SURTSEY RESEARCH PROGRESS REPORT

VII

THE SURTSEY RESEARCH SOCIETY · REYKJAVÍK, 1974

SURTSEY RESEARCH PROGRESS REPORT

VII

PRIMARILY 1971 AND 1972 FIELD SEASONS

THE SURTSEY RESEARCH SOCIETY
REYKJAVIK, 1974

PRINTED BY SETBERG · REYKJAVIK · ICELAND

Index

Introduction

The volcanic island, Surtsey, approximately 20 miles off the south coast of Iceland, is a reality. It will remain so for centuries to come. The island is unique as the most recent addition to Iceland. It is even more unique for the fact that it has from its birth been strictly protected as a nature reserve. Extensive scientific studies started as soon as the island was formed.

The Surtsey Research Society was formed shortly after the beginning of the Surtsey eruptions in November 1963. It is a private non-profit scientific society. Members are Icelandic scientists and, as associate members, scientists from various foreign countries, who have taken interest in the development of Surtsey. The objective of the Society is to strengthen the scientific work on Surtsey.

The research work on Surtsey was to begin with primarily concentrated in the geosciences. Gradually the work has shifted more towards the field of biology, but with continued observations of the geological and geomorphological processes. The overall development of Surtsey has slowed down. Although the island is still subject to changes, the process is now more evolutionary than before. The same is true with respect to its biological development. Life has established itself on the island and on its socle, but the process is in many respects slower now than it was at its beginning. In several fields of science it has therefore not been found necessary any longer to undertake yearly investigations.

The Surtsey Research Society has published progress reports on the scientific work on Surtsey from the time it began. This report is the 7th in that series. In charge of this publication has been an editing committee consisting of the following scientists:

Aðalsteinn Sigurðsson, marine biologist
Eythór Einarsson, botanist
Sveinn Jakobsson, geologist

The report covers work done on Surtsey since the publication of the last report in April 1972. It is hoped that it will be found a valuable addition to the series.

The scientific work on Surtsey has been supported from several sources. The Icelandic government, research institutions, the Icelandic Coast Guard and others in this country have given support, either with financial appropriations, scientific personnel, facilities or transportation. Financial support has also been received from foreign agencies, especially the U.S. Atomic Energy Commission and the Max-Planck Gesellschaft. This is highly appreciated. It should though also be stressed that the scientific work on Surtsey would not have been possible without the unselfish work of several scientists from Iceland and from abroad and the excellent cooperation that exists between them.

It can be said that the scientific work on Surtsey has slowed down. This may be considered natural, as previously mentioned. It is though extremely important that the observations be continued on a long term basis. Hopefully this will be possible. The opportunity is unique. There is no doubt that through studies of Surtsey, important steps may be taken for better understanding of our environment.

On behalf of the Surtsey Research Society,

Steingrímur Hermannsson
Chairman

BIOLOGY

Lichen Colonization in Surtsey 1971–1973

By
HÖRDUR KRISTINSSON,
Náttúrugripasafnið á Akureyri, Akureyri, Iceland

Lichens were first detected on Surtsey in the summer of 1970, when three species were found on the island, *Trapelia coarcata, Placopsis gelida,* and *Stereocaulon vesuvianum* (H. Kristinsson 1972). The present article deals with the results of three visits to Surtsey, in June 1971, July 1972 and in August 1973, when 2–3 days were spent there each year.

METHODS

Different habitats were searched for initial stages of lichens throughout the island by the aid of hand lens. Samples were collected of all species detected in the field. Final indentification was carried out in the laboratory by microscope and comparison with known samples from the mainland of Iceland, whenever such were available. In certain cases chemical analysis by thin layer chromatography was used to verify the identification. These methods have been described in detail by C. F. Culberson & H. Kristinsson (1970). All species found in Surtsey were numbered for convenience, so that even unidentified species could be referred to in this and eventually in subsequent papers.

The distribution of lichens in Surtsey was recorded by the aid of the local grid system of 100x100 m squares, already used for the distribution of vascular plants and mosses (S. Friðriksson et al. 1972). All squares were visited at least once, and the more common lichens were noted in the field, but all others collected for later identification.

LIST OF SPECIES

1. Trapelia coarctata (Sm. & Sow.) Choisy (Fig. 1A). First found in Surtsey in 1970 on the north facing rocky slope on the outside of the crater Surtur II. It is widely distributed around the craters Surtur II and Surtur I, and also found in the lava field south of Surtur II, where steam emission is still efficient, but nowhere else (distribution map, fig. 3). Under such conditions its growth rate is very rapid.

Trapelia coarctata forms in Surtsey light brown to whitish thallus of several cm in diameter. Apothecia are always present in great number, formed below the thallus surface, and braking through the cortex as they get mature. The apothecia are dark brown, 0.3-0.5 mm across, without exciple, but bordered by the ruptured cortex, until they get old. Epithecium and hypothecium brown, the hymenium 120-160 μ, the ascospores 12-20x7-11μ, colorless, subglobose to ellipsoid.

2. Placopsis gelida (L.) Linds. was first seen in 1970 in the same locality and habitat as *Trapelia coarctata.* Next year it was found in several localities in the most recent lava flow, which was formed in 1967. In contrast to *Trapelia coarctata* this species is now distributed throughout most of the lava flows independent of the steam emissions.

In the first stages of this lichen, scattered, white thalli are found distributed like dots through a patch of 2-10 cm² size (Fig. 1F). Their growth advances relatively fast, and soon small cephalodia are seen at the margin of many of the thallus dots. Through subsequent growth the thallus pieces finally coalesce and cover the rock surface to form an almost coherent thallus of the same diameter as the orginal patch (Fig. 1B). In that stage the thallus has lobed margin and is dotted with many, brown cephalodia. The largest thallus measured had a diameter of 6 cm. Soredia are soon formed in round soralia on the thallus surface, but no apothecia have been seen in Surtsey, and they are not frequent in Iceland either.

3. Stereocaulon vesuvianum Pers. appeared first on the lava fields north and northeast of Surtur II and in the northern outside slope of the same crater in 1970, both habitats influenced by warm steam. In the next year (1971) it was seen at several localities in the lava flows from 1967, where it now has a wide distribution independent of the steam holes. Its distribution extends now also to the lava of 1965 (Fig. 3), but it is still lacking in some parts of it.

Stereocaulon vesuvianum appears first as small, rounded warts (phyllocladia) scattered throughout the surface of the lava, either growing single out of small air bubbles, or frequently concentrated along delicate surface cracks of the rock. For that reason it grows frequently in long and narrow lines (Fig. 1D). The phyllocladia are not grouped into round plots, like is the case with *Placopsis gelida* and *Stereocaulon capitellatum* (Fig. 1E). As the growth advances, a dark, depressed spot appears in the center of the phyllocladia, a characteristic feature of the phyllocladia of *S. vesuvianum*. In general the development of this species is in Surtsey still at the stage of single phyllocladia. The growth is very slow, only at a few favorable sites had it in 1973 already formed about 4 mm long, erect pseudopodetia with many phyllocladia (Fig. 1C). Neither soredia nor apothecia were seen. Even cephalodia have not been noticed in the Surtsey specimens, but in Iceland the species generally bears cephalodia with either *Nostoc* or *Stigonema* as parasympiont, occasionally both occurring on the same plant.

4. Stereocaulon capitellatum Magn. In 1971 small, more or less erect, light grey lichen lobes were found in different places of the lava field of 1967. The single lobes were 1-2 mm in diameter but growing scattered in patches of 1-3 cm diameter. (Fig. 1E). The lobes were partly with recurved margins, on which the underside or the margin broke up to form soredia. Thin layer chromatography of such lobes showed that they produced the same combination of compounds as found in *Stereocaulon capitellatum* and *S. farinaceum* (lobaric acid, anziaic acid and perlatolic acid). In 1972 and 1973 the recurved lobes started erect growth at favorable sites, to form pseudopodetia with spherical soredial heads, typical morphological feature of these same species. At the same time cephalodia with Nostoc were found interspersed between the pseudopodetia of well developed specimens. At present this species has almost as wide distribution in the lava fields as *S. vesuvianum* and *Placopsis gelida*. It is not obvious to which of the two species these young plants belong, but the substrate would rather indicate *S. capitellatum*, since *S. farinaceum* generally grows on soil.

5. Lepraria incana (L.) Ach. *(L. aeruginosa* (Sm.) Wigg.) In the summer of 1971 attention was paid to light green patches interspersed with dark green algal coats on overhanging rocks and cave mouths throughout the lava fields. The light green thallus consists of one-celled green alga of *Trebouxia* type, enveloped by fungal hyphae. The surface of the thallus is at first crustose, granulose-verruculose, but soon the total surface breaks out into soredia. Apothecia are never produced on this thallus.

Lepraria incana is very common in Iceland on overhanging rocks or soil banks and in cave mouths, and was by some earlier authors called *Lepraria latebrarum*.

6. Acarospora. In one sample collected on the north slope of Surtur II in 1971 there were some sterile thallus lobes, which on better samples from 1972 could be identified as *Acarospora*. In 1973 this same species was found in several other localities. It is fairly frequent on the margin top of Surtur II and in the slope below the top, and it also occurs on bird-manured lava outcrops.

The thallus consists of small squamules, about 1 or maximal 2 mm across, pale grey-brown to straw-colored, single or more often crowded together, each with the lobe margin slightly recurved. On older squamules there are one to several, brown, immersed apothecia. In section the hymenium measures 120-150 μ, the ascospores are many hundreds per ascus, 2.5-3x1.2 μ. This species has not been identified yet, but could well be either *A. fuscata* or *A. smaragdula*. The specimens are still too small to obtain distinct chemical reactions indispensible for their identification.

7. Bacidia. One species of *Bacidia* was found 1972 in the western outside margin of Surtur II, growing among *Trapelia coarctata* and *Acarospora* 6. Only small sample was available of this species, and it has not been finally identified (fig. 2A). The thallus is areolate-verrucose, light-colored, pycnidia abundant, apothecia dark

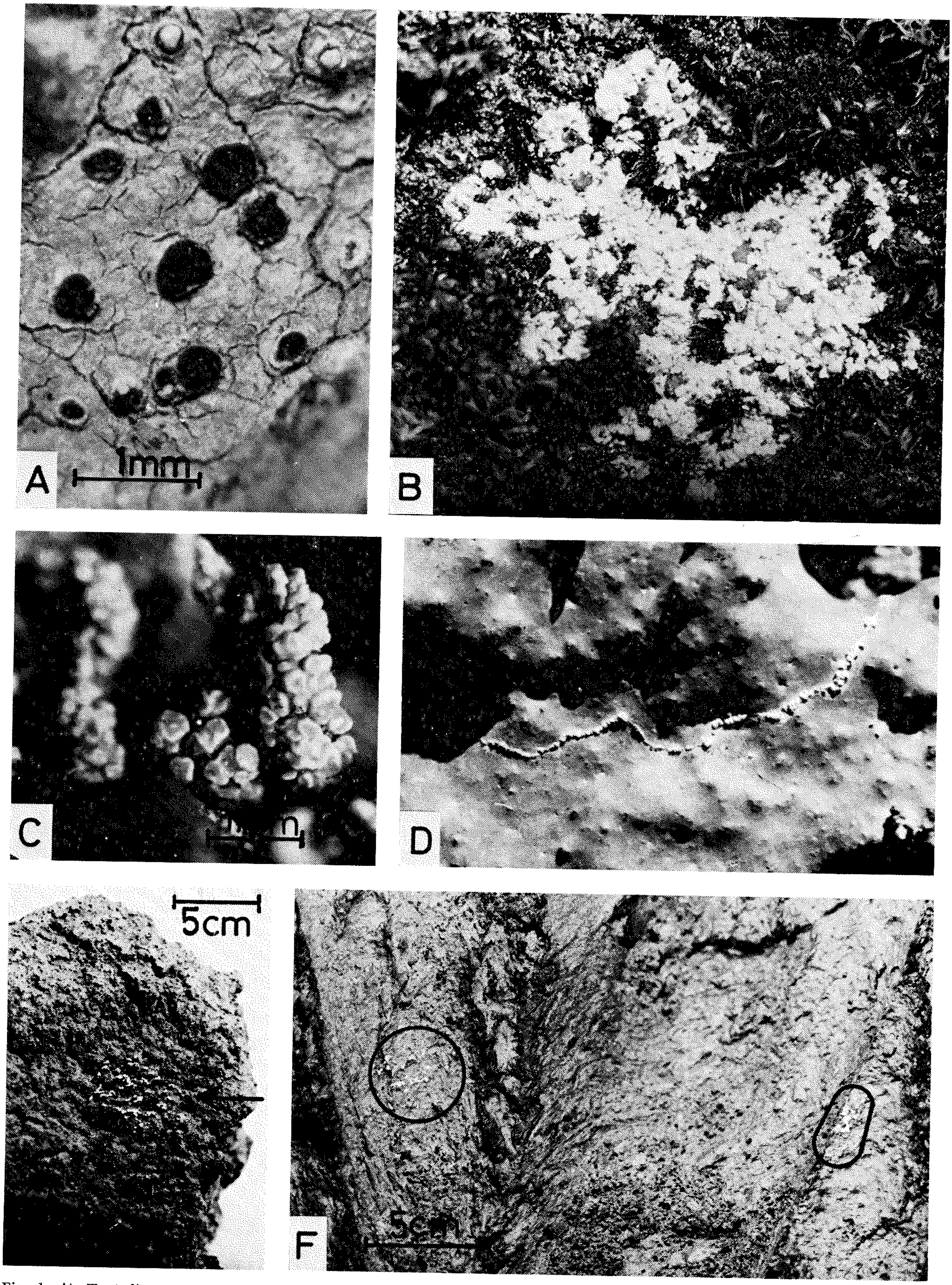


Fig. 1. A) *Trapelia coarctata* from Surtsey 1972. Thallus with apothecia. B) *Placopsis gelida,* a specimen collected in Surtsey in 1972 in a sheltered habitat in the Aa-lava from 1967. C) *Stereocaulon vesuvianum,* pseudopodetia from a sheltered habitat in the Aa-lava from 1967 (1973). D) *Stereocaulon vesuvianum* growing along a crack in lava block (1972). E) A circular plot of *Stereocaulon capitellatum* on lava block. No thallus lobes are found outside the plot (1973). F) Two plots of *Placopsis gelida* (encircled), separated by a distance of 20 cm devoid of any thallus lobes (1973).

brown to blackish, short stalked, concave. The hymenium measures 50-60μ, colorless, the epithecium brown, the hypothecium colorless, paraphysae simple, with brown head at top, the spores hyaline, 4-celled, 20-30μ long.

8. Lecidea. At the same locality as *Bacida* 7, a species of *Lecidea* was also collected in 1972 (fig. 2B). The thallus is thin, light colored, slightly areolate, the apothecia sessile, black, first concave, then plane, with elevated margin. The hymenium measures 100-120μ, colorless, the epithecum is dark brown to black, the hypothecium dark brown, the excipulum blackish near the outside, the ascospores colorless, one-celled, 12-15x7-9μ.

9. Lecidea. Another species of *Lecidea* was detected in a sample from the western slope of Surtur II collected in 1972. The thallus is sorediate, ochraceous, the soralia are erumpent, blue-grey, round and clearly delimited, about 0.1-0.3 mm across. No apothecia vere present. An identification must await for better samples, and better knowledge of the Icelandic species of the genus *Lecidea,* than we now have.

10. Xanthoria candelaria (L.) Th. Fr. This species was seen in one locality both in 1972 and 1973. Several plants were found in an area of 1-2m² around a spot where an artificial plastic pool had been set up as a trap for fresh water organisms (Maguire 1968). This species is foliose, but the thallus lobes are narrow and more or less erect, of bright orange-yellow color. It is very common throughout Iceland on places where birds rest, on top of boulders, rock outcrops and fence posts.

11. Arthonia. A specimen provisionally referred to the genus *Arthonia* was collected in 1973 on exposed rock around a lava peak in the lava flow from 1967. *Acarospora* was found on the top of this same outcrop, but the rock below the top was overgrown with *Arthonia.* Besides growing directly on rock, its thallus also extends over hardened accumulations of volcanic ash in the air bubbles on the rock surface. The thallus is very thin, hardly visible, the apothecia are black, tiny, 0.05-0.2 mm in diameter, plane to slightly convex. The hymenium is 40-50μ high, the epithecium greenish black, the hypothecium 8-11x 4μ, inequal twocelled. These specimens belong probably to *A. lapidicola* (Tayl.) Zahlbr., but the identification needs to be checked.

12. Lecanora. A fertile specimen belonging to the genus *Lecanora* was collected in 1973 by Skúli Magnússon, growing on bone and dead straw. The specimen has not been identified, but probably belongs into the relationship of *L. varia* and *L. conizaeoides.*

HABITATS

The lichens presently known from Surtsey grow in four different habitats:

1. Rock affected by warm steam. This habitat is found all around the craters Surtur I and II. The steam emanates from small holes which open out through the elevated crater margin or in the surrounding lava field. The condensation water from the steam keeps the surrounding lava surface wet. The steam is blown by the wind, so that some areas are only periodically exposed to the steam, but others seem to be constantly moistened by steam from the surrounding steam holes at any wind direction.

The steady supply of water provided by the steam is of primary significance to the lichen growth in this habitat. Even though lichens in general can survive long periods without water, they stop growth as soon as they get dry, because they are unable to maintain water in the thallus at dry air conditions. The speed of growth is therefore directly related to the length of time they are kept moist.

The raised temperature caused by the steam is probably only of secondary importance. At a certain distance from the hole lichen growth may possibly be promoted by the raised temperature, but around the opening their development is prevented by the heat.

The most successful colonizer of these steam habitats is *Trapelia coarctata,* which apparently grows and distributes very rapidly under these conditions. It has not been found in any other habitats in Surtsey. When originally found in 1970, it had already thousands of mature apothecia, so that local dissemination probably had taken place for some time in Surtsey. Some indications were seen for distribution by rain water running down the slope.

Another member of this community is *Placopsis gelida,* which developes well under these conditions, but is not dependent on the steam water.

Bacidia 7, *Lecidea* 8, and *Lecidea* 9, all only found in one sample, were collected in this same habitat. Other lichens, like *Stereocaulon vesuvianum* and *Acarospora,* which actually belong to other habitats, as will be pointed out later,

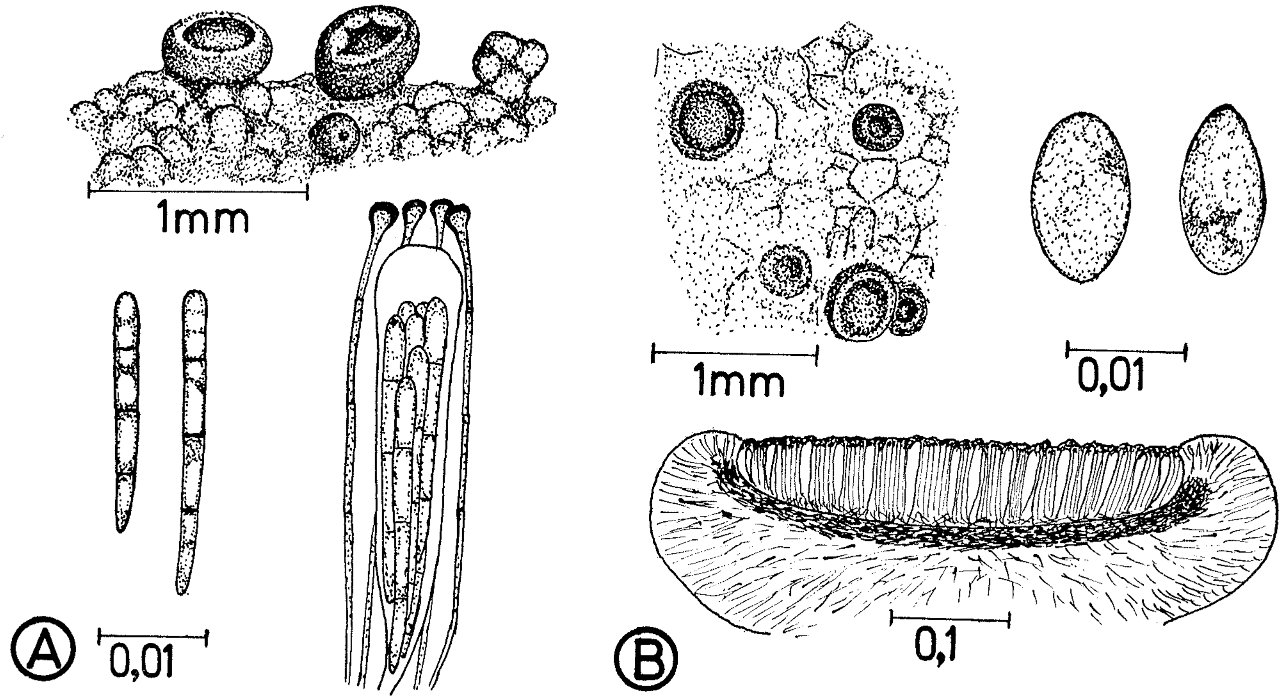


Fig. 2. A) *Bacidia* 7, a portion of thallus with apothecia and a pycnidium; ascospores, paraphysae and an ascus. B) *Lecidea* 8, thallus with apothecia, ascospores, and a section through an apothecium.

were also first found at the crater margin, simply because their growth was faster here than elsewhere.

2. Bird manured rocks. There are numerous lava outcrops in Surtsey frequently visited by birds, which both can act as dispersal agents and also as providers of nitrogen. Most of these outcrops, however, are still devoid of vegetation, primarily because water is too scarce. The first colonizer of these habitats in Surtsey is *Acarospora* 6. It is found in several localities on lava peaks and on the margin tops of Surtur I and Surtur II. It developes faster where it is subjected to the moisture of a warm steam. It is presumed, that the extreme dryness of most exposed lava peaks is probably the reason why the development of this community advances slowly and only in relatively few places.

Other colonizer of a similar habitat is *Xanthoria candelaria* which only occurred in one locality, around a plastic fresh water basin, which was set up 1967 and later removed again. This is a species, which in Iceland generally grows on bird manured outcrops like the *Acarospora*. In Surtsey, however, it either did not happen to be carried to such places, or they are too dry for it. The fresh water basin acted as an attraction for seabirds, and this was stationed on a less exposed spot than most of the bird manured lava peaks, and therefore offering better water conditions. The propagules of *Xanthoria candelaria* were probably brought in by birds, which washed them off in the water, and then splashed them around. This idea is supported by the single occurrence at this one locality, and by its frequency within the splashing distance from the water basin.

3. Overhanging rock walls and caves. Only one lichen species, *Lepraria incana,* is found in this type of habitat, which is charcterized by its shade, and moist, stagnant air. Besides the lichen, a species of green alga of *Chlorococcus* type is also widely distributed in this same habitat.

4. The lava fields. The dry rock surface of the lava fields represents the most widely distributed habitat of all, but it raises higher demands to the water deficiency tolerance of its inhabitants, than habitat 1 and 3. Consequently the growth in this habitant is generally slow, and there is a marked difference between the exposed lava peaks, which quickly dry out, and the deeper depressions and hollows, where the moisture is longer preserved. The water supply is evidently the factor, that limites the speed of growth here. The initial development of this vegetation starts in small air bubbles on the rock surface; these serve to accumulate diaspores and dust brought by the wind, as well as to reduce the drying effects of the wind and preserve the moisture longer than is possible on the smooth rock surface. Small cracks or fissures on the rock surface also serve similar purpose.

These dry lava fields are colonized chiefly by three species of lichens: *Stereocaulon vesuvianum, S. capitellatum* and *Placopsis gelida*. Several mosses belong to the same community, mainly *Rhacomitrium lanuginosum* and *R. canesens*. Especially *Placopsis gelida* grows much more rapidly in the depressions, and the same applies to *Rhacomitrium*. *Stereocaulon vesuvianum* seems to have the highest tolerance for water deficiency, it is a slow growing species, and relatively indifferent to the position of its habitat.

EARLY STAGES IN LICHENIZATION

Some facts about the early stages in development of *Placopsis gelida* and *Stereocaulon capitellatum* are worth special consideration, since they can serve as a basis for experimental work on the reproduction of these lichens. The new lava fields offer good opportunities to study the individual development of the young lichen thalli, because the presence of older thalli can be completely eliminated.

Both *Placopsis gelida* and *Stereocaulon capitellatum* start growth as single lobes in each of many adjacent, tiny surface cavities, formed as air bubbles in the molten lava. In the surface cavities outside these lobe groups no lichenization is found, but other lichenized plots are usually present at some distance (Fig. 1E,F). It is inconceivable, that the propagules arriving from the mainland, whether soredia or ascospores, would only settle in such regular, round plots, leaving the extensive spaces in between uncolonized. On the contrary, they would rather be expected to distribute more or less at random throughout the whole rock surface. In fact the colonized plots themselves seem to be distributed at random and not the single lobes.

This supports the conclusion, that the whole plot of adjacent lobes must derive from one diaspore, and that the lichen fungus must be able to reach the adjacent air bubbles through hyphal growth from its original center, either before or soon after the first lichenization starts.

Later on the single lobules of *Placopsis gelida* coalesce through growth and the colonized plot becomes what appears to be single lichen thallus, of as much as 4-5 cm diameter in only 5 years (Fig. 1B), containing several cephalodia.

Further observations and experimental work are needed to decide on the number and nature of propagules which initiate a plot of the type described above.

The development of *Stereocaulon vesuvianum* differs from the species mentioned above. It appears to grow out from every suitable cavity or surface crack in the area colonized, not forming round plots.

DISTRIBUTION

During my first search for lichens in the lava fields of Surtsey (1968, 1970), primary attention was paid to the oldest lava from 1965, since vegetation development was expected to start there. Nevertheless, the colonization of lichens and mosses started in the new lava flow from the last effusive phase of the eruption in 1967. In 1971 both the *Stereocaulon, Placopsis* and *Rhacomitrium* were widely distributed there, but could hardly anywhere be encountered in the lava from 1965. Still in 1973 the vegetation of this lava was extremely scarce, and large areas of it were completely devoid of vegetation.

In an effort to find the explanation of this difference, it was noticed, that the surface structure in certain parts of the new lava (the Aa lava) is more porous than the old lava, which probably means improved water retaining capacity. The colonization is much further advanced than in the older lava of 1965. Consequently the surface structure can not explain the more advanced colonization there.

The presence of a trace of some toxic substances has also been suggested as possible reason, but no support for that hypothesis has been obtained from chemical analysis made by the geologists.

Another and perhaps a more satisfying explanation of the different success in colonization of the old and the new lava suggests that the retarded growth in the old lava is due to lack of water, caused by heat emission, which dries out the rock surface more quickly than in the new lava, where apparently no heat emission occurs. Although not perceptible in the field during summer, this heat emission has been demonstrated by air photos taken in the winter. While thin snow layer covered the lava from 1967, large parts of the old lava remained free of snow.

No lichens at all have been found anywhere in the northern part of the island, neither along the shore nor in the palagonite area.

CONCLUSIONS REGARDING LICHEN DISPERSAL TO SURTSEY

There are no direct observations available on how the 12 lichen species dispersed to Surtsey. Without success lichen propagules were searched for on the feet and plumage of birds caught in

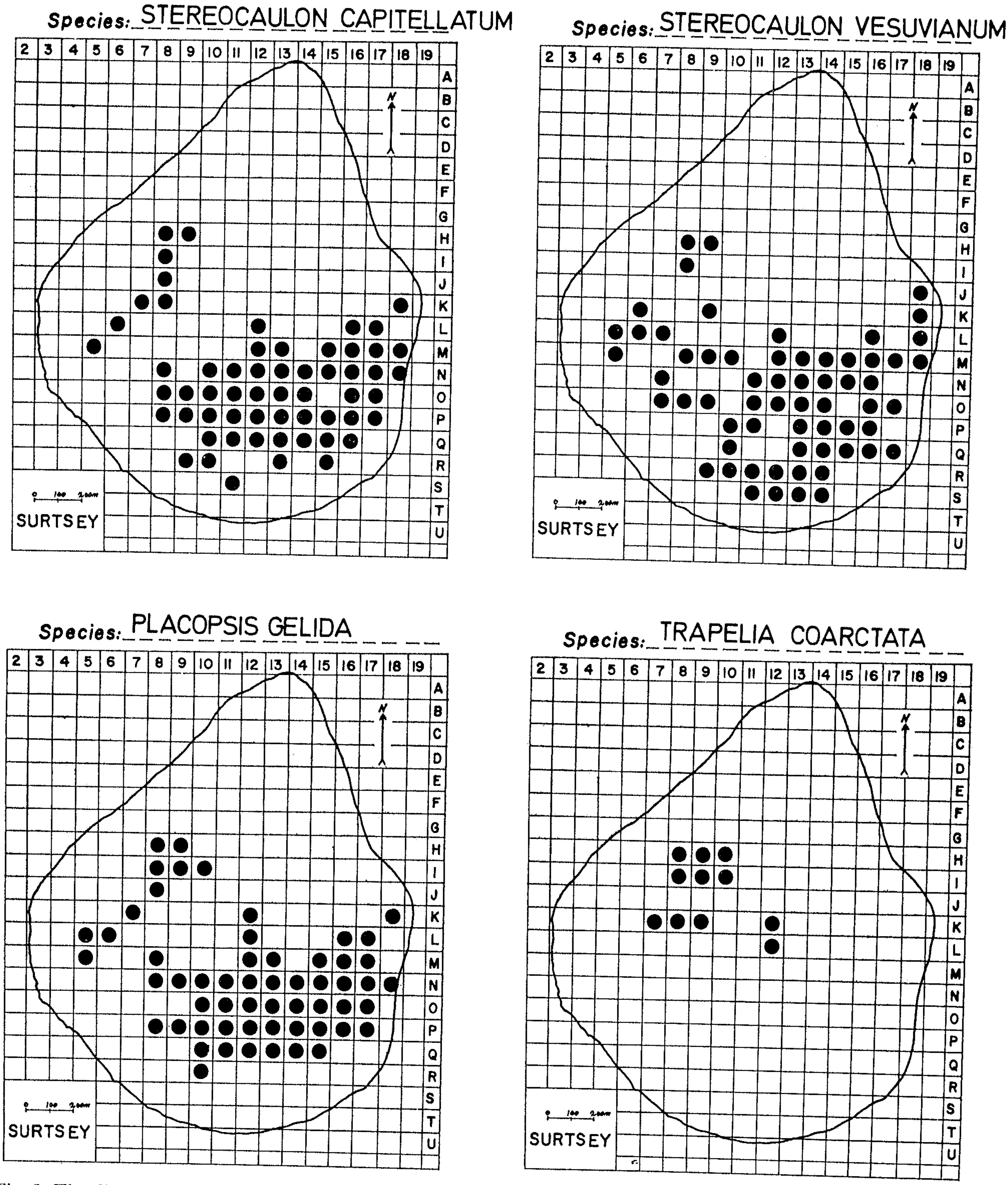


Fig. 3. The distribution of *Stereocaulon capitellatum*, *S. vesuvianum*, *Placopsis gelida* and *Trapelia coarctata* in Surtsey in 1973.

Surtsey and made available through Dr. Sturla Friðriksson in 1969 and 1970. Some other plant material was, however, found like green and blue-green algae, moss parts, fern sporangia, and tissue fragments of vascular plants. It would have been of interest to have samples taken of the air plankton around Surtsey, to investigate its content of lichen and moss diaspores, but no attempts have been made in that direction.

Through indirect observations it seems reasonable to conclude, that at least 4 species *(Stereocaulon vesuvianum, S. capitellatum, Placopsis gelida* and *Lepraria)* were dispersed to Surtsey by wind, and that one species *(Xanthoria candelaria)* was born there by birds. For the 7 species left, no conclusion has been drawn.

The four species supposed to have come by wind, were all evenly distributed throughout the island, wherever the appropriate conditions for their growth were present, before any local dissemination could be accomplished. No dispersal agents other than the wind could possibly ensure for such and even distribution into every small corner in the lava fields in these few years. All of these four species do form soredia which can be air born, and simultaneously carry the green algal component and the fungus. Three of the species have cephalodia with blue green algae *(Nostoc)* and these appear later than the mycobiont and the green algal symbiont. I presume, that they distribute separately by wind and are captured by the fungus. Free *Nostoc* colonies have been isolated from the lava fields of Surtsey (Schwabe, personal communication) so we know that they do easily reach the island. We do however not know for sure, whether free living *Nostoc* cells can be captured by the fungus to form cephalodia in *Stereocaulon* and *Placopsis,* as is know for several other lichens, or whether some special physiological adaptation is needed for the life in the cephalodia. Three of the four species do form ascospores in Iceland, but sparcely compared to the soredia.

Xanthoria candelaria, which is supposed to have been dispersed by birds, was until 1973 only found in one locality, but many plants were within 1,5 meter distance from the spot, where one of the fresh water basin was stationed few years before. It probably was born by birds into the basin, then washed off in the water and splashed around.

This species does sometimes form ascospores in Iceland, but distribution by air born ascospores to Surtsey would hardly result in several plants in a plot of ca 2 m^2 size, with all other parts of the island uncolonized. Soredia are not formed by *X. candelaria,* but the finely branched, erect lobes do very easily fragment, and have a suitable shape to get attached to birds. The probability of being carried by birds increases through its habitat, since it is coprophil and specializes in the resting places of birds.

Of the seven species about which no conclusion was made concerning their transport to Surtsey, six appear to reproduce by ascospores, and one, *Lecidea* 9, by soredia. Most of them were first found on the elevated crater margin of Surtur II. They could easily be air born, and the reason that they first appear at this locality may be simply because the conditions for their growth are best there, due to the condensation water from the steam emissions. If that is the case, they would be expected to turn up in other places later. Consequently we do not need birds to explain their presence there. Because of the tremendous transport and dispersal capacity of the wind, the role of birds is in my opinion negligible for species with effective wind dispersal. Only in cases, where wind distribution fails for some reason, occasional bird transport becomes important. On the other hand, the crater margin of Surtur II projects several meters above its surrounding and is frequently visited by birds.

ACKNOWLEDGEMENTS

These studies have been financed by the Surtsey Research Society, Reykjavík. I thank Dr. H. Hertel, Botanische Staatssammlung, München, and Dr. P. W. James, British Museum, for their valuable efforts to identify specimens from Surtsey.

References

Culberson, Chicita F. & Hörður Kristinsson. 1970. A standardized Method for the Identification of Lichen Products. Jour. Chromatog. 46: 85-93.

Fridriksson, Sturla, Ágúst H. Bjarnason and Bjartmar Sveinbjörnsson. 1972. Vascular Plants in Surtsey 1969. Surtsey Research Progress Report 6: 30-33.

Kristinsson, Hördur. 1972. Studies on Lichen Colonization in Surtsey 1970. Surtsey Research Progress Report 6: 77.

Maguire, Bassett. 1968. The Early Development of Freshwater Biota on Surtsey. Surtsey Research Progress Report 4: 83-88.

On the Terrestrial Microfauna of Surtsey during the Summer 1972

By

OLOF HOLMBERG and BIRGER PEJLER

Zoological Institute, University of Uppsala, Sweden.

INTRODUCTION

During the expedition to Surtsey in July 1972, led by Prof. C. H. Lindroth, material for microbiological investigations was collected and brought to the Institute of Plant Physiology in Uppsala by Drs. Elisabet and L. E. Henriksson. By their generosity the cultures could also be used for the study of microfauna. Some of our material was kindly sent to us from Dr. G. H. Schwabe and derives from his cultures reared at the Max-Planck-Institute in Plön, Germany. Samples containing nematodes were sent to Dr. B. Sohlenius, Stockholm.

DESCRIPTION OF THE LOCALITIES

The material cultured at Uppsala was collected at 21 separate localities, which are described in more detail and marked on a map by Henriksson and Henriksson (1974 and 1975). Only the 7 localities where microscopic animals were found are dealt with below. In addition, microzoa were studied in cultures from two of Dr. Schwabe's localities, viz. 428 and 476.

All these localities inhabited by microzoa are situated above the highest water level close to steam exhalations. Locality 1 is situated in the passage between the tephra cones of Surtur I and Surtur II, 476, on the eastern slope of „New Year Crater“ (Strompur), 12 and 428, immediately S of the head crater of Surtur I, 2, 3 and 4 in the crater area of Surtur II. Locality 15 lies just outside "the Bell" (see Holmberg and Pejler 1972)

The localities were subjectively chosen, mostly because mosses were seen. That part of the island covered by visible, though minute, vegetation is very small (much less than 1‰). If a corresponding number of localities had been selected at random probably no microscopic animals would have been found.

METHODS

The methods of sampling and cultivation were the same as in the previous years. The reader is referred to Behre and Schwabe (1970) concerning the laboratory work in Plön and to Henriksson, Henriksson and Pejler (1972) and Holmberg and Pejler (1972) concerning that in Uppsala.

TABLE 1.
OCCURRENCE OF THE FORMS IN THE DIFFERENT LOCALITIES DURING 1972.

	Locality								
	1	2	3	4	10	12	15	428	476
RHIZOPODA, AMOEBIDA									
Vahlkampfia sp.	..	..	×	..	×	..	×	..	..
Hartmanella sp.	..	..	×	..	..	..	×	..	..
Vanella sp.	..	..	..	..	×	..	..	..	..
Mayorella sp.	×	..	×	×	..	..	..	..	..
("*Astramoeba* sp.")	..	..	..	×	..	×	..	..	..
Thecamoeba sp.	×	×	..	..	..	×	..	×	×
Thecamoeba terricola Greeff	..	×	..	..	..	..	..	..	..
RHIZOPODA, TESTACEA									
Corythion dubium Taranek	..	..	..	..	..	..	..	×	..
ROTATORIA, BDELLOIDEA									
Philodina acuticornis odiosa Cohn	..	×	×	..	..	..	..	×	..
Habrotrocha constricta Dujardin — *elusa vegeta* Milne	..	..	..	..	..	..	..	×	..

COMMENTS ON THE DETERMINATION OF THE RHIZOPODS

As the investigation of the rhizopods did not imply the rearing of clones from the material or any other more advanced technique, the naked amoebae could mostly be determined only to their generic level.

No procedure in order to encourage the development of flagellate stages was undertaken, which can be the reason why the widespread *Naegleria gruberi* Schardinger is missing in the list of species.

In order to facilitate comparisons with the data from 1970, the genus *"Astramoeba"* is included, though it is shown to constitute merely a form which can appear in many groups of Amoebida under certain environmental conditions. Thus the name has no taxonomic validity, which is also the case for *"Dactylosphaerium"*, mentioned in the list from 1970.

The determinations were made according to Hoogenraad and de Groot (1940) and to several papers by F. C. Page, e. g. those included in the reference list.

TABLE 2.
COMPARISON OF FINDS FROM 1970 AND 1972.

	1970	1972
AMOEBIDA		
Vahlkampfia, "limax-type"	×	×
Vahlkampfia, "guttula-type"	×	×
Hartmanella sp.	×	×
Naegleria soli	×	..
Naegleria bistadialis	×	..
Trichamoeba sp.	×	..
Mayorella sp.	×	×
Mayorella vespertilio	×	..
"Dactylosphaerium sp."	×	..
"Astramoeba sp."	×	×
"Astramoeba stella"	×	..
Vanella sp.	..	×
Thecamoeba sp.	×	×
Thecamoeba striata	×	..
Thecamoeba terricola	..	×
Nuclearia sp.	×	..
TESTACEA		
Euglypha sp.	×	..
Corythion dubium	..	×
BDELLOIDEA		
Philodina acuticornis odiosa	×	×
Habrotrocha constricta — elusa vegeta	×	×

COMPOSITION OF THE FAUNA IN 1972

As will be evident from Tab. 2 the list from 1972 agrees as a whole with that from 1970 (see Holmberg and Pejler, 1972). E. g., both years exactly the same two rotifer taxa were found in the terrestrial localities. This ought to be regarded as a proof of the reliability of the methods and the material. It should be stressed that the material has been cultured in two separate laboratories (in Uppsala and Plön, respectively) on several different substrates. Furthermore, it has been collected during different years from a great number of different localities on the island. As there is still so much agreement, the conclusion also may be drawn that the results are really representative of the island at the present stage and that we have got a comprehension of the present microfauna which is about as good as possible in regard to the available methods and resources. However, the species enumerated should, of course, be considered a minimum, because our methods imply that animals which are difficult to culture or to distinguish will be missing.

As the number of forms has not increased noticeably between 1970 and 1972, it is evident that the developmental curve of the biocenose is still in the lag phase, which impression is strengthened by the study of other groups of terrestrial plants and animals (see other contributions in this volume).

As stated in 1970, the microfauna is composed of widespread and tolerant forms. As a complement it could be mentioned that one of the two rotifers encountered, viz. *Philodina acuticornis odiosa,* has recently been the object of experiments by Koehler (1967) and Koehler and Johnson (1969), whereby its remarkable resistance to diverse environmental stresses was strikingly shown.

As far as is known, all forms hitherto encountered feed on algae, bacteria and/or detritus, which means that no predator has been found, and the ecological pyramid should still be formed by only two trophic levels.

