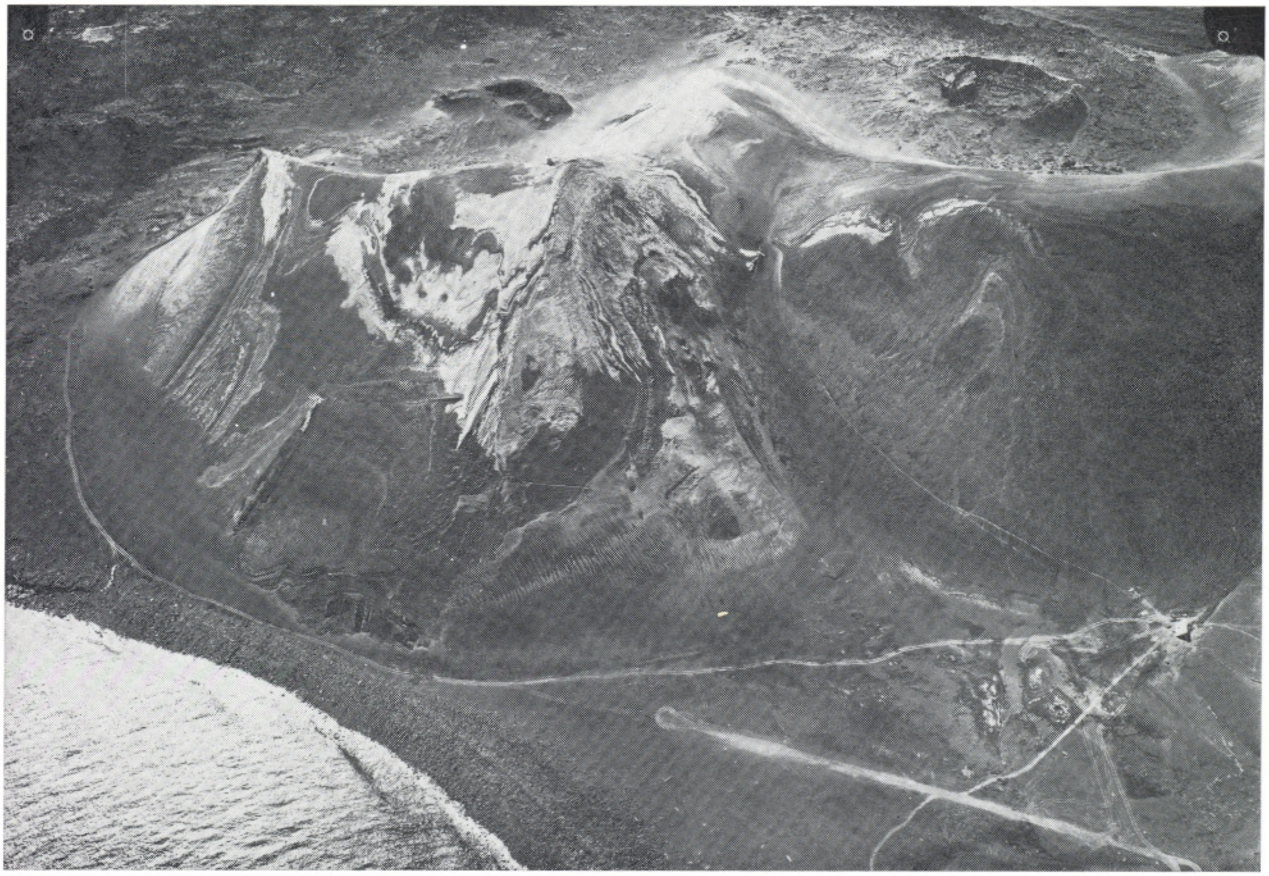
SURTSEY RESEARCH PROGRESS REPORT

IX



SURTSEYJARFÉLAGIÐ

THE SURTSEY RESEARCH SOCIETY · REYKJAVÍK 1982

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THE SURTSEY RESEARCH SOCIETY
REYKJAVÍK, 1982

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Introduction

Surtsey was created in an eruption which started in November 1963 20 miles off the south coast of Iceland. It immediately aroused much scientific interest which led to the Surtsey Research Society being formed shortly after the eruption. The founders were Icelandic scientists, administrators and many volunteers who in different ways supported the scientific work on Surtsey. Several foreign scientists became associate members.

