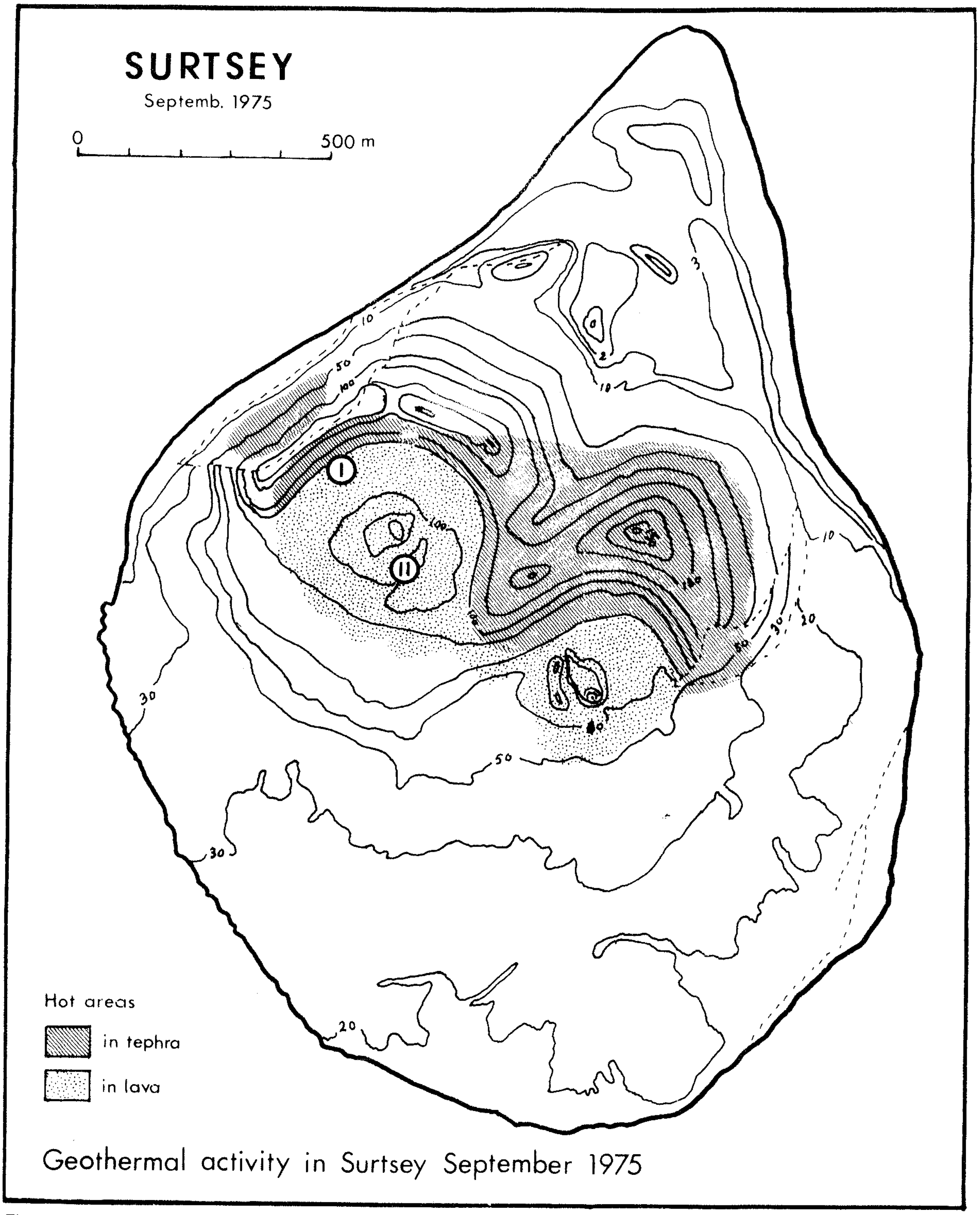

Fig. 1. A map of Surtsey showing thermal areas. Explanations in the text.

measurements at greater depth. According to a preliminary investigation the outflow of heat seems to slow down as the tephra hardens, probably owing to the decreasing permeability of the tephra. This heat is mostly carried in the form of steam, ascending through the un-solidified tephra. When the tephra solidifies the steam moves on laterally to easier outlets, and as those outlets successively close, the steam must go still farther sideways. Thus, the thermal areas in the tephra gradually increase in circumference while the temperature is lowered in the centre. This process will most likely continue as long as the heat ascends from below in the form of steam.

If this theory is correct, the thermal areas will continue to expand and most of the tephra will harden in the next few years. The theory is supported by the fact that most of the Vestmann Islands were built up in a manner similar to that of Surtsey and, like Surtsey, they consist largely of hardened tephra. These islands would not have been large enough in the beginning to withstand destruction by the sea, had the tephra not hardened comparatively quickly, as is the case in Surtsey. This indicates that post-eruptional heatflow through tephra is not an isolated phenomenon occurring only in Surtsey, but a link in a natural chain of events, and that the formation of móberg is often — if not always — due to such heating.