ABSTRACT

Samples of moss and algal vegetation from the island of Surtsey/Iceland were cultured in the same way as in 1970. The species encountered in these cultures are roughly the same as in those from previous years, indicating that the material is reliable and representative and, furthermore, that the biocenose still remains in the lag phase of its developmental curve.

References

Behre, K. and Schwabe, G. H. 1970: Auf Surtsey/Island im Sommer 1968 nachgewiesene nicht marine Algen. — Schr. Naturw. Ver. Schlesw.-Holst., Sonderband, pp 31-100.

Henriksson, L. E. and Henriksson, E. 1974: Studies on the nitrogen cycle of Surtsey in 1972. — Surtsey Res. Progr. Rep. 7, pp 36-44.

Henriksson, L. E. and Henriksson, E. 1975: Occurrence of fungi on the volcanic island of Surtsey, Iceland. — Acta Bot. Iceland. 3, pp 82-88.

Henriksson, E., Henriksson, L. E. and Pejler, B. 1972: Nitrogen fixation by blue-green algae on the island of Surtsey/Iceland. — Surtsey Res. Progr. Rep. 6, pp 66-68.

Holmberg, O. and Pejler, B. 1972: On the terrestrial microfauna of Surtsey during the summer 1970. — Ibid. 6, pp 69-72.

Hoogenraad, H. R. and de Groot, A. A. 1940. Zoetwaterrhizopoden en -heliozoen. *In:* Fauna van Nederland.

Koehler, J. K. 1967: Studies on the survival of the rotifer Philodina after freezing and thawing. — Cryobiology 3, pp 392-399.

Koehler, J. K. and Johnson, L. K. 1969: Food supply as a factor in the survival of frozen and thawed rotifers. — Ibid. 5, pp 375-378.

Page, F. C. 1967: Taxonomic criteria for Limax Amoebae with description of 3 new species of Hartmanella and 3 of Vahlkampfia. — J. Protozool. 14 (3), pp 499-521.

Page, F. C. 1968: Generic criteria for Flabellula, Rugipes and Hyalodiscus, with description of species. — Ibid. 15 (1), pp 9-26.

Page, F. C. 1971: A comparative study of five freshwater and marine species of Thecamoebida. — Trans. Amer. Microsc. Soc. 90 (2), pp 157-173.

Report on the Sampling of the Benthic Fauna of Surtsey 1970, 1971 and 1974

By
AÐALSTEINN SIGURÐSSON
Marine Research Institute
Reykjavík, Iceland

All the submarine sampling was carried out by SCUBA-divers, and both in 1970 and 1971 by the crew of m/s "Sæör" as in the previous years.

The sampling of littoral and sublittoral benthic fauna of Surtsey was carried out in the period July 21st to August 4th 1970 on nine traverses. Some quantitative samples were taken by placing a square iron frame on the bottom and collecting, as far as possible, all organisms within it.

Square frames 1x1 and 0.5x0.5 m divided into subsquares (10x10 cm) were also used to estimate the coverage of the animals on the seabed. The SCUBA-divers listed the organisms which could be spotted within the frame, and estimated how many subsquares were covered by each species. Several photographs were taken of the life on the seabed.

The identification of the material is still incomplete. Nevertheless, it is obvious that the sublittoral benthic fauna had increased as expected, but the littoral fauna was still negligible.

Attempts were made to mark large boulders on the seabed by buoys for comparison from one year to another. The buoys, however, had all disappeared the next summer. This was not unexpected as considerable transport of material, including large rocks, is known to take place at the coasts of Surtsey during the winter months. The material originates from the coastline of Surtsey broken down by surf during the winter storms. Obviously this exerts an unfavourable influence on the living conditions of the fauna.

In 1971 sampling was very difficult on account of bad weather. We were only able to work 3 traverses off the east-, south- and westcoast of Surtsey. No sampling was made in the littoral zone of the island but according to information from other sources the fauna there was very limited.

As in previous years some samples were taken from sheltered places at Heimaey.

Although the identification of the 1971 material is not completed it has been worked further than that of 1970.

A list of animals found at Surtsey in these two years, would be very similar to tables published in previous reports (Sigurðsson 1970 and 1972), but account will be given here of those animals already identified as new for Surtsey.

From the 1970 material only two species of bivalves *(Lamellibranchia)* new for Surtsey have been found. Both are common in the vicinity of the island. In the 1971 material we have found 27 species new for Surtsey, 2 of which are new for Iceland.

Belonging to *Bryozoa* 11 species are new for Surtsey and one of them *Callopora dumerili* (Aud.) is new for Iceland. Of *Amphipoda* 8 species are new for Surtsey and one of them, *Metopa pusilla* G. O. Sars, is new for Iceland. The other new species for Surtsey are two *Isopoda,* one *Prosobranchia,* one *Lamellibranchia,* one *Echinoidea* and one *Ascidiacea.*

In the years 1972 and 1973 the benthic fauna of Surtsey was not sampled.

In July 1974 sampling of the bottom fauna around Surtsey was carried out on the same traverses as in 1971 but under better weather conditions. Furthermore some samples were taken off the northern part of the west coast indicating rich benthos in that area. None of the samples have been worked up. Many underwater photographs were taken.

In August the tidal zone was sampled. Scattered barnacles *(Balanus balanoides* (L.) Bruguière) were found on the rocky coast covered. All of them belonged to the O-group, and as in previous years they are expected to disappear during the coming winter. Other animals were negligible. The coastline is still far too unstable for animal communities usually found in the tidal zone and this will most likely be so for a long time to come.

Prior to the sampling at Surtsey in July 1974 some samples were taken off Dyrhólaey on the central south coast of Iceland. Those samples were taken on hard bottom for comparison with the Surtsey material.

Two Danish biologists, Jean and Hanne Just took part in the sampling at Dyrhólaey and partly worked up the material. They had also intended to work at Surtsey, but unfortunately, unforeseen delays prevented this.

ACKNOWLEDGEMENTS

This research has been a part of the Surtsey Research Society's program and has been sponsored by the Max-Planck-Institut, the S. R. S., The Icelandic Science Foundation and Sáttmálasjóður. This is highly appreciated.

Thanks are also due to Danish biologists for their help in identification of the 1971 material and the sampling in 1974, as well as all the others who have assisted in carrying out the research program.

References:

Sigurðsson, A. 1970: The Benthonic Coastal Fauna of Surtsey in 1968. Surtsey Research Progress Report V.

Sigurðsson, A. 1972: The Benthic Coastal Fauna of Surtsey in 1969. The Surtsey Research Progress Report VI.

Nitrogen fixing blue-green algae as pioneer plants on Surtsey 1968–1973

By
G. HELMUT SCHWABE
Max-Planck-Institut für Limnologie, D-232 Plön, Postfach 165,
Federal Republic of Germany

Nitrogen is the most critical limiting major nuttrient in the terrestrial area of Surtsey (Henriksson & Henriksson 1974). If the water supply is sufficient, nitrogen undoubtedly limits the development of the algal vegetation. This finding is, among other things, supported by several hundred enrichment cultures which were kept in our laboratory during the study period. The cultures were set up on N-poor media, and were compared with controls containing sufficient N, in which the typical substrate types of Surtsey (lava, tephra of different grain sizes, fine fractions of windblown dust and sediments scoured out by precipitation) were tested in varying quantities added to the nutrient medium. The resulting number of species and the total production in all cases increased with the N-content of the medium, at least up to concentrations of about 30 mg N (as NO_3) per 1000 ml.

Under these conditions, biological N-fixation is of great importance both in soil formation and in ecogenesis. It has been apparent since 1968 that compared with nitrogen compounds, all other mineral nutrients are present in plentiful supply – some trace elements in toxic excess. The *Cyanophyta,* among which many are nitrogen fixers, were collected and propagated in N-deficient enrichment cultures. The results of this work are only summarised here under the heading of N-fixing species since the processing of all the data will require more time.

At the place of collection, sterile plates and nutrient solutions were inoculated with substrate samples. Other samples of the same substrate were also taken to the laboratory in Plön and cultivated in different media and under different conditions of light and temperature.

The collections on the island were made during 7 visits:
28-30 July 1968, 29 July - 1 August 1969, 21 May 1970, 5-7 August 1970, 15-17 July 1971, 8-11 July 1972, 25-27 July 1973.

For the collections, all substrate types above the high water mark on the shore which could be distinguished visually were considered from the first visit. Close attention was given to the sites which, as shown by examination with a hand lens, were seen to be colonized with Cryptogams (algae, mosses), or obviously had a good water supply (steam fissures, secondary craters, temporary pools, rock pools etc.). Algal developments have been followed in situ with a hand lens or microscope since 1968. Populations of algae were at first found by direct observation only in the immediate vicinity of steam vents, mostly (although not always) near moss plots (especially *Funaria hygrometrica).* These consisted mainly of members of the group *Schizothrix-Plectonema* (with trichome diameter less than 2.5μm) and sometimes also of pennate diatoms which formed shiny brownish deposits up to about 1 mm in diameter. Up to the summer of 1973, such small algal deposits, often only visible with a hand lens and usually consisting of several species, occurred in open areas apparently only periodically or temporarily. There are two independent causes for this fact:

1. The predominant species in such stands are actively motile (Behre & Schwabe 1970), so that they can avoid the occasional dry periods by withdrawing below the surface of the substrate.

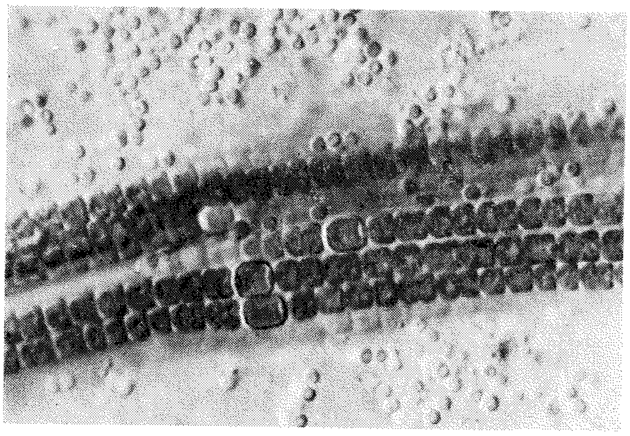


Fig. 1. *Nodularia harveyana Thur.* Together with *Aphanocapsa* cf. *elachista* (2-2,5 μmΦ). From the lava flow in Surtur I (8.8.1970).

Fig. 2. *Hapalosiphon hibernicum* W. et G. S. West. Typically branched primary trichome and secondary trichomes. From Strompur (5.8. 1970).

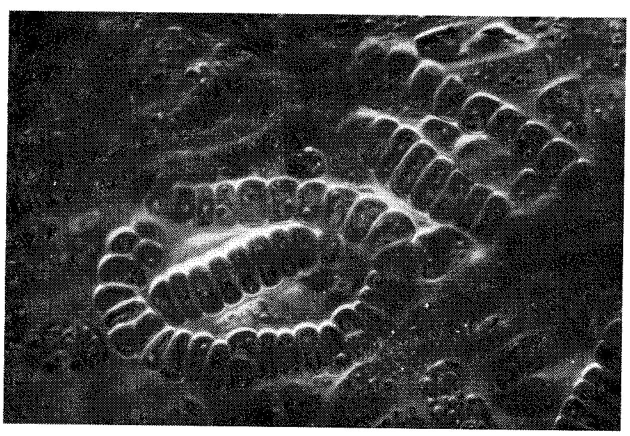


Fig. 3. *Hapalosiphon hibernicum* W. et G. S. West. An older culture. The trichomes almost completely transformed into chains of akinetes. From Strompur (5.8.1970).

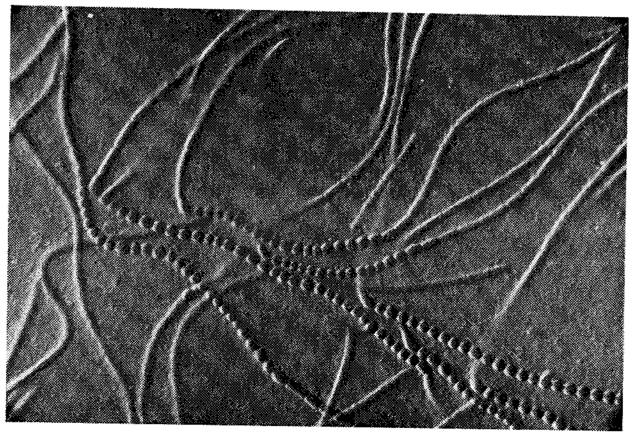


Fig. 4. *Mastigocladus laminosus* Cohn. In full development with typically differentiated trichomes. From the main crater of Surtur II, steam vent (16.7.1971).

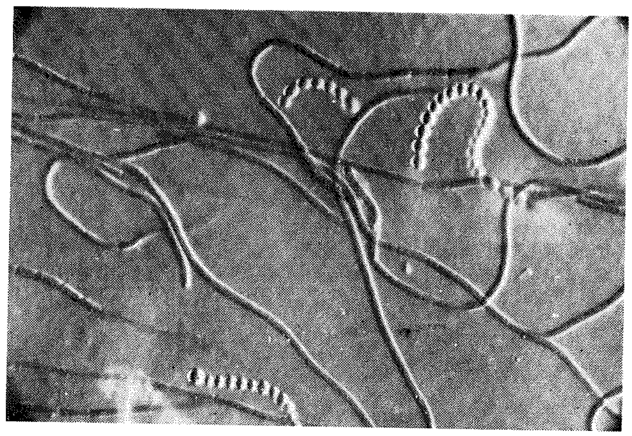


Fig. 5. *Mastigocladus laminosus* Cohn. An older culture with characteristic formation of akinetes in chains. From same locality as in Fig. 4.

Fig. 6. *Tolypothrix tenuis* Kütz. f. *terrestris* Boye-Pet. From the same place as *Mastigocladus* (16.7.1971) in Fig. 4. On warm, moist substrate together with musci.

2. The mineral dust deposited by weak winds straight on the damp surfaces completely covers such algal stands with a very thin layer for some time.

In the last few years we have often watched, with a hand lens, such changes in algal stands occurring within a few hours in places supplied with capillary water. N- fixers could not, however, be seen in situ, but were found in abundance in cultures of the substrates. Their N-fixing activity has been demonstarted by Henriksson et al. (1972, 1974). Large patches of algae (up to more than $0.1m^2$) occurred since 1968 only on the inner sides of hollows with sufficient light (secondary craters, more or less perpendicular lava walls), which are continuously moistened by steam. Several nitrogen fixers have been found here also in situ since 1970 (*Nostoc* sp. A. *"Nostogloea"* ad interim, *Mastigocladus).* Different N-fixers show a strong affinity for moss stands, particularly for *Funaria,* attached themselves to the protonemata. The joint occurrence of mosses and *Anabaena* is so marked and regular that it is possible to speak of a facultative symbiotic relationship. In the last two years it was only on exceptional occasions that stands of moss turfs were not associated with *Nostacaceae.* – In contrast to other musci, *Rhacomitrium* seems to hinder or completely suppress the development of the *Cyanophyta.* – *Nodularia* sp. shows, at least in early development, a strong affinity for protonemata, but then it spreads extensively. It has been noticed that at the place where the species is most abundant (on the southern side of "Lýsuhóll"), the moss turfs are also widely distributed. The *Nodularia* strains from there are different from the other *Nostocaceae* found on Surtsey in many respects:

1. Since 1970 the species has been found at only a few places in the young lava of the large crater Surtur I, and appears to be absent from the entire remaining region.

2. Both the places where it occurs most abundantly ("Lýsuhóll" and "Funaria-fissure" in the southern part of the main crater Surtur) I occasionally are resting-grounds for birds. About half way between these two places is another rather dense stand of *Nodularia;* birds were often found at the plastic tubs installed here some years ago.

3. One conspicuous feature distingunishes the strains of *Nodularia* collected on Surtsey from those on Heimaey and on Iceland itself, and from all the other *Nostocaceae* on Surtsey: under varying culture conditions, akinetes were generally not produced at all, or late and in small numbers.

From these findings it can be concluded that, unlike the other blue-green algal pioneers, *Nodularia* is not brought to Surtsey by wind, but probably by birds. – The thermophilic species *(Mastigocladus laminosus* (cf. Fig. 4 and 5) etc.) had no relationship with moss stands but were distributed on steam vents under 50° also in mixed stands with other species. *Rivulariaceae* have hitherto not been found. Until the summer 1973 *Scytonemataceae* have been represented by only one species *(Tolypothrix tenuis,* cf. Fig. 6).

At present, three N-fixing species (including the variety-rich collective species *Nostoc muscorum)* are distributed over the entire island surface, one (*Nodularia,* cf. Fig. 1) is common only in the lava fields of Surtur I, and four are restricted to thermal sites or areas permanently moistened by steam. The distribution area of *Anabaena* and *Nostoc muscorum* is at least as large as that of the moss stands (except *Rhacomitrium*) or perhaps larger. From these observations a definite close association between the two groups is clear. Up to now, the ecogenesis has obviously proceeded more rapidly in the young lava flows of Surtur I than in the older ones of Surtur II (compare moss distribution to that of *Nodularia;* see also Behre & Schwabe 1970). The reasons for this are not known.

The expansion of *Anabaena* and the *Nostoc* species on the island, which are not markedly thermophilic, is strongly influenced by the abundance and very rapid development of resting spores (akinetes). All the initial colonizers (strains) of these species found on Surtsey show this characteristic in the early development stages. Furthermore the akinetes of these pioneers, which are formed in chains, separate promptly from each other so that a short period of drying out enables further dispersal. Viable resting spores are commonly found in the so far completely uncolonized accumulations of wind-transported material everywhere on the island. *Nodularia* is the only exception.

Typical resting spores of *Hapalosiphon hibernicum* (cf. Fig. 2 and 3) are also frequently found, whereas *Tolypothrix tenuis* forms occasional hormocysts which likewise favour its local dispersion. The distribution of these two species is presumably restricted by their ecological requirements. Briefly, it can be stated that, at least since 1970, several N-fixing *Nostocaceae* are distributed over the entire island surface covered by lava above the high water mark, and are always frequently found in local associations of typical soil algae.

The above listed species thrive together in media extremely poor in nitrogen, and respond to additions of nitrate (1 to 50 mg N/1000 ml) with a reduction in the relative frequency of heterocysts and often also with a marked general reduction in growth (> 10 mg N/1000 ml). Since 1968, N-fixing blue-green algae have occurred regularly in association with moss stands

SPECIES	1968	1969	1970	1971	1972	1973
Anabaena variabilis	××	×××	×××	×××	×××	×××
Nostoc muscorum 1)	..	[×]	××	×××	×××	×××
Nostoc sp. A	..	×	××	×××	×××	×××
Nostoc sp. B (t) 4)	..	[×]	××	××	××	××
Nodularia harveyana	..	[×]	××	×××	×××	×××
Mastigocladus laminosus (t) 2)	..	×× 2)	××	××	××	××
"Nostogloea" (ad int.) (t) 3)	..	×× 3)	××	××	××	××
Hapalosiphon hibernicum	..	..	×	..	××	..
Tolypothrix tenuis	..	..	..	×	××	××
Scytonema sp. 403	..	..	..	..	[×]	..
Cylindrospermum c.f. *muscicola*	..	..	..	..	[×]	..

1) Definitely a collective species which cannot be satisfactorily separated using the normal taxonomic methods. The variety of forms has increased markedly since 1970.
2) Originally discovered by Castenholz (1972).
3) As in (2) above and described as "non-branching form of *Mastigocladus laminosus*".
4) Perhaps identical with Castenholz's *"Mastigocladus laminosus* short filament type" (1969, a).

[×] found once
× only distributed in one locality
×× only distributed in a few stands
××× widely distributed
(t) thermophilic/or thermobiont.

(except *Rhacomitrium*), so that one may speak of a facultative symbiosis. Nitrogen is at present the most critical limiting factor in the plant nutrient supply on Surtsey (see Henriksson & Henriksson 1974), so that blue-green algae play an essential role in the progression of ecogenesis. Nitrogen fixation by blue-green algae was already known on Surtsey in 1970 (Henriksson & Henriksson 1972). They have recently shown that N-fixation by blue-green algae was much greater on Surtsey than in similar substrates on Hekla. The results of Henrikson et al. and those presented here complement and confirm each another.

The effects of the rapidly spreading *Cyanophyta* on Surtsey since 1968 are certainly not restricted to N-fixing but are also shown in the mechanical aspect of soil formation, a feature also of very great importance. All the species found to date produce, to a greater or lesser extent, mucous coatings, which together with the movement of those species which form long trichomes result in fixation of the fine rock and mineral fractions of the soil into porous structures (crumb formation). In contrast to the stands of the *Chlorococcales* which have been spreading rapidly since 1969/1970, and which are conspicuous because of their green colour, the *Cyanophyta* cannot be seen with the naked eye from distances greater than 1 m and generally they can not be found by microscopical examination of the natural substrate. This can easily lead to the underestimation of the role of the *Cyanophyta, Diatoms* and a few other groups, because in places with a suitable microlimate (adiabatic humidity) the typical aerophytes spread out superficially, while the genuine soil-building algae remain unvisible (compare T. D. Brock 1972, 1973). Here, the ecological and physiological distinction between genuine soil algae and aerophytic algae strongly bound only on the surface of lava or tephra (resembling those on tree bark and rock surfaces) should be emphasized.

These studies on the ecogenesis of Surtsey, which have been conducted since 1968, have all been supported in various ways by the German Research Council, and by the Surtsey Research Society.

References:

Behre, K. und Schwabe, G. H. 1970: Auf Surtsey/Island im Sommer 1968 nachgewiesene nicht marine Algen. — Schr. Naturw. Ver. Schlesw.-Holst. Sonderband, 31-100.

Brock, Th. D. 1972: Microbiological observations on Surtsey, 1970. — Surtsey Progr. Rep. *6*, 11-13.

— 1973: Primary colonization of Surtsey, with special reference to the blue-green algae. — Oikos *24* (2), 239-243.

Castenholz, R. W. 1969a: Thermophilic Cyanophytes of Iceland and the upper Temperature Limit. — J. Phycol. *5*, 360-368.

— 1969b: Thermophilic Blue-Green Algae and the Thermal Environment. Backer. Rev. *33* (4), 476-504.

— 1972: The Occurrence of the Thermophilic Blue-Green Algae Mastigocladus laminosus on Surtsey in 1970. — Surtsey Progr. Rep. *6*, 14-19.

Henriksson, E., Henriksson, L. E. and Pejler, B. 1972: Nitrogen fixation by blue-green algae on the Island of Surtsey, Iceland. — Surtsey Progr. Rep. *6*, 66-88.

Henriksson, L. E. and Henriksson, E. 1974: Studies in the nitrogen cycle of Surtsey in 1972. — Surtsey Progr. Rep. *7*.

Schwabe, G. H. 1974: Zur Ökogenese auf vulkanischen Substrat. — Symposium 1969 "Vegetation und Substrat". Berichte Intern. Ver. Vegetationskde.

Temperatures, steam emission and moss cover in thermal areas of Surtsey

By

ERIK A. SJÖGREN

Institute of Ecological Botany, Uppsala University, Sweden

INTRODUCTION

In August 1972, four days were spent on Surtsey, 12-15/8. In the years after 1968, colonization by mosses on the island has been followed in detail (cf. Bjarnason and Fridriksson, 1972; Fridriksson, Bjarnason and Sveinbjörnsson, 1972; Fridriksson, Sveinbjörnsson and Magnússon, 1972a). The largest patches of danse moss cover are found in the thermal area of the island (cf. Magnússon, Sveinbjörnsson and Fridriksson, 1972). This does not mean, however, that the largest number of recorded localities with primary colonization by bryophytes are to be found within the thermal area.

At the beginning of 1972, I received the generous invitation of the Surtsey Research Society to come to Surtsey. My intention put forward at that time was to study microclimatic conditions in the thermal area in places where moss cover was present. The main question to be studied were the influence of heat, steam and windtransported material (accumulation and erosion) on colonization by mosses.

A "Grant multipoint temperature recorder, model D, was used for the temperature recordings. With this instrument, it is possible to record temperatures from 28 thermistor probes within 3 minutes, i.e., almost simultanously. The recordings are made automatically at intervals of one hour. Reading the recorded values, and calibration of the instrument, including the necessary use of a conversion chart, allows the measurement of temperatures to ± 0.2°.

The probes used during the measuring series were equipped with radiation shelters of aluminium foil. The full capacity of the instrument could not be used, as there were difficult problems with short circuit because of the permanent steam in the measuring areas.

Meteorological measurments in August on Surtsey (cf. Sigtryggsson, 1970) indicate a mean temperature of 10.7°, wind velocity at 2 m above ground level of 3.9 m/sec. (13 days) and precipitation of 25.4 mm (13 days).

MEASURING AREAS

A. A total of 13 probes were scattered within and in the vicinity of the so-called "Bell", which is a cave formed by tephra and accumulated sand. It has a W-facing entrance and a hole in the roof. The "Bell" is situated in the section J 13 (110 m above mean sea level) to the NE of the so-called Surtur I crater (cf. below). It is situated on a S-facing slope with an inclination of about 30%. In the area are numerous steam-emitting holes. Steam comes out continuously from places in and close to the cave. Moss cover is concentrated in the vicinity of the steam holes, in the interior of the cave and at the top of the cave where the sand is permanently moist. In this locality, sand covers 90-100% of the new lava (cf. Fridriksson, Sveinbjörnsson and Magnússon, 1972b).

B. A total of 21 probes were placed in the northern part of the crater "Surtur I" (local names cf. Thórarinsson, 1968) in the section L 12. This part of the crater has very many steam fissures and holes. There is continuous condensation of water in the area, and the accumulation of sands is considerable. 17 probes were placed within the crater; 2 probes on the northern rim; and 2 in a place with no steam emission, E of the rim. Moss cover is frequently present close to places of steam emission. The degree of cover within sample plots of the size ¼ m^2 exceeds 50% in several places.

RECORDINGS

A. Locality: "The Bell".

Time period: 12/8 14.00-14/8 13.00 (1972).

Weather: 12/8 14.00, 100% cloud cover, winds from SE about 10 m/sec. In the night 12-13/8, strong winds and scattered rain showers. 13/8 12.00, generally 100% cloud cover, winds from W-SW, about 15 m/sec., scattered rain showers. 14/8 after 07.00, about 75% cloud cover, winds from S-W, 5-10 m/sec.

All measuring points (fig. 1: 1-5): Temperatures measured at intervals of one hour have been connected in the diagrams. Values from 13 probes will be discussed below. Mean, maximum and minimum temperatures refer to the whole measuring period of 48 hours. Probe numbers followed by (a) indicate that the position was below the soil surface, if followed by (b) the position was at the soil surface.

Probes 1a and 2b (fig. 1:1).

Position: Inside "the Bell". (1a ——) at the base of the northern wall, 1 cm below the soil surface in moist loose sand; (2b . . . . . .) same locality, at the surface.

1a.	max. 19.0°	min. 8.7°	mean temp.	13.8°
2b.	„ 14.8°	„ 5.6°	„	10.5°

At short intervals steam is blown into the cave from the steam hole to the W and it is also emitted from the bottom of the cave. The steam keeps the sand permanently warmer than the air at the sand surface where steam is frequently removed by the winds blowing through "the Bell". Condensation of water is especially abundant on the N vertical wall in the cave, where the moss cover has the highest degreee of cover. — Bryophytes: *Atrichum undulatum, Leptobryum pyriforme.*

Probes 3a and 4b (fig. 1:2).

Position: Inside "the Bell". (3a ——) at the S wall, 1 m above the bottom of the cave, 1 cm below the surface in densely packed moist sand; (4b . . . . . .) same locality, sand surface.

3a.	max. 26.0°	min. 14.5°	mean temp.	20.9°
4b.	„ 22.5°	„ 4.2°	„	12.9°

The sand is kept permanently warm by the penetrating steam. Air temperatures are much less, because of the rapid air circulation in the cave.

Probes 5b, 6b and 7b (fig. 1:3).

Position: 1 m to the W of the entrance to "the Bell". (5b — . . — . . —) 5 dm S of a stem hole; (6b . . . .) 8 dm S of the steam hole, (7b —.—.—) 10 dm S of the same steam hole. All the probes at the surface, hard surface with very little loose windblown sand.

5b.	max. 26.2°	min. 9.4°	mean temp.	15.5°
6b.	„ 20.4°	„ 7.4°	„	11.0°
7b.	„ 23.1°	„ 8.0°	„	11.7°

Size of the oval steam hole at the opening, 15-20 cm in diameter. Hot steam is continuously blown out, generally in a southward direction down the slope. The steam moves continuously over a narrow field from the opening of the hole to 5 dm to the S of it. The field between 5-8 dm is less in contact with the steam and is wetted by the condensation of water from the cooled steam. During windy weather the steam is frequently forced down by the winds on to a small area to the S of 6b, which explains the higher maximum and minimum and mean temperatures at probe 7b than at 6b. There was less wind after 07.00 14/8 and the steam could not then reach probe 7b so easily. — There is moss cover in a narrow band from 5-8 dm to the S of the steam hole. — Bryophytes: *Bryum argenteum, Funaria hygrometrica.*

Probes 8a, 9a, 10b and 11b (fig. 1:4).

Position: To the N of the opening in the roof of the cave. (8a ——) in densely packed sand 5 cm below the surface, 2 dm to the N of the edge of the opening in the roof of the cave, (9b . . . . .) same locality but at the surface, (10a — — — — —) in densely packed sand 5 cm below the surface, 8 dm to the N of the edge of the opening in the roof of the cave, (11b —.—.—.—) same locality but at the surface.

8a.	max. 44.6°	min. 33.4°	mean temp.	39.0°
9b.	„ 27.2°	„ 7.8°	„	18.0°
10a.	„ 39.0°	„ 30.0°	„	34.3°
11b.	„ 31.2°	„ 8.8°	„	17.4°

Steam permanently warms the sand of the roof of the cave. The air at the surface is, however, cooled down by the permanent turbulence round the cave. Slightly higher maximum and minimum temperatures at 11b than at 9b might be explained by random downward movement of the steam by the winds. There is moss cover between 9b and 11b where moisture is provided by the cooled steam. — Bryophytes: *Funaria hygrometrica, Dicranella crispa.*

Probes 12a and 13 b (fig. 1:5).

Position: 5 m SW of "the Bell" between small steam holes. (12a ——) 5 cm below the surface in densely packed sand; (13b . . . . .) same locality at the surface.

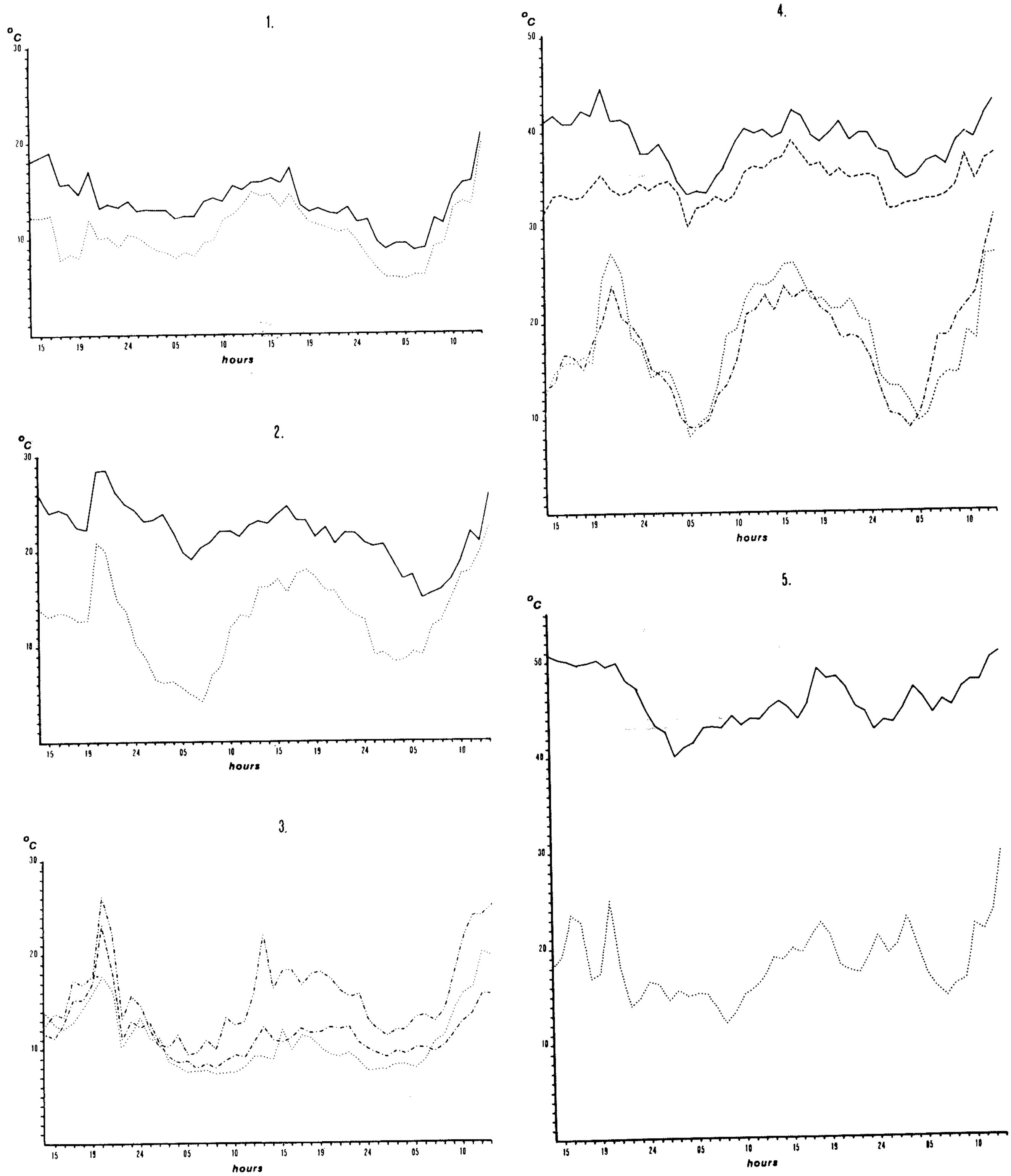


Fig. 1:1—5. Temperatures recorded with 13 thermistor probes at intervals of 1 hour, inside and close to "the Bell", section J 13 in the thermal area. (The position of the probes is described in the text).

12a. max. 50.8° min. 41.1° mean temp. 46.1°
13b. „ 28.8° „ 12.1° „ 18.2°

These were the highest maximum, minimum and mean temperatures recorded with soil thermistors within the area. Turbulence in the air strata close to the ground is most efficient in the locality, but the high soil temperatures mean that 13b recorded the highest minimum temperatures of the air thermistors in the area. – Bryophytes: *Bryum argenteum, Pohlia albicans.*

Comments: Temperatures in the thermal area in and around "the Bell" are already comparatively high at a depth of 5 cm in loose sand or in tephra. They are characterized by rather small diurnal amplitudes. Low air temperatures at night seem to have only a small effect on the ground temperatures, which are regulated by the hot steam penetrating from below. The diurnal temperature amplitudes are thus much larger at the soil surface as shown, especially clearly by the probes of fig. 1:4. In the temperature gradients indicated by Jóhannesson (1972, p. 129 ff.), there is no information about temperatures between 0-20(30) cm depth. His curve of point 11 ("the Bell") indicates temperatures of only 35° at a depth of 30 cm, which seems to be much too low for this area (cf. also Jakobsson 1972, p. 122).

B. Northern part of "Surtur I" (70-72 m above sea level).

Time period: 14/8 14.00–15/8 13.00 (1972).

Weather: 14/8, 14.00 to 18.00, 75-100% cloud cover, winds 5-10 m/sec. 15/8, after 04.00, winds below 5 m/sec. and 75-100% cloud cover.

All measuring points (fig. 2:1-9): Temperatures measured at intervals of one hour have been connected in the diagrams. Values from 21 probes will be discussed below. Probes with numbers followed by (a) are situated below the soil surface and those by (b) at the surface.

Probes 1a and 2b (fig. 2:1).

Position: 2 dm above vertical oval opening with steam emission. Diameter of the hole is 10-15 cm. (1a ——–) 1 cm below the surface in loosely accumulated moist sand; (2b . . . . .) same place at the surface.

1a. max. 25.6° min. 7.1° mean. temp. 17.1°
2b. „ 24.3° „ 9.1° „ 19.9°

Steam emission in the vicinity of the hole during the morning hours with rather light winds clearly increases the temperatures in the air close to the ground surface above the temperatures in the sand. Between 14.00-24.00, the winds blow the steam downwards in a SW direction from the hole (cf. probes 12a and 14b).

Probes 3a and 4b (fig. 2:2).

Position: 3 m SW of the same steam hole as above. (3a ——–) 1 cm below surface in moist, fine, densely packed sand; (4b . . . . .) same place at the surface of the sand.

3a. max. 19.2° min. 12.2° mean temp. 14.5°
4b. „ 18.7° „ 8.9° „ 12.4°

The winds do not continuously blow the steam as far as 3 m from the hole. Sand temperatures are thus almost continuously higher than air temperatures. Values should be compared with the lower values recorded at 15a and 17b, at the same distance from the steam hole but in a place with loose sand where the percentage content of fine grain material is small and penetration of steam is apparently easier.

Probes 5a and 6b (fig. 2:3).

Position: 5 m E of rim of the crater, on slope facing E. (5a ——–) 1 cm below the surface in dry loose sand; (6b . . . . .) same place, at the surface.

5a. max. 17.9° min. 8.7° mean. temp. 11.3°
6b. „ 18.5° „ 7.9° „ 10.1°

Lowest minimum and maximum air temperatures recorded within the area. Comparatively low minimum temperatures and the lowest maximum temperatures recorded at a depth of 1 cm in the area. The lowest mean temperatures were at these probes.

Probes 7a and 8b (fig. 2:4)

Position: Rim of crater, 1 m to the E of steam hole mentioned above and 5 m W of position of 5a and 6b. (7a ——–) 1 cm below the surface in moist sand; (8b . . . . .) same place, at the surface.

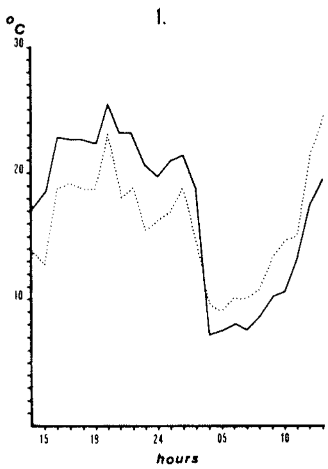
7a. max. 18.5° min. 10.7° mean temp. 13.0°
8b. „ 19.7° „ 9.6° „ 13.0°

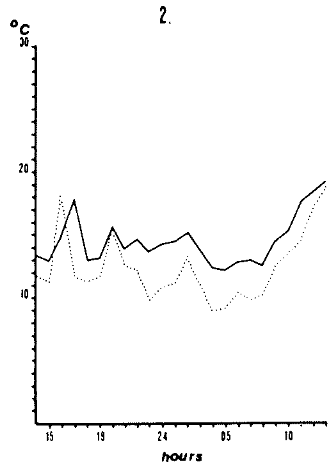
During morning hours with light winds, only slight influence of steam at probe 8b, much weaker than at 2b. Comparatively low minimum and maximum values at both probes. – Bryophytes: *Dicranella crispa, Leptobryum pyriforme.*

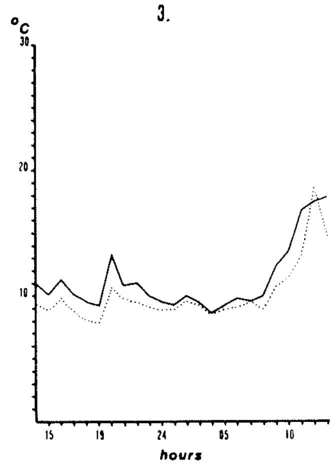
Probes 9a, 10a and 11b (fig. 2:5).

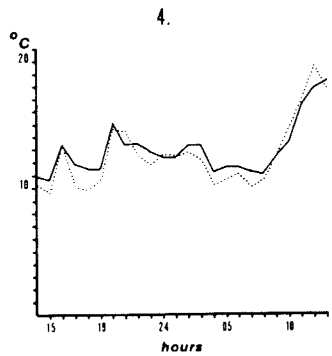
Position: 3 dm W of steam hole (same as above). (9a ——–) 1 cm below the surface in moist sand; (10a – – – –) same place, 5 cm depht; (11b . . . .) same place, at the surface.