The Society was quite active during the eruption and for several years after. It sponsored and coordinated the scientific work, several international scientific conferences were held and financial support was obtained both from Icelandic and foreign sources.

In order to facilitate this work Surtsey was soon after its creation declared a nature reserve to be protected for scientific purposes.

Reports on the scientific work on Surtsey have been published regularly by the Surtsey Research Society, this one being the ninth in that series. Thus the Society wishes to make results from this interesting work available to the scientific community with as little delay as possible.

The editing committee in charge of this report consists of the following scientists:

Adalsteinn Sigurdsson, marine biologist.
Eythór Einarsson, botanist.
Sveinn P. Jakobsson, geologist.

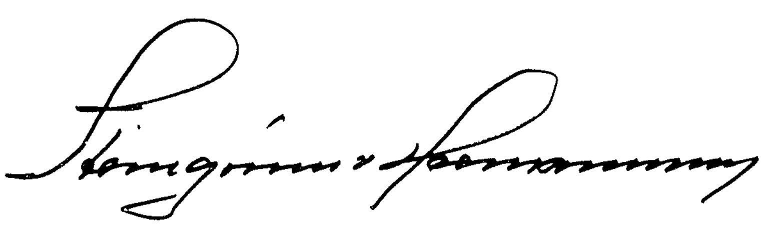
During the 20 years of Surtsey's existence much has changed. The island itself is being shaped by nature's forces, the material out of which Surtsey is made is changing and life which soon settled on the island is progressing fast. But there is still much to be learned.

Several outstanding scientists and individuals who pioneered work on Surtsey have passed away. Others continue and new ones have taken up work on Surtsey. The island will remain and the scientific work must continue.

The well documented work already done will serve as invaluable background for continued studies of the development of Surtsey.

Surtsey was and is a unique opportunity to further man's knowledge of nature.

For the Surtsey Research Society,



Steingrímur Hermannsson,
chairman

BIOLOGY

Concerning the biological nitrogen fixation on Surtsey

By

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The possibility to follow up the succession of microbial life in a virgin soil quite free from organic substances has been fascinating. In 1972, five years after the eruptions ended on Surtsey, soil samples could still be gathered which did not show any evidence of microbial life (Henriksson and Henriksson 1974 a). During the initial period the mineral nitrogen content in the Surtsey soil was at such a low level that it was hardly detectable (Ponnamperuma et al. 1967).

Thus it was not unexpected that free-living blue-green algae with the ability to use sun energy and the molecular nitrogen of the air for growth and development, were among the primary immigrants of Surtsey (Schwabe 1970, 1974). These algae, which nowadays frequently occur on the island, are also found to live in associations with mosses (Schwabe 1974, Rodgers and Henriksson 1976).

The first evidence of biological nitrogen fixation on Surtsey was recorded in 1970, when it was found in laboratory experiments that microorganisms in Surtsey soils showed the activity of nitrogenase, the enzyme which is necessary for all biological nitrogen fixation. The organisms involved were found to be light-depended. By cultivating it was found that the nitrogenase activity was derived from the blue-green algae *Anabaena variabilis* Kütz. and *Nostoc muscorum* Ag. (Henriksson et al. 1972).

During the field-work of 1972 (Henriksson and Henriksson 1974 b) and 1974 and 1976 (Henriksson and Rodgers 1978) determinations of the nitrogen fixation *in situ* at 46 localities on the island were recorded and found to be in the range of 0.2—82 ng N_2 fixed cm^{-2} h^{-1}. The analyses were made at sites where biological nitrogen fixation might be expected and are therefore not representative for the island as a whole, but the values showed obvious indications of active nitrogen fixation. Also in these observations, the blue-green algae *Anabaena variabilis* and *Nostoc muscorum* were found to be the most important nitrogen fixers.