The measurements in 1970 showed heat up to 98°C at a depth of only a few cm. This time 60—70°C was the maximum at a depth of 100 cm. Closer investigations and more extensive measurements within the thermal anomaly might, however, reveal higher temperatures. Most of the measurements performed by the present author were restricted to defining the outlines of the thermal areas where the temperature is generally lower than near the centre. However, forcing measuring instruments into the tephra, when its hardening has reached a certain point, is very difficult and temperature values in such localities are therefore inadequately known. In steam vents within the crater of Surtur II 97—98°C were obtained, similar to the results in 1970. The same was the case in the crater Strompgígur.

TEMPERATURES IN THE LAVA.

Compared to 1970 the temperatures measured in the lava average considerably lower at all stations measured.

On a fissure NW of Surtur II, here called Area I, the maximum temperature measured in 1970 was 460°C, now it was only 50°C, cf. Fig. 2. In area II, SW of Surtur II, the highest temperature measured in 1970 was 220°C, now 160°C, cf. Fig. 2. In the so-called "Grill", SA of Surtur II, the temperature was now 73°C compared to 150°C in 1970. In steam vents elsewhere in the lava maximum temperature measured was 80—90°C, or less.

The areal extent and distribution of the thermal anomaly within the lava appeared similar to that of 1970, but the actual temperatures measured were considerably lower and the steam emission through fissures and holes has diminished.

Hlöðver Johnsen, who was in Surtsey in late August 1975, measured the temperatures in a few steam vents within the tephra ring of Surtur I. During the measurements the flow of steam from the holes increased greatly with a simultaneous rise in temperature, so that, whereas the recorded temperature was certainly over 200°C, it probably reached 400°C shortly afterwards. This occurrence was accompanied by a faintly whining sound. As mentioned above, the temperature in this locality measured only 98°C on September 5, 1975.

POSSIBLE EXPLANATION OF THE THERMAL ANOMALY IN SURTSEY

HEAT IN THE TEPHRA.

During the initial phase of eruptions of the Surtsey type, which originate in sub-aquatic or sub-marine vents, certain amounts of pillow lava can be expected to form and pile up around the vents before the eruption becomes visible at the surface of the sea. When the initial phase is powerful, as it may be assumed to have been in the Surtsey eruption, the speed of uprush is so great that the sea can only cool a thin film around each layer of pillow lava before the next layer is deposited on top of it, preventing further cooling. When the pile of pillow lava has grown to a height of a few tens of metres short of the surface the water pressure diminishes so far as to allow steam from the contact between lava and water to escape to the surface. This steam, in turn, tears away bits of the lava and blows them up to the surface, where the water cools the lava so fast that it pulverizes into fine-grained glass. The glass powder sinks down again to be deposited on top of the pillow lava, isolating it from the water. If the eruption continues, this glass, called tephra, will be piled up on top of the pillow lava in a layer tens of meters in thickness. The tephra is at first saturated with water, but through contact with the hot pillow lava its lowermost strata are quickly heated up to the boiling point of water at that depth. As a result