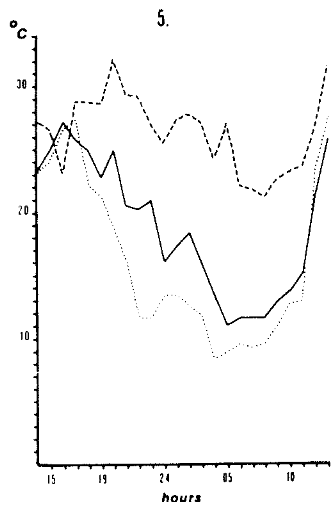
9a. max. 27.2° min. 11.1° mean temp. 18.9°
10a. „ 32.2° „ 21.3° „ 26.4°
11b. „ 27.6° „ 8.3° „ 16.7°

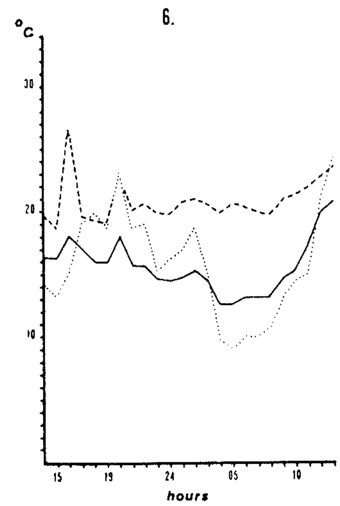


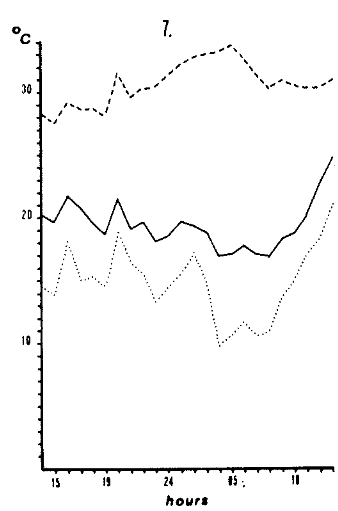


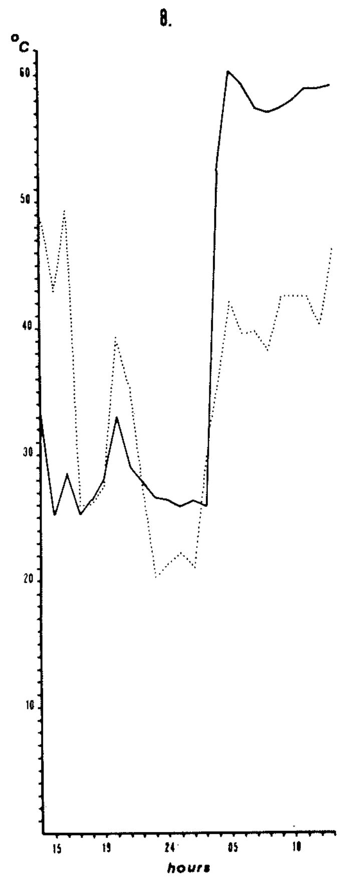












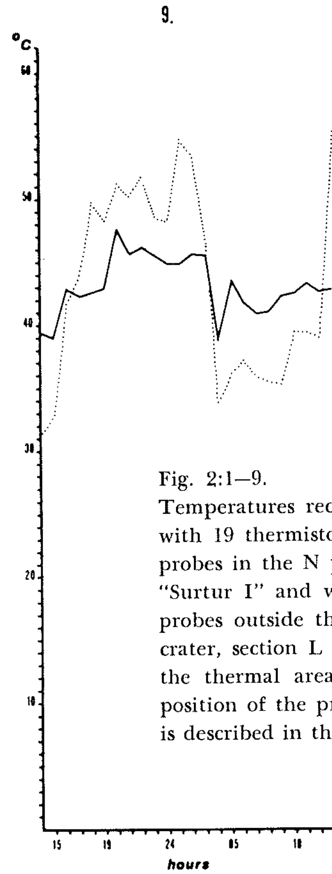


Fig. 2:1—9. Temperatures recorded with 19 thermistor probes in the N part of "Surtur I" and with 2 probes outside the crater, section L 12 in the thermal area. (The position of the probes is described in the text.)

There is a steep rise in temperature from the surface to a depth of 5 cm in the sand. – Bryophyte: *Pohlia nutans.*

Probes 12a, 13a and 14b (fig. 2:6).

Position: 1 m W of the steam hole. (12a ——) 1 cm below the surface in moist sand; (13a - - - -) same place, 5 cm depth; (14b . . . . .) same place, at the surface.

12a.	max. 20.8°	min.	12.6°	mean temp.	15.7°
13a.	„ 26.7°	„	18.8°	„	21.0°
14b.	„ 24.4°	„	9.1°	„	15.8°

The three probes measured series of temperatures of special importance to the understanding of conditions close to steam emission holes. The increase of temperatures with depth of only 5 cm is very marked. The air temperatures at the surface are influenced by steam blowing down from the hole in the first half of the time period; during the second half the influence decreases as the wind decreases. A comparison of air temperatures at a distance of 3 dm and 1 m from the hole shows that the steam emerges from the hole in a steep upward direction and then is carried down by winds to the ground further away. These conditions were also observed at probes 6b and 7b outside "the Bell" (fig. 1:3).

Temperatures very close to a steam hole are evidently subject to larger and more frequent changes (cf. probes 9a, 10a, 11b) than at a longer distance from it. – Bryophyte: *Bryum argenteum.*

Probes 15a, 16a and 17 b (fig. 2:7).

Position: 3 m to the W of the steam hole (2 m W of 12a, 13a, 14b). (15a ——) 1 cm below the surface in moist loose sand deposits; (16a - - - - -) same place, at a depth of 5 cm; (17b . . . .) same place, at the surface.

15a.	max. 24.8°	min.	16.9°	mean temp.	19.4°
16a.	„ 33.7°	„	27.5°	„	30.6°
17b.	„ 21.1°	„	9.8°	„	14.8°

The heat provided from below to the accumulated sand and to the air above in this thermal area depends on the depth of the deposited sand layer. There was a much thinner sand layer above the lava here than at a distance of 3 dm or 1 m from the steam hole.

Probes 18a and 19b (fig. 2:8).

Position: At a distance of 1 m W of the large steam hole, 10 cm from the opening of a small round steam hole with horizontal opening 3 cm in diameter. (18a ——) 1 cm below the surface in moist loose sand; (19b . . . .) same place, at the surface.

18a.	max. 60.3°	min.	25.2°	mean temp.	40.3°
19b.	„ 49.4°	„	20.1°	„	35.2°

Largest temperature ranges recorded within the area both in air and sand. The very large increase in temperatures between 03.00-05.00 can not be correlated with similar changes in conditions at the other probes. Temperatures very close to steam holes change rapidly and frequently (cf. 20a, 21b).

Probes 20a and 21b (fig. 2:9).

Position: At a distance of 1 m W of the big steam hole, 3 cm from 2 dm long narrow fissure in the sand. (20a ——) 1 cm below the surface in moist loose sand; (21b . . . .) same place, at the surface.

20a.	max. 47.6°	min.	39.1°	mean temp.	43.1°
21b.	„ 55.4°	„	31.3°	„	46.6°

Highest maximum air temperature recorded. Highest mean temperatures both in air and sand. – Bryophytes: *Pohlia albicans, Bryum argenteum.*

Comments The series of records have shown the same conditions as within the first described area: generally lower temperatures at the soil surface than at a depth of 1 cm in sand or tephra. The further increase in temperatures until the depth of 5 cm appears to be very steep. Strength and direction of winds influence air temperatures, in relation to the contribution of hot steam in localities close to steam emission holes. Depth of accumulated sand probably has an influence on amounts of heat penetrating up to the surface but not on the frequency and time of change in temperatures.

Steam from holes and fissures is apparently carried by the wind in a curve from the opening down to areas around, unless the winds are very weak. Amounts of steam emitted depend on the size of the holes; the direction of the steam depends on the inclination of the holes and the exposure of the situation to the wind.

DISCUSSION

Thermal areas on Surtsey locally provide suitable conditions for colonization by mosses. Such localities are situated in the vicinity of steam emission holes and fissures. In these places there are now coherent moss carpets with fairly large degrees of cover. The colonized areas are frequently distinctly limited, with few specimens growing outside the dense carpets.

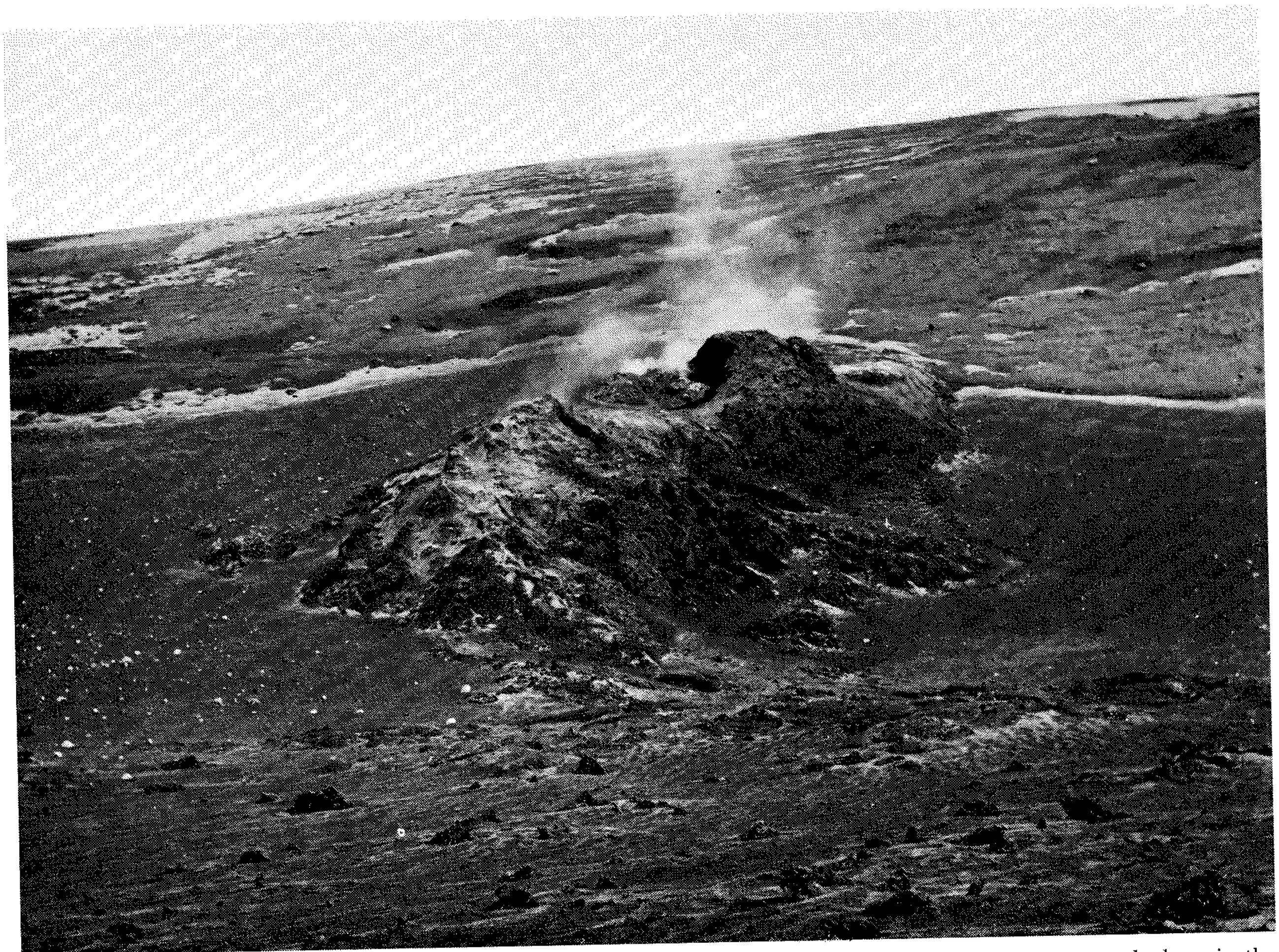


Fig. 3. "The Bell", situated on the S facing slope to the N of the crater "Surtur I". Steam emission from several places in the area. – 14.88.1972. E. Sjn.

The steam provides heat and condensed water to areas close to the emission holes. It was supposed by Bjarnason & Fridriksson (1972, p. 10) that water condensed from the steam is a more probable explanation of the development of bryophyte diaspores than the heat. The stabilizing effect of the steam on the sand was also mentioned. This supposition can be further verified.

The large amount of heat with no steam emission provided to several places in the thermal area where mosses are absent supports this idea. There is an increase in heat towards the opening of big steam holes, but often a sharp limit of moss cover at some distance from them. However, high temperatures are tolerated around small emitting holes. The high temperatures, often reaching 60°C, are thus not likely to be able to support or to hinder the moss colonization.

Condensation of water takes place around the steam holes, up to a certain distance not generally reached by the steam. The steam is carried further from the holes during windy weather. The transport of steam from the holes with inclined openings seems to be always in one direction, even if winds are blowing towards the opening of the hole, For example, this was the case at the large steam hole at a distance of 1 m W of "the Bell" on 13/8, when strong SW winds were blowing. Steam was then first carried from the S-facing opening in a southwards direction, to nearly exactly the far limit of the moss cover situated to the S of the hole. It was then carried by the wind in a curve towards the N. The emission of steam from the holes during very windy conditions takes place in a curved direction in a way probably providing less steam and heat to places very close to the holes and more to a more distant area. These conditions have been illustrated by the temperature series both from "the Bell" and from "Surtur I".

The correlation between position of moss cover and contribution of steam – condensation of water – seems to be well-established. However, the reason for the absence of mosses in areas closest to big steam holes remains to be discussed. In that connection, the stabilization of sand and finer material by the condensed water should be

Fig. 4. "The Bell" seen from S (cf. temperature diagrams fig. 1:1—5). In the foreground, probes 12a and 13b (fig. 1:5). To the left, probes 5b, 6b and 7b (fig. 1:3), located 1 m W of the entrance to the cave and to the S of the steam hole. — 14.8.1972. E. Sjn.

Fig. 5. Northernmost part of "Surtur I" with temperature recording instrument (cf. fig. 2: 1—9). To the left, probes 18a, 19b, 20a and 21b (fig. 2: 8, 9). To the right, rim of crater, position of probes 7a and 8b (fig. 2:4). Behind the instrument, which was protected by a plastic envelope, are probes 1a, 2b, 9a, 10a and 11b (fig. 2:1, 5). — 15. 8. 1972. E. Sjn.

Fig. 6. "Surtur I" seen from the N from the slope just below "the Bell" The location of the temperature recording instrument is visible. Steam emission from the area is strong. — 15. 8. 1972. E. Sjn.

stressed. In the vicinity of the steam holes, there is often a building up of cones of accumulated material. The accumulation decreases away from the holes and drops rather abruptly to small amounts at the far limit of the general range of the steam. Just around the holes there is probably an accumulation of wind-transported material which is too rapid to allow diaspores of mosses to develop. Within the range of moss colonization, the water supply is certainly essential but also the stabilization of the substrate, with accumulation not rapid enough to lead to oversanding of the growing diaspores. Differences in accumulation of wind-blown material might be explained by a more permanent moistering of the zone nearest to the holes than in places further away, in the usual direction of movement of the steam emitted, where moss cover is present.

Outside the area reached by the steam, there is a lack of moisture and also frequent change between accumulation and erosion of deposited material. Such conditions are here unfavourable to the attachment and further development of moss diaspores.

The size of the steam emission holes and fissures regulate the amounts of steam provided to the surroundings. The accumulation of wind-blown material close to the holes and the building up of cones often means that the openings are inclined, situated on the slopes of the small cones. The emission of heat and steam takes place in one general direction. The development of a moss cover then depends quantitatively on the amounts of steam emitted; and its sitution depends on the direction of the steam outflow. A concentric coherent moss zone round steam holes is therefore rare. Moss cover is often observed within a narrow segment extending away from the holes.

Temperature records: One of the general features of the temperature sequences within the two measuring areas is the sharp increase in temperature from the surface down to a depth of 5 cm. There are also distinctly higher temperatures at 1 cm depth than at the surface. 5 m SW of "the Bell", the mean temperature at a depth of 5 cm in the tephra was within the temperature range (40-60°), earlier recorded in 1970 at a depth of 20 cm (cf. Magnússon - Sveinbjörnsson - Fridriksson 1972, p. 83). Temperatures recorded at a depth of 5 cm in "Surtur I" were also within the range of 20-40°, indicated from a depth of 20 cm for that area (op. cit.). The further very steep rise in temperature down to 60 cm was recorded by Jakobsson (1972, p. 122). His values seem to be more proable than those showing a much less steep gradient, obtained by Jóhannesson (1972, p. 135).

Weakening turbulence may for a short time increase the surface air temperatures close to steam holes above those measured at a depth of 1 cm in the sand, especially if the accumulated sand layer is deep. Diurnal temperature ranges at the surface are larger than within the sand or tephra. The ranges at 5 cm depth would in a larger number of series of records show comparatively very small diurnal ranges with changes not always correlated with day or night. The supply of heat to the air nearest the ground close to steam holes is parallel to the supply of steam — condensed water.

To sum up, moss cover on Surtsey is not favoured by heat supply. Localities are now numerous outside thermal areas. Mosses do not seem to be hindered from colonising habitats where there are continuously high temperatures. Lack of water is certainly limiting factor. Too much supply of water is, however, proably also unfavourable, because of the secondary effect of too rapid an accumulation of vind-transported material. A moderate water supply is required, with a favourable balance between accumulation and wind-erosion of supplied sand of finer material.

ACKNOWLEDGEMENTS

The work on which this paper is based was sponsored by the Surtsey Research Society with a grant from the U.S. Atomic Energy Commission, Division of Biology and Medicine.

References:

Bjarnason, A. H. and Fridriksson, S. 1972: Moss on Surtsey, Summer 1969. Surtsey Research Progress Report VI, 9—10.

Fridriksson S., Bjarnason A. H. and Sveinbjörnsson, B. 1972: Vascular Plants in Surtsey 1969. Ibid. VI, 30—33.

Fridriksson, S., Sveinbjörnsson, B. and Magnússon, S. 1972a: Vegetation on Surtsey — Summer 1970. Ibid VI, 54—59.

Fridriksson, S., Sveinbjörnsson, B. and Magnússon, S. 1972b: Substrate Map of Surtsey 1970. Ibid VI, 60—63.

Jakobsson, S. P. 1972: On the Consolidation and Palagonitization of the Tephra of the Surtsey Volcanic Island, Iceland. Ibid. VI, 121—128.

Jóhannesson, A. 1972: Report on Geothermal Observations on the Island of Surtsey. Ibid. VI, 129—136.

Magnússon, S., Sveinbjörnsson, B. and Fridriksson, S. 1972: Substrate Temperature Measurements and Location of Thermal Areas on Surtsey, Summer 1970. Ibid. VI, 82—84.

Sigtryggsson, H. 1970: Preliminary Report on the Results of Meteorological Observations on Surtsey 1968. Surtsey Research Progress Report V, 119—120.

Thórarinsson, S. 1968: The Surtsey Eruption. Course of events during the year 1967. Surtsey Research Progress Report IV, 143—148.

Nematodes from Surtsey II

By
BJÖRN SOHLENIUS
Department of Zoology. University of Stockholm, Sweden.

The first nematodes reported from Surtsey were found in algal cultures started during the summer 1971 by Dr. G. H. Schwabe (Sohlenius 1972). In order to investigate if any active nematode populations could be detected in the island Dr. L. E. Henriksson kindly collected 14 soil samples during his visit to Surtsey in July 1972. The samples were transported to Sweden and extracted at the Zoological Department in Stockholm by means of a modified Baermann method (Sohlenius 1973). Nematodes were found in just one of the samples taken from the soil under a piece of wood close to the shore. The wood was covered with an extensive mycelial growth. Just two juvenile nematodes belonging to the genus *Ditylenchus* were obtained from this sample.

Nematodes were also found in algal cultures started by Dr. Schwabe in 1972. Three species were found in one culture started with material from place S 414. The locality is described by Dr. Schwabe as: "Dampffeuchte mit nasser Asche bedeckte Wand gegenüber dem Eingang des Nebenkraters Glocke. Die Fläche ist von lockeren Algenbeständen bedeckt und wird nur kurzfristig von direktem Sonnenlicht erreicht."

Following species were found: *Acrobeloides nanus* (de Man, 1880) Anderson, 1968, *Plectus rhizophilus* de Man, 1880 and *Monhystera filiformis* Bastian, 1865. The identity of *A. nanus* and *M. filiformis* may be somewhat uncertain.

Acrobeloides nanus was earlier found in an algal culture from 1971 and some features of its biology and ecology have been mentioned in an earlier report (Sohlenius 1972).

Plectus rhizophilus is a species which is extremely resistant to changes in temperature and water supply and may well resist desiccation (Nielsen 1967). It has been found in several places in Europe and also in Arctis and Antarctis (Schneider 1939). It is considered cosmopolitan (Meyl 1960). As *Acrobeloides nanus* it is a bacterial feeder but it was not established in agar cultures on Nigon's medium. *P. rhizophilus* was also found in an algal culture inoculated by Dr. Schwabe in the summer 1973.

Also the species *Monhystera filiformis* is considered cosmopolitan (Meyl 1960). Its feeding habits are unknown but probably it feeds on bacteria or algae (Nielsen 1967). Whether it may survive desiccation is not known to the author.

Ditylenchus sp. was the only nematode obtained from the soil samples. Members of this genus are known to resist desiccation (Wallace 1963). Some Ditylenchus species are fungal feeders (Decker 1969) and probably the extracted species belongs to that category.

The poor result of the sample series indicates that no extensive nematode colonization had occurred in 1972.

References:

Decker, H., 1969: Phytonematologie. Veb Deutscher Landwirtschaftsverlag, Berlin. 526 S.

Meyl, H., 1960: Die freilebenden Erd- und Süsswassernematoden (Fadenwürmer). In Tierwelt Mitteleuropas, 1. Bd., Lief. 5a, Verlag Quelle & Meyer, Leipzig, 164 S.

Nielsen, C. O., 1967: Nematoda. In: Soil biology (eds. Burges and Raw). Academic Press, London. 192–211.

Schneider, W., 1939: Freilebende und pflanzenparasitische Nematoden. In Tierwelt Deutschlands 36. Verlag von Gustav Fischer, Jena. 260 S.

Sohlenius, B. 1972: Nematodes from Surtsey. Surtsey Res. Progr. Rep. 6: 97–98.

Sohlenius, B. 1973: Influence of food supply on population structure and length distribution in Acrobeloides nanus (Nematoda: Cephalobidae). Pedobiologia 13: 205–213.

Wallace, H. R. 1963: The biology of plant parasitic nematodes. Edward Arnold Ltd, London. 280 pp.

Studies in the nitrogen cycle of Surtsey in 1972

By
LARS ERIC HENRIKSSON
and
ELISABET HENRIKSSON
Institute of Physiological Botany of the University of Uppsala,
S-751 21 Uppsala, Sweden.

INTRODUCTION

Blue-green algae with ability to fix nitrogen seem to have good qualifications for growth on Surtsey, owing to the low content of bound nitrogen and organic substances in the lava and tephra sand of this island. Behre and Schwabe have confirmed in several investigations that blue-green algae are among the first pioneers (Behre and Schwabe 1970, Schwabe 1970 a, 1970 b, 1971, 1974, Schwabe and Behre 1972). Their results also support the opinion that most of the blue-green algae are cosmopolites and are easily dispersed by water, air, and animals (Fogg et al. 1973). Biological nitrogen fixation in soil samples from Surtsey has been demonstrated, and the algae involved were species of *Anabaena, Nodularia, Nostoc,* and *Tolypothrix* (Henriksson et al. 1972 b).

In order to determine the biological nitrogen fixation *in situ,* the authers visited Surtsey on July 5-10, 1972. At that time soil samples also were taken from the locations studied and from some other sites as well, for the purpose of investigation in the laboratory of other activities in the inorganic nitrogen cycle, specially microbial nitrification and denitrification. In addition, the amount of nitrogen available for other plants was analysed. Special interest was also paid to the occurrence of nitrogen fixing blue-green algae and *Azotobacter.* The locations mentioned in this paper are plotted in Figure 1, and the descriptions of them are found in Table 1. The same sites and soil samples were also used for studies of the terrestrial fungi (Henriksson and Henriksson 1974) and of the terrestrial microfauna (Holmberg and Pejler 1974).

In this paper, nitrogen fixation on Surtsey is compared with nitrogen fixation in some other Icelandic volcanic areas (Hekla), and in Swedish uncultivated and cultivated fields (Uppland). The chemical characteristics of the soil of Surtsey are also compared with those from Swedish wheat fields.

The microflora of Surtsey, including algae, fungi, and bacteria, has been studied also by Brock (1972, 1973) and Schwartz and Schwartz (1972). Some of their results are discussed in this paper.

MATERIAL AND METHODS

Samplings

The soil samples were aseptically deposited in small sterilized plastic capsules (Cerbo, Sweden, No. 18010) of 20 ml volumes with sample spoons attached inside the screwcaps. One spoonful of lava or tephra sand was found to be equivalent to about 0.5 g. Four spoon samples from 5 spots of the surface layer of each site (about 1 m^2) were put in the plastic capsules and carefully mixed.

With respect to the very limited number of higher plants on the island, the rhizosphere of only one plant was examined (locality No. 13). The occurrence of the microorganisms studied, was also tested in the vicinity and on the surface of stranded wood in the lowland of Surtsey (localities No. 6, 8, and 11). In addition, samplings were made outside and inside two caves (localities No. 9, 10, 15, and 16). In the cave, "The Bell" (locality No. 16), thermophilic species of the microflora have been verified (Castenholtz 1972, Schwabe 1974).

The enrichment tests started in the laboratory one week after the samplings. In the meantime

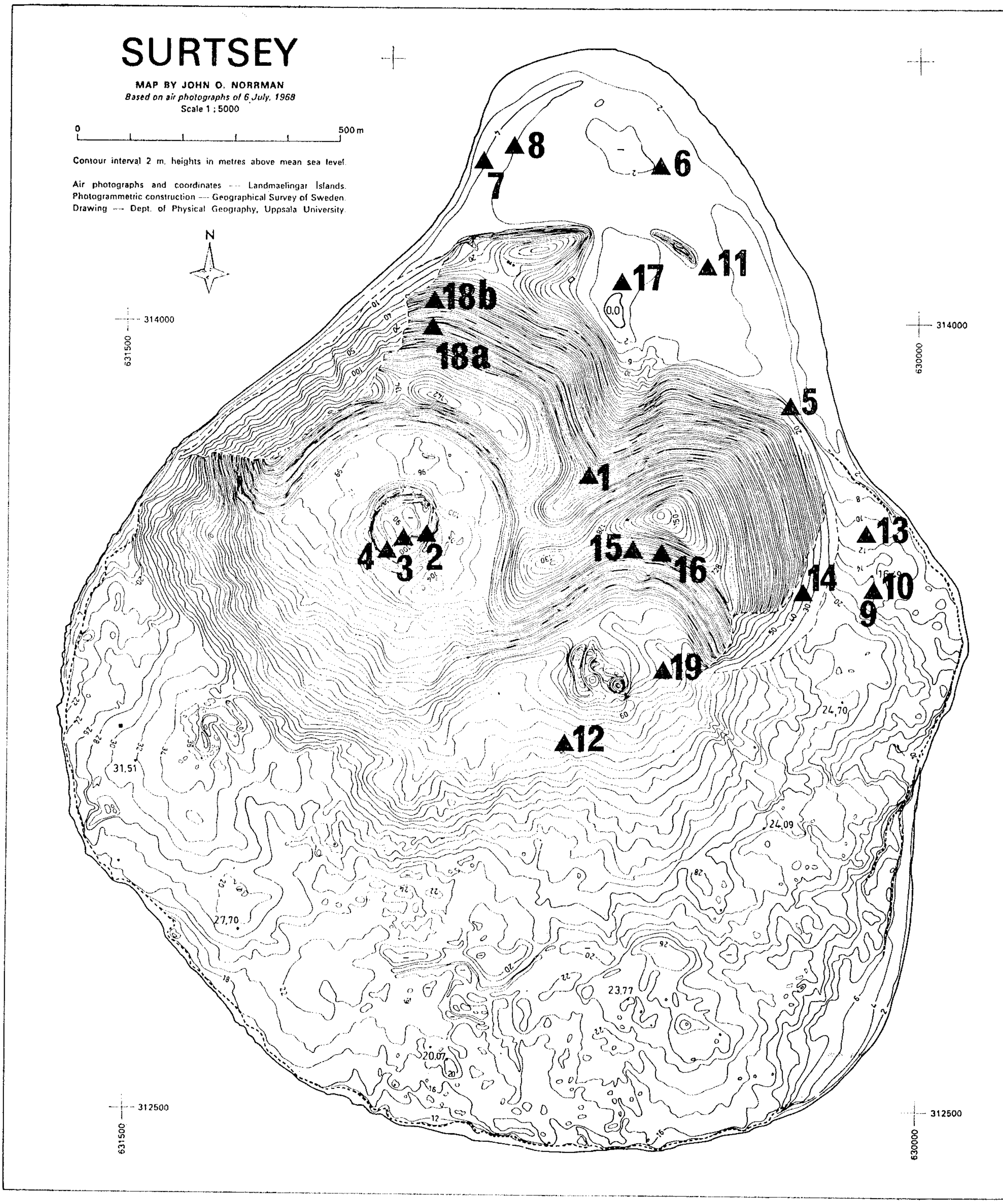


Figure 1. The symbols show the locations for the samplings and the nitrogen fixing experiments *in situ*, July 1972. – Map of Surtsey by John O. Norrman, Uppsala.

TABLE 1

Sample location No.	ng N_2 fixed $cm^{-2} h^{-1}$ Mean of 9 samples	Occurrence of nitrogen fixing blue-green algae	*Azotobacter*	nitrifying organisms	denitrifying organisms	Description of the locations and temperature and light conditions at time of sampling and during the *in situ* experiments
1	2.1 ± 0.2	–	–	+	+	Light-colored tephra, green-colored surface (olivine). Moist. Soil temp. 42°C, 24500 Lux.
2	5.5 ± 0.3	*N. musc.*	–	+	+	Crater border. Sparsely moss-covered. Black soil. Rather moist. Soil temp. 42°C, 26000 Lux.
3	2.0 ± 1.2	*N. musc.*	–	+	+	Crater border. Sparsely moss-covered. Salt crystals. Rather moist. Soil temp. 42°C, 28000 Lux.
4	11.7 ± 2.9	*N. musc.*	–	+	+	Crater border. Sparsely moss-covered. Black soil. Steam. Rather moist. Soil temp. 28°C, 34000 Lux.
5	0.2 ± 0.0	–	–	–	+	Rock-wall. Light colored lava. Soil temp. 21°C, 38000 Lux.
6 A			–	+	+	Lava-sand, sampled near a piece of drifted wood. Soil temp. 14°C.
6 B			–	–	+	Lava-sand, sampled under the same piece of wood. Soil temp. 14°C.
7	0.3 ± 0.1	–	–	+	+	Tephra. Traces of bird excrements. Soil temp. 14°C, 31000 Lux.
8			–	+	+	Tephra. Near an old piece of air-exposed, drifted plywood. Soil temp. 14°C.
9	62.0 ±23.7	*An. var.*	–	–	+	Cave ceiling. Rather moist. Soil temp. 11°C, 13100 Lux.
10	4.0 ± 1.9	*An. var.*	–	+	+	Bottom of the same cave. Soil temp. 12°C, 8000 Lux.
11			–	–	+	Driftwood (unplaned pine wood) with myceliumspots of *Trichoderma viride* Pers. ex. S. F. Gray.
12 A	64.5 ±12.5	*An. var.*	–	+	+	Moss-covered gray lava-stones. Ground temp. 21°C, 44000 Lux.
12 B	26.0 ±11.5	–	–	–	+	Moss-covered red lava-stones. Ground temp. 24°C, 44000 Lux.
12 C	0.3 ± 0.1	*An. var.*	–	+	+	Rather moist soil without mosses. Soil temp. 18°C, 64000 Lux.
13			–	+	+	Rhizosphere of *Honkenya peploides* (L.) Ehrh. ssp. *diffusa* (Hornem.) A. Löve.
14 A			–	+	+	Lava-sand. From the surface.
14 B			–	+	+	Lava-sand. From 10–15 cm deep layer.
14 C			–	–	+	Lava-sand. From 20–25 cm deep layer.
15			–	+	+	At the entrance of the cave "The Bell" (according to G. H. Schwabe). Moss-covered. Moist. Soil temp. 22°C, steam temp. 54°C. Moss-covered.
16			–	+	+	On the wall, inside the same cave. Temp. 15°C. Moist. Moss-covered.
17	0.3 ± 0.1	–	–	+	+	Former old lagoon. Moist fine lava-sand 105 cm above sea-water-table. Soil temp. 17°C, 34000 Lux.
18 A	0.4 ± 0.2	–	–	+	+	Tephra. Surface layer. Soil temp. 17°C, 28000 Lux.
18 B			–	–	+	Tephra. From 15–20 cm deep layer. Soil temp. 22°C.
19 A			–	+	+	Just near a steam-hole. Light colored lava. Soil temp. 45°C.
19 B			–	+	+	30 cm from the same steam-hole. Light colored lava. Soil temp. 28°C.
19 C			–	+	+	60 cm from the same steam-hole. Light colored lava. Soil temp. 22°C.

Table 1. The occurrence of some different types of microorganisms involved in the nitrogen cycle of Surtsey, the results of the nitrogen fixing experiments *in situ*, and a description of the locations studied. Location numbers refer to Fig. 1. Organisms present +, absent –.

the samples were stored at low temperatures.

The samples from the lava fields of Hekla were collected Oct. 15-16, 1972 by Á. H. Bjarnason in the same manner, and the results obtained will also be used by him in his plant ecological investigation of Iceland.

Determinations of nitrogen fixation in situ and under controlled conditions

The acetylene reduction technique, introduced by Stewart et al. (1967, 1971) and adapted for analyses *in situ* by Henriksson et al. (1972 a), was used for determinations of nitrogen fixation. The method as slightly modified is as follows: Soil samples were taken with a sterilised cork borer (1.6 cm^2 in area) from the surface layer 5-7 mm) and put aseptically in separate serum bottles of 7 ml volume. Each soil sample represented about 1 ml. The bottles were sealed with screw caps and suitable rubber discs, specially tested for this type of analysis (free from ethylene). To avoid leakage after injections the rubber discs were coated with small amounts of silicone grease (Dow Corning nontoxic stopcock grease). In each bottle 0.6 ml pure acetylene at normal pressure was injected by a hypodermic syringe and incubated *in situ* for 1 hour. Every analysed site is represented by nine separate samples evenly dispersed on an area of 1 m^2. The nitrogenase activity was then stopped and the samples preserved by adding 0.5 ml saturated water solution of ammonium sulphate to each bottle. In the laboratory the gas phases were analysed for ethylene by a gas chromatograph (Perkin-Elmer model 880) fitted with a 2.5 m long, 3.18 mm diameter column of Porapac T (50-80 M). The column had a temperature of 100°C and pure nitrogen gas served as carrier gas at a flow of 25 ml/min. The amount of ethylene per sample was quantitatively determined by comparison with runs of ethylene of known concentrations. The ethylene content of the acetylene gas was measured in the same manner and applied as a correction factor to the experimental data. The calculations of nitrogen fixation were based on the theoretical value 3:1 as the molar ratios of ethylene produced and N_2 fixed (Stewart 1968).

The determinations of nitrogen fixing capacities of the soil samples from Hekla and Uppland, discussed in this paper, were performed exactly in the same way as the Surtsey samples of 1970 (Henriksson et al. 1972 b, 1972 c, 1975).

Enrichment cultures of blue-green algae and Azotobacter

The enrichment medium for nitrogen fixing blue-green algae was as follows (after Gorham et al. 1964, modified): K_2HPO_4 17.4 mg, $FeCl_3$ 0.3 mg, E.D.T.A. 7.4 mg, $MgCl_26H_2O$ 19.0 mg, $MgSO_47H_2O$ 49.0 mg, $CaCl_22H_2O$ 14.7 mg, NaCl 58.5 mg, and redist. water up to 1000 ml. In addition trace elements were added according to Clendenning et al. (1956). The cultures in duplicate were placed at 20°C and 3000 Lux (Philips TL/33). The identification of algae was made after Geitler (1932). About 2 g of soil were tested from each locality.

For *Azotobacter* the enrichment nutrient solution recommended by Gebhardt and Anderson (1958) was used. The composition was as follows: mannitol 10 g, K_2HPO_4 0.5 g, $MgSO_47H_2O$ 0.2 g, NaCl 0.2 g, $FeCl_3$ 5 mg, $MnSO_44H_2O$ 5 mg, redist. water up to 1000 ml. In addition 50 g sterilized $CaCO_3$ was added after autoclaving. The cultures in triplicate were placed at 25°C in dark for 7 weeks and were visually observed at intervals. About 1.5 g of soil were tested from each locality.

TABLE 2

Locality	Soil dated year	Number of locations	ng N_2 fixed $g^{-1}h^{-1}$	References
Hekla, Iceland				
Katlar	1766	10	2.2 ± 1.0	
Krakatindshraun (Nýjahraun)	1878	10	1.4 ± 0.9	
Lambafitarhraun	1913	10	4.3 ± 2.4	
Surtsey, Iceland	1963—67	9	16.0 ± 6.0	Henriksson et al. (1972 b)
Uppsala, Sweden, uncult. soils	—	8	$(2.7 \pm 0.1) \cdot 10^3$	Henriksson et al. (1972 c)
Uppsala, Sweden, cult. soils	—	6	$(2.1 \pm 0.5) \cdot 10^3$	Henriksson et al. (1975)

Table 2. The nitrogen fixing capacities under controlled conditions of volcanic soils from Hekla and Surtsey, Iceland and of precambrian sedimentary soils from Uppland, Sweden.

TABLE 3

Constituents	mg / 100 g air dried soil		
	Surtsey sample 14/1972 Lava	Surtsey sample 18A/1972 Tephra	Means from 6 Swedish wheat fields
Phosphorus, P-AL	12.7	6.3	11.3
P-HCl	81.	77.	69.
Potassium, K-AL	13.3	15.5	27.6
K-HCl	370.	360.	388.
Magnesium, Mg-AL	56.0	61.0	29.6
Mg-HCl	3.550.	3.900.	950.
Calcium, Ca-AL	112.	122.	860.
Ca-HCl	3.200.	3.125.	1.060.
Sodium, Na-AL	60.	65.	10.6
Na-HCl	2.018.	2.190.	38.
Sulfur, S	20.	68.	52.
Nitrogen, NH_4-N	6.	7.	6.
NO_3-N	<1.	<1.	26.5
N-Kjeldahl	2.0	2.0	290.
Iron, Fe-AL	193.	200.	31.
Copper, Cu-HCl	40.4	43.7	3.2
Manganese, Mn	0.40	0.31	0.50
Boron, B	0.53	0.16	0.90
Spec. conductance, 20°C	$90 \cdot 10^{-6}$	$100 \cdot 10^{-6}$	$50-190 \cdot 10^{-6}$
pH	6.6	6.8	6.2–7.4

Table 3. Analyses of the virgin lava and tephra sand of Surtsey compared with cultivated soils from Uppland, Sweden. For the interpretation of the terms –AL and –HCl, see Material and Methods.

Qualitative analyses of nitrification and denitrification organisms

In order to find out if nitrification and dentrification processes are commonly present in the soil of Surtsey, enrichment cultures of nitrifying and denitrifying organisms were made from soil samples, and the presence of NO_3^-, NO_2^-, and NH_4^+ ions in the culture media were analysed after 3, 6, and 8 weeks of incubation in the dark at 25°C.

The enrichment medium for the nitrite and nitrate forming bacteria of the genera *Nitrosomonas* and *Nitrobacter,* aerobic chemosynthetic autotrophs, was as follows (Aaronson 1970, slightly modified): $(NH_4)_2SO_4$ 0.66 g, NaCl 0.29 g, KH_2PO_4 0.68 g, $MgSO_4 7H_2O$ 0.25 g, $CaCO_3$ 10 g, $FeCl_3$ 5 mg, redist. water up to 1000 ml.

The enrichment medium for the denitrifying organisms, including several species, was as follows (slightly modified from Cunningham 1947, the nitrate addition according to Aaronson 1970): Oxoid bact. peptone 10 g, KH_2PO_4 0.5 g, $MgSO_4 7H_2O$ 0.5 g, $NaNO_3$ 1.0 g, $FeCl_3$ 5 mg, and redist. water up to 1000 ml.

To 15 ml of the autoclaved media 0.5 g soil was added aseptically. All the series were made in triplicates. Uninoculated controls were incubated and treated in the same way as the soil cultures.

The analyses of NO_3^-, NO_2^-, and NH_4^+ ions were made after detailed instructions and reagent descriptions made by Aaronson (1970). However, the test volumes used were half those recommended by Aaronson.

Soil analyses

The soil analyses recorded (Table 3) were carried out by the National (Swedish) Laboratory of Agricultural Chemistry, Uppsala. The analytical standard methods used are confirmed by Royal Proclamation of the National (Swedish) Board of Agriculture (1965).

The easily soluble constituents, in table marked -AL (e.g. P-AL, K-AL), are extracted by standard AL-solution (0.10 M NH_4-lactate, 0.40 M acetic acid). Values from 2.0 M HCl extractions (e.g. P-HCl, K-HCl) also include stored constituents.