The annual mean temperature of Surtsey can be calculated to be about 5-6°C (Veðráttan, 1944-76). Most of the *in situ* analyses were performed at temperatures in the range of 10-15°C. This shows that algal nitrogen fixation is of importance in this temperature range. The algae are probably adapted to the temperature conditions of Surtsey, as adaptation phenomena have been demonstrated to occur, for instance, by free-living algae in Swedish soils (Henriksson et al. 1975), in wet minerotrophic moss communities of a subarctic mire (Basilier et al. 1978), and in subarctic lichens (Kallio 1974).

Nitrogen fixation by lichen algae has been demonstrated at low and at sub-zero temperatures (Kallio et al. 1972, Englund and Meyerson 1974, Alexander 1975, Kallio et al. 1976). Crittenden (1975) has studied the nitrogen fixation by lichens at the glacier Sólheimajökull on the south coast of Iceland, where he found conditions suitable for lichen nitrogen fixation during extensive periods of the year. The following lichens with nitrogen-fixing blue-green algae as phycobionts in cephalodia have been recorded

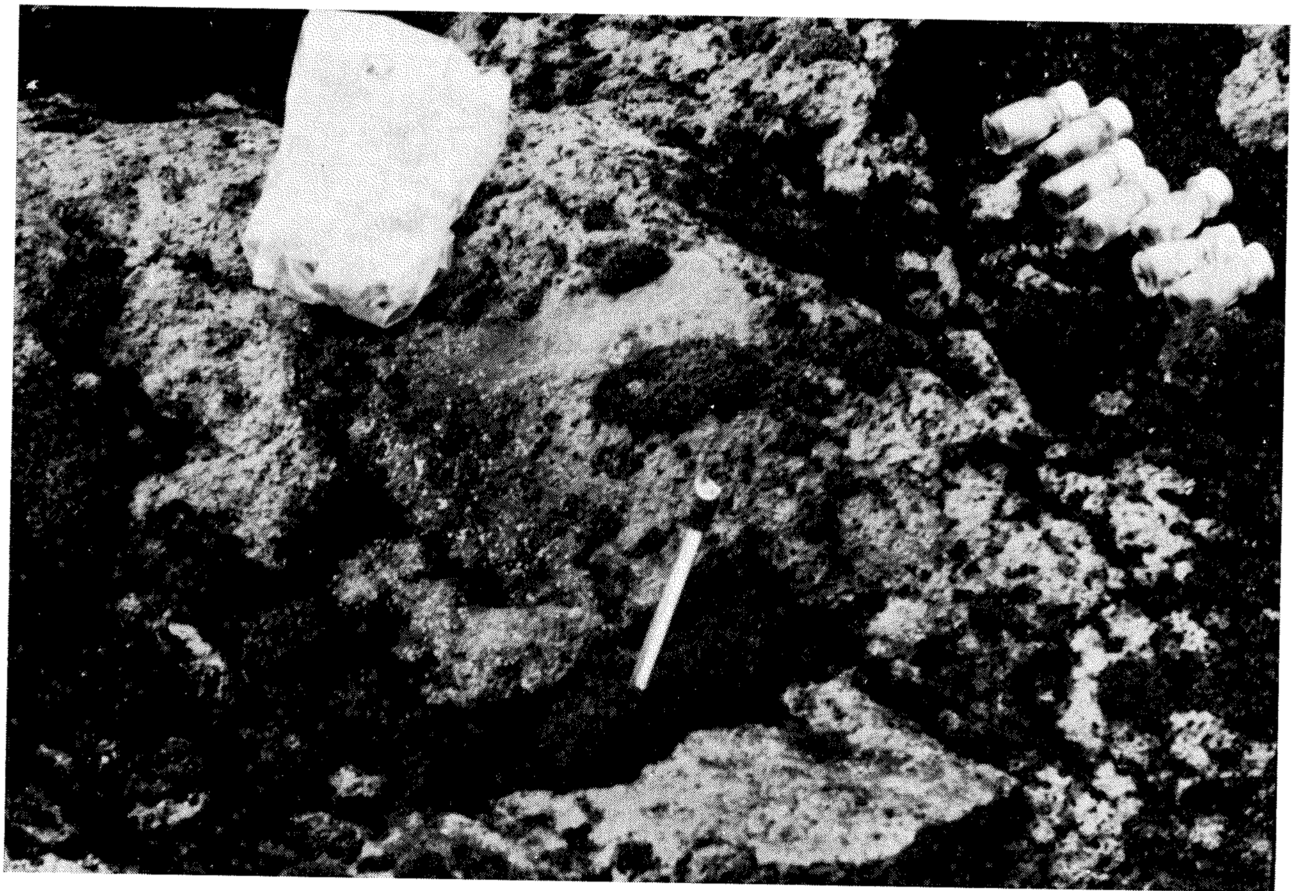

Fig. 1. *A typical site with mosses for demonstration of nitrogen fixation.*
For the determinations of the nitrogen fixation (nitrogenase activity) soil samples 1.6 cm2 in area (about 1 ml in volume) were taken with a cylindrical sampler and put in serum bottles (7 ml capacity). Acetylene (0.6 ml) was injected from a hypodermic syringe, and the samples were incubated *in situ* for one hour. Reactions were terminated by the injection of saturated $(NH_4)_2SO_4$ solution (0.5 ml). The gas phase was analysed for ethylene by gas chromatography at the laboratory in Uppsala. The calculation of the N_2 fixation were based on the theoretical 3:1 ratio for C_2H_2 reduced: N_2 fixed. – July 1976.

on Surtsey: *Placopsis gelida* (L.) Lind., and *Stereocaulon vesuvianum* Pers. (Kristinsson 1972), *S. capitellatum* Magn. (Kristinsson 1974). Thus it is of interest to note that lichens with blue-green algae also are among the pioneers on Surtsey.