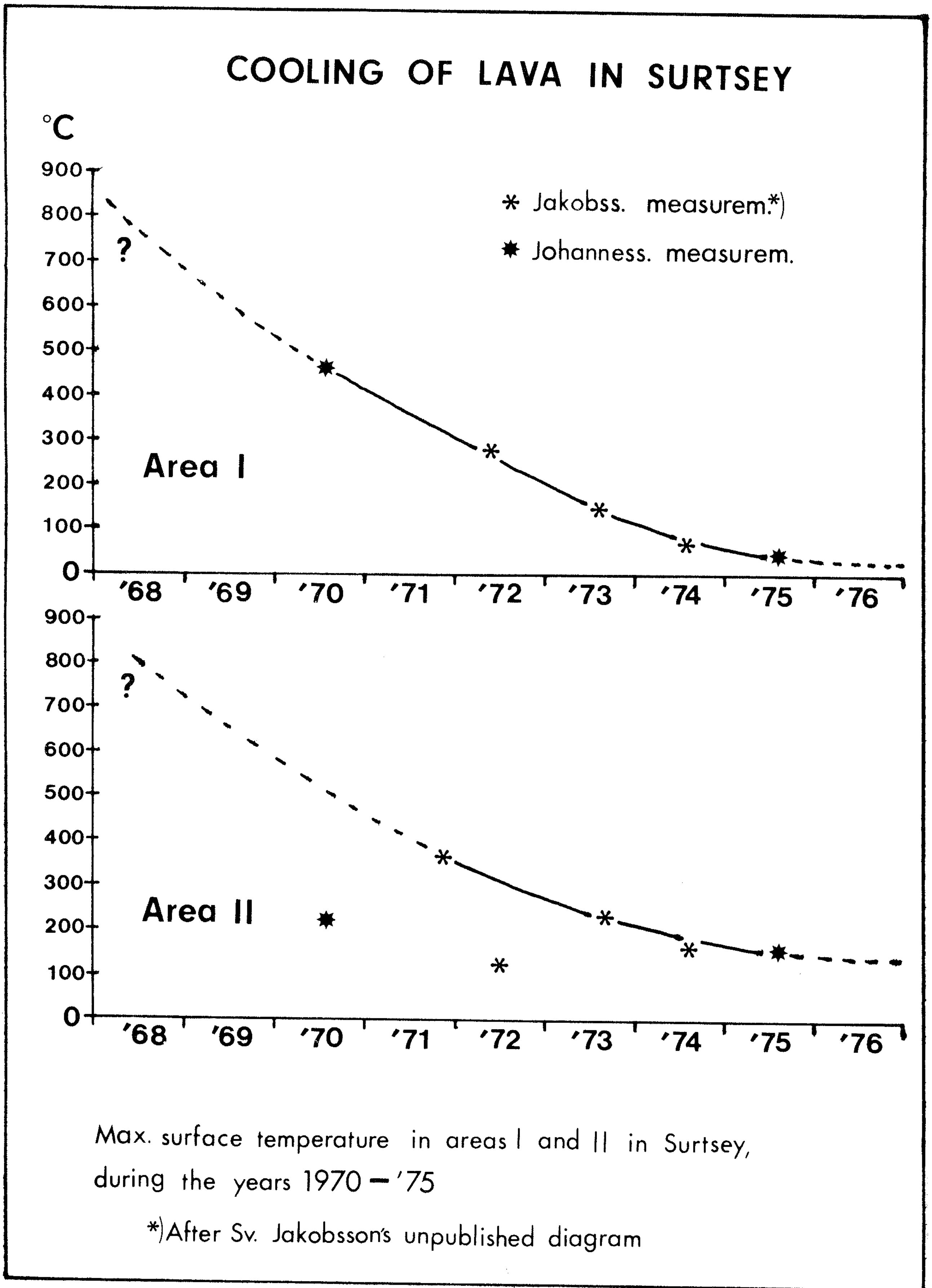

Fig. 2. Cooling of lava in Surtsey.