In comparison to the soil samples of Surtsey from localities No. 14 (lava sand) and No. 18 (tephra sand), both about 40 m above sea level, mean values from six Swedish wheat fields from the surroundings of Uppsala are included (Table 3).

The soil samples of Surtsey and the Swedish ones represent the upper surface layers.

RESULTS

Biological nitrogen fixation in situ

The analytical results, together with a short description of the 13 investigated localities, are recorded in Table 1. The resulting *in situ* values, 0.2-64.5 ng N_2 cm^{-2} h^{-1}, show biological nitrogen fixation at all localities studied and verify the assertion that active nitrogen fixation is established on Surtsey. It was found by enrichment cultures that the nitrogen fixing activities could be attributed to the presence of nitrogen fixing blue-green algae in the soil. The algae were unevenly dispersed in the surface layer of the soil, which is reflected in the varying nitrogen fixing values. For the same reason some of the enrichment cultures did not contain any nitrogen algae at all in spite of the occurrence of nitrogen fixation, since the sampling spots for the algal cultures were not the same as the spots used for the measurement of nitrogen fixation. As in earlier investingation (Henriksson et al. 1972 b) the cosmopolitan *Nostoc muscorum* Ag. and *Anabaena variabilis* Kütz. were recorded. This coincides with the observations of Schwabe (1974), who has found them well dispersed over the island. The values here reported are probably not typical for the hole island, since several of the sites were selected with the intension of obtaining positive results for nitrogen fixation. Conditions favouring the occurence of nitrogen fixing algae are, for instance, moist soil and presence of mosses (Schwabe 1974).

Biological nitrogen fixation in Surtsey soil in comparison to volcanic soils of the mainland and to Swedish uncultivated and cultivated soils

The determinations of nitrogen fixation performed *in situ* show the actual activities under present conditions of water content, temperature, light, and nutrient constituents. Since the conditions in nature are varying, the values received under field conditions fluctuate and depend on the water and weather conditions. However, biological nitrogen fixation in a soil can be more precisely stated by capacity measurements at standard conditions, and the results of such measurements from soils of differen districts will be comparable (Henriksson et al. 1972 c). For that reason soil samples from 9 localities on Surtsey were analysed in 1970. The analyses showed values between 2-54 ng fixed N_2 g^{-1} h^{-1} at 20°C and 3000 Lux (Henriksson et al. 1972 b). The intension is to follow up the development of nitrogen fixation on the island continuously.

In order to have some idea of the development of biological nitrogen fixation on Surtsey, samples from three Icelandic lava flows from Hekla, formed in 1766, 1878, and 1913 respectively, were analysed. This was performed under laboratory conditions, and the technique was exactly the same as for the samples of Surtsey. The results from these newly formed Icelandic soils are also compared with results from uncultivated and cultivated soils from the surroundings of Uppsala in Sweden. The results are brought together in Table 2. From these values it is evident that nitrogen fixation is relatively high on Surtsey compared to the nitrogen fixation found in the volcanic soils of Hekla, but low compared to the soils of Uppland (Sweden). The lava flows of Hekla are all well colonised by mosses and lichens. The pH is 6.1-6.9, and the structures are of the same specially sandy character as that of Surtsey. The lower values of Hekla may be explained by higher competition in older lava flow. The same tendency may occur later on Surtsey, when biological life there is established to the same level. Anyhow, the Swedish soils of precambrian provenience show capacity values of much higher dimensions.

In this experiments little or no nitrogen fixation occurred in the dark showing that heterotrophic nitrogen fixing bacteria such as *Azotobacter* and *Clostridium* are of very little or no importance. In addition, the enrichment cultures of *Azotobacter* showed negative results, which is also in accordance with the investigation of Schwartz and Schwartz (1972). It is, however, possible that photosynthetic bacteria with ability to fix nitrogen may be of certain smaller importance (Henriksson 1971, Stewart 1973).

Nitrification and denitrification processes on Surtsey

The nitrifying processes caused by *Nitrosomonas* and *Nitrobacter* are known to be most favourable in soils at a pH of about 7. Higher alkaline conditions support the activity of *Nitrosomonas* and retard that of *Nitrobacter*, resulting in a nitrite accumulation in the soil, which, however, can be reduced by present denitrifying organisms (Campbell and Lees 1967). On the other side, the activity of these organisms is inhibited in acid conditions. The Surtsey soils show pH reactions of very slight acidity, near the neutral point (Table 3). This fact indicates a good environment for nitrogen reducing organisms, which are also activated in more or less anaerobic conditions, which are common in a normal soil.

The intension of the reported investigation is to give some indication of the dispersion of these two significant groups of organisms. The results are given in Table 1. In every sample tested, activities of nitrogen reducing organisms were found, also from the stranded wood. After 8 weeks no traces of the nitrate, supplied to the culture medium, could be recovered. The analyses after 3 and 6 weeks showed that the expected processes were going on.

In the case of *Nitrosomonas* and *Nitrobacter* the results showed the presence of these organisms in all surface layers except localities No. 5, 9, 12 B, 14 C, and 18 B, where no evidence was observed at all. Samples No. 14 C and 18 B represent deeper layers in the soil, where aerobic conditions, necessary for the organisms involved, are suppressed. On the other side, in the rhizosphere of *Honkenya peploides* (No. 13) the organisms were represented.

No traces of NH_4^+, NO_3^-, or NO_2^- were recorded after 8 weeks in the cultures of No. 2, 4, 13, 14 A, and 18 A, indicating a total conversion of NH_4^+ to N_2. The analyses after 3 and 6 weeks showed that the expected processes were going on.

The soil analyses of Surtsey compared to cultivated Swedish soils

The hitherto published chemical analyses of the lava of Surtsey (Thorarinsson et al. 1964, Jakobsson 1968) show primarly the mineralogical state. However, those results do not represent the actual nutrient availability for biological requirements. In respect to this, analyses in the agricultural chemical way appear to be more useful (Table 3).

One of the most remarkable differences between the virgin Surtsey-soils and the Swedish ones is the very high content of readily available iron on Surtsey. This iron, derived from the alkali olivine basalts (about 13% olivine), will certainly be reduced as time goes on. The olivine components will then be transformed to more insoluble compounds. The copper analyses of the Surtsey samples show also very high values; the recorded Swedish ones are more typical. On the other hand, boron shows low values in the soils of Surtsey.

The presence of high quantities of available sodium on Surtsey can be explained by contributions from the sea. In addition, magnesium and calcium show high values, especially in the stored fractions. In the case of Mg-HCl and Ca-HCl it is evident that these constituents are present in less soluble forms, magnesium in olivine and calcium as $CaSO_4$. Calcium is enriched in the soils of Surtsey by salt spray from the sea and precipitates as sulphate (Sigvaldason and Fridriksson 1968).

The phosphorus content on Surtsey is high compared to common uncultivated soils in the northern temperate zone, and the valus recorded are of the same magnitude as in fertilized cultivated Swedish soils.

Regarding sulfur, the analyses of the lava show surprisingly low values, as much higher could be expected on account of the frequent smell of hydrogen sulfide. However, this sulfur-fraction is easily lost at the time of sampling, and is therefore not included in these actual analyses.

Compared to the Swedish soils the most striking, but not unexpected, observation is the extremely low content of nitrogen compounds available for biological life on the island. In uncultivated soils nitrogen deficit is common, but in the virgin soils of Surtsey it is definitely pronounced. On the other hand, the NO_3-AL value (26.5 mg/ 100 g soil) for the Swedish cultivated soils is high and can be explained by fertilizer application shortly before the sampling. However, this NO_3-value will shortly be reduced by rain, drainage, and by assimiliation.

The pH of the Surtsey soils shows values just under neutrality, and the specific conductances of the soils are of the same order as those of the cultivated Swedish ones. However, on Surtsey the composition of the salt mixture in the soil can be easily changed by leaching rainfalls and repeated deliveries from the sea. Sigvaldason and Fridriksson (1968) found 121.5 mg dissolved salts per 100 g tephra after thoroughly leaching with distilled water. Their sample was from the same area as locality No. 18.

At present time the Surtsey soils contain negligible quantities of organic matter and are free from humus and subsoil. These organic compounds are a requirement for many microorganisms and higher plants, not only for their growth but also for sufficient water holding capacity. Pure lava is not characterized by this latter quality, but on Surtsey the low water retension can be balanced by the high air humidity and normally abundant rainfalls.

The differences between the recorded analyses of the elements of the lava sand (No. 14) and tephra (No. 18) are remarkably small, and the two types of soil will probably be of about the same initial qualities with respect to biological development.

The analyses show that the preliminary limiting factor for general plant development on Surtsey is the very low content of nitrogen compounds. For this reason the Surtsey pioneers must have extremely small requirements for available nitrogen in the soil.

DISCUSSION

The vascular plants on Surtsey registered up to 1972, have been located on the shores or on those parts of the lowlands which are flooded by rough sea. In the locations they are frequently destroyed by sea and wind erosion or by becoming totally covered by light sand.

However, on other parts of the island mosses and lichens are stationary botanical pioneers (Fridriksson et al. 1972). 18 different species of mosses on 120 localities and 3 species of lichens on 2 localities were registered in 1970, and this development has increased during the last years.

In addition, the microflora is represented by algae, fungi, and bacteria, which has been verified by a number of investigations.

The content of nitrogen compounds of biological interest has not increased in time since the preliminary analyses of Ponnamperuma et al. (1967) were carried out. Consequently only those organisms which have small requirements for available nitrogen compounds are suited to be stationary and active pioneers on this island, and for that reason the photoautotrophic nitrogen fixing microorganisms are especially well-qualified.

The mosses and lichens are well-known to have low requirements for nutrients. Schwabe (1974) has demonstrated a general close association between mosses and nitrogen fixing blue-green algae on Surtsey. It is also evident from other investigators that mosses are supplied with nitrogen by nitrogen fixing blue-green algae (Vlassak et al. 1973) and *Azotobacter* (Snyder and Wullstein 1973). The latter have also made similar observations on lichens in pioneer ecosystems.

As a result of this investigation blue-green algae seem to be an important contributor of combined nitrogen to the studied ecosystem. However, Brock (1972, 1973) declared after visual observations on Surtsey, and microscopical examinations of soil samples in the laboratory, that "blue-green algae are quite unimportant as primary colonizers of Surtsey. Mosses and lichens are of greater importance, and coccoid algae (*Chlorophyta*) are of lesser importance." Brock neglects in that way the elementary significant physiological activity of the nitrogen fixing blue-green algae on Surtsey. Especially as considerable growth of only blue-green algae was observed in our cultures, where redistilled water or nitrogen-free nutrient solution was added to the soil samples.

Several of the investigated Surtsey localities (Table 1) show biological nitrogen fixation of the same order as has been measured from other soils. Henriksson (1971) and Henriksson et al. (1972 a) found in *in situ* determinations of uncultivated Swedish soils a nitrogen fixation of 1-450 ng N_2 cm^{-2} h^{-1}, of which the high value was measured under special conditions. Stewart and Harbott (published in Fogg et al. 1973) recorded 4 ng N_2 cm^{-2} h^{-1} for arable and 14 ng N_2 cm^{-2} h^{-1} for pastureland in Scotland.

The demonstrations of general occurrence of nitrifying and denitrifying organisms on Surtsey will not give any informations about their activities *in situ*, but the results indicate the presence of these catabolic parts of the nitrogen cycle.

Finally, blue-green algae are of essential importance for the asymbiotic development of heterotrophic microorganisms in virgin soil and for the primary stages of soil formation (Harley 1970, Shtina and Nekrasova 1971, Vlassak 1972). Because of them the floristic and faunistic colonization of Surtsey will accelerate (Lindroth et al. 1973).

ACKNOWLEDGEMENTS

The authors had the good fortune to visit Surtsey as members of the *Swedish Biological Surtsey Expedition* in the summer 1972. For this privilege we are deeply indebted to the leader, Prof. Carl H. Lindroth, University of Lund. We are also grateful to Prof. Nils Fries, Head of the Institute of Physiological Botany, University of Uppsala, for his valuable interest and provision of facilities, to Dr. Bo Thente, Uppsala, for valuable discussions and to Mr. Ágúst H. Bjarnason, Reykjavik, for collecting the samples from Hekla. Our thanks are also due to Dr. Howard Bonnett, Uppsala, for careful revision of the English of our manuscript.

Support for travel to Surtsey was provided by the *Swedish Natural Research Council* and accomodation on Surtsey by the *Surtsey Research Society*.

ABSTRACT

Nitrogen fixation in *in situ* determinations at 13 locations on Surtsey amounted to 0.2—64.5ng N_2 cm^{-2} h^{-1}. The algae involved were *Anabaena variabilis* and *Nostoc muscorum*. *Azotobacter* were not found in either these 13 or in the other 5 locations studied. On the other hand, nitrifying and denitrifying organisms were found to be commonly occurring. The nitrogen fixing capacities of Surtsey soil samples were higher than those of soils from earlier lava flows formed by Hekla in 1766, 1878, and 1913, but much lower than the nitrogen fixing capacities of uncultivated precambrian Swedish soils. Lava and tephra sand were analysed by agricultural chemical methods, and the nutrients available for plants are discussed. The values are also compared with similar ones from Swedish wheat fields. At the present time a pronounced deficit of nitrogen compounds characterizes the Surtsey soil.

References

Aaronson, S., 1970: Experimental microbial ecology. — Acad. Press. N.Y. 236 pages.

Behre, K. and Schwabe, G. H., 1970: Auf Surtsey/Island im Sommer 1968 nachgewiesene nicht marine Algen. — Schr. Naturw. Ver. Schleswig-Holst. Sonderband Surtsey: 31—100.

Brock, T. D., 1972: Microbiological observations on Surtsey,

1970. — Surtsey Research Progress Report 6: 11—13.
Brock, T. D., 1973: Primary colonization of Surtsey, with special reference to the blue-green algae. — Oikos, 24: 239—243.
Campbell, N. E. R. and Lees, H., 1967: The nitrogen cycle. — In Soil Biochemistry (ed. McLaren, A. D. and Peterson, G. H.). Marcel Dekker, Inc. N.Y. 509 pages.
Castenholz, R. W., 1972: The occurrence of the thermophilic blue-green alga, *Mastigocladus laminosus*, on Surtsey in 1970. — Surtsey Research Progress Report 6: 14—19.
Clendenning, K. A., Brown, T. E. and Eyster, H. C., 1956: Comparative studies of photosynthesis in *Nostoc muscorum* and *Chlorella pyrenoidea*. — Canad. J. Bot. 34: 943—966.
Cunningham, A.; 1947: Practical bacteriology. — Oliver and Boyd. Edinb. 222 pages.
Fogg, G. E., Stewart, W. D. P., Fay, P. and Walsby, A. E., 1973: The blue-green algae. — Acad. Press. London. 459 pages.
Fridriksson, S., Sveinbjörnsson, B. and Magnússon, S., 1972: Vegetation on Surtsey — summer 1970. — Surtsey Research Progress Report 6: 54—63.
Gebhardt, L. P. and Andersson, D. A., 1958: Laboratory instructions in microbiology. 2nd ed. — C. V. Mosby Co. St. Louis. 261 pages.
Geitler, L., 1932: Cyanophyceae von Europa unter Berücksichtigung der anderen Kontinente. — Rabenhorts Kryptogamenflora 14. Leipzig. 1162 pages.
Gorham, P. R., MacLachlan, R., Hammer, U. and Kim, W. D., 1964: Isolation and culture of toxic strains of *Anabaena flos-aquae* (Lyngb.) de Bréb. — Verh.int. Ver. Limnol. 15: 796—803.
Harley, J. L., 1970: Importance of microorganisms to colonising plants. — Trans. Bot. Soc. Edinb. 41: 65—70.
Henriksson, E., 1971: Algal nitrogen fixation in temperate regions. — Plant and Soil, Spec. vol. Biological nitrogen fixation: 415—419.
Henriksson, L. E., Enckell, P. H. and Henriksson, E., 1972 c: Determination of the nitrogen fixing capacity of algae in soil. — Oikos 23: 420—423.
Henriksson, E., Englund, B., Hedén, M.—B. and Was, I., 1972 a: Nitrogen fixation in Swedish soils by blue-green algae. — In Taxonomy and Biology of Blue-green Algae (ed. Desikachary, T. V.). Univ. Madras. 591 pages.
Henriksson, L. E. and Henriksson, E., 1974: Occurrence of fungi on the volcanic island of Surtsey, Iceland. — Acta Bot. Icelandica 3: 82—88.
Henriksson, E., Henriksson, L. E. and DaSilva, E. J., 1975: A comparison of nitrogen fixation by algae of temperate and tropical soils. — In Nitrogen Fixation in the Biosphere (Eds. Stewart, W. D. P. and Nutman, P. S.). Cambridge Univ. Press. p: 199—206.
Henriksson, E., Henriksson, L. E. and Pejler, B., 1972 b: Nitrogen fixation by blue-green algae on the island of Surtsey, Iceland. — Surtsey Research Progress Report 6: 66—68.
Holmberg, O. and Pejler, B., 1974: On the terrestrial microfauna of Surtsey during the summer 1972. — Surtsey Research Progress Report 7: 17—19.
Jakobsson, S., 1968: The geology and petrography of the Vestman Islands. — Surtsey Research Progress Report 4: 113—130.
Lindroth, C. H., Andersson, H., Bödvarsson, H. and Richter, S. H., 1973: Surtsey, Iceland. The development of a new fauna, 1963—1970. Terrestrial invertebrates. — Entemol. Scand. Suppl. 5. 280 pages.
National Swedish Board of Agriculture, 1965: Royal proclamation regarding the stipulations for soil analyses and methods. (In Swedish.) Proclam. No. 1 with suppl. Stockholm.
Ponnamperuma, C., Young, R. S. and Caren, L. D., 1967: Some chemical and microbiological studies of Surtsey. — Surtsey Research Progress Report 3: 70—80.
Schwabe, G. H., 1970 a: On the algal settlement in craters on Surtsey during summer 1968. — Surtsey Research Progress Report 5: 68—69.
Schwabe, G. H., 1970 b: Zur Ökogenese auf Surtsey. — Schr.d. Naturw. Ver. Schleswig-Holst. Sonderband Surtsey: 101—120.
Schwabe, G. H., 1971: Die Ökogenese im terrestrischen Bereich postvulkanischer Substrate, schematische Übersicht bisheriger Befunde auf Surtsey/Island. — Peterm. Geograph. Mitt. 115: 268—273.
Schwabe, G. H., 1974: Nitrogen fixing blue-green algae as pioneers on Surtsey 1968—1973. — Surtsey Research Progress Report 7: 22—25.
Schwabe, G. H. and Behre, K., 1972: Algae on Surtsey in 1969—1970. — Surtsey Research Progress Report 6: 85—89.
Schwartz, W. and Schwartz, A., 1972: Geomikrobiologische Untersuchungen. X. Besiedelung der Vulkaninsel Surtsey mit Mikroorganismen. — Zeitsch. f. allg. Mikrobiol. 12: 287—300.
Shtina, E. A. and Nekrasova, K. A., 1971: The direct and indirect contribution of soil algae to the primary production of biocoenoses. — Int. Nat. de la Recherche Agronomique, Paris, 71: 37—45.
Sigvaldason, G. and Fridriksson, S., 1968: Water soluble leachate of volcanic ash from Surtsey. — Surtsey Research Progress Report 4: 163—164.
Snyder, J. M. and Wullstein, L. W., 1973: Nitrogen fixation on granite outcrop pioneer ecosystems. — The Bryologist 76: 196—199.
Stewart, W. D. P., 1968: Acetylene reduction by nitrogen fixing blue-green algae. — Arch. Mikrobiol. 62: 336—348.
Stewart, W. D. P., 1973: Nitrogen fixation by photosynthetic microorganisms. — Ann. Rev. of Microbiol. 27: 283—316.
Stewart, W. D. P., Fitzgerald, G. P. and Burris, R. H., 1967: *In situ* studies on N_2 fixation using the acetylene reduction technique. — Proc. Nat. Acad. Sci. Wash. 58: 2071—2078.
Stewart, W. D. P., Mague, T., Fitzgerald, G. P. and Burris, R. H., 1971: Nitrogenase activity in Wisconsin lakes of differing degrees of eutrophication. — New Phytol. 70: 497—509.
Thorarinsson, S., Einarsson, T., Sigvaldason, G. and Elisson, G., 1964: Submarine eruption off the Vestmann islands. — Bull. Volc. 27: 444.
Vlassak, K., 1972: Biologische Stikstofffixatie (Biological nitrogen fixation) (In Dutch). — Agricultura 4: 4—52.
Vlassak, K., Paul, E. A. and Harris, R. E., 1973: Assessment of biological nitrogen fixation in grassland and associated sites — Plant and Soil 38: 637—649.

Moss Vegetation on Surtsey in 1971 and 1972

By
SKÚLI MAGNÚSSON and STURLA FRIDRIKSSON*
* Agricultural Research Institute, Reykjavík

INTRODUCTION

Moss was first found on Surtsey, in two locations, in the year 1967 (Jóhannsson, 1968). This situation prevailed during 1968, and it was not until 1969 that moss was found to any significant degree (Bjarnason and Fridriksson, 1972). The distribution map for that year showed that moss had been found in 29 of the island's quadrats. In 1970 the distribution was even greater (Fridriksson et al., 1970), at which time it was thus clear that the island had finally been colonized by mosses. Until this year, observations had been somewhat at random and directed solely at collecting samples of moss for analysis and keeping track of general distribution.

From 1969 to 1970 the number of moss species more than doubled, increasing from 6 to 16. This fact, in addition to a great jump in distribution pointed to the need for more exact observation of the island's moss flora. It was therefore decided to organize a careful and systematic investigation of the island in 1971. A division of the island into quadrats (Fridriksson et al., 1968) formed the basis of this research, and each and every quadrate (100×100 m) was investigated separately. This method produced a picture not only of general distribution but also af species count and the spread of each individual species.

In 1972 it was decided to carry out the same kind of investigation of distribution but to include observation of the habitat choice of the species and their covaregae in these habitats, and thereby attempt to discover which species were found together in communities and which species were typical for these communities.

RESEARCH PROCEDURES

1971: A careful search for mosses was made in all quadrats of the lava. It was considered unnecessary to make such a careful search on that part of the island consisting of volcanic ash and sand, since moss does not yet appear to thrive in such environments.

An exception, however, was made in those quadrats containing fumaroles (such as I-12 and H-13). It was customary to confine the search for mosses to one quadrat at a time, and to cover this area thoroughly. The distribution of species identified on the spot was recorded on a chart, whereas samples of other species were taken for laboratory identification. A drawback of the sampling procedure was the way in which all samples from the same quadrat were collected in one box, which prevented a means of ascertaining a species' frequency of occurrence in each particular quadrat. The procedure established earlier (Fridriksson et al., 1970) was used to determine general distribution. An aerial photograph, with the quadrat boundaries drawn in, and a compass were used in determining location within a quadrat. In making up the maps showing general distribution for each species, a species was assigned to one of three groups according to its frequency of occurrence in that quadrat. (See Table I.)

1972: The area in question was combed in the same manner as in 1971. Collection procedures, however, were modified so that each sample was kept in a special container designated by a catalogue number and a quadrat number. For each species that was found in a quadrat, the investigators noted the extent of coverage and the habitat at the first ten discovery sites in the quadrat. If the species was found in ten or fewer spots, then its coverage and habitat were noted at each location. Habitats were described as soon as they were observed, and were designated by a number that was used later for cataloguing purposes. The following categories were used:

1. Perpendicular lava cliffs in hollows and narrow crevices.
2. Moist sand in caverns shaded by a lava formation, from which water drips onto the sand.
3. A thin layer of tephra on a lava surface; fully exposed and unaffected by fumaroles.
4. Same as Habitat 3, but affected by fumaroles.
5. Naked, exposed lava surface without sand.
6. Hollows with sandy bottoms, moist and somewhat shaded.
7. Narrow cracks in lava, filled with sand.
8. Moist shaded sand, warm from fumaroles.
9. Sand-covered lava, fully exposed.
10. Sand on a lava slope, partly shaded, more moist than in Habitat 9.
11. Moist, naked, and shaded lava slopes.
12. Sand at the bottom of deep and narrow cracks in the lava; shaded.

Cover was estimated as the average cover of the species in its habitat, which was determined with the use of a steel frame (25×25 cm) that contained a wire mesh with ten equal squares.

Cover was recorded in percentage, and the symbol + was used to designate cover less than 1%. In calculating the average cover for each species in the quadrats, + was counted as 0.2% cover.

Information about a species' frequency of occurrence in a quadrat was obtained later when the data was compiled. (Table I.)

In addition to the above-mentioned details, investigators noted which species were found with capsules and gemmae.

TABLE I

The following categories were used as criteria in determining the distribution symbols for each species in a quadrat:

Distribution Symbol	1971 Categories	1972 Categories
●	Species found often	Species found in 10 or more locations
◑	Species found in several locations	Species found in 2—9 locations
○	Species found once	Species found once

CONCLUSIONS

General distribution: Between 1970 and 1971 the general distribution of mosses increased considerably on the island, but further increase between 1971 and 1972 was little. The clearest overview of these trends will be obtained by comparing the attached distribution maps with that from the year 1970 (Fridriksson et al., 1972).

The maps show that the main increase in the moss distribution occurred in the west, especially in 1971. Most of this area is on the slopes south of Surtur II, that is, in quadrats J-6 and J 8-9, K 6-10, L 6-9, and M 6-9. In this area the lava is very rough, 50% to 90% covered with volcanic ash (cf Fridriksson, Magnússon, and Sveinbjörnsson, 1972, p. 62). The area is very dry, with caverns and small overhangings that provide good conditions for moss vegetation. The species *Racomitrium canescens* grew in this newly colonized area in very small and widely-scattered patches, and was responsible for the increase in distribution between 1971 and 1972 in quadrats J 5-6 and K 5-6. Mounds of volcanic ash limit the spread of moss to the north, since moss is not able to take hold there.

A minor constriction appears to have developed on the southeastern coast from 1971 to 1972, and is probably the result of coastline erosion and, as a consequence, increased proximity to the sea.

Although the rate of change in the distribution boundaries was slower in 1972 than in the previous year, this does not mean that propagation in moss areas came to a halt, since the general coverage of moss steadily increases from year to year.

LIST OF MOSS SPECIES IN SURTSEY FROM 1967—1972

The two first columns in the list show the distribution of each species in 1971 and 1972 according to the following legend.

+ =	found	in		1	quadrat
1 =	—	—		2—10	quadrats
2 =	—	—		11—20	—
3 =	—	—		21—30	—
4 =	—	—		31—40	—
5 =	—	—		41 or more	—

The six following columns in the list show the occurrence of each species each year from '67—'72.

LIST OF MOSS SPECIES IN SURTSEY FROM 1967–1972

	'71	'72	'67	'68	'69	'70	'71	'72
POLYTRICHALES:								
Atrichum undulatum (Hedw.) Beauv.	1	2	..	..	..	x	x	x
Pogonatum urnigerum (Hedw.) Beauv.	1	2	..	..	x	x	x	x
Polytrichum alpinum Hedw.	+	1	..	..	..	..	x	x
Polytrichum longisetum Brid.	+	+	..	..	..	..	x	x
Polytrichum piliferum Hedw.		+	..	..	..	..	x	x
Polytrichum sphaerothecium (Besch.) Broth.		1	..	..	..	..	..	x
Psilophilum laevigatum (Wahlenb.) Lindb.		1	..	..	..	..	..	x
FISSIDENTALES:								
Fissidens adianthoides Hedw.	+	..	..	..	..	..	x	..
DICRANALES:								
Aongstroemia longipes (Sommerf.) B. S. G.	..	1	..	..	..	x	..	x
Ceratodon purpureus (Hedw.) Brid.	4	5	..	x	..	x	x	x
Dichodontium pellucidum (Hedw.) Schimp.	2	3	..	..	..	x	x	x
Dicranella crispa (Hedw.) Schimp.	2	2	..	x	x	x	x	x
Dicranella heteromalla (Hedw.) Schimp.	..	+	..	..	..	..	..	x
Dicranella schreberiana (Hedw.) Schimp.	+	..	..	..	..	..	x	..
Dicranella subulata (Hedw.) Schimp.	..	+	..	..	..	..	..	x
Dicranella varia (Hedw.) Schimp.	+	1	..	..	..	..	x	x
Dicranoweisia crispula (Hedw.) Lindb.	..	1	..	..	..	..	..	x
Distichium capillaceum (Hedw.) B. S. G.	+	1	..	..	..	..	x	x
Ditrichum cylindricum (Hedw.) Grout.	..	1	..	..	..	..	..	x
Ditrichum heteromallum (Hedw.) Britt.	..	+	..	..	..	..	..	x
Onchophorus virens (Hedw.) Brid.	+	+	..	..	..	..	x	x
POTTIALES:								
Barbula fallax Hedw.	..	1	..	..	..	..	..	x
Barbula ichmadophila C. Muell.	..	+	..	..	..	..	..	x
Barbula recurvirostra (Hedw.) Dix.	1	1	..	..	..	..	x	x
Barbula unguiculata Hedw.	..	+	..	..	..	..	..	x
Barbula vinealis Brid. var *Cylindrica* (Tayl.) Boul.	..	+	..	..	..	..	..	x
Encalypta ciliata Hedw.	+	1	..	..	..	..	x	x
Encalypta sp.	..	+	..	..	..	..	..	x
Trichostomum brachydontium Bruch.	..	+	..	..	..	..	..	x
GRIMMIALES:								
Grimmia apocarpa Hedw.	1	4	..	..	..	..	x	x
Grimmia maritima Turn.	+	1	..	..	..	..	x	x
Grimmia stricta Turn.	1	5	..	..	..	..	x	x
Grimmia torquata Hornsch.	..	1	..	..	..	..	..	x
Racomitrium canescens (Hedw.) Brid.	5	5	..	..	x	x	x	x
Racomitrium heterostichum (Hedw.) Brid. var. *sudeticum* (Funck) Grout.	..	+	..	..	..	..	..	x
Racomitrium lanuginosum (Hedw.) Brid.	5	5	..	..	..	x	x	x
FUNARIALES:								
Funaria hygrometrica Hedw.	5	5	x	x	x	x	x	x
BRYALES:								
Amphidium lapponicum (Hedw.) Schimp.	..	+	..	..	..	..	..	x
Anomobryum filiforme (Dicks.) Husn.	+	1	..	..	..	..	x	x
Aulacomnium palustre (Hedw.) Schwaegr.	..	+	..	..	..	..	..	x
Bartramia ithyphylla Brid.	1	3	..	..	..	..	x	x
Bryum spp.	5	5	..	x	x	x	x	x
Bryum algovicum Sendtn.	+	1	..	..	..	..	x	x
Bryum arcticum (R. Br.) B. S. G.	1	1	..	..	..	..	x	x
Bryum argenteum Hedw.	2	3	x	x	x	x	x	x
Bryum calophyllum R. Br.	..	1	..	..	..	..	..	x
Bryum klinggraeffii Schimp.	..	+	..	..	..	..	..	x
Bryum pallens Sw.	1	1	..	..	..	x	x	x
Bryum pallescens Schwaegr.	..	1	..	..	..	..	..	x
Bryum stenotrichum C. Muell.	2	5	..	..	..	..	x	x
Leptobryum pyriforme (Hedw.) Wils.	2	4	..	..	x	x	x	x
Mnium hornum Hedw.	1	1	..	..	..	..	x	x
Phiolonotis spp.	3	5	..	..	..	x	x	x
Philonotis fontana (Hedw.) Brid.	..	1	..	..	..	..	..	x
Plagiomnium cuspidatum (Hedw.) Kop.	..	1	..	..	..	..	..	x
Pohlia annotina (Hedw.) Loeske var. *decipiens* Loeske	+	..	..	..	..	..	x	..

Pohlia cruda (Hedw.) Lindb.	1	4	..	x	..	x	x	x
Pohlia proligera Kindb.	..	+	..	..	..	..	..	x
Pohlia schleicheri Crum.	..	+	..	..	..	..	..	x
Pohlia wahlenbergii (Web. & Mohr.) Andr.	3	5	..	..	..	x	x	x
HYPNALES:								
Amblystegium serpens (Hedw.) B. S. G.	..	1	..	..	..	..	..	x
Brachythecium albicans (Hedw.) B. S. G.	..	1	..	..	..	..	..	x
Brachythecium rivulare B. S. B.	..	+	..	..	..	..	..	x
Brachythecium salebrosum (Web. & Mohr) B. S. G.	..	1	..	..	..	x	..	x
Calliergon stramineum (Brid.) Kindb.	+	+	..	..	..	..	x	x
Campylium polygamum (B. S. G.) C. Jens.	1	2	..	..	..	..	x	x
Drepanocladus aduncus (Hedw.) Warnst.	..	1	..	..	..	..	..	x
Drepanocladus uncinatus (Hedw.) Warnst.	1	2	..	..	..	x	x	x
Hypnum lindbergii Mitt.	..	+	..	..	..	..	..	x
Isopterygium pulchellum (Hedw.) Jaeg. & Sauerb.	..	1	..	..	..	..	..	x
Rhytidiadelphus squarrosus (Hedw.) Warnst.	1	+	..	..	..	..	x	x
MARCHANTIALES:								
Marchantia polymorpha L.	+	+	..	..	..	..	x	x
JUNGERMANNIALES:								
Cephaloziella sp.	..	+	..	..	..	..	..	x
Scapania sp. (*curta* or *scandica*)	..	+	..	..	..	..	..	x
Solenostoma sp. (*Atrovirens* or *pumilum*)	..	+	..	..	..	..	..	x

LIST OF SPECIES

A great increase of species has occurred since 1970. In that year 16 species were known to exist on the island (cf. Fridriksson et al., 1972). When samples from the summer of 1971 had been analyzed, the number of known species had risen to 37, that is, an increase of 20, or more than half the total number. All these new species were rare that year, except *Bryum stenotrichum,* which in all probability had arrived on the island earlier, but specimens of which had not been identified as a distinct species as the fruiting bodies had not developed until 1971. All specimens had, up to this point, been recorded as *Bryum spp.*

It is significant that the first liverwort species to be detected on Surtsey, *Marchantia polymorpha,* was among these new species. Two or three small individuals of this species were found on a rock in a moist hollow of a cavern in quadrat 0-17. After all the samples collected in the summer of 1972 had been identified, the number of species had risen to 72, or twice the number noted in 1971. Like the new species identified in 1971, the new species in 1972 were all rare, – found only in a few places.

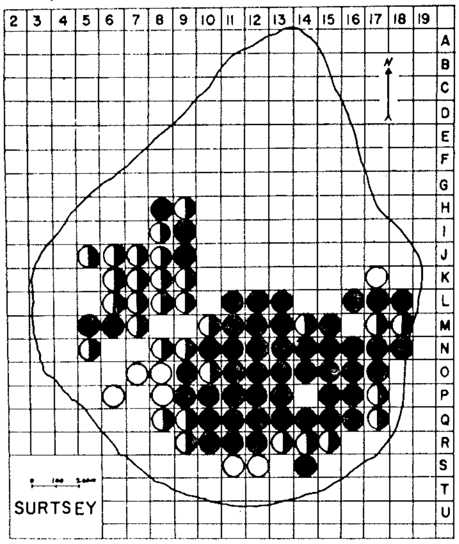
Three new liverworts were added to the list of known species, but it did not prove possible to assign them to a species with any certainty. They are species of the genera *Cephaloziella, Scapania,* and *Solenostoma,* all of which belong to the order *Jungermanniales.* The *Scapania* species is a member of either *S. scandica* or *S. curta,* whereas the *Solenostoma* species belongs either to *S. atrovirens* or *S. pumilum.*

Reference to the accompanying list discloses that two species that were observed in 1970 and 1972 were not found in 1971. These are the species *Aongstroemia Longipes* and *Brachythecium Salebrosum.* Both were found in one place in 1970; in 1972 the former was found in two quadrats, the latter in eight. This indicates that both species were present in 1971, but went undetected. This is particularly true of the latter species.

In 1972 three species on the 1971 list, *Fissidens adianthoides, Dicranella schreberiana,* and *Pohlia annotina,* were not rediscovered. There is reason to believe that *F. adianthoides* has died out on the island, in view of the fact that its precise location was known, that is, a small cave in L-12, where steam emission and optimum conditions were present. In 1972 the steam emission had ceased and a great deal of sand had blown in, so that the moss eventually dried up and perished for the most part.

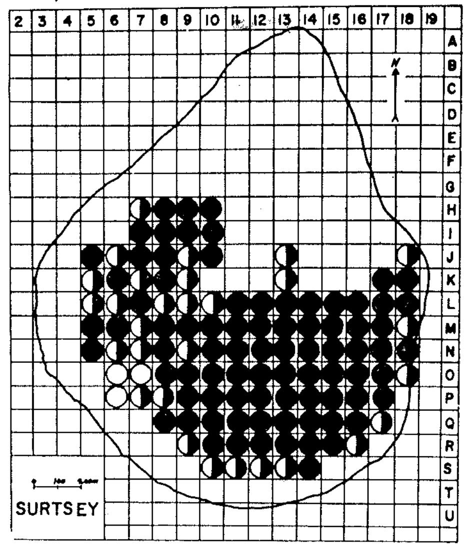
The other two species are probably still subsisting, although there was no trace of them, but it is of course never possible, in terrain like that of Surtsey, to make a corroborative search. Thus, whatever rare species are found each year is largely a matter of coincidence. The species *Bryum klingraeffii Schimp.,* which was discovered in quadrat H8 at a tephra fumarole, had not previously been found in Iceland and is therefore new to the region.

Species: *Racomitrium canescens (Hedw.) Brid.*



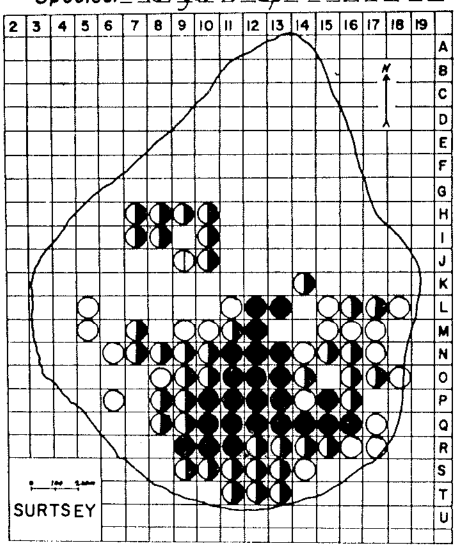
Distribution of moss species 1971.

Species: *Racomitrium canescens (Hedw.) Brid.*



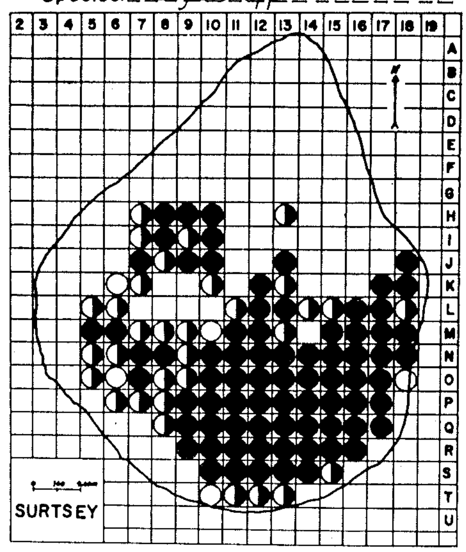
Distribution of moss species 1972.

Species: *Bryum sp.*



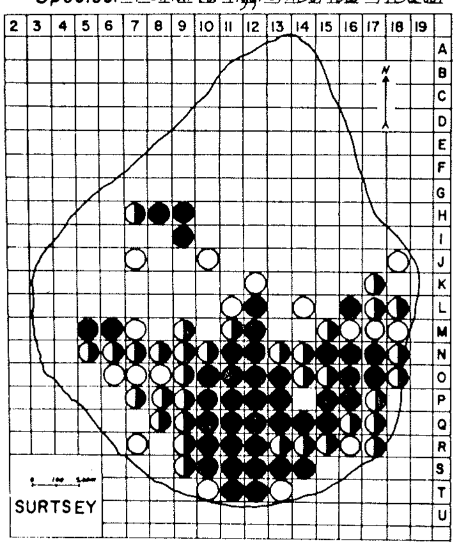
Distribution of moss species 1971.

Species: *Bryum spp.*



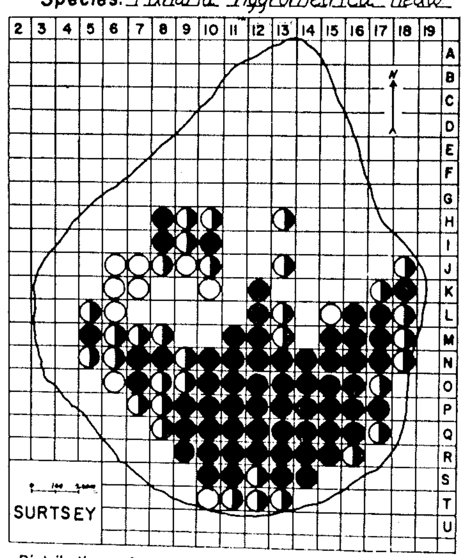
Distribution of moss species 1972.