It may be surprising that algal nitrogen fixation at a high level can be recorded in soils where blue-green are not visible to the naked eye. Fig. 1 shows a typical site on Surtsey, where nitrogen fixation was recorded. Bare soil with mosses has always given good positive results on nitrogen fixation, provided the nitrogen capacity values were based upon nine separate analyses from the same site, which is the rule in our determinations. Fig. 2 shows another area, apparently rather sterile, where nitrogen fixation was proved. Therefore, the postulations of Brock (1972, 1973) must be queried and certainly are incorrect when he declares that blue-green algae are unimportant as primary colonisers of Surtsey, since he could not detect them, and according to his opinion "blue-green algae are in general not nearly as adaptable to environmental extremes as has often been asserted by phycologists". Unfortunately the hypothesis of Brock seemed to have been uncritically referred to by Fridriksson (1975) in his Surtsey volume, where he writes that "the nitrogen fixation cannot be considered of major ecological importance in the development of life on Surtsey". In fact, the nitrogen-fixing activities on Surtsey are well established and are of major importance for the nitrogen input and nitrogen economy during the primary ecological stage of development, as even very small additions of nitrogen to a nitrogen-deficient soil result in more favourable conditions for the primary colonisers.

Photosynthetic bacteria are other phototrophic microorganisms with the ability to fix nitrogen. Analyses for the occurrence of purple and green photosynthetic sulphur bacteria in Surtsey soil have hitherto given negative results. Nevertheless, the purple photosynthetic non sulphur bacteria

Fig. 2. *An area for demonstration of nitrogen fixation.*
A necessary condition for nitrogen fixation (nitrogenase activity) is moisture. Vast areas of Surtsey are therefore often unsuitable for nitrogen fixation and growth of nitrogen-fixing microorganisms. Sterilized plastic capsules of 20 ml volumes with sample spoons attached inside the screwcaps were used for sampling of soils for the analyses of the occurrence of living microorganisms performed at the laboratory in Uppsala. — August 1972.