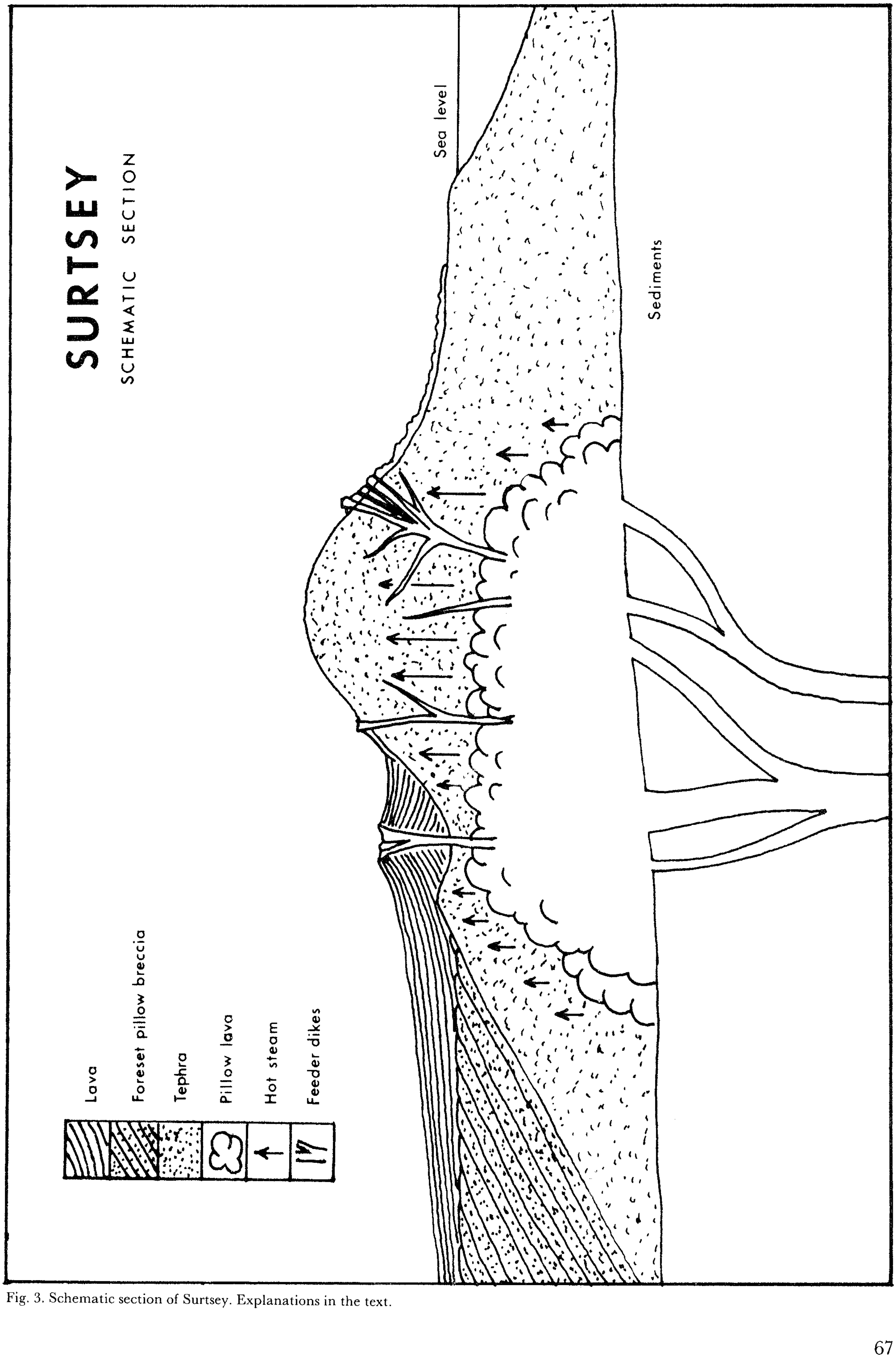

Fig. 3. Schematic section of Surtsey. Explanations in the text.

the water-content is distilled out of the lowermost layers and the steam presses its way upwards through the tephra pile. As the tephra gets drier its isolation increases and the uprush of heat from the pillow lava through the tephra pile slows down. The boiling point isotherm in the tephra pile gradually moves farther from the heat source until equilibrium is obtained through surface cooling of the tephra at a boiling point of water at that particular depth. Outside this area the temperature keeps below the boiling point of water and the tephra remains saturated with water, whereas farther down the tephra is dry and the temperature at, or above, the boiling point. In an eruption of long duration the tephra piles up far above sea level, and the thickness of the pile may amount to hundreds of metres. For some years the equilibrium area will expand outwards and upwards through the tephra pile and where 100°C steam passes through the cooler layers of tephra it must heat it up before it can eventually be detected at the surface. This may take a few years, as has been the case in Surtsey. The first detectable increase in temperature can be expected in areas where the tephra cover on the pillow lava is thinnest. From there the outflow will gradually expand in all directions.

This idea assumes a mean temperature of 600—900°C in the pillow lava during the initial phase of phreatic activity. The estimate is, admittedly, uncertain, but probably not far from the mark, at least not in Surtsey. It seems probable that in an eruption of the Surtsey type minor intrusions will be formed within the pile of pillow lava. These intrusions increase the main temperature in the pile. Minor eruptions occurring outside the tephra crater of Surtur II in late December 1966 and early January 1967 probably derived from such intrusions beneath the tephra ring, so that the material erupted may have been "reactivated" magma from the first weeks of the Surtsey eruption. This might possibly be tested by chemical analysis.

The volume of pillow lava in Surtsey is roughly estimated about 0,1 km^3. Thermal energy of 0,1 km^3 of pillow lava at 600—900°C would be sufficient to heat all the tephra deposited above sea level in Surtsey up to 100°C. There may be some additional thermal processes in the tephra caused by oxidation of iron, although this would be of minor consequence compared with the heat from the pillow lava.

It seems, therefore, safe to conclude, that the thermal areas in Surtsey will continue to expand, changing most of the tephra to móberg before the sea can break it down. The future of the island seems therefore to be comparatively secure as far as destruction by the sea is concerned.

HEAT IN THE LAVA.

As mentioned above, the temperature in the lava is at all stations lower than in 1970. The decrease has, however, been least in the area around Surtur II. The lava layer is thicker there than elsewhere on the island, and will therefore take longer time to cool. In areas where hot air blows out of the lava, this seems to be fresh, atmospheric air, heated by the passing through the lava. Probably this air has entered cracks further down and, when heated, has forced its way up through crevices, helped by its lower weight, as up a chimney, finding outlets at the top of the pile. All these areas have cooled down considerably during the last years, most of them appear to be approaching complete cooling. This is in harmony with the above explanation.

In the hot areas at Surtur II fairly high temperatures still prevail, but will presumably decrease slowly in the coming years. It may take a number of years, or even some decades, before the state is reached when the thermal anomaly has completely disappeared.

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