Species: *Funaria hygrometrica Hedw.*



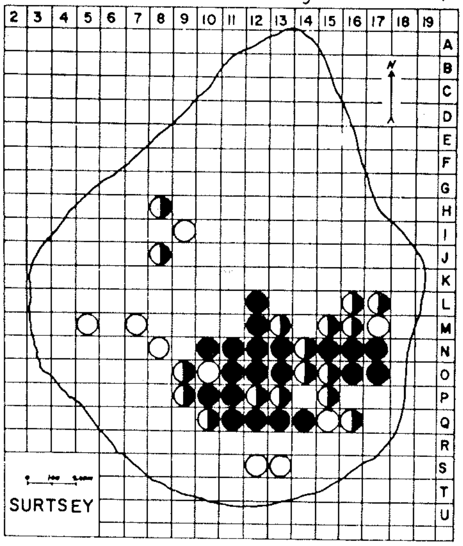
Distribution of moss species 1971.

Species: *Funaria hygrometrica Hedw.*



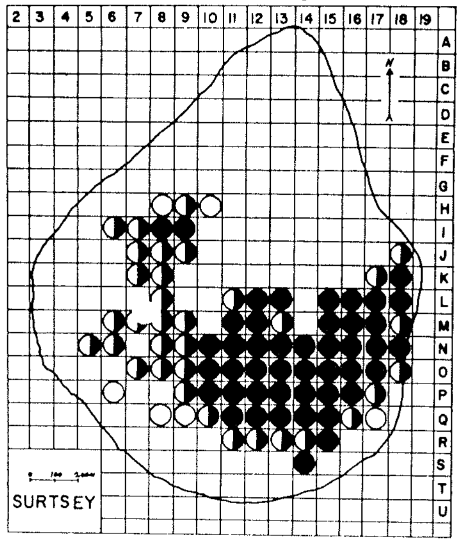
Distribution of moss species 1972.

Species: Racomitrium lanuginosum (Hedw.) Brid.



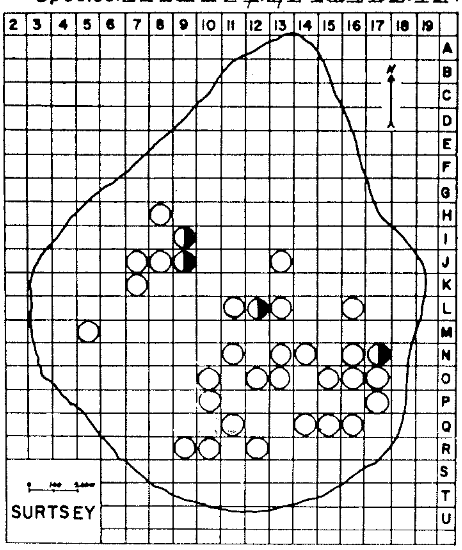
Distribution of moss species 1971.

Species: Racomitrium lanuginosum (Hedw.) Brid.



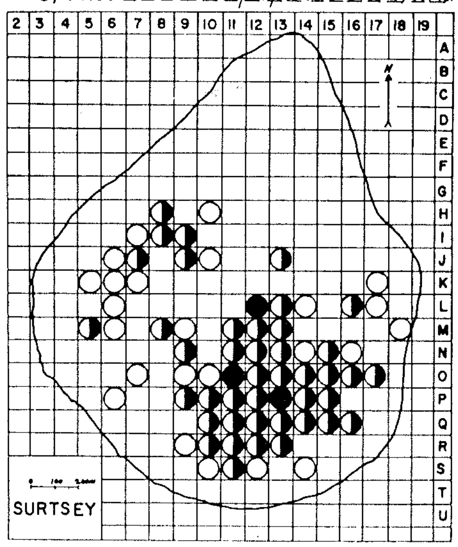
Distribution of moss species 1972.

Species: Ceratodon purpureus (Hedw.) Brid.



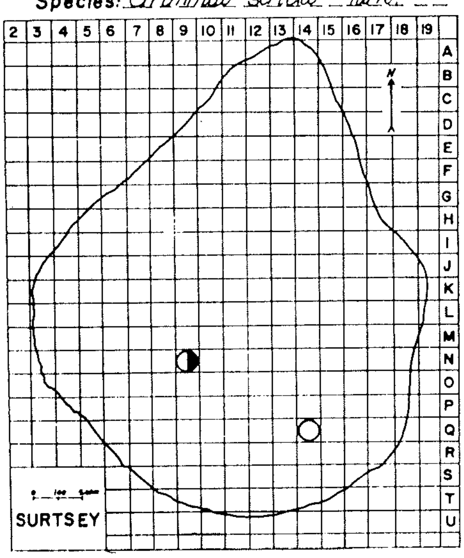
Distribution of moss species 1971.

Species: Ceratodon purpureus (Hedw.) Brid.



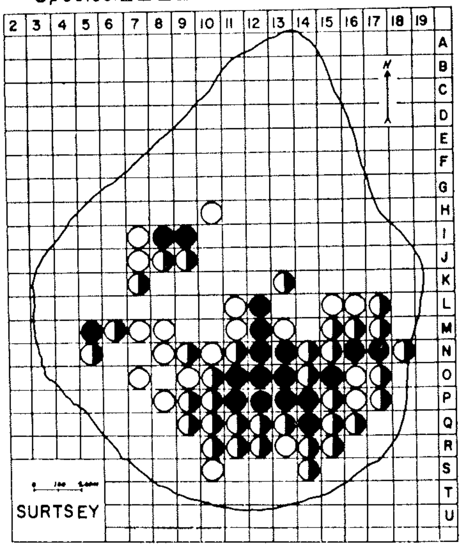
Distribution of moss species 1972.

Species: Grimmia stricta Turn.



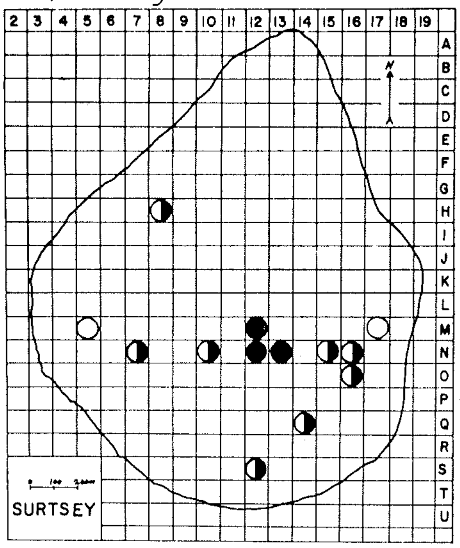
Distribution of moss species 1971.

Species: Grimmia stricta Turn.



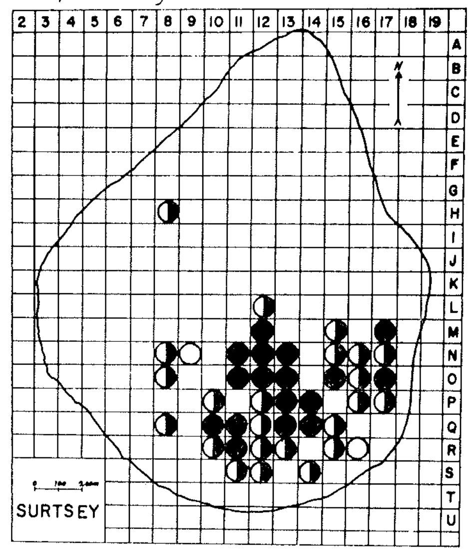
Distribution of moss species 1972.

Species: *Bryum stenotrichum C. Muell*



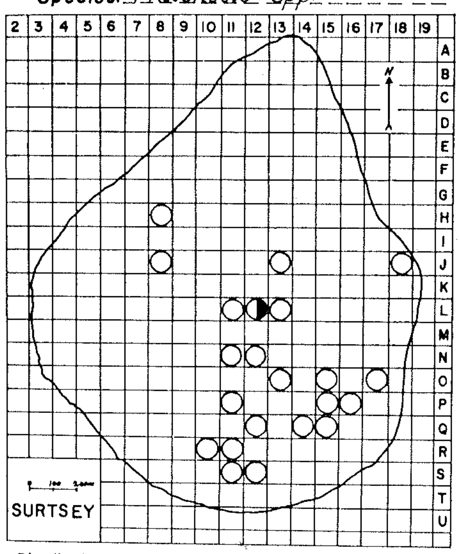
Distribution of moss species 1971.

Species: *Bryum stenotrichum C. Muell.*



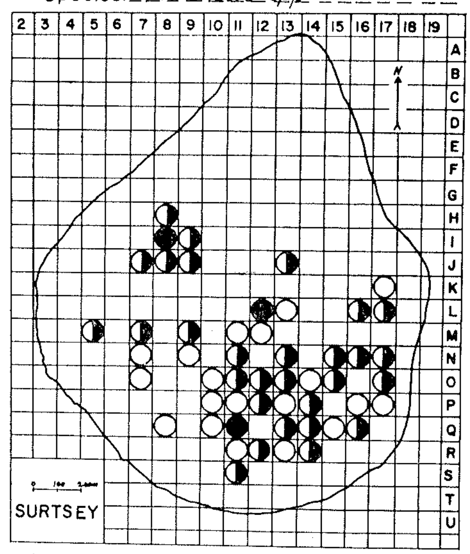
Distribution of moss species 1972.

Species: *Philonotis spp.*



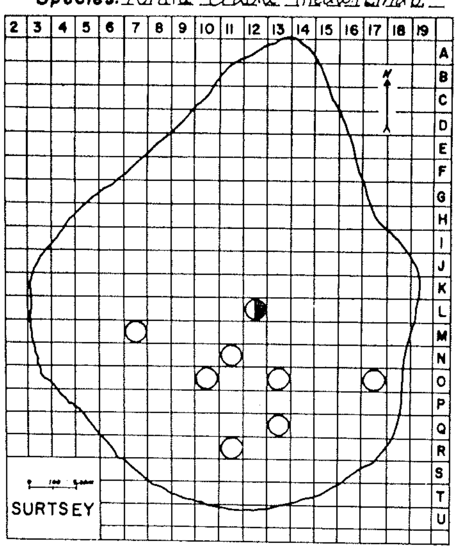
Distribution of moss species 1971.

Species: *Philonotis spp.*



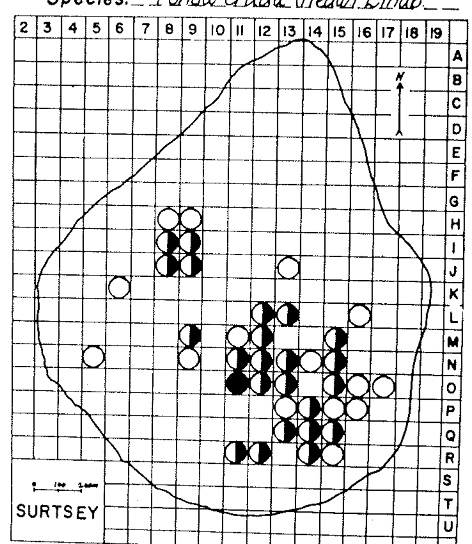
Distribution of moss species 1972.

Species: *Pohlia cruda (Hedw.) Lindb.*



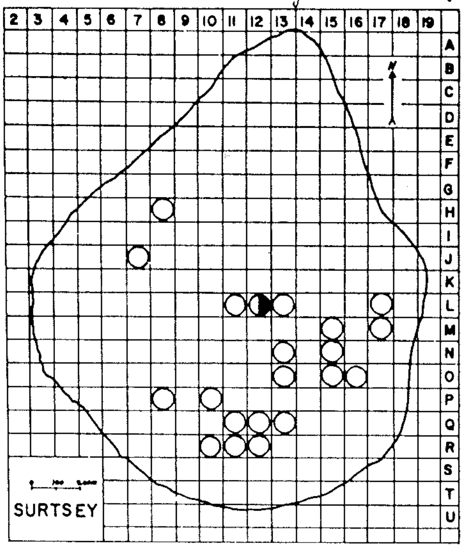
Distribution of moss species 1971.

Species: *Pohlia cruda (Hedw.) Lindb.*



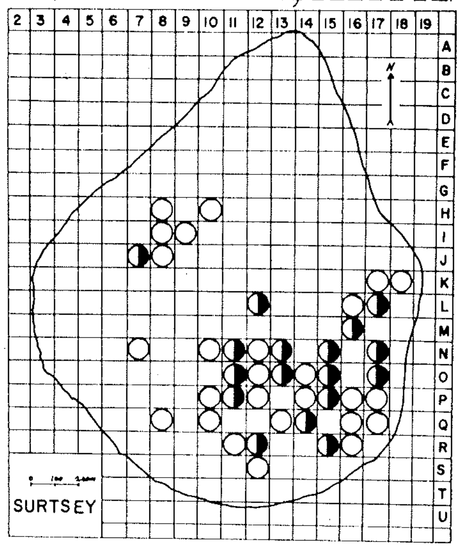
Distribution of moss species 1972.

Species: *Pohlia wahlenbergii* (Web. & Mohr) Andr.



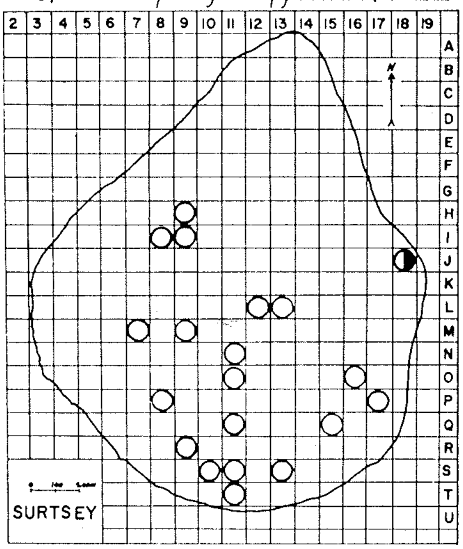
Distribution of moss species 1971.

Species: *Pohlia wahlenbergii* (Web. & Mohr) Andr.



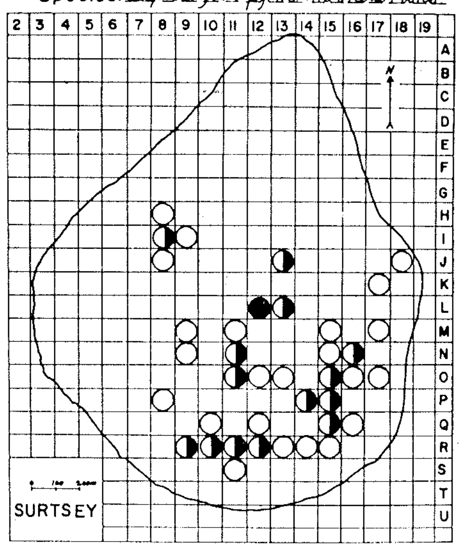
Distribution of moss species 1972.

Species: *Leptobryum pyriforme* (Hedw.) Wils.



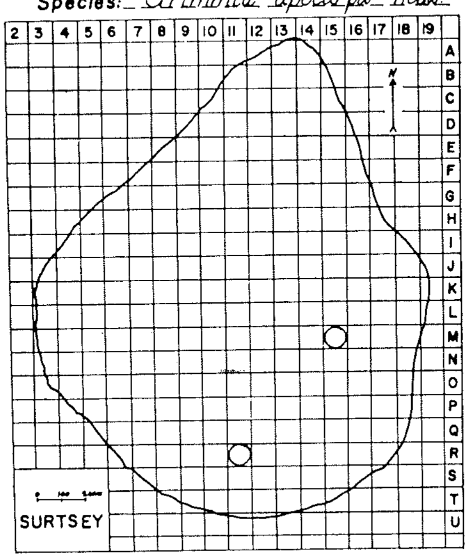
Distribution of moss species 1971.

Species: *Leptobryum pyriforme* (Hedw.) Wils.



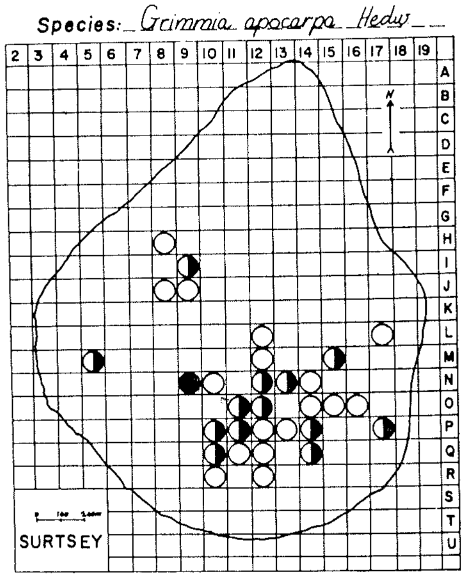
Distribution of moss species 1972.

Species: *Grimmia apocarpa* Hedw.



Distribution of moss species 1971.

Species: *Grimmia apocarpa* Hedw.



Distribution of moss species 1972.

SPECIES DISTRIBUTION

The accompanying maps show the distribution of only the most common species, since there is not adequate space for maps comprising all the species in a short article like this one. This omission is justifiable, since only the most common species have real ecological significance in the formation of soil and vegetation cover on the island. When reviewing the maps it should be remembered that they show only what the moss search revealed, and, as mentioned earlier, it was often coincidence that determined what species were found in a quadrat and the frequency with which they were observed. The frequency of species not shown on the maps may be found in the distribution signs in the list of species.

All the major species that were observed in 1971 spread greatly in 1972, not a surprising fact in view of the rapid increase that was apparent from 1969 to 1971. Unexpected, however, was the spread of the species *Grimmia stricta* and *G. apocarpa* in 1972, both of which were found in 1971 in only two quadrats. By 1972 they had become common species and were often found with capsules.

Difficulties in classifying *Bryum spp.* made it necessary to represent their distribution combined on one map. The *Bryum* species are among the island's most common, but it is not yet possible to state with any precision the role of each species in the general distribution. (Exceptions are *B. argenteum* and *B. calophyllum.)* It was possible to map the distribution of particular *Bryum* species as some specimens bore capsules and could be identified with certainty.

There is no doubt, however, that *Bryum stenotrichum* is the most common *Bryum* species on Surtsey, since by far the greatest number of capsulated specimens that have been found are of this species.

The *Philonotis spp.* map shows the general distribution of all *Philonotis* species on the island, that is to say, if there are any other species than *P. fontana.* It has been possible to assign only a few specimens to species, and they are all af *P. fontana,* so it is likely that most of the *Philonotis* samples belong to this species. These identification difficulties stem from the immaturity of the specimens.

SPORE DISPERSAL

The following table shows which species were found with spores in 1971 and 1972 and their location:

TABLE II

This table shows which species were found growing with capsules in '71 and '72 and where on the island this was found.

Species:	Found in '71	Found in '72
Funaria hygrometrica	Common	Common
Bryum stenotrichum	Common	Common
Ceratodon purpureus	R-10	
Dicranella crispa	O-17, S-10, M-5	I-8, M-5, N-14, O-7, O-11
Racomitrium canescens	O-6, 0-12	
Bryum algovicum	P-10	M-18, N-11, O-11, O-13, P-13, Q-14, R-12, R-13
Leptobryum pyriforme	R-12	
Encalypta ciliata	N-13	
Grimmia stricta		N-17, N-18, O-17, P-9, P-10, Q-11, Q-13
Grimmia apocarpa		L-17, M-15, N-14, I-9, N-17, N-18, O-16
Racomitrium lanuginosum		I-8, L-12, P-11, Q-12
Barbula recurvirostra		P-11
Dicranoweisia crispula		N-12
Bryum pallescens		H-8, M-12, N-8, N-13, O-11, O-12, P-12, P-13, O-14, R-10
Bryum arcticum	N-10, N-13	N-11, O-11, O-12, P-16, R-10

When a species reaches the stage of forming spores and capsules, its chances for spreading on the island are no doubt increased all the more. But in general it is not known exactly to what extent propagation by spore contributes to the increase of each distinct species. In addition to sexual reproduction, asexual reproduction by means of gemma and other plant parts, is very common.

Gemmae (asexual reproduction) have been found on the following species:

Marchantia polymorpha
Bryum Klingraeffii
Bryum pallens
Pohlia proligera
Pohlia annotina var. decipiens
Pohlia schleicheri

Although asexual reproductive organs have been found only on those species mentioned above, it is certain that other species have propagated asexually on the island, that is, with plant bodies, such as leaves and stalks, which break off the parent plant and are carried to a new location where they form new colonies.

HABITATS

As indicated earlier, investigators recorded the various habitats for each species observed in the different quadrats on Surtsey.

The following table represents the conclusion of these observation for 23 of the most common species on the island. They are arranged according to distribution, with the most common listed first, and so forth.

This arrangement, however, does not apply to the *Bryum species,* except *B. argenteum,* which is easily identfiable with the naked eye. The others were recorded as *Bryum spp.*

The frequency figures indicate how often species were recorded in the various habitat categories. Thus, for example, the species *R. canescens* was recorded at a total of 966 locations, being in the habitat category No. 5 in 954 instances.

According to the number of samples, category No. 5 is the most common habitat on the island. It is favoured by various species, such as *Racomitrium canescens* and *R. lanuginosum, Grimmia stricta* and *G. apocarpa,* all of which can be said to be characteristic for this habitat.

These four species seem to thrive well on the island but have not yet undergone the competition that will show which one will eventually dominate this community in the future. Several other species were found growing in this habitat, but they are so far only associate species in this primary succession. An example of these is *Bartramia ithyphylla,* a species which also grows under various other conditions.

TABLE III

Samples of moss in Surtsey '72 arranged according to habitats.

Species:	Number of samples in each habitat: 1	2	3	4	5	6	7	8	9	10	11	12	Total observations
Racomitrium canescens	1				954	1	2	1	6	1			966
Bryum spp.	41	124	62	59	25	329	19	10	132	81	5	10	897
Funaria hygrometrica	25	72	23	23	13	274	22		216	82	1	6	780
Racomitrium lanuginosum	15	2			556	4	2	1	2			1	583
Grimmia stricta	13				331	4	5		1				354
Ceratodon purpureus	10	7	4	21	17	64	8	6	90	20	1	1	249
Philonotis sp.	8	5	4	13	2	70	1	4	20	30	1		158
Pohlia cruda	11	5		7	6	40	1		26	16			112
Pohlia wahlenbergii	7	4		6	2	59		5	8	5		1	97
Bryum argentum			21	25		6			7	4			63
Leptobryum pyriforme	2	20		7		12		1	2	17			61
Bartramia ithyphylla	10			3	14	12			9	5		1	54
Grimmia apocarpa	4				46		1		1				52
Dichodontium pellucidum	5	1	2	5	4	20			6	7		1	51
Dicranella crispa	5		3	14	6	2	1	1	3	5			40
Pogonateum urnigerum				3		7		1	9				20
Atrichum undulatum	3			3		4		1	4	3			18
Drepanocladus uncinatus	3				6	3			2	2			16
Campylium polygamum	6				3	2			1	1	1		14
Distichium capillaceum	3				2	1			2	1			9
Polytrichum alpinum				2		4			2				8
Barbula recurvirostra	3	2								2			7
Brachythecium salebrosum	1	1			1	3				1			7
Total	176	243	119	191	1988	921	62	31	549	283	9	21	4593

An other common habitat on Surtsey is the category No. 6. It is favored by many species, such as various *Bryum* species like *B. stenotrichum,* as well as *Funaria hygrometrica,* which are still the most dominant species. Associate species are *Pohlia cruda, Pohlia wahlenbergii, Philonotis sp., Ceratodon purpureus, Bartramia ithyphylla,* and others.

The other habitats can be examined in the same way as these two.

This arrangement is based on 4.593 observations. Classical sociological measurements could not be applied because the moss colonies are still rather scattered.

COVER

The total cover of mosses on Surtsey is still very small, and exact measurements of their cover are therefore very difficult to obtain. The roughness of the lava surface also adds to these difficulties.

As mentioned above, the cover of each species in its habitats was recorded in each quadrat. The accompanying cover maps show the mean cover value in each quadrat for the six most common species, as estimated in 1972.

The maps reveal that although *Racomitrium canescens* is the most common species on the island, it ranks only third in cover, the patches being usually much smaller than those of *Bryum spp.* (mostly *B. stenotrichum)* and *Funaria hygrometrica,* which show the highest cover values. Other species have much less average cover per quadrat.

ACKNOWLEDGEMENTS

Bergthór Jóhannsson of the Museum of Natural History, Reykjavík, has checked all of the identifications on which this paper is based, in addition to identifying all uncertain specimens. The writer extends his deepest thanks for this invaluable assistance.

The work on which this paper is based was sponsored by the Surtsey Research Committee, with a grant from the U.S. Atomic Energy Commission, Div. of Biology and Medicine, under contract No. AT (11-1)-3531.

References:

Einarsson, E. 1968: Comparativ Ecology of Colonizing Species of Vascular Plants. Surtsey Res. Progr. Rep. IV pp. 9—22.

Fridriksson, S. and Johnsen, B. 1968: The Colonization of Vascular plants on Surtsey in 1967. Surtsey Res. Progr. Rep. IV pp. 31—38.

Jóhannsson, B. 1968: Bryological observations on Surtsey. Surtsey Res. Progr. Rep. IV p. 61.

Fridriksson, S. 1970: The Colonization of Vascular plants on Surtsey in 1968. Surtsey Res. Progr. Rep. V pp. 10—14.

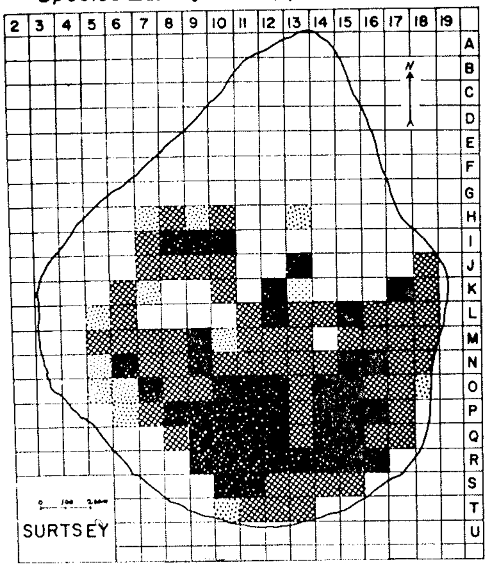
Fridriksson, S. Sveinbjörnsson, B. and Bjarnason, A. H. 1972: Vascular plants in Surtsey 1969. Surtsey Res. Progr. Rep. VI pp. 30—33.

Bjarnason, A. H. and Fridriksson, S. 1972: Moss on Surtsey, Summer 1969. Surtsey Res. Progr. Rep. VI pp. 9—10.

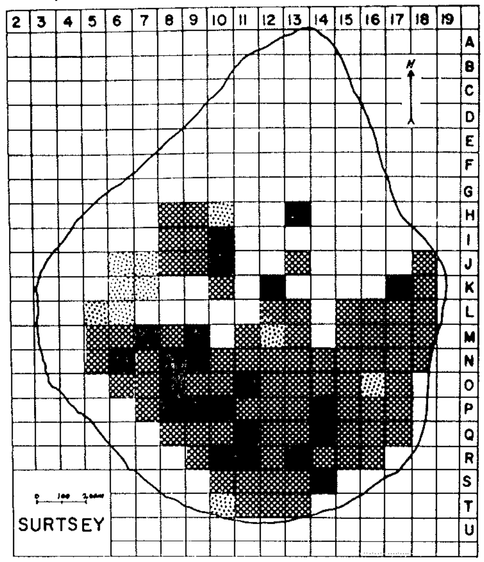
Fridriksson, S. Sveinbjörnsson, B. and Magnússon, S. 1972: Vegetation on Surtsey Summer 1970. Surtsey Res. Progr. Rep. VI pp. 54—59.

Nyholm, E. 1954—1969: Illustrated Moss Flora of Fennoscandia. Musci. Fasc 1—6. Malmö and Lund, Sweden.

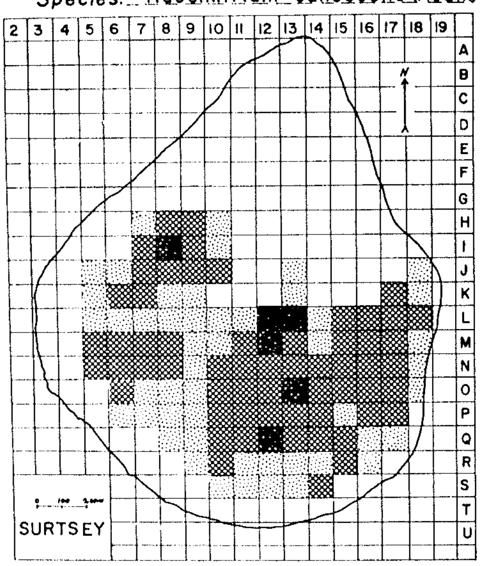
Species: Bryum spp.



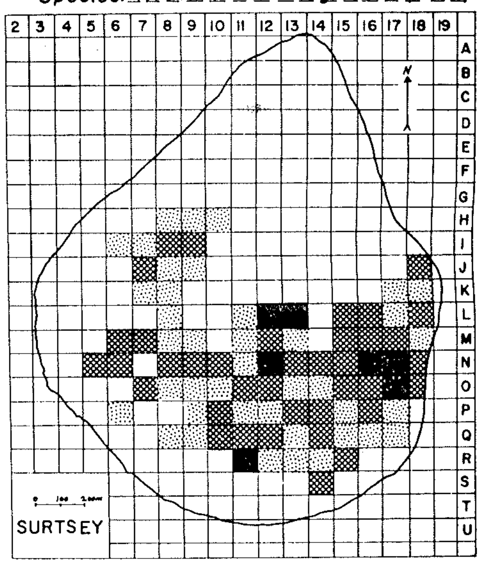
Species: Funaria hygrometrica Hedw.



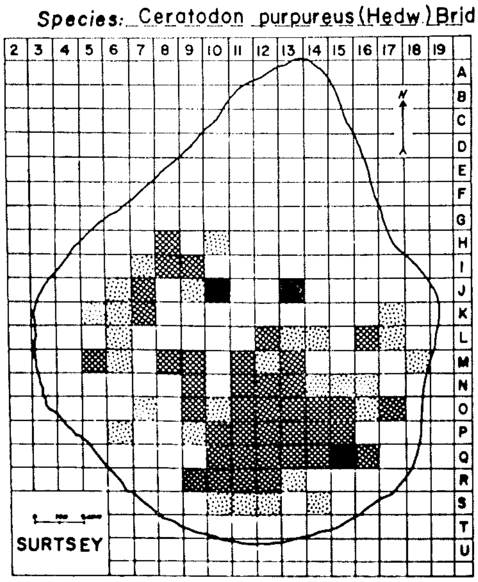
Species: Racomitrium canescens (Hedw) Brid.



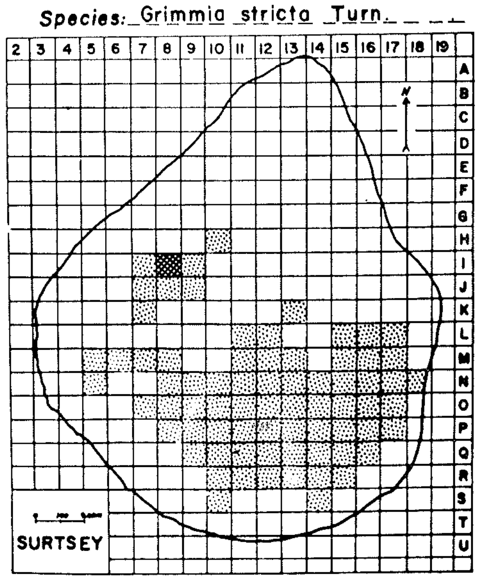
Species: Racomitrium lanuginosum (Hedw) Brid.



Species: Ceratodon purpureus (Hedw.) Brid.

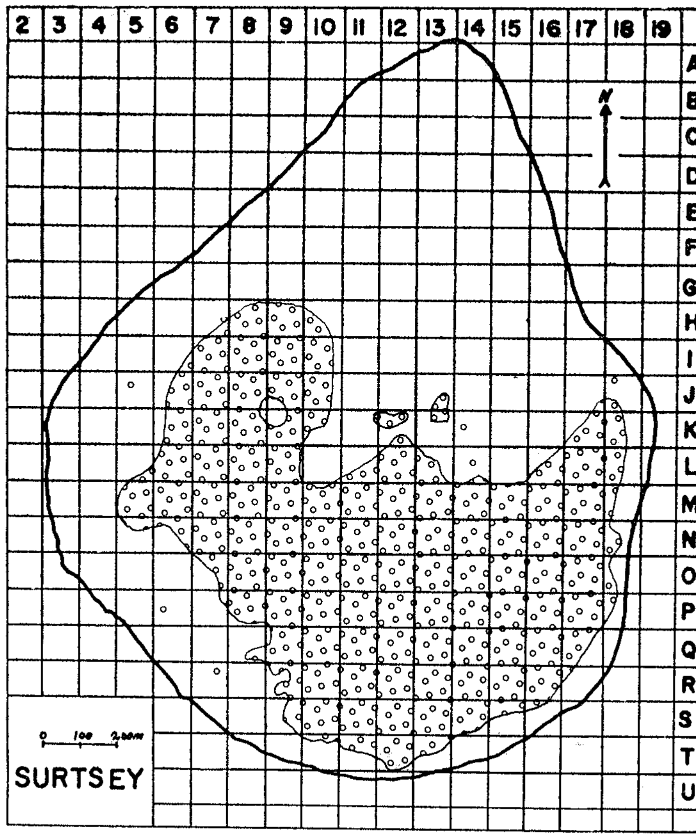


Species: Grimmia stricta Turn.

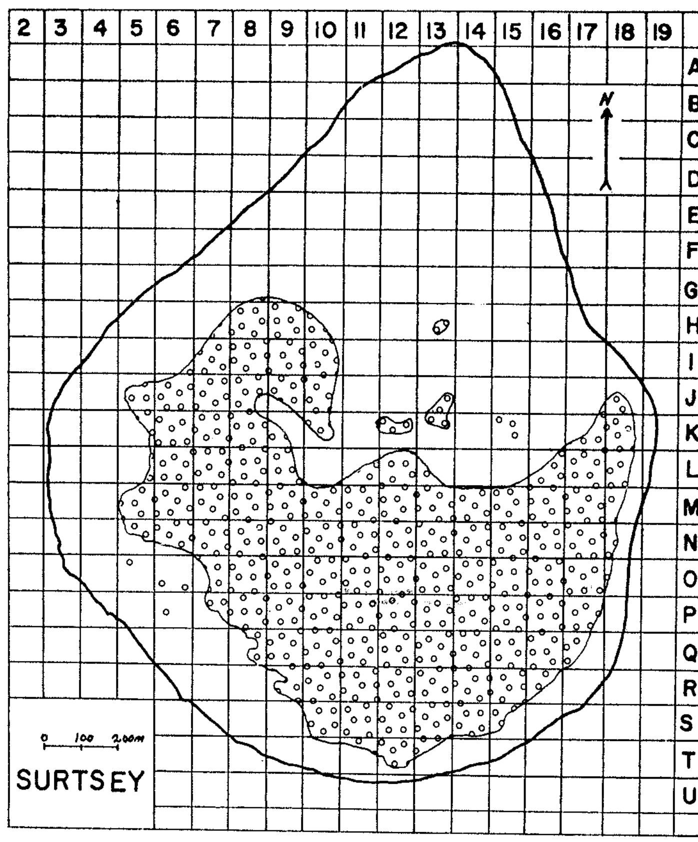


0 - 1,0 % Cover
1,1 - 10,0 % -
> 10,0 % -

Total distribution of mosses 1971



Total distribution of mosses 1972



GEOLOGY AND GEOPHYSICS

The geomorphology of Surtsey Island in 1972

By
JOHN O. NORRMAN, BENGT CALLES,
and
ROLF Å. LARSSON
Department of Physical Geography,
Uppsala University, Sweden

INTRODUCTION

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

SOIL STUDIES

Soil distribution

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

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

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

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

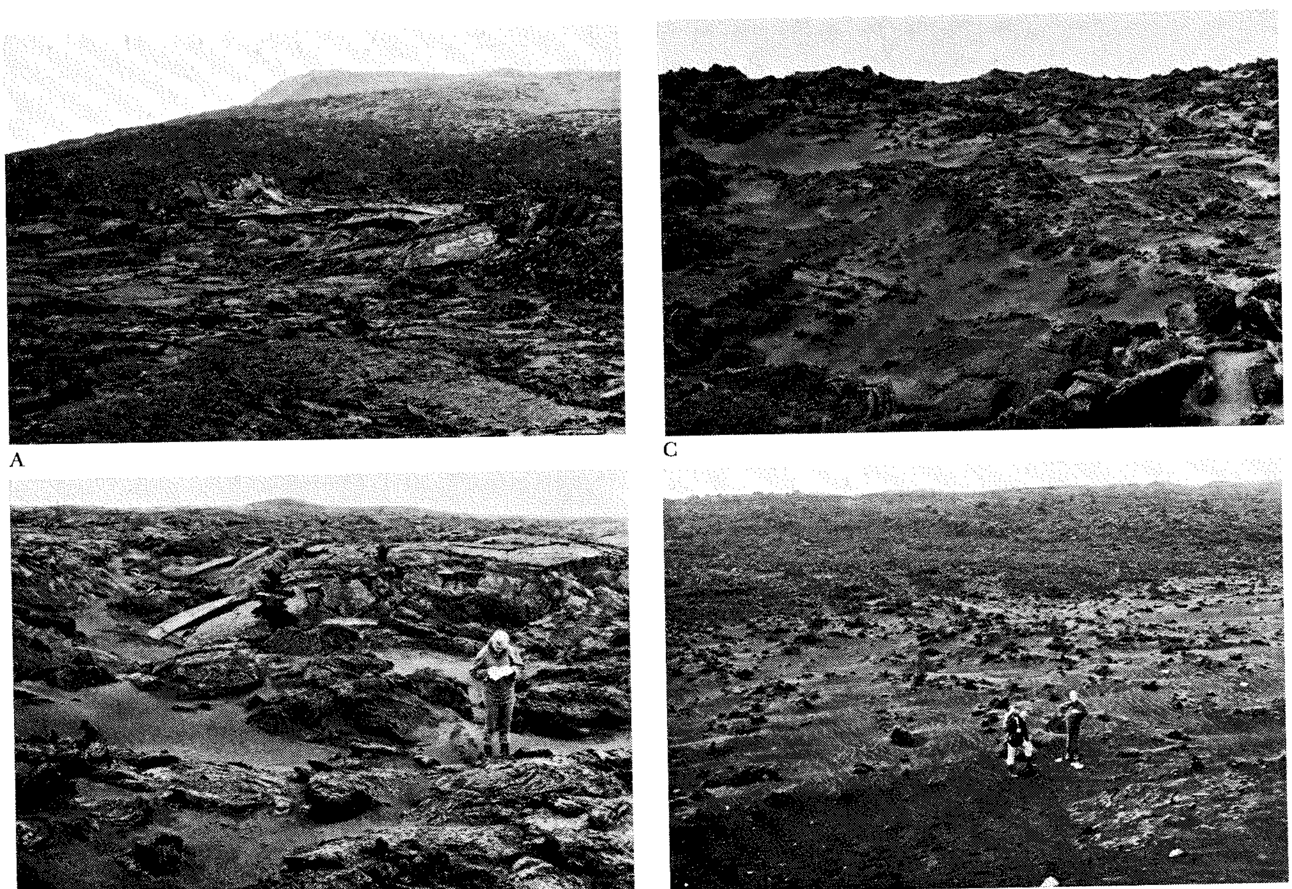
Fig. 1. Aerial photograph of Surtsey Island, 7 August 1972. The nrs. 1-5 denote test areas for terrester photogrammetry. Site nr. 3 is exemplified in Fig. 9. Photograph by Landmælingar Íslands.