Rhodospirillum sp. has been found in samples gathered at the beach close to drifted wood. However, it seems to be improbable that photosynthetic bacteria are of importance in the nitrogen-cycle of Surtsey, especially as they fix nitrogen only under anaerobic conditions.

Since all biological nitrogen fixation requires a high level of activation energy, the nitrogen-fixing organisms unable to use light as energy source, have poor possibilities to fix nitrogen and grow in the Surtsey soil with its low content of organic matter. In the *in situ* experiments no heterotropic nitrogen fixation has been recorded. However, the bacterium *Azotobacter* sp. has been found to occur frequently in samples from 1976 (Henriksson and Henriksson 1978).

The importance of the chemoautotropic *Beggiatoas* which are frequently occurring on Surtsey together with mosses and blue-green algae is still unknown (Henriksson and Henriksson 1981).

During the last decade the plants of *Honkenya peploides* (L.) Ehrh. have increased greatly in number on Surtsey. Many plants have been buried under sand drifts and new ones have arrived. These circumstances must result in accumulation of organic matter into the soil. Old roots are decomposed, and from living roots organic substances are exudated into the root environment. Therefore, it can be expected that a new phase of the biological nitrogen fixation is under development, in which a great part of the biological nitrogen fixation will occur in the soil and especially in the vicinity of the phanerogame roots, where the demands for nitrogen are greatest.

Preliminary results based upon root material from *Honkenya peploides* gathered in 1980, showed activity in nitrogen-fixing organisms which were growing in association with the roots. These results tempt further studies in this research field.

ABSTRACT

The development of the biological nitrogen fixation in the originally sterile soil of Surtsey, Iceland, is dicussed. The blue-green algae *Anabaena variabilis* and *Nostoc muscorum* which nowadays frequently occur on Surtsey, have proved to be the most important of the im-

migrated nitrogen fixers. The nitrogen input from the air to the nitrogen-deficient ecosystem of this new island is obviously of advantage to the biological succession.

ACKNOWLEDGEMENTS

This investigation was sponsored by the Swedish National Research Council and the Surtsey Research Society. The authors are also indebted to the Swedish Geo-Group for Surtsey Research, Uppsala, for kind assistance.

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Green and yellow-green terrestrial algae from Surtsey (Iceland) in 1978

By

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INTRODUCTION

The first record of the occurrence of microscopic terrestrial algae on Surtsey was made by Maguire (1968) who cultured five green algae from ash samples. The first extensive survey was conducted in 1968 and reported by Behre and Schwabe (1970) and Schwabe (1970). Follow up studies were made in the years to 1973. Schwabe and Behre (1972) reported on all groups of algae recovered from samples removed up to 1970. Schwabe (1972, 1974) examined the role of blue-green algae between 1968 and 1973 and disputed the claim made by Brock (1973) who regarded these algae to be of minor importance as primary colonizers. Castenholz (1972) examined blue-green algal growths on soil adjacent to steam vents and Henriksson and others (1972) and Henriksson and Rodgers (1978) measured nitrogen fixation by blue-green algae in the juvenile soils. To date the emphasis of studies has been placed on the blue-green algae. The present study is concerned solely with the green and yellow-green algae with could be important contributors of organic material to the soils. This would support the establishment and development of a decomposing microflora and fauna.

Terrestrial algae of the Icelandic mainland have been studied by Petersen (1928a, 1928b). Schwabe (1970) examined some mainland samples as well as those from Surtsey. In 1977 a survey of the terrestrial algae of Glerárdalur, near Akureyri, was conducted by Broady (1978).