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

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

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

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



A C B D

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

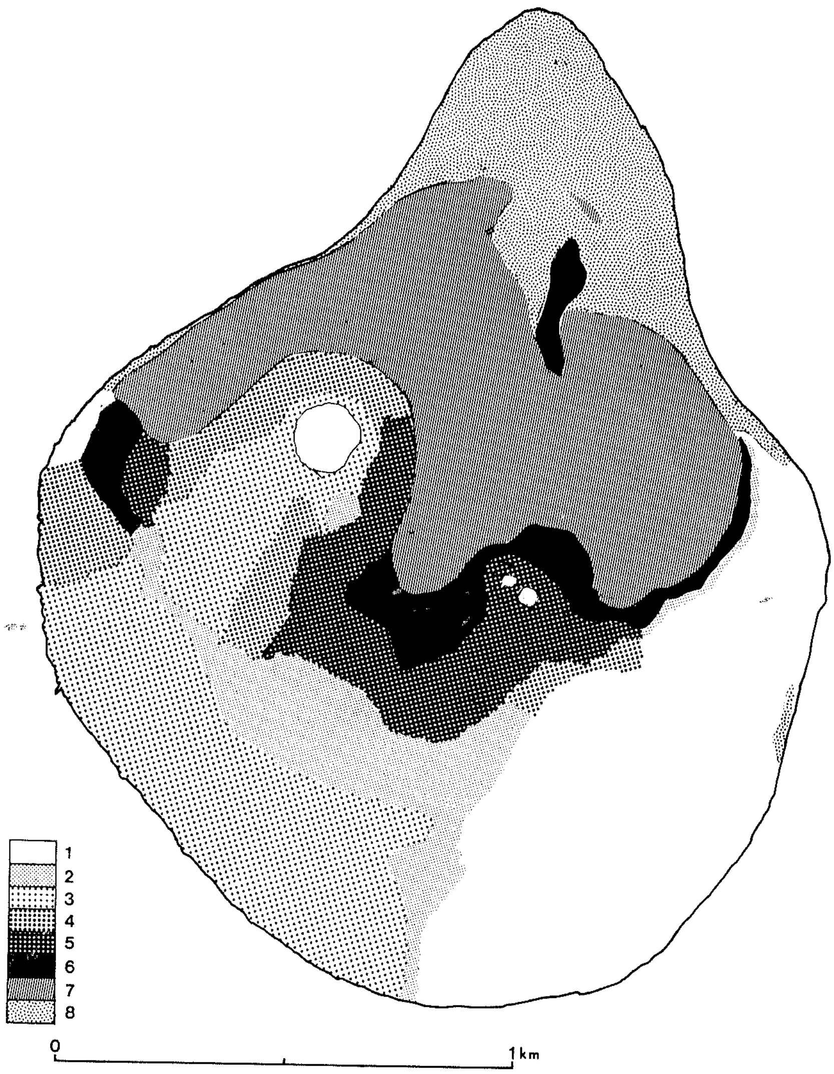


Fig. 3. Map showing the distribution of shore material, primary tephra and lava areas covered by tephra sand. Legend: 1. < 10% sand cover, 2. 10-20%, 3. 20-40%, 4. 40-60%, 5. 60-80%, 6. > 80%, 7. Primary tephra cones, 8. Shore sediments.

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

Grain size distribution of tephra sand

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

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

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

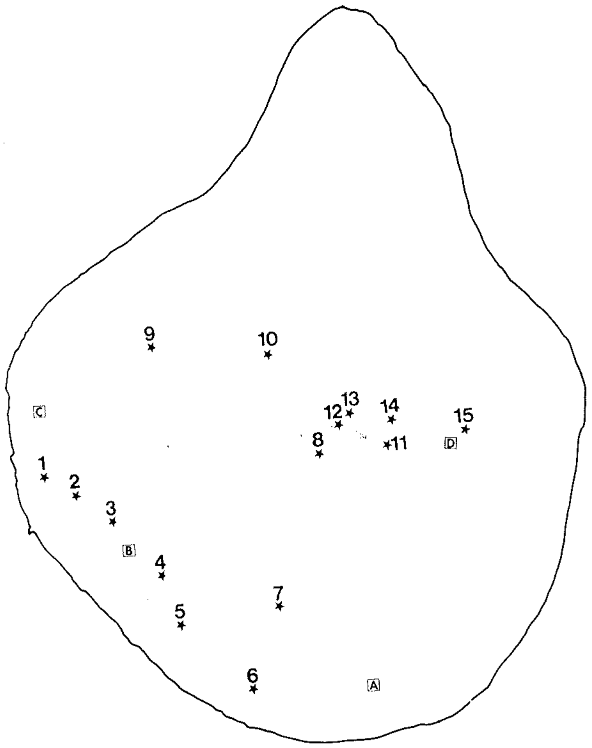


Fig. 4. Sampling sites for grain size analyses (1-15) and location of photographs shown in Fig. 2 (A-D).

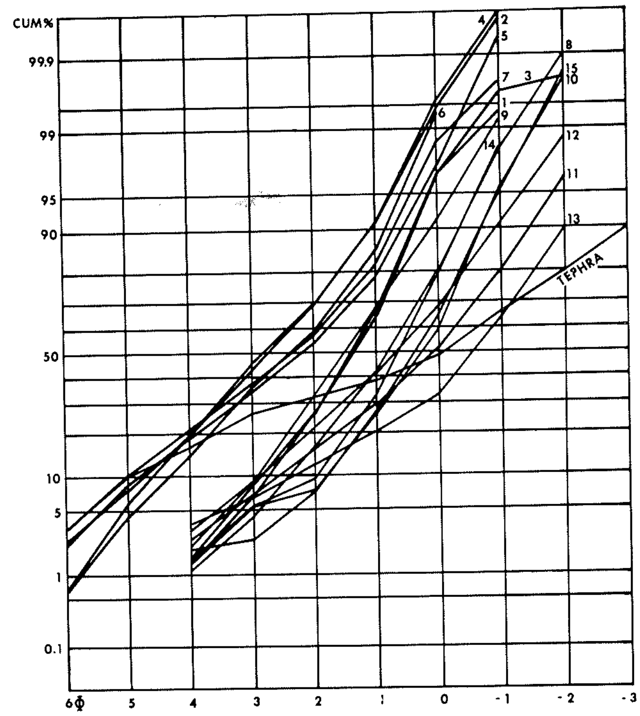


Fig. 5. Grain size distribution curves for samples from tephra sand in the lava area (1-15) and for one sample of primary tephra from the cone of Surtur II. For sampling locations see Fig. 4.

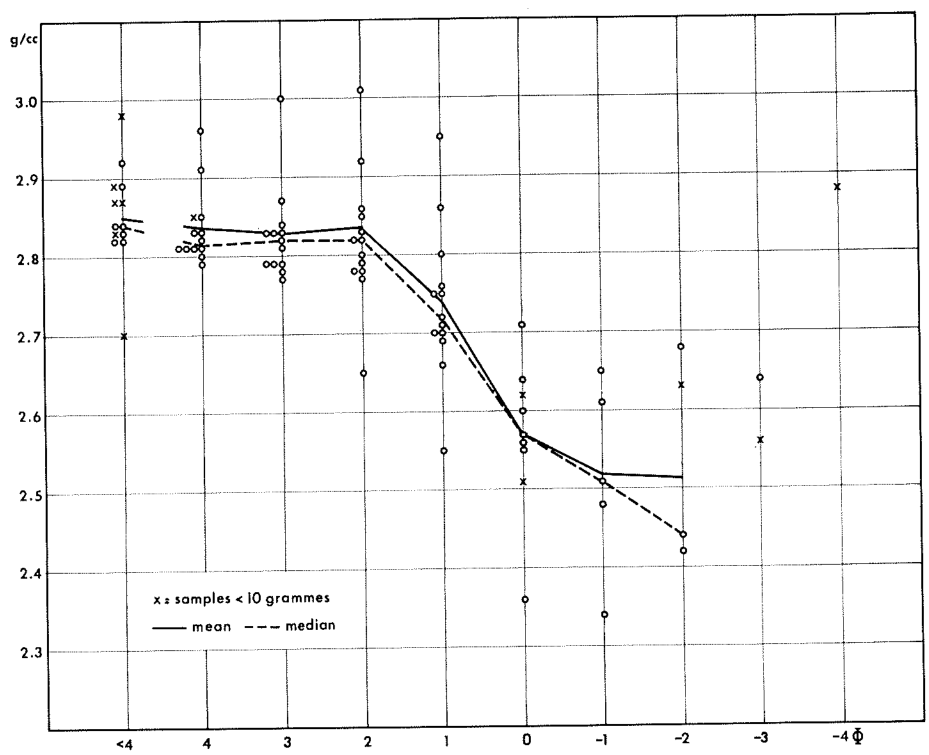


Fig. 6. Density determinations for individual grain-size classes of samples nrs. 1-14.

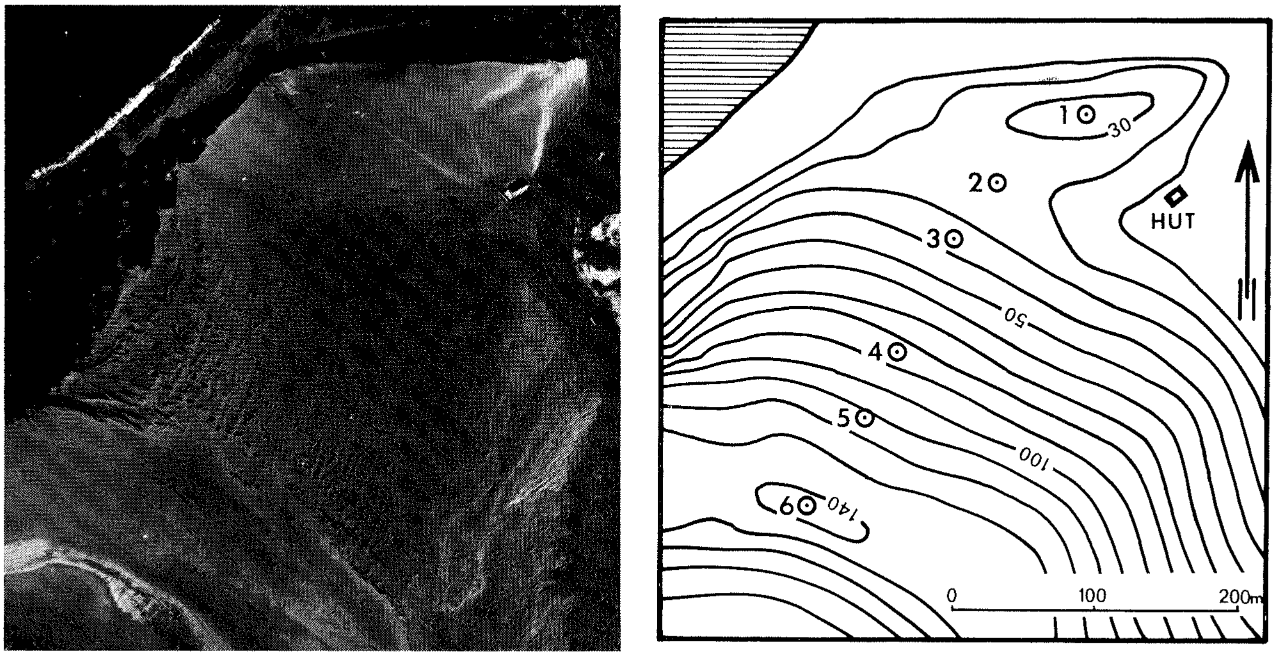


Fig. 7. A. Mud flow rills in the tephra slope SW of the research hut have been eroded by wind drift transverse to the slope direction. Aerial photograph of 7 August 1972. B. Sample sites for pH and conductivity determinations. Height contours of 1970.

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

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

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

TABLE 1

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

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

Variation in density with grain size

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

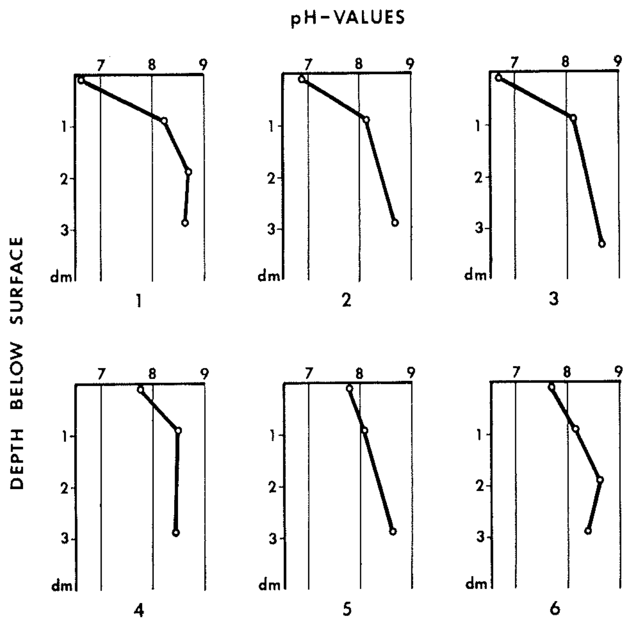


Fig. 8. pH values at different levels in the sampling pits.

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

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

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

pH and conductivity measurements

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

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

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

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

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

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

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

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

PHOTOGRAMMETRIC SURVEYS

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

TABLE 2

Objects of terrestrial photogrammetry

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

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

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

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

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

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

COASTAL CHANGES

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

The lava cliffs

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

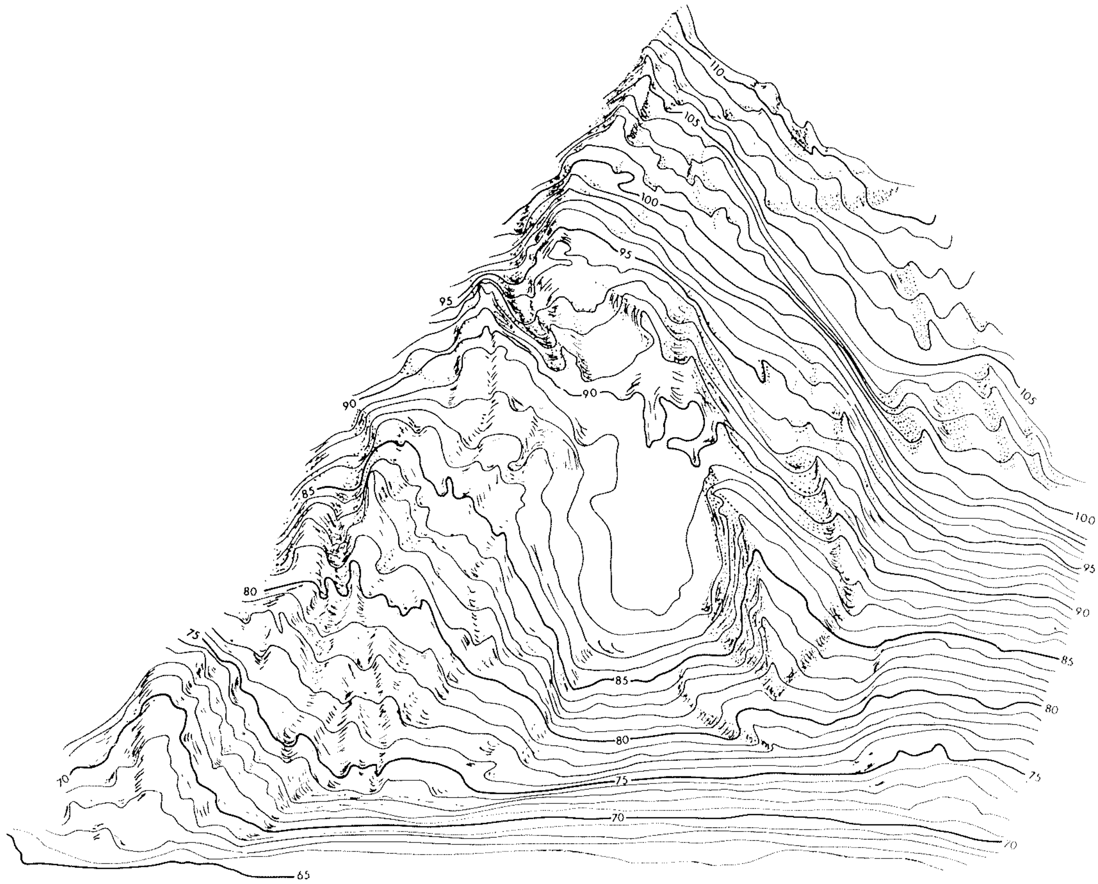


Fig. 9. Distance-contour map and photograph showing the tephra wall E of Surtur I. (No. 3 in Fig. 1). Reproduction scale approx. 1:500. Camera: Zeiss TMK, c=60 mm.

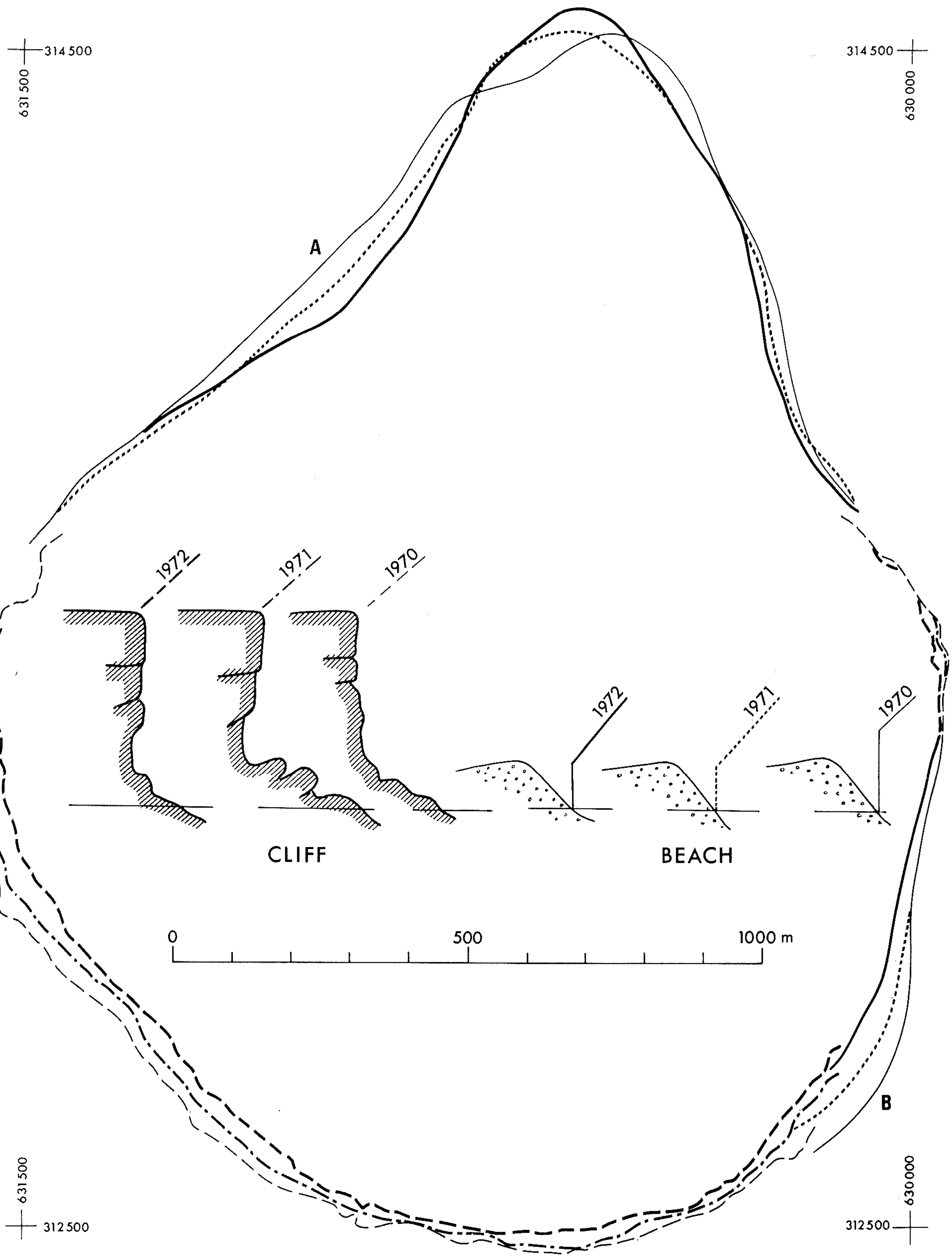


Fig. 10. Cliffline and shoreline of 3 September 1970, 15 July 1971 and 7 August 1972. A: Western boulder terrace, B: Eastern boulder terrace. Photogrammetric construction by Rolf Å. Larsson based on aerial photographs by Landmælingar Íslands and ground control by the authors.

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

The boulder terraces

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

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

The northern ness

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

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

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

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

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

Areal changes

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

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

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

ACKNOWLEDGEMENTS

The 1972 field study was supported by the Swedish National Science Research Council (NFR contract 2160-012) and the Surtsey Research Society. The photogrammetric maps were drawn in the Department of Physical Geography, Uppsala University by Miss Kjerstin Andersson.

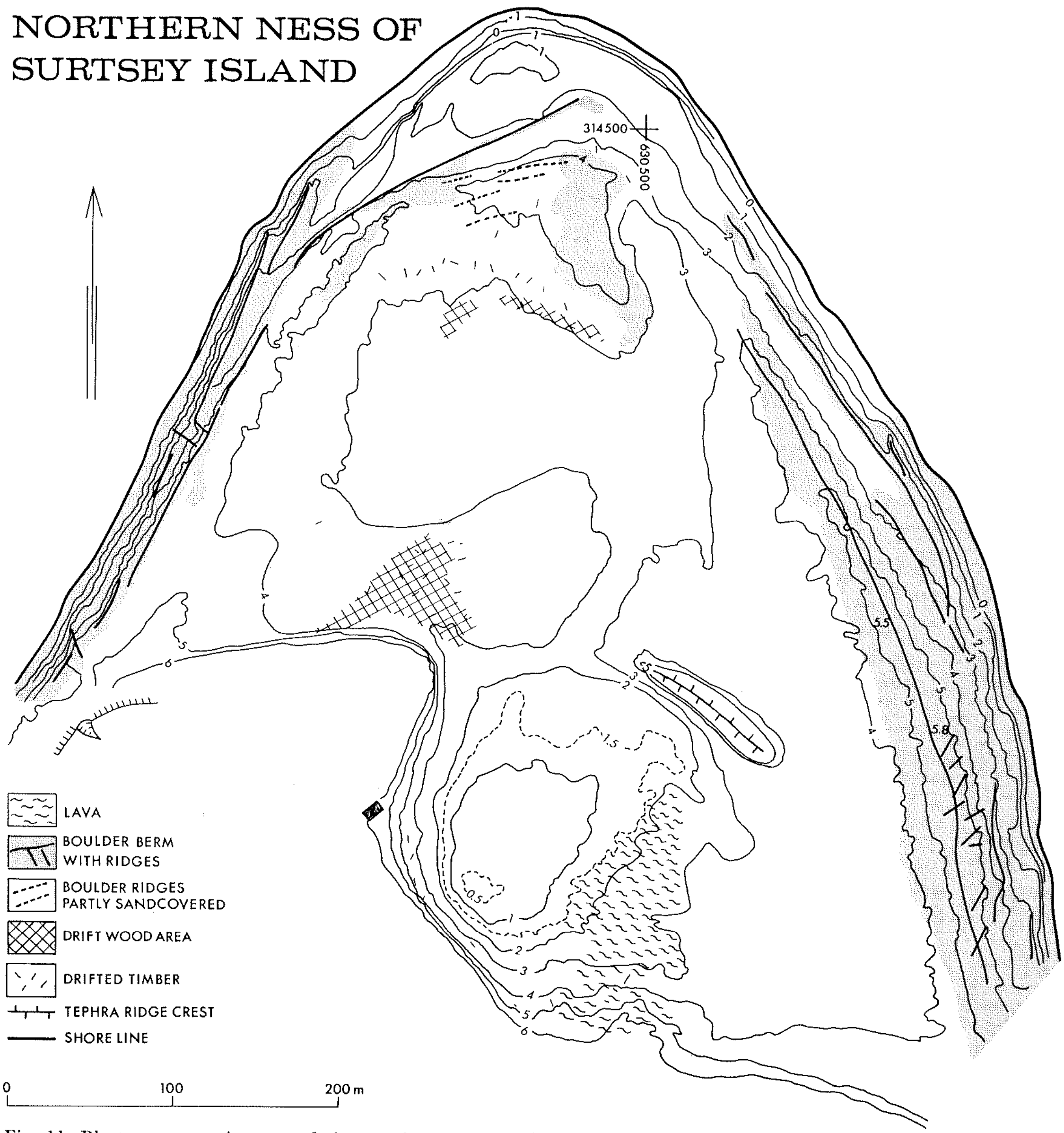


Fig. 11. Photogrammetric map of the northern ness as developed on 7 August 1972. Contour interval 1 metre. Height in metres above mean sea level. Shore line of low tide. Photogrammetric construction by Rolf Å. Larsson based on photographs by Landmælingar Íslands and ground control by the authors.

References

Fridriksson, S., Magnússon, S., and Sveinbjörnsson, B., 1972: Substrate map of Surtsey 1970. Surtsey Res. Progr. Rept. VI: 60-63.

Imman, D. L., 1952: Measures for describing the size distributions of sediments. J. Sed. Petr. 22:125-145.

Jakobsson, S. P., 1972: On the consolidation and palagonitization of the tephra of the Surtsey volcanic island, Iceland. Surtsey Res. Progr. Rept. VI:121-128.

Larsson, R. Å., and Sundborg, Å., 1972: A photogrammetric instrument system in geo- and bioscientific research and teaching. UNGI Rapport 18.

Norrman, J. O., 1968: Shore and offshore morphology of Surtsey. Report on preliminary studies in 1967. Surtsey Res. Progr. Rept. IV:131-137.

— 1969: Kustmorfologiska studier på Surtsey (Coastal morphology of Surtsey Island). Svensk Naturvetenskap 1969, Stockholm.

— 1970: Trends in postvolcanic development of Surtsey Island. Progress report on geomorphological activities in 1968. Surtsey Res. Progr. Rept. V:95-112.

— 1972a: Coastal development of Surtsey Island, 1968-69. Progress report on geomorphological activities during 1969. Surtsey Res. Progr. Rept. VI:137-143.

— 1972b: Coastal changes in Surtsey Island, 1969-1970. Surtsey Res. Progr. Rept. VI:145—149.

Schwabe, G. H., 1970: Zur Ökogenese auf Surtsey. Schr. Naturw. Ver. Schlesw.-Holst. Sonderband Surtsey, Island. 101-120.

— 1971a: Surtsey. Kosmos 67, H. 12.

— 1971b: Ökogenese der Insel Surtsey 1968 bis 1970. Naturw. Rundschau 24, H. 12.

Sheridan, M. F., 1972: Textural analysis of Surtsey tephra. A preliminary report. Surtsey Res. Progr. Rept. VI:150-151.

Thorarinsson, S., 1967: The Surtsey eruption. Course of events during the year 1966. Surtsey Res. Progr. Rept. III:84-90.

Studies of the Surtsey tephra deposits

By
VOLKER LORENZ
Geologisches Institut der Universität Mainz, Germany

ABSTRACT

Similar to other tuff-rings Surtur I, Surtsey, is characterized by a major unconformity interpreted as the result of large-scale slumping owing to possible formation of a ring fault at depth.

The last deposits of the phreatomagmatic activity of Surtsey indicate that they are either the result of very good or of relatively little magma/-sea-water contact. The first type of deposit is characterized by base surge deposits that show phenomena like syn-sedimentary formation of mud-flow channels, gravity flowage ripples, and joints. The base surge deposits consist mainly of vesiculated tuffs. Vesiculated accretionary lapilli are indicative of very rapid accretion in wet eruption clouds. The second type of deposit contains cauliflower bombs and lapilli that received their particulate size prior to contact with water. During subsequent contact with water the surface of the particles was chilled and solidified to form sideromelane whereas the interior stayed fluid slightly longer and formed tachylite. Many cauliflower bombs impacted while still having a fluid interior and consequently they deformed.

INTRODUCTION

Various aspects of the phreatomagmatically formed tephra of Surtsey have already been studied by Jakobsson (1972); Sheridan (1972); Thorarinsson (1965, 1968); Thorarinsson et al. (1964) and Walker & Croasdale 1972). In this study, performed on Surtsey in June 1972, some additional features will be reported concerning mainly the youngest deposits of phreatomagmatic origin of Surtur I and Surtur II.

UNCONFORMITIES

At the SE edge of the Surtur I crater rim a major unconformity is exposed (fig. 1, 2). The older tephra layers underlying it dip with approximately 10° towards the crater and are covered by ash layers that dip on average 30-40°, locally up to 72° towards the crater centre. Angular fragments of partly bedded tuffs lie on the lowermost part of the unconformity and indicate their being the result of a slide or slump. These fragments are overlain by approximately 1 m of unbedded tuff that may have accumulated by grains sliding or rolling down the slip face. This bed dies out upslope rather rapidly and is, in turn, overlain by bedded tuffs, some of which are vesiculated (see below) whereas some other beds show faint low angle cross-bedding directed upslope. The beds successively step onto older tuff layers. Locally, here the unconformity reaches dips of up to 72°, these beds, in part, are plastered against the older tuffs.

The unconformity can be traced along the rim edge up to a level where the younger tuffs completely drape over the older ones so that no indication of the unconformity is seen anymore (fig. 3).

A similar unconformity is exposed, locally, in the SE wall of Surtur II.

It has been pointed out recently (Lorenz 1973) that many tuff-rings display unconformities indicative of slumping as a result of subsidence along a ring-fault at depth. Examples in Iceland are Hverfjall, Lúdent and Hrossaborg.

The unconformities on Surtsey are interpreted likewise and would, in the case of Surtur I, indicate a ringfault of a diameter of approximately 250-300 m near the surface.

During its final stages of activity the adjacent tuff-ring Jólnir developed subcircular ring-faults of a diameter of 400 and 600 m respectively — in May 1967 but stopped eruption only at the end of August 1967 (Thorarinsson 1968). This

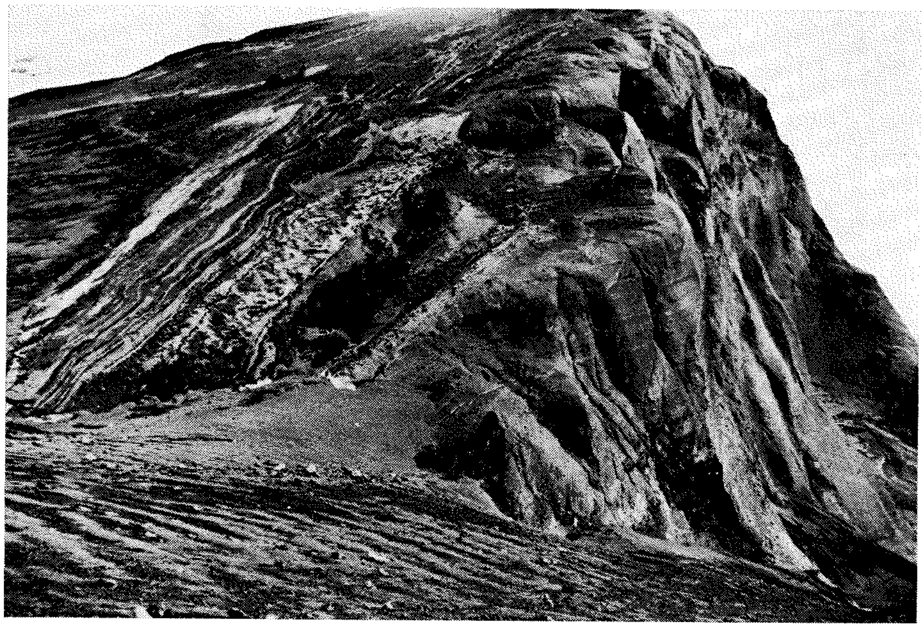


Fig. 2. Unconformity at SE edge of Surtur I rim.

clearly indicates instability at depth that results in subsidence; ash-layers from the following eruptions then cover the faults and drape over the older beds.

PYROCLASTIC DEBRIS BELOW THE UNCONFORMITY OF SURTUR I AND SURTUR II

The older tephra of both Surtur I and II are well exposed in the cliffs at the E and W side of Surtsey. They are rather monotonous, well bedded, rather homogenous in grain-size variation and thickness of beds. Many of the tuffs are vesiculated indicating a base surge origin. The few included blocks or bombs rarely indent the underlying beds; most of them, therefore, were emplaced by base surges.

The layers above the unconformities, however, display a much greater variety in grain-sizes and block and bomb content and are discussed below.

VESICULATED TUFFS

Vesiculated tuffs, i.e. tuffs or lapilli-tuffs with vesicles between the particles, occur in two varieties on Surtsey. The first one is rather coarse grained and largely confined to the older tuffs exposed in the cliffs. Owing to the grain size of the lapilli-tuffs the vesicles are irregular in shape and 0.1-1 cm in diameter. The second type is found in the ash layers above the unconformity of Surtur I. Differential erosion and preservation of these tuffs owing to recent rise of heat and consequent hardening and palagonitization (Jakobsson 1972) provides an excellent change to study these beds in detail.

The vesiculated tuffs are, in general, 1—6 cm thick and contain vesicles 0.1-2 mm, rarely 1 cm in size. The walls of the vesicles are rather smooth; small zeolite crystals frequently are attached to them but are also found in the interstitial pore space of the rocks (Jakobsson 1972). Palagonitization, identified by the brown colour,

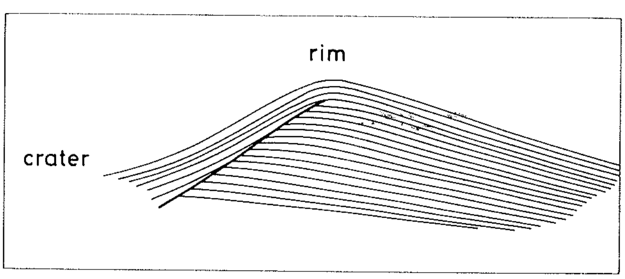


Fig. 3. Schematic cross-section through rim of tuff-ring similar to Surtur I E rim.

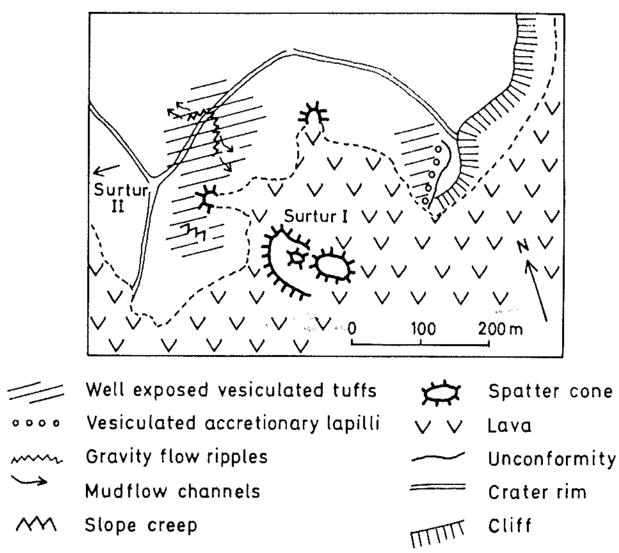


Fig. 1. Index map of Surtur I.

Fig. 4. Mudflow channels at upper part of Surtur I NW inner slope.

effects the ceiling of many vesicles, especially the larger ones, earlier than the main part of the rock. If heat keeps rising long enough on Surtsey palagonitization of the whole rock will ultimately give rise to amygdaloidal tuffs.

Vesiculated tuffs are an excellent indicator of phreatomagmatically formed base surges (Lorenz 1974) which are known to have taken place on Surtsey (Moore 1967, Thorarinsson et al. 1964).

MUDFLOW CHANNELS

On the W rim of Surtur I there is a graded vesiculated tuff layer, a few cm thick, that can be traced from the inner crater wall over the rim onto the outer wall. On the rim where the bed dips less than 20° there are no associated surface phenomena. On both the inner and outer crater wall, however, this vesiculated bed displays mudflow channels at dips greater than 20° (fig. 1). At an angel of approximately 20° there are only small and faint channels 1-3 cm wide. At a dip of approximately 25° they are more frequent, wider, and deeper. Typical mudflow channels are 6-8 cm wide, several cm deep (up to 5 cm), and have marginal ridges, 1—3 cm high, that are lined with finegrained ash to give a smooth surface. Some channels unite to form larger ones (fig. 4) and some show meandering. Inside the channels there are faint ridges their convex side pointing downslope. Accretionary lapilli and the overlying also vesiculated bed fill and cover the channels the latter without showing any depressions above the channels at its own surface. This clearly indicates that the channels formed immediately after deposition of the vesiculated tuff, and that the ash layer gave off excess water and formed the mudflow channels prior to deposition of the next younger layer. It is assumed that this particular bed approximately contains 20—30 vol% of water at the time it was deposited by a base surge (Lorenz 1974).

At dips greater than 35° (at the inner slope) the whole bed broke up into fragments several cm to 20 cm in size and began to slide down the slope as a mass of these fragment (fig. 5). Some of the fragments even indicate that prior to sliding the bed formed small gravity flowage ripples of a type described below. The slide also affected some of the underlying, coarser-grained beds. Even farther down the slope some remains of larger mudflow channels, up to 50 cm wide, can be recognized on this particular bed.

RIPPLE LAYER

One ash layer, 6—8 cm above the just described one, is also developed as a graded vesiculated tuff and is 1—4 cm thick. It contains particles up to 5 mm at its base whereas at the top the ash is very fine-grained. In the upper 0.3 to 1 cm there are vesicles up to 1-2 mm in diameter. Some vesicles are inclined downslope and indicate a small degree of shear movement owing to slight downslope flow. In the lower part of the bed the vesicles may be interconnected and reach 0.5 cm in size.

At the top of the rim there are no surface phenomena associated with this bed. Several tens of meters down the outer slope where the slope reaches an angle of 15-20° there are faint signs of ripples elongated parallel to the slope. With increase in slope angle the ripples become more pronounced (fig. 6) and asymmetric. Their wavelengths are 3-8 cm, the amplitudes up to 1 cm with the downslope sides being steeper and shorter than the upslope sides. With increase in slope angle the wavelength of the ripples decreases slightly.

From the rim towards the crater this bed increases in grain size slightly. And the vesicles become fewer and finally disappear nearly completely probably as a result of the increasing ease of escape of the gas phase in the coarser ash. The ripples also are less well developed on the uppermost part of the inner crater wall and disappear completely downslope.

The overlaying bed covers the ripples without showing irregularities at its own surface indicating that the ripples formed prior to its deposition. Ripples of this type associated with vesiculated tuffs were already interpreted as the result of very wet ash being deposited on a slope by a base surge and consequently starting to flow downslope because of its high water content (Lorenz 1970). Beds of this type are also considered to have contained, at the time of their deposition, 20-30 vol% of water (Lorenz 1974).

JOINTS

Approximately 1 m above the unconformity as well as in the W part of the Surtur I crater bowl pyroclastic beds, both vesiculated and non-vesiculated, show joints antithetic to slope and bedding (fig 1, 7). These joints are similar to those described by Fürlinger (1972) in slaty quartzphyllities and interpreted by him, likewise, as a result of slope movements. This jointing is restricted to specific bed sequences and covered by undisturbed ash layers. These beds, therefore, already must have acquired a certain degree of consistency and hardness to react in such a manner prior to deposition of the younger beds. Hardening of the ash immediately after its deposition and some drying, again probably due to a specific water content (Carr 1969), is suggested to explain this mechanical behavior.

VESICULATED ACCRETIONARY LAPILLI

Approximately 3 m above the unconformity at the SE edge of the Surtur I crater rim there is a layer 3-5 cm thick, and dipping 30-40° towards the crater centre. This bed contains many accretionary lapilli. They vary in size from 0.5-3.5 cm and contain as a core a piece of basalt. The outer layer, 1-6 mm thick, consists of vesiculated tuff the vesicles reaching 0.2—0.5 mm in diameter, rarely 1 mm (fig 8-9). The accretionary lapilli are found in flat accumulations the largest accretionary lapilli lying downslope and the smaller ones having accumulated behind them upslope. This seems to indicate their having rolled and slid downslope to some extent.

Halfway up the inner slope, i.e. slightly farther away from the source of eruption, the accretionary lapilli of this bed, which at this locality dips with approximately 40° towards the crater, become smaller in size, reaching only 1.5 cm, and the amount of vesicles in the outer layer decreases. Even higher up the slope the vesicles nearly disappear and the accretionary lapilli decrease to 0.5-1 cm in size.

At this last locality only, the vesiculated tuff bed underlying the accretionary lapilli shows

Fig. 5. Slide of mudflow-channel-layer at upper part of Surtur I NW inner slope.

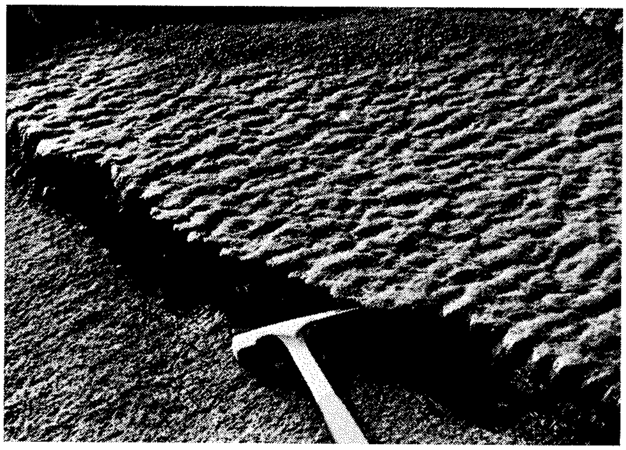


Fig. 6. Ripple layer at uppermost part of NW outer slope of Surtur I.

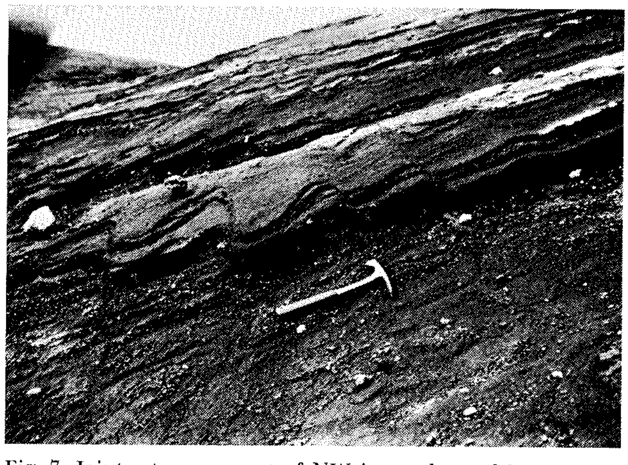


Fig. 7. Joints at upper part of NW inner slope of Surtur I.

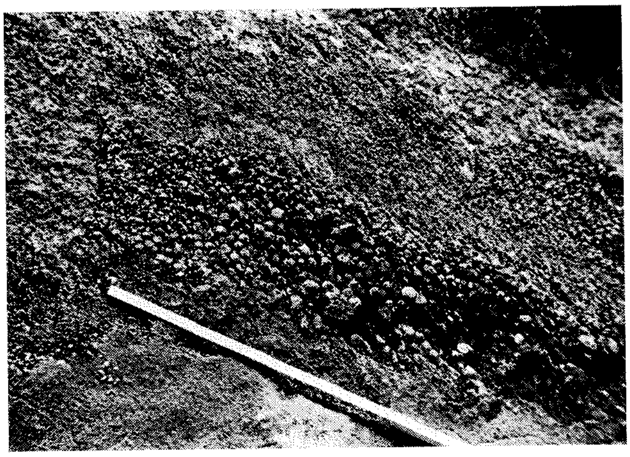


Fig. 8. Accumulation of vesiculated accretionary lapilli approximately 3 m above lower part of unconformity, SE edge of Surtur I rim, left side is upslope.

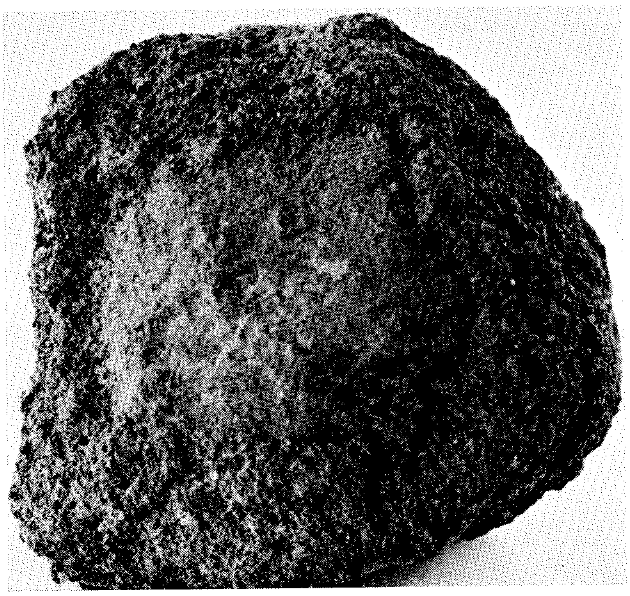


Fig. 9: Vesiculated accretionary lapilli, same locality as fig. 8, diameter of lapilli is 2.5 cm.

pronounced linguoid flowage ripples the lee sides of which are oriented downslope. These ripples are also thought to have formed as a result of gravity flowage owing to a very high content of water in the newly deposited vesiculated base surge deposit.

Elsewhere vesiculated accretionary lapilli have been observed only at the tuff-rings Hverfjall and Ludent, and in palagonite tuffs at Askja. Their formations points to very rapid accretion of ash around a core within a very wet eruption cloud (maybe even within a base surge), i.e. an eruption cloud of phreatomagmatic origin like the Surtsey eruption clouds (Lorenz, 1974).

CHANNELS

Relatively few radial base surge channels are found exposed on Surtsey (fig. 12). 3 channels exist at the N rim of Surtur II and are 3-5 m wide and 10-20 cm deep. The largest channel, however, is exposed in the small ridge NE of the Surtsey hut. It is approximately 20 m wide and has a maximum depth of 1 m. The tuffs and lapilli-tuffs within the channels are characterised by a decrease in thickness and grain-size of the individual layers towards the margins of the channels.

IMPACT STRUCTURES

Below the unconformities most blocks and bombs do not show impact sags in the underlying beds. This indicates that they were emplaced by base surges.

There are a few beds above the unconformity of Surtur I, especially near the top of the SW rim, with many bombs and blocks that indented the underlying beds on impact, i.e. they landed ballistically (fig. 10). The bedding sags are commonly elongated with their long axes oriented radially to the crater centre of Surtur I. This would indicate that the blocks and bombs were ejected from Surtur I. Jakobsson (1972, personal communication) points out, however, that the ash of the youngest layers of Surtur I, at least in part, was erupted from Surtur II. The only explanation in this case would be that the blocks and bombs, after having been ejected from Surtur II onto the upper inner crater wall of Surtur I, started to slide down the slope to a small extent.

Where the bed has just been eroded the blocks and bombs are still attached to the ground (fig. 10) and surrounded by a rim that represents the deformed remains of the ash layer into which the ejecta impacted. These crater rims, therefore, must have been compacted and hardened on impact in order to be more resistant to erosion. Such impact sags are indicative of wet, cohesive ash were the bedding is preserved but deformed plastically upon impact (Lorenz et al. 1970; Waters & Fisher 1970).

CAULIFLOWER BOMBS

In the final tuff layers of both Surtur I and II there are many cauliflower bombs whereas hardly any were observed in the older tuffs in both cliffs.

Cauliflower bombs were first described by Nakamura & Krämer (1970) from a maar in the Eifel (Germany) where they especially mention their "characteristic particulate structure: the scoria is broken up locally (around the rim and in wedges) into subangular fragments, but these fragments are weakly to firmly welded together". Nakamura & Krämer also point out that this structure is "Included in the product of phreatomagmatic explosions" which is confirmed by the author's studies. So far they are known from most maars in the Eifel and Massif Central and tuff-rings in Iceland.

Typical cauliflower bombs (fig. 11) are, in general, round and have a surface resembling cauliflowers (term suggested by H. U. Schmincke 1971). Similar to breadcrust bombs fractures extend for a few mm or cm into the bombs. The crust is thus devided into subangular to round, bud-like fragments that adhere weakly to firmly to the bomb depending on the extend of continuity with the bomb. At the bottom of some fractures of a few cauliflower bombs vesicles are elongated at right angle to the length of the fracture indicating that the fractures were formed while the interior of the bomb was still fluid. Some threads of pele's hair, up to 1 mm long adhere to the walls of the fractures and rarely extend across the fracturs from wall to wall. Cauliflower bombs from Jólnir, collected by the author in June 1966 on Surtsey also display many small threads of pele's hair.

The surface of the cauliflower bombs consists of a layer, one to several mm thick, of shiny sideromelane whereas the interior is made of tachylite. Vesicles in the sideromelane layer increase in size from the surface towards the interior of the bombs and are rather round whereas the more frequent vesicles of the interior part of the bombs are slightly irregular in shape and much more frequently interconnected.

All this indicates that the surface of the bombs was formed while the interior was still fluid and exsolved gas. The surface was chilled and solidified very rapidly as pointed out by the existance of the sideromelane crust.

Many cauliflower bombs on Surtsey have the typical surface pattern on one side only, the other side being rather flat. Impacted bombs, investigated in situ, clearly show that the flat side is the side with which the bombs had impacted and which consequently deformed. Extremely deformed bombs may reach 16 cm in maximum diameter and only 3-4 cm in minimum diameter. This deformation could only have taken place if the interior of the bomb had not yet solidified at the time of impact so the whole bomb reacted plastically. The surficial crust, the result of a certain degree of chilling, could not prevent deformation of the whole bomb, i.e. chilling could not have been very intense. On the other hand, however, chilling must have been intense enough

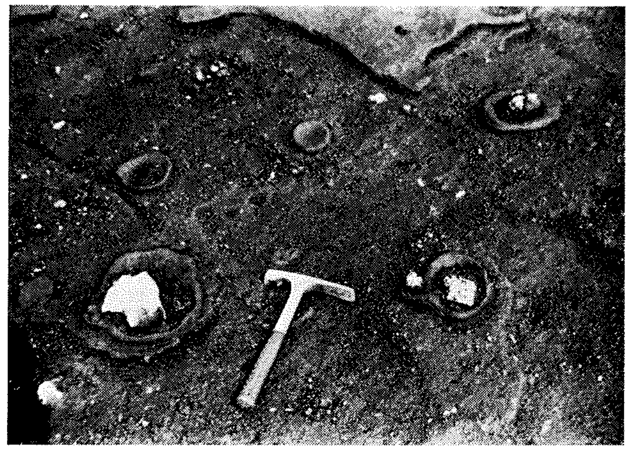


Fig. 10. Impacted blocks and bombs with impact craters at upper part of NW inner slope of Surtur I.

Fig. 11. Cauliflower bombs from final phreatomagmatic layers of Surtur II.

Fig. 12. Small channel in NE upper slope of Surtur I rim.

to prevent disintegration of the bomb during flight and impact.

Rarely the bombs contain small fragments of basalt of slightly different state of crystallization and/or vesiculation. Cauliflower bombs of the Eifel and Massif Central maars typically contain many chips of country-rocks that were caught up in the eruption channel during intense wall-rock spalling ,prior to formation of the bombs. In the eruption channel of tuff-rings that have a shallow magma/water contact level wall-rock spalling seems to be much less intense than in maars (Lorenz 1973), and probably therefore, fewer xenoliths are incorporated in the respective bombs.

These and other studies in Iceland, Eifel and Massif Central suggest that cauliflower bombs only form if there is not a very good contact between magma and water, or not very much water contacting the magma. The magma erupts inside the eruption channel forming the bombs which only subsequently contact water and become chilled. On Surtsey rapid chilling accounts for the sideromelane crust and the typical surface pattern whereas the fluid interior still exsolved gas and solidified slightly less rapidly after impact forming tachylite.

DARK LAYERS

Near the top of Surtur II rim and on the ridge between Surtur I and II there is a coarse dark layer, 20-30 cm thick, that is very rich in bombs, blocks, and vesicular black juvenile lapilli. The blocks consist in part of basalt pillow fragments, marine sediments etc. In addition to many cauliflower bombs there are a few cow-dung bombs, some of them reaching a maximum diameter of 1.25 m.

Approximately 4 m higher up on Surtur II W rim there is a second dark layer, 0.5-1 m thick and very rich in cauliflower bombs and vesicular black juvenile lapilli. In addition to the cauliflower bombs and cow-dung bombs some ordinary basaltic scoriaceous bombs with smooth or bread-crust surfaces are found. Country-rock fragments from the sea-floor are frequent too.

The juvenile lapilli of these two layers contrast to the ones of the other lapilli-tuffs of Surtsey in so far as they are, in general, several cm in size, and relatively more vesicular. The core is made up of vesicular black tachylite, whereas the rim consists of 1 to several mm thick, shiny, yellowish-brown sideromelane, that is slightly less vesicular than the tachylite. Thus even these lapilli were chilled rapidly only at their surface whereas their interior cooled and solidified less rapidly. The interior resembles ordinary cinder, i.e. the magma was in the process of high-level vesiculation and eruption when the eruption products contacted some sea-water. The relatively small amount of sea-water consequently chilled only the surface whereas the interior of the lapilli was less effected.

The ordinary basaltic bombs, cow-dung bombs and cauliflower bombs as well as the vesicular black juvenile lapilli all indicate that during their formation there was only little contact between sea-water and magma. Thorarinsson (1965, 1967) in fact, points out that magma could only reach the surface of the tuff-ring Surtur II after the sea could not breach the crater rim anymore. Close to the end of the phreatomagmatic activity the crater rim was breached repeatedly by the sea. Juding from the final deposits there must have been two periods where the magma nearly reached the surface and, at this shallow level, contacted during its own eruption only a minor amount of sea-water. The already formed bombs and lapilli then were chilled rapidly only to the extent that their surfaces solidified into sideromelane whereas their interior stayed fluid slightly longer depending on the size of the particles.

ACKNOWLEDGEMENT

The author greatly enjoyed discussions held with S. P. Jakobsson, G. E. Sigvaldason, and S. Thorarinsson.

Permission for fieldwork on Surtsey by the National Research Council of Iceland and the Surtsey Research Society is gratefully acknowledged.

Financial support was granted by DFG grant Lo 171/2.

References

Carr, R. L., 1969: Properties of solids. – Deskbook issue, Chem. Engineering, 7-16, Oct. 13, 1969.

Fürlinger, W. L., 1972: Mechanismus einer Hangbewegung in Quarzphyllitten und dessen Kontrolle im gefügeäquivalenten Modellversuch. – Geol. Rundschau, *61*, 871-882.

Jakobsson, S. P., 1972: The consolidation and palagonitization of the tephra of the Surtsey volcanic island, Iceland. A preliminary report. – Surtsey Res. Progr. Rep. IV, 121-128.

Lorenz, V., 1970: Some aspects of the eruption mechanism of the Big Hole maar, central Oregon. – Geol. Soc. Amer. Bull., *81*, 1823-1830.

– 1973: On the foramtion of maars. Bull. volcanologique, *37*, 183-204.

– 1974: Vesiculated tuffs and associated features. – Sedimentology, *21*, 273-291.

Lorenz, V., McBirney, A. R., and Williams, H., 1970: An investigation of volcanic depressions. Part III. Maars, tuff-rings, tuff-cones, and diatremes. – 198 p., NASA progr. rep., (Clearings-house for Federal Scientific and Technical Information, Springfield, Va.: NASA CR-115236).

Moore, J. G., 1967: Base surge in Recent volcanic eruptions. – Bull. Volcanologique, *30*, 337-363.

Nakamura, K. and Krämer, F., 1970: Basaltic ash flow deposits from a maar in West-Eifel, Germany. — N.Jb.Geol. Paläont. Mh., Jg. 1970, H. 8, 491-501.

Sheridan, M. F., 1972: Textural analysis of Surtsey tephra. A preliminary report. — Surtsey Res. Progr. Rep. VI, 150-151.

Thórarinsson, S., 1965: Sitt af hverju um Surtseyjargosið. (Some facts about the Surtsey eruption. In Icelandic, with English summary). — Nátt.fr., *35,* 153-181.

— 1967: Some problems of volcanism in Iceland. — Geol. Rundschau, *57,* 1-20.

— 1968: Síðustu þættir Eyjaelda. (The last phases of the Surtsey eruption. In Icelandic, with English summary). — Nátt.fr. *38,* 113-135.

—, Einarsson, Th., Sigvaldason, G. E., and Elísson, G., 1964: The submarine eruption off the Westman Islands 1963-1964. — Bull. volcanologique, 27, 1-11.

Walker, G. P. L. and Croasdale, R., 1972: Characteristics of some basaltic pyroclatics. — Bull. volcanologique, *35,* 303-317.

Waters, A. C. and Fisher, R. V., 1970: Maar volcanoes. — Prov. sec. Columbia River Basalt Symp., 157-170, EWSC, Cheney, Wash.

Fossils from Surtsey – A preliminary report

By
LEIFUR A. SÍMONARSON
Science Institute, University of Iceland
Jarðfraeðahús Háskólans, Reykjavík

During the Surtsey eruption 1963-1967 fossiliferous sedimentary xenoliths were carried upwards with the hot magma and are now found in the tephra on Surtsey (Fig. 1). Similar fossil-bearing xenoliths are also known on Heimaey (Jakobsson, 1968 p. 115). Data from a 1565 m deep drillhole on Heimaey (Pálmason et al., 1965) show a thick series of sedimentary layers in the stratigraphic column below the Vestmann Islands (Fig. 2). Those beds have probably supplied the fossiliferous xenoliths on the islands. The petrological aspect of the xenoliths from Surtsey has been dealt with by Alexandersson (1970, 1972). Furthermore, Alexandersson had some fragments of *Arctica islandica* (Linné) dated radiometrically, but according to him (1970 p. 86) it was possible to identify four species of marine invertebrates from the xenoliths. The dated *Arctica* fragments were taken from two blocks; "one block (mainly "outer fraction") was approximately 11.000 years old while the other (mainly "inner fraction") was 6.200 years." (Alexandersson, 1972 p. 106). These dates indicate Late Quaternary age.

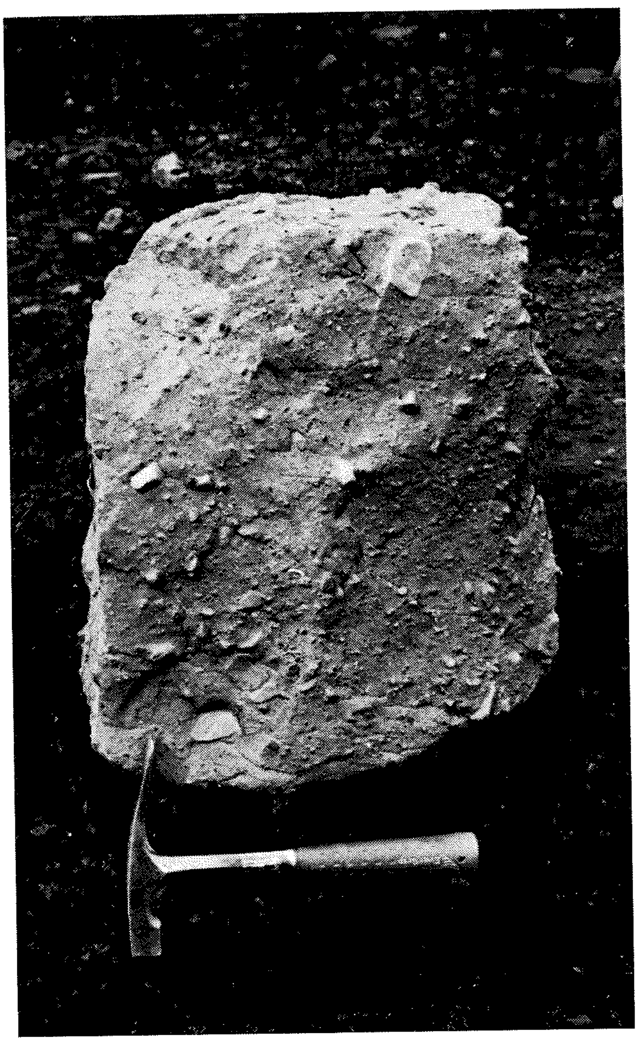


Fig. 1. Fossiliferous sedimentary xenolith on Surtsey. Length of hammer 28 cm. – Photo L. A. Símonarson, 4. VII. 1972.

The present author has during the last years investigated fossils in sedimentary xenoliths from Surtsey. These were partly collected by the author, partly by others. The fossils found in the xenoliths in question are listed below.

A. Foraminifera:
Quinqueloculina seminulum (Linné, 1758) (15 specimens).
Triloculina trihedra Loeblich & Tappan, 1953 (1 specimen).
Pyrgo williamsoni (Silvestri, 1923) (3 specimens).
Miliolinella subrotunda (Montagu, 1803) (3 specimens).
Miliolinella cf. *enoplostoma* (Reuss, 1851) (7 specimens).
Polymorphinidae (1 specimen).
Oolina acuticosta (Reuss, 1862) (3 specimens).
Oolina melo d'Orbigny, 1839 (1 specimen).
Fissurina danica (Madsen, 1895) (1 specimen).
Fissurina marginata (Walker & Boys, 1784) (4 specimens).
Parafissurina lateralis (Cushman, 1913) forma *simplex* (Buchner, 1940) (1 specimen).

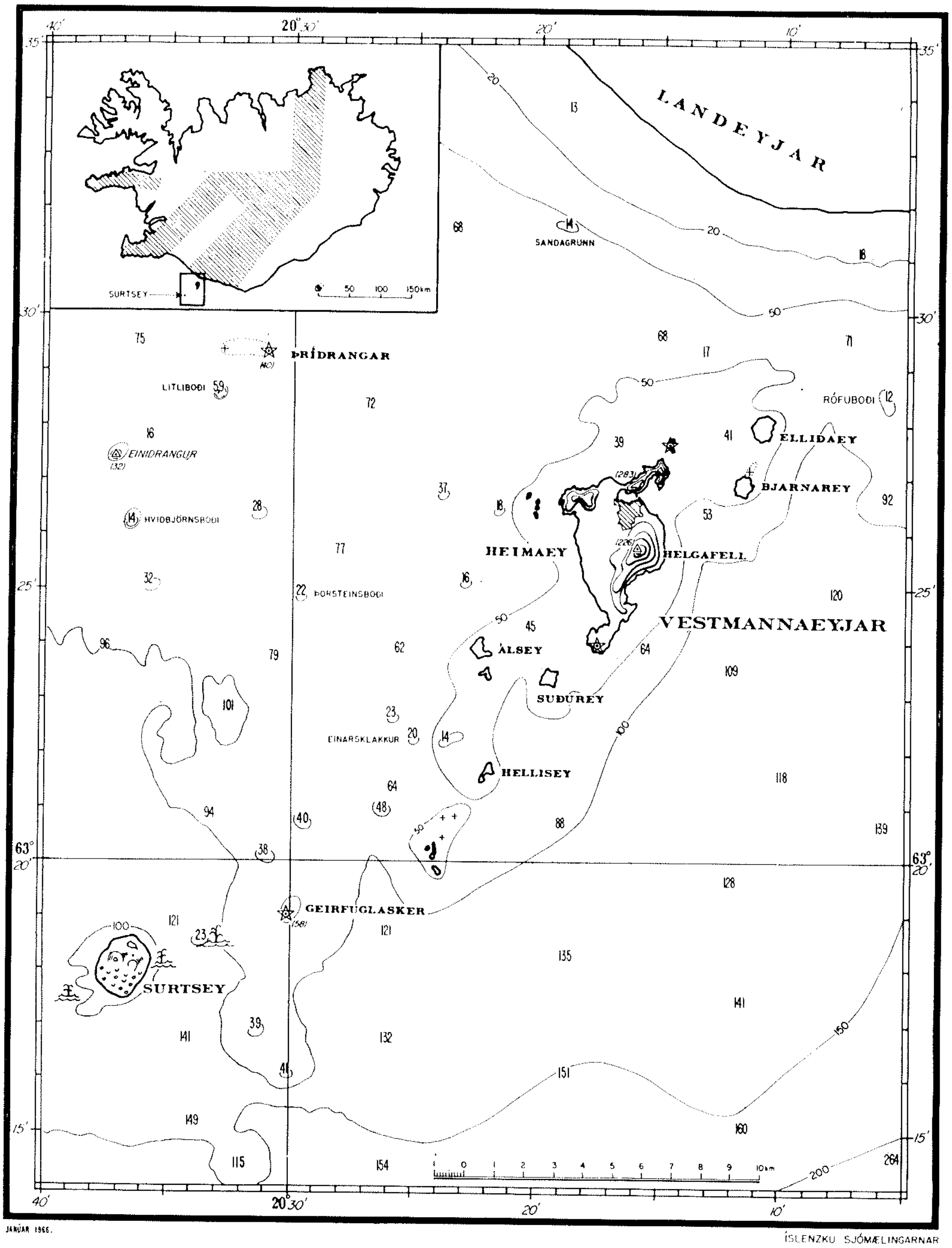


Fig. 2.
Map showing the location of the Vestmann Islands. Striated on the key map is the neovolcanic areas. (From Thorarinsson, 1965).

Bulimina marginata d'Orbigny, 1826 (1 specimen).
Trifarina angulosa (Williamson, 1858) (7 specimens).
Trifarina fluens (Todd, 1947) (1 specimen).
Cassidulina crassa d'Orbigny, 1839 (39 specimens).
Cassidulina laevigata d'Orbigny, 1826 (2 specimens).
Buccella frigida (Cushman, 1922) (4 specimens).
Cibicides lobatulus (Walker & Jacob, 1798) (299 specimens).
Nonion barleeanum (Williamson, 1858) (19 specimens).
Astrononion gallowayi Loeblich & Tappan, 1953 (4 specimens).
Pullenia subcarinata (d'Orbigny, 1839) (1 specimen).
Elphidium albiumbilicatum (Weiss, 1954) (12 specimens).
Elphidium clavatum Cushman, 1930 (40 specimens).
Elphidium groenlandicum Cushman, 1933 (3 specimens).
Elphidium macellum (Fichtel & Moll, 1798) (2 specimens).
Elphidium subarcticum Cushman, 1944 (33 specimens).
Globigerina bulloides d'Orbigny, 1826 (32 specimens).
Globigerina pachyderma (Ehrenberg, 1861) (30 specimens).
Globigerina sp. (8 specimens).

B. Serpulidae:

Pomatoceros triqueter Linné, 1761 (several tubes).

C. Mollusca:

Lepeta caeca (Müller, 1776) (1 fragmentary specimen).
Eumetula (Laskeya) costulata (Møller, 1842) (1 fragmentary specimen).
Trichotropis cf. *borealis* Broderip & Sowerby, 1829 (2 fragmentary specimens).
Aporrhais pespelecani (Linné, 1758) (1 complete and 21 fragmentary specimens).
cf. *Natica (Tectonatica) affinis* (Gmelin, 1789) (1 fragment).
Colus glaber (Verkrüzen, 1876) (1 spire).
Dentalium entale Linné, 1758 (10 specimens; some of them are fragmentary).
Nuculana cf. *minuta* (Müller, 1776) (1 valve).
Mytilus edulis Linné, 1758 (1 fragment without umbo).
Crenella decussata (Montagu, 1808) (2 valves).

Chlamys islandica (Müller, 1776) (1 fragment without umbo).
Pododesmus (Heteranomia) squamula (Linné, 1758) (22 valves and 10 umbonal fragments).
Tridonta (Tridonta) borealis (Chemnitz, 1784) (1 valve).
Tridonta (Tridonta) elliptica (Brown, 1827) (4 umbonal fragments).
Tridonta (Nicania) montagui (Dillwyn, 1817) (2 valves and 1 umbonal fragment).
Arctica islandica (Linné, 1767) (several fragments without umbo).
Acanthocardia echinata (Linné, 1758) (1 umbonal fragment and 3 fragments without umbo).
Spisula elliptica (Brown, 1827) (1 valve).
Macoma calcarea (Chemnitz, 1782) (2 valves).
Hiatella arctica (Linné, 1767) (2 fragments without umbo).

D. Cirripedia:
Balanus sp. (1 fragmentary parietal plate).
Balanus (Chirona) hameri (Ascanius, 1767) (1 parietal plate).

E. Bryozoa:
Tessaradoma gracile (Sars, 1863) (1 fragment).
Escharella cf. *immersa* (Fleming, 1828) (2 fragments).
Indet. encrusting ascophoran (1 fragment).

The marine fauna consists entirely of species living at the present time which is in agreement with the radiocarbon dates. The fauna is, moreover, north boreal, i.e. similar to the fauna of South Iceland today. Several species of foraminifera found in the xenoliths have not been recorded as living nowadays in Icelandic waters. However, the recent foraminifera fauna of Iceland is not sufficiently well known, so a comparison is probably of no great importance. The same seems to be true of the bryozoans. The species are all benthonic with the exception of a few plankton forms of foraminifera belonging to the genus *Globigerina*. It is noteworthy that the shells are generally out of growth position and certainly somewhat transported. The fauna seems, however, to indicate a depth of formation somewhat greater than 100 m. In this context it must be mentioned that the Surtsey eruption penetrated the Icelandic shelf where the water depth was about 130 m (see also discussion in Alexandersson, 1970 p. 88).

A more detailed paper dealing with the fossils from Surtsey is now in progress.

ACKNOWLEDGEMENTS

The author is most indebted to Dr. phil. R. W. Feyling-Hanssen and cand. scient. K. L. Knudsen, Department of Micropalaeontology, University of Aarhus, Denmark, for their great help rendered towards the identification of the foraminifera. Thanks are also due to cand. scient. E. Håkonsson, Institute of Historical Geology and Palaeontology, University of Copenhagen, Denmark, for the identification of the bryozoans. At last, but not least, the author is grateful to all the collectors who have handed over to him sedimentary xenoliths from Surtsey.

References:

Alexandersson, T. 1970: The sedimentary xenoliths from Surtsey: Marine sediments lithified on the sea-floor — A preliminary report. Surtsey Res. Progr. Rep. V; 83-89.

Alexandersson, T. 1972: The sedimentary xenoliths from Surtsey: Turbidites indicating shelf growth. Surtsey Res. Progr. Rep. VI; 101-116.

Jakobsson, S. 1968: The geology and petrography of the Vestmann Islands — A preliminary report. Surtsey Res. Progr. Rep. IV; 113-130.

Pálmason, G., Tómasson, J., Jónsson, J. & Jónsson, Í. 1965: Djúpborun í Vestmannaeyjum. State Electricity Authority, Reykjavík. 43 pp. Mimeographed.

Thorarinsson, S. 1965: Sitt af hverju um Surtseyjargosið. Náttúrufr. 35 (4); 153-181.

Seismic Activity Recorded In Surtsey During The Summer Of 1966

By

PÁLL EINARSSON

Lamont-Doherty Geological Observatory and Department of Geology
Columbia University, Palisades, New York[1]

ABSTRACT

A tripartite array of short period seismometers was operated in Surtsey from June 1 to September 25, 1966 with a few interruptions. Most of the recorded seismicity appeared to be associated with the decrease and cessation of volcanic activity in Jólnir and subsequent beginning of the lava eruption in Surtsey. The earthquakes occurred mostly in swarms, each swarm emanating from relatively small source volume. The hypocenters that could be located were at depths of 0 to 5 km and seemed to follow the tectonic trend defined by the Jólnir-Surtsey-Syrtlingur-Surtla row of volcanic centers. A swarm of small, shallow earthquakes was recorded shortly before the beginning of the lava eruption in Surtsey on August 19. The lava eruption was accompanied by continuous volcanic tremor with predominant frequency of 3 Hz.

INTRODUCTION

During the summer of 1966 an arry of short-period seismometers was operated in Surtsey. The purpose was to obtain a continuous record of the volcanic activity and to get information about the origin of the seismic activity.

Seismic activity near a volcano can be generated in a number of ways, for example:

1. Release of preexisting tectonic stress in the region.
2. Release of stress set up by intrusion of volcanic material under the volcano.
3. Release of stress generated by the additional loading of the crust and settling of the volcanic pile.
4. Movement of magma underground and in the crater.
5. Explosions in the crater.

This paper is a preliminary report on the analysis of seismological data obtained during the summer of 1966. The analysis of similar data recorded in 1967 and other seismological data obtained during the Surtsey eruption will be the subject of later papers.

When the seismic recording began in Surtsey on June 1, 1966 the crater of Jólnir was erupting, building up a small island off the south-western coast of Surtsey. Towards the end of July the intensity of this eruption diminished and after August 10 no activity was seen in Jólnir. There was a period of nine days with no visible volcanic activity in the Surtsey region. On August 19 a lava eruption began on a fissure in Surtsey itself. Similar shifts in the activity were observed at least six times during the entire Surtsey eruption.

This shift in the volcanic activity during the seismic recording in Surtsey offers an excellent opportunity to study the relationship between the volcanic activity and the seismicity. Indeed, it appears that most of the seismic activity during the summer of 1966 was in some way associated with this change in the volcanic activity.

INSTRUMENTATION AND DATA ANALYSIS

The seismic array in Surtsey consisted of one central station in the northern part of the island where three components of motion were detected, one station in the southern part and one station in the western part of Surtsey where only one component of motion was detected. The seismometer signals were brought by cable to the

[1] Lamont-Doherty Geological Observatory Contribution No. 2246.

research hut where they were amplified and recorded on magnetic tape. The recorder was a seven channel FM magnetic tape recorder. The recording speed was 15/160 i.p.s. and the center frequency 84.4 Hz, which allows 10 days of recording on one reel of tape. One track on the tape was used for continuous recording of a radio time signal as well as a chronometer time signal. The array was in operation from June 1 to September 25 with a few interruptions.

To demonstrate the experimental difficulties with seismic recordings in a harsh environment, a few entries in the log book of the seismometer will be cited: "The cable to geophone 1 had broken in a storm and was reconnected. The geophone was also moved a little because it had been buried by blowing sand and heated so that the mass sagged". "Cable on the east coast broken by an avalanche". "The lava flowed over the cable to geophone 6 and the geophone was removed about 14h".

The seismic records of interest were reproduced on paper with a time resolution of 25 mm/sec. When sufficient data were available the earthquake hypocenters were calculated using the relative arrival times of the P- and S-waves at the three stations. The method of analysis is described by Einarsson and Björnsson (paper in preparation) and Ward and Gregersen (1973), and will not be repeated here. The precision of the hypocentral locations is considered to be better than ± 1 km in horizontal dimension and ± 1.5 km in dept. It is encouraging to note that most of the locations of earthquakes within individual earthquake swarms cluster within volumes smaller than the error estimates of a single location.

Since only three seismic stations were in operation, only a minimum amount of data is available for the location of an earthquake. This lack of redundancy means that a misinterpretation of the data is not detectable and will result in a mislocated earthquake.

In locating the earthquakes it is assumed that the crust under Surtsey is made up of horizontal layers. Any deviation from this structure will cause systematic errors in the locations. It is desireable to set off explosions around a seismic array in order to detect any systematic errors. No such tests are available from Surtsey. It is therefore not possible to estimate to what extent the precision of the locations represents the true accuracy. This limitation should be born in mind when reading this paper.

SEISMICITY

The seismic activity as recorded by the seismic array on Surtsey is summarized in Figure 1. From this figure it is obvious that the earthquakes do not occur randomly in time, but are concentrated into bursts of activity. Most of these bursts are earthquake swarms, i.e., a sequence of earthquakes occurring close together both in time and space and without an outstanding main shock. The most intense activity of the swarms usually lasted less than one hour.

The seismic activity in June and July was generally low. During this time the crater of Jólnir, SW of Surtsey, was erupting. Towards the end of July the eruption in Jólnir became intermittend and at the same time the seismic activity increased (Fig. 1), culminating on August 9 and 10 when the volcanic activity in Jólnir ceased. The bulk of the seismicity is thus seen to be associated with changes in the eruption, i.e., the decrease and cessation of activity in Jólnir. Unfortunately no records are available for the period August 11-18, but prior to the outbreak of the lava eruption in Surtsey on August 19 an earthquake swarm was recorded. After the beginning of that eruption the high tremor level in Surtsey prevented any further detection of earthquakes.

Because of uncertainty in the polarity of the seismic detectors no systematic study could be made of the first motion of P-waves. It can be said, however, that not all earthquakes had the same first motion on the same station. Therefore it can be concluded that if the source of the earthquakes is monopolar it is not always in the same sense, i.e., sometimes it is dilatational and other times it is compressional. Most likely the source is nonmonopolar, probably the result of a shear dislocation.

Hypocentral location could be determined for 76 earthquakes occurring in the time interval July 27 to August 18. The earthquakes originated east, south and west of Surtsey as well as under the island itself at the depths of 0-5 km (Fig. 2, 3, and 4). The events of individual earthquake swarms were tightly clustered in space as well as in time. The source areas of the different swarms are shown in Figures 2, 3, and 4.

The epicenters define an ellipse shaped zone with the major axis trending ENE. This trend is even more pronounced if earthquakes during shorter time intervals are considered, e.g. the time intervals July 31-August 2 (Fig. 2), August 8-18 (Fig. 4). The trend of the epicentral zone coincides with the trend of the row of volcanic

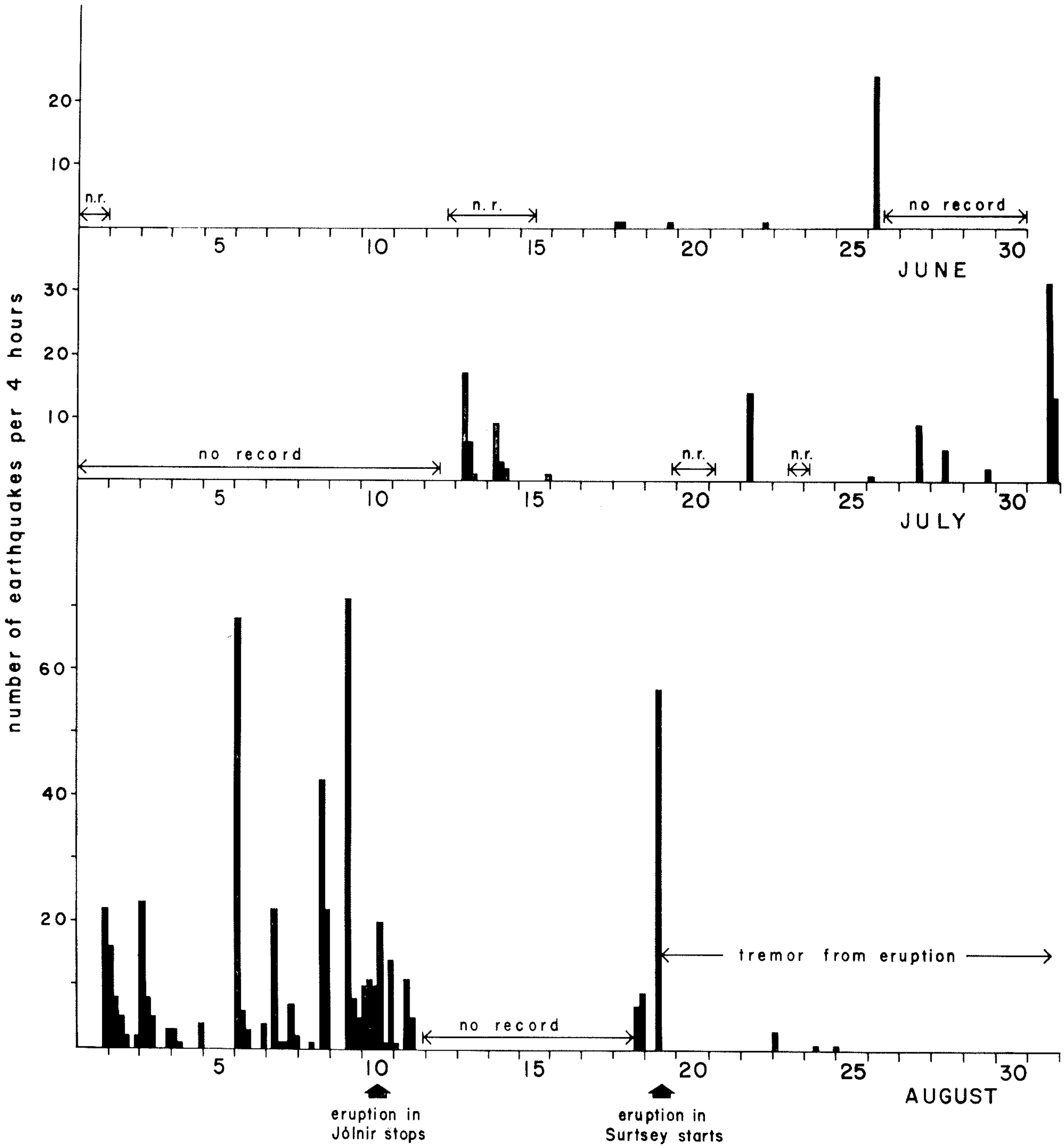


Fig. 1. Earthquake rates for June, July and August 1966 as recorded by the seismometers in Surtsey. Each bar represents counts for four hours. An earthquake was counted if it was recorded by two or more stations. After August 19 only very few earthquakes could be recognized on the records because of the intense volcanic tremors accompanying the lava eruption that started on August 19 in Surtsey itself.

vents Jólnir-Surtsey-Syrtlingur-Surtla. Individual eruptive fissures within this row, however, have a more northerly trend, as was pointed out by Thórarinsson (1966) and Jakobsson (1968). The eruptive fissure active in November 1966 had a trend of N 35° E (Thórarinsson, 1965), the Jólnir fissure had a trend of N 25° E (Thórarinsson, 1967) and the fissure that opened on August 19, 1966 in Surtsey had a trend of N 10°E (Thórarinsson, 1967). This en echelon arrangement of the eruptive fissures suggests a component of left-lateral strike-slip motion along an elongated zone with an ENE trend. It should be noted, however, that the motion does not need to be of a pure strike-slip nature. A component of opening perpendicular to the zone may also be present. In the case of the Reykjanes Peninsula oblique spreading motion was demonstrated along an ENE trending zone (Klein et al. 1973). Volcanic fissures are arranged en echelon with

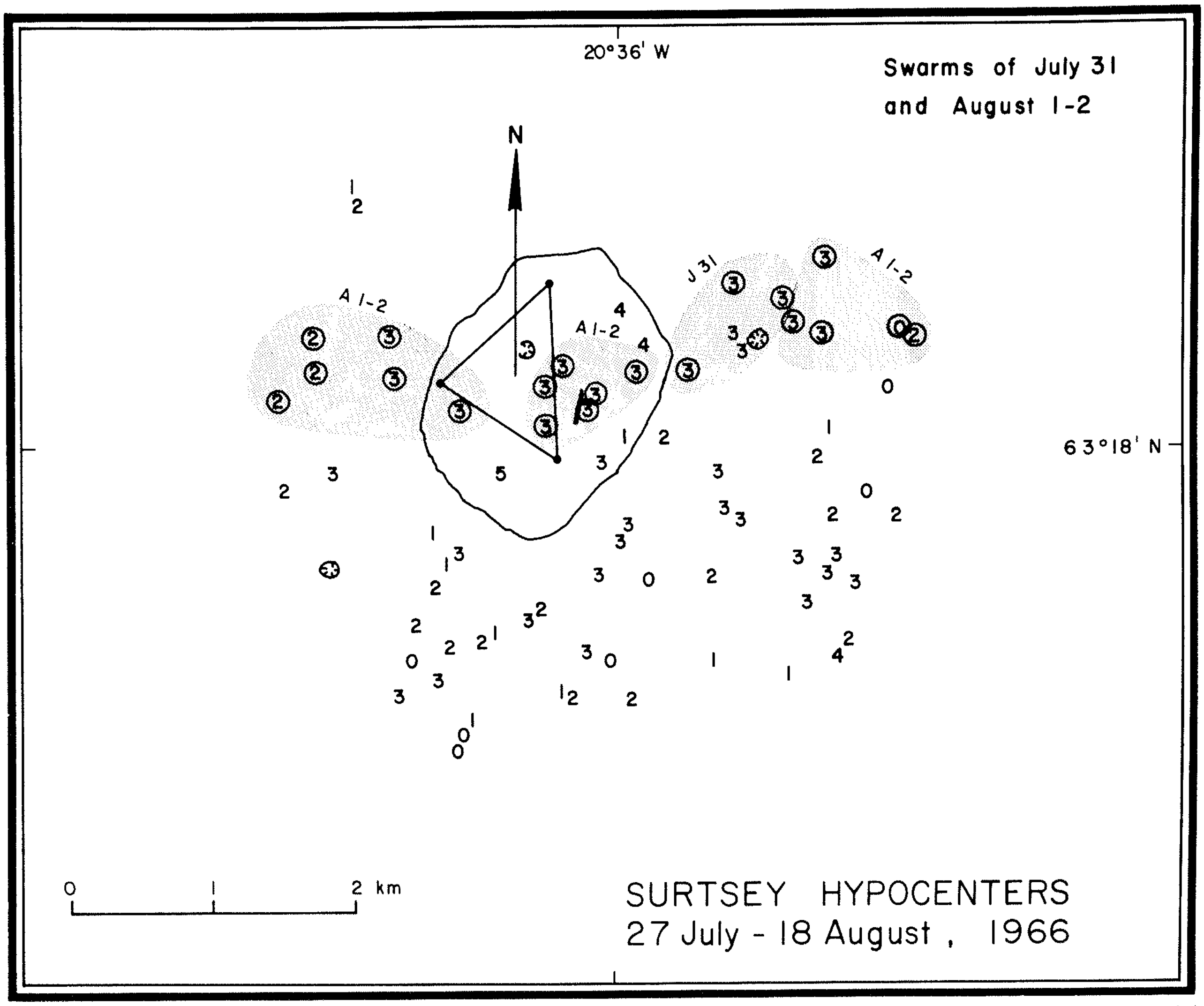


Fig. 2. Epicenters of all earthquakes between July 27 and August 18 large enough to be located are shown in Figures 2, 3, and 4. An epicenter is marked with a number that gives the depth of the hypocenter to the nearest km. A shaded area groups together all events belonging to the same swarm of earthquakes. The events belonging to the swarm are marked with a circle or a square. The date of the particular swarm is indicated near the edge of the shaded area. The craters of Syrtlingur, Surtur II and Jólnir as well as the eruptive fissure of August 19, 1966 are shown for reference. The outlines of Surtsey are those of August 1966. The seismometers were at the corner points of the triangle.

respect to the volcanic zone and the seismic belt on the Reykjanes Peninsula. Focal mechanism solutions for earthquakes in that seismic belt show that the minimum compressive stress is consistently horizontal and has a NW trend, perpendicular to the tensional structures on the surface. By analogy we infer that the minimum compressive stress in the Surtsey region is horizontal and has a WNW trend.

Course of Events

June 26: A swarm of earthquakes clustered under the south and south-west coast of Surtsey, depth about 3 km.

July 13: A swarm of very small earthquakes recorded.

July 14: An earthquake recorded with a few fore- and aftershocks.

July 27: A swarm of earthquakes, one of which was located under Surtsey at 4 km depth.

July 28: An earthquake recorded with a few fore -and aftershocks. One aftershock was located 2 km SE of Surtsey at 4 km depth.

July 29: Two small earthquakes, one was located under Surtsey at 5 km depth.

July 30: "No eruption in Jólnir 05:45-06:05 GMT" (seismometer log book).

July 31: A swarm of earthquakes located under Syrtlingur at 3 km depth (Fig. 2).

August 1: A swarm of earthquakes begins, located mostly under Surtsey at 3 km depth. Earthquakes felt in Surtsey. "The eruption in Jólnir

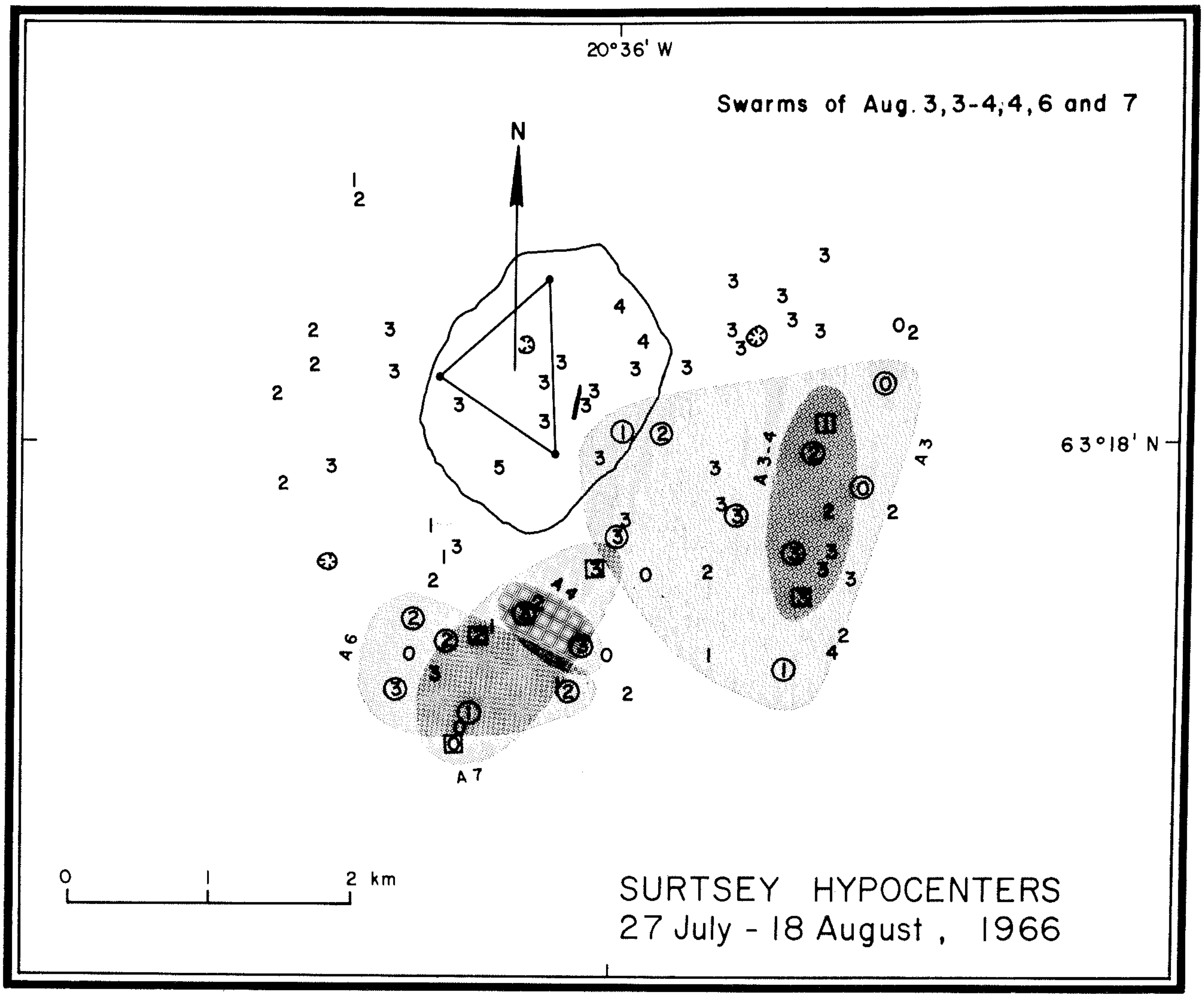


Fig. 3. Earthquake swarms of August 3-7. Symbols as in Figure 2.

very small with long intermissions between 13:15 and 14:00 GMT" (seismometer log book).

August 2: The earthquake swarm continues. The activity appears to migrate east of Syrtlingur, later also towards the west. Together with the swarm of July 31 this activity defines a narrow zone, trending nearly E-W (Fig. 2).

August 3-7: Several earthquake swarms and isolated events located east and south of Surtsey at the depth of 0-3 km (Fig. 3). One earthquake on August 4, located about 2 km south of Surtsey at the depth of 3 km, was followed by a burst of volcanic tremors lasting for about 7 minutes. The predominant frequency of these tremors was about 3 Hz.

August 8: A relatively large swarm of earthquakes located south of Surtsey at the depth of 0-3 km, mostly around 1 km depth (Fig. 4).

August 9: An earthquake swarm started at 15:00 GMT, the most intense activity lasted about one hour and was located under the east coast of Surtsey at 3-4 km depth. Seismic activity continued at a fairly constant level until about 16h on August 10. This activity was mostly located in two groups, one under Syrtlingur at 3 km depth, the other about 2 km SE of Surtsey at the depth of 3 km (Fig. 4).

August 10: Eruptive activity last seen in Jólnir. A small earthquake swarm, one event located near Jólnir.

August 11: A small earthquake swarm, located near Jólnir (Fig. 4).

August 11-18: Seismic array not in operation.

August 18: Some seismic activity, two events were located SSE of Surtsey, 0-2 km deep (Fig. 4).

August 19: Between 00h and 09:30 no earthquakes recorded. A swarm of small earthquakes started at 09:30, the last earthquake occurred 10:29 (Fig. 5). No earthquake could be located, but the swarm is probably shallow and near the northernmost and the southernmost stations. This conclusion is based on the observation that

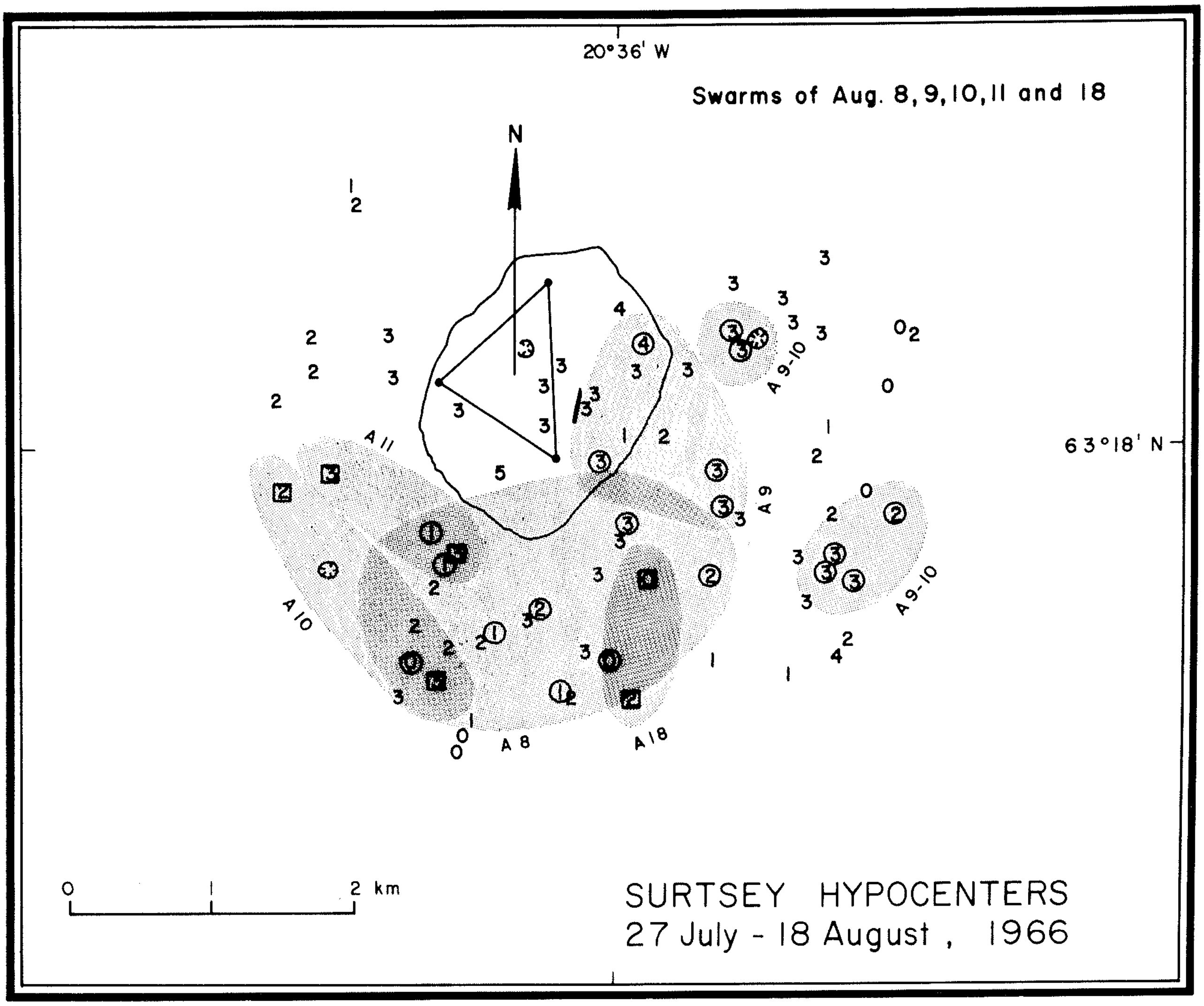


Fig. 4. Earthquake swarms of August 8-11 and August 18. Symbols as in Figure 2.

some of the earthquakes appear on the southern station only, while some earthquakes appear on the northern station only (Fig. 5). After 10:30 GMT volcanic tremors became visible on the seismic records, their amplitude increasing threefold in the next twenty minutes. The predominant frequency of these tremors was about 3 Hz. At 10:50 GMT the tremor amplitude increased suddenly (Fig. 5). After that time very few earthquakes could be identified on the records because of the high level of tremors. The continuous tremors were frequently felt in Surtsey.

The new lava eruption in Surtsey was first seen about 13h and by then lava had already spread 150-200 m from the fissure. It is natural to conclude that the lava eruption started about 10:50 GMT when the amplitude of the tremors increased suddenly. Note that the lava eruption was previously assumed to have started at 07h (Thórarinsson, 1967) which is inconsistent with the seismic records.

CONCLUSIONS AND DISCUSSION

The conclusions of this data analysis can be summarized as follows:

1. The bulk of the seismic activity near Surtsey in the summer of 1966 was associated with the changes in the volcanic eruption when the activity in Jólnir diminished and ceased and the lava eruption in Surtsey started.
2. The earthquakes occurred mostly in swarms, tightly clustered in space and time.
3. The earthquakes appear to have a shear dislocation source.
4. The earthquakes that could be located were of shallow origin, between 0 and 5 km deep.
5. The epicenters appear to follow the tectonic trend defined by the Jólnir-Surtsey-Syrtlingur-Surtla row of eruptive centers.

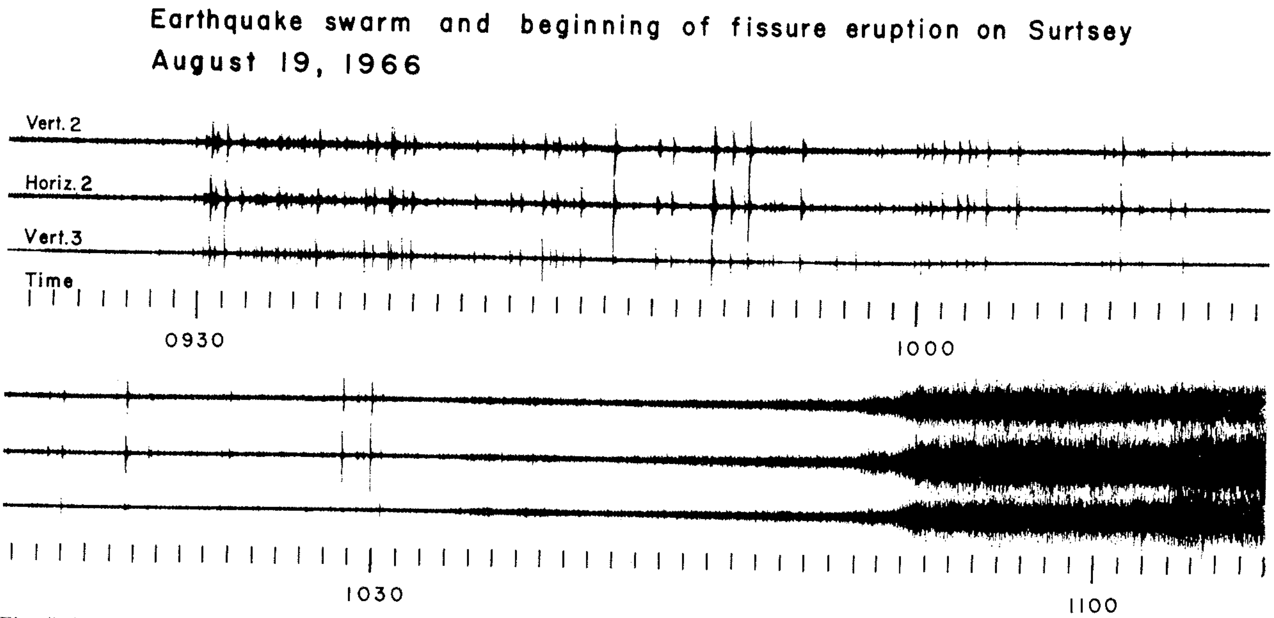


Fig. 5. The seismograms of August 19, 1966 showing the seismic activity associated with the beginning of a lava eruption on Surtsey. Shown are the seismograms of the vertical and one horizontal component of the northernmost seismic station and a vertical component of the southernmost station which was situated about 400 m from the fissure where the eruption broke out. The time is GMT.

A similar correlation between the increase in seismicity and changes in the eruption was found to hold during the Hekla eruption in 1970 (Einarsson and Björnsson, paper in preparation). This observation may be of some value when trying to predict the behavior of an eruption already in progress. An increase in seismicity implies higher probability for a change in the behavior of the eruption. The type of change, of course, cannot be determined with this empirical relationship.

The physical significance of the observation that most of the earthquakes occur in swarms as opposed to foreshock-mainshock-aftershock sequences is not clear. Earthquake swarms are frequently associated with volcanic regions (see e.g. Sykes, 1970) and are possibly related to the heterogeneity of the material or stress concentrations. The observation that the hypocentral domain is a volume rather than a plane (fault) may also be significant in this relation.

The depth of the Surtsey earthquakes is comparable to the depth of earthquakes on the Reykjanes Peninsula (Klein et al. 1973), which tend to occur in swarms but are clearly of tectonic origin. Earthquakes recorded during the Heimaey eruption 1973, however, occurred at depths of 20-30 km (Björnsson and Einarsson, paper in preparation), but appeared to be related to the rate of extrusion of lava at the surface. Such deep earthquakes produce complex seismograms at the surface above, which are difficult to interprete with limited amount of data available. Therefore, if small deep earthquakes occurred during the Surtsey eruption, they would have been missed in the data analysis.

It appears likely that the Surtsey earthquakes were of tectonic origin and occurred in response to some stress change. The earthquakes were related in space to the tectonic structure and in time to the changes in the eruption at the surface. At least two hypotheses can account for these relationships:

1. The earthquakes were caused by the regional stress being concentrated around the magma conduit. The tectonic displacements associated with the earthquakes blocked the Jólnir crater and the magma found another escape route to the surface.

2. The earthquakes were caused by a stress field produced by a decrease of the pressure in the magma conduit, resulting in a partial collapse. When the pressure increased again the easiest escape was no longer through the Jólnir crater.

The first hypothesis assumes that the pressure of the magma remains constant whereas in the second hypothesis the pressure fluctuates. The observation that the intensity of the Jólnir eruption diminished considerably before the seismicity increased would favor the second hypothesis.

ACKNOWLEDGEMENTS

The seismograph system was acquired through a grant from the U.S. National Science Foundation to the University of Iceland (Grant GP-4815). The field work was carried out under the supervision of Professor Thorbjörn Sigurgeirsson of the University of Iceland. The data analysis was partially supported by the National Science Foundation (Grant GA-29405) and the Icelandic Science Foundation. The computer program for locating the earthquakes was written by P. L. Ward and modified by S. Gregersen.

References

Jakobsson, Sveinn, 1968, The geology and petrography of the Vestmann Islands, (a preliminary report), Surtsey Research Progress Report IV, pp. 113-130.

Klein, F., P. Einarsson and M. Wyss, 1973, Microearthquakes on the Mid-Atlantic plate boundary on the Reykjanes Peninsula in Iceland, J. Geophys. Res., 78, 5084.

Sykes, L. R., 1970, Earthquake swarms and sea-floor spreading, J. Geophys. Res. 75, 6598.

Thórarinsson, S., 1965, The Surtsey eruption. Course of events and the development of the new island, Surtsey Research Progress Report I, pp. 51-55.

Thórarinsson, S., 1966, The Surtsey eruption. Course of events and the development of Surtsey and other new islands, Surtsey Research Progress Report II, pp. 117-123.

Thórarinsson, S., 1967, The Surtsey eruption. Course of events during the year 1966, Surtsey Research Progress Report III, pp. 84-91.

Ward, P. L. and S. Gregersen, 1973, Comparison of earthquake locations determined with data from a network of stations and small tripartite arrays on Kilauea volcano, Hawaii, Bull. Seismol. Soc. Amer., 63, 679.

Final Report on Geomagnitic Measurements on Surtsey

By
THORBJÖRN SIGURGEIRSSON
University of Iceland, Science Institute, Reykjavík

Since my report in 1968 (Sigurgeirsson 1968) the following total field intensity measurements have been made at the three fixed geomagnetic stations Surtsey I, Surtsey II and Surtsey III. The field intensity, F, is givin in gammas and compared with the value at Leirvogur Geomagnetic Observatory.

TABLE 1

Station	Date			U. T.	F.	$F_{Leirv.}$	ΔF
Surtsey I	1968	Dec.	27	13:28	51390	51187	203
„ „	1970	May	8	17:52	51442	51286	156
„ „	1971	Oct.	19	12:35	51400	51276	124
„ „	1973	May	13	19:16	51488	51391	97
Surtsey II	1968	Dec.	27	12:30	51634	51198	436
„ „	1970	May	8	16:45	51713	51278	435
„ „	1971	Oct.	19	12:35	51702	51277	425
„ „	1973	May	13	19:50	51823	51390	433
Surtsey III	1968	Dec.	27	14:24	49117	51178	−2061
„ „	1970	May	8	18:26	53273	51292	+1981
„ „	1970	June	14	12:05	53300	51208	2092
„ „	1971	Oct.	19	13:05	53717	51279	2438
„ „	1973	May	13	18:44	53954	51393	2561

Fig. 1 shows the location of the magnetic stations inserted on the map of John Norrman (Norrman 1970) together with the profile a going SE and E through Surtsey III and b going SSW through Surtsey III.

Between December 1968 and May 1970 there has been a drastic change in the magnetic field at Surtsey III as total field intensity has increased by some 4000 gammas. This station was originally established in 1966 to investigate the nature of a deep magnetic low just SSW of the rim of the crater Surtur II.

Fig. 2 shows the magnetic field intensity on two cross sections (profiles a and b) through this magnetic trough, as it was in 1966 one year after the end of eruptions in Surtur II. The trough is about 100 m across with field intensity of about 49000 gammas at the bottom while the rim in places reaches a hight of 57000 gammas. The measurement was repeated in 1970 on approximately the same profiles as in 1966 and again in 1971 on profile a. The field is measured about 3 m above the surface of the lava. The later measurements show an increased field intensity in the area surrounding Surtsey III and also in the area east of the station.

The mean magnetic field intensity in the Surtsey area is about 51450 gammas as referred to Aug. 31, 1965 when a detailed areomagnetic survey was made (Sigurgeirsson 1968). Since then the field intensity at Leirvogur Geomagnetic Observatory has increased by about 50 gammas per year (Sæmundsson 1973) and this also seems to apply to the Surtsey area. To refer all magnetic profiles of fig. 2 to this date the profiles of 7.4'66 should be reduced by 50 gammas, those of 14.6.'70 by 240 gammas and the profile 19.10.-'71 by 310 gammas.

The sudden increase in field intensity at Surtsey III during 1969 and early 1970, as seen on fig. 3, indicates that large amounts of underlying basalt were cooled down through the Curie point and became magnetized during this time. The Curie point of the basalt may be assumed to lie around 580°C, the Curie point for magnetite. For comparison a temperature of 460°C was found in August 1970 in gas ascending from a fissure in the lava NV of Surtur II. (Jóhannesson 1972).

Whereas we find increasing field intensity at a place on top of lava with increasing magnetization, a place outside the lava will at the same time experience a decrease in field intensity. This is demonstrated in fig. 4 showing the time

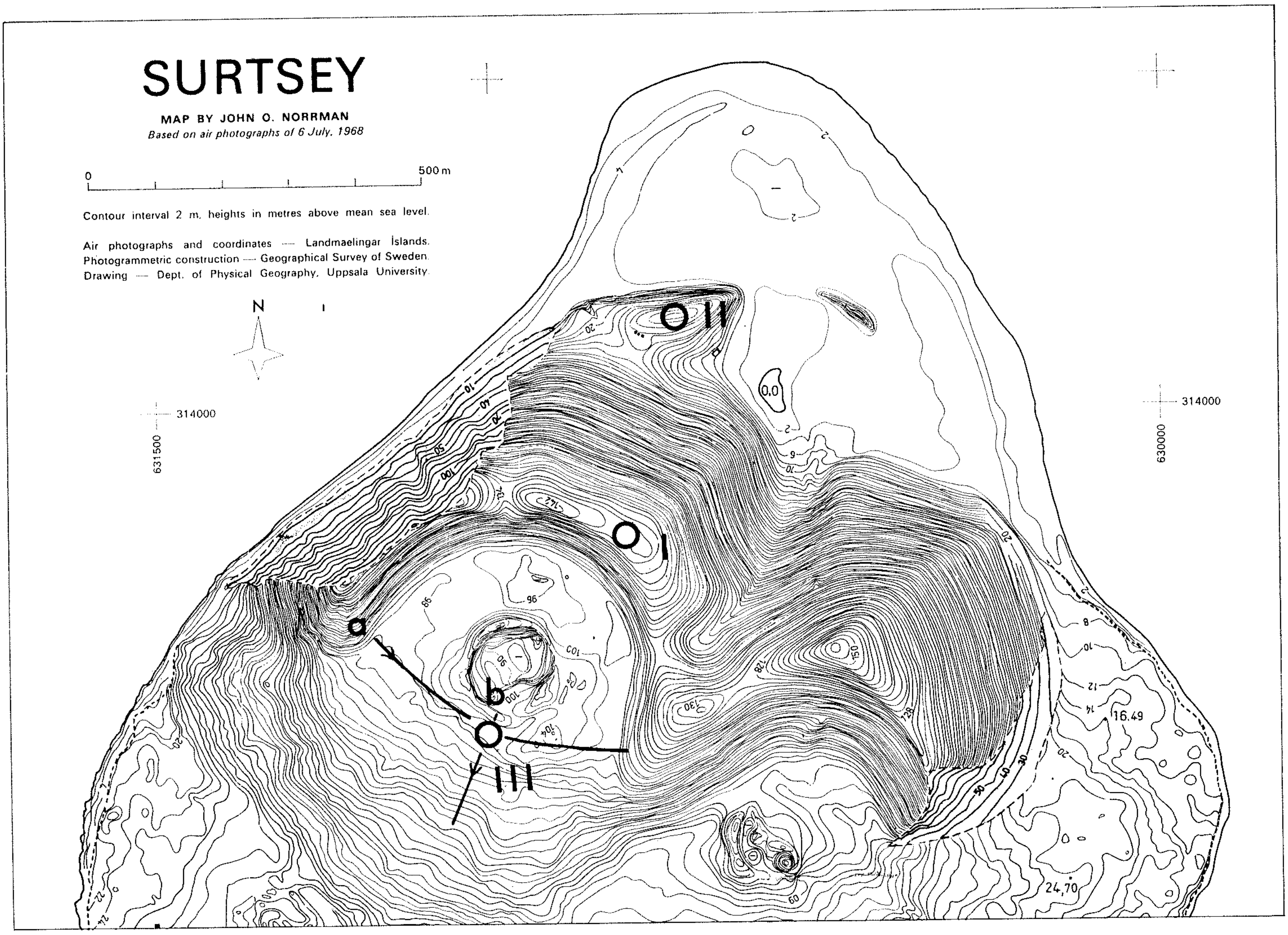

SURTSEY
MAP BY JOHN O. NORRMAN
Based on air photographs of 6 July, 1968
0
500 m
Contour interval 2 m, heights in metres above mean sea level.
Air photographs and coordinates — Landmaelingar Íslands.
Photogrammetric construction — Geographical Survey of Sweden.
Drawing — Dept. of Physical Geography, Uppsala University.
N
314000
631500
630000
I
II
III
a
b
16.49
24.70

Fig. 1

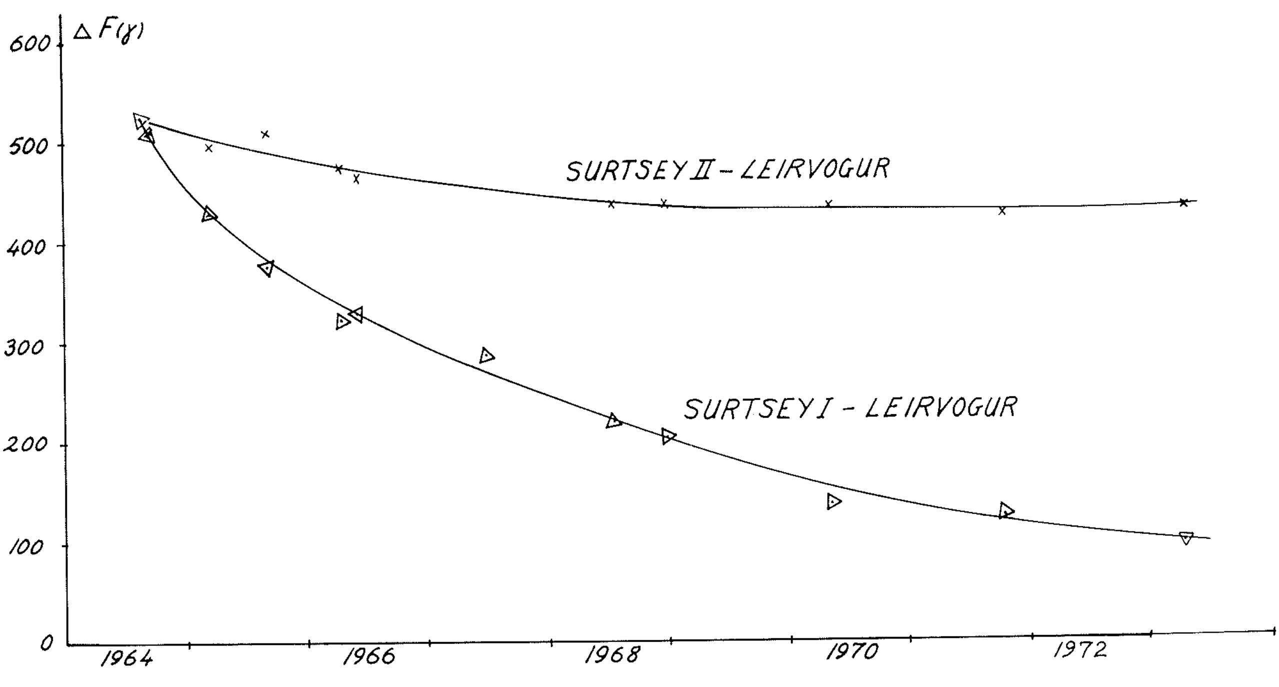
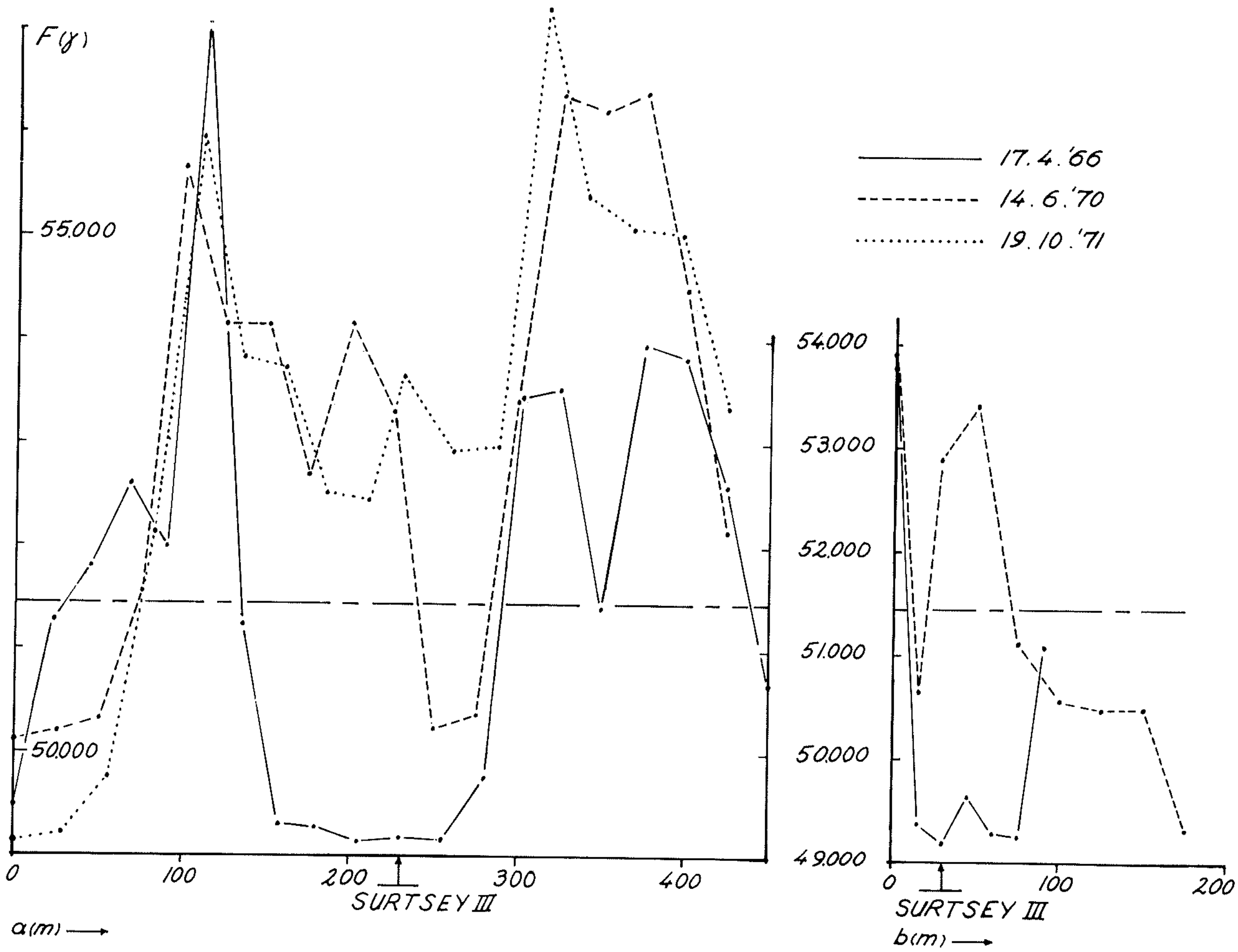
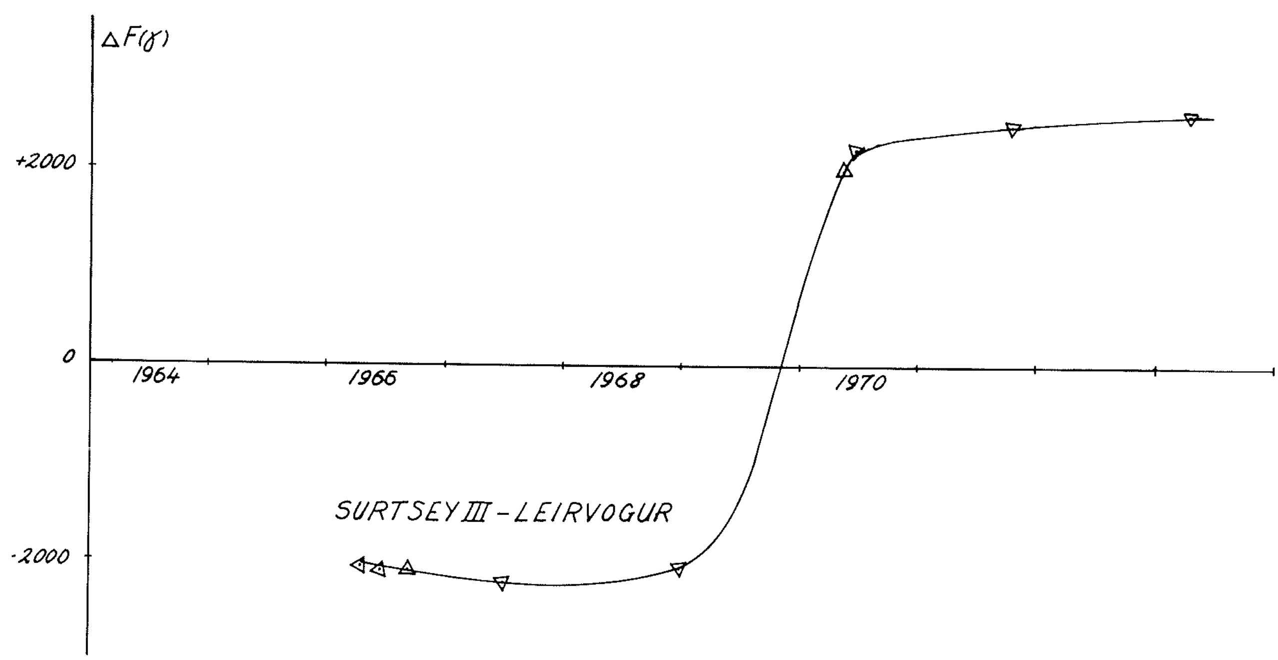

ΔF(γ)
600
500
400
300
200
100
0
1964
1966
1968
1970
1972
SURTSEY II – LEIRVOGUR
SURTSEY I – LEIRVOGUR

Fig. 4


F(γ)
55.000
50.000
17.4.'66
14.6.'70
19.10.'71
54.000
53.000
52.000
51.000
50.000
49.000
0
100
200
300
400
SURTSEY III
a(m) ⟶
0
100
200
SURTSEY III
b(m) ⟶
Fig. 2


ΔF(γ)
+2000
0
-2000
1964
1966
1968
1970
SURTSEY III - LEIRVOGUR
Fig. 3

varition of $\Delta F = F - F_{Leirv.}$ at Surtsey I, 100 m from the edge of the lavafield, and at Surtsey II which is 400 m from the lava. At the begining of measurements in 1964 the field intensity was the same at these two stations. At Surtsey II ΔF decreased slightly during the first three or four years, altogether some 60 gammas, but has remained constant since 1968. This is due to weak magnetization of the underlying tephra formation and a large distance to the magnetic lavapile. At Surtsey I ΔF has decrased about 400 gammas from 1964 to 1973, but seems to be reaching a final value.

As a whole the basaltic pile of Surtsey seems to be about to reach its full magnetization in 1973.

References:

Johannesson, Ae., 1972: Report on Geothermal Observations on the Island of Surtsey. Surtsey Res. Progr. Rep. VI pp 129-136.

Norrman, J. O., 1970: Trends in Postvolcanic Development of Surtsey Island. Progress Report on Geomorphological Activities in 1968. Surtsey Res. Progr. Rep. V, pp 95-112.

Sæmundsson, Th., 1973: Leirvogur Magnetic Results 1971. Published by Science Institute, University of Iceland, Reykjavík. p 101.

Sigurgeirsson, Th., 1968: Continued Geomagnetic and Seismic Measurements on Surtsey. Surtsey Res. Progr. Rep. IV, pp 173-176.

ODDI HF.