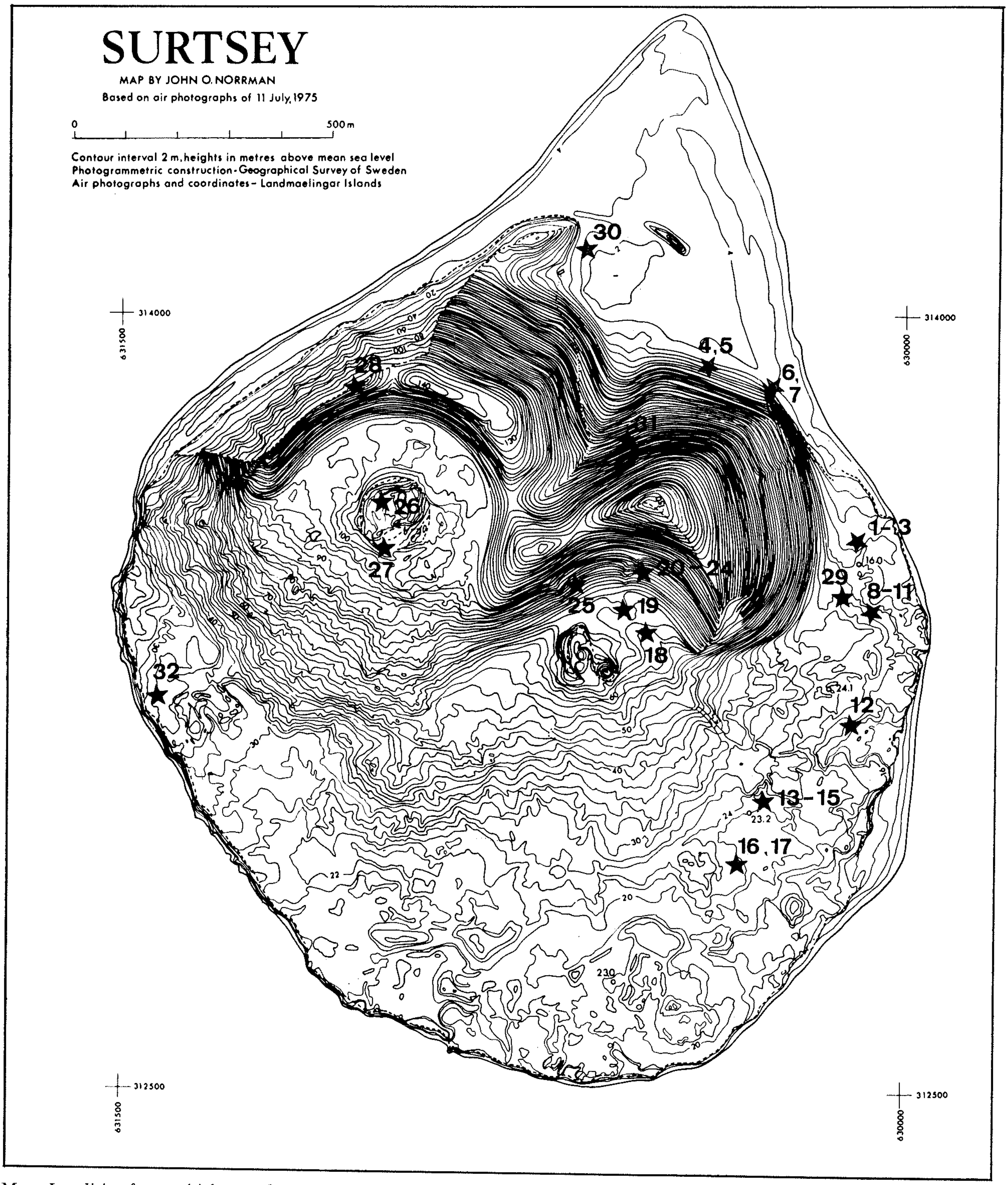
The present work can only be regarded as a preliminary survey as only a single day was spent in the removal of just 32 samples of tephra, lava and vegetation. Presence or absence of the algae was recorded for each sample and little information regarding their abundance was obtained. Difficulties were encountered in identifying several isolates which will require prolonged detailed examination in culture for their characterization. However, it was thought to be worthwhile to provide descriptions and illustrations of difficult forms in order to place their presence on record.

METHODS AND MATERIALS

Sampling. Samples were collected on the 28th July. About 25 gm. of the superficial substratum was scooped or chipped into sterile plastic containers using a sterile spoon fixed within the lid of each container.

Treatment of samples. Samples were treated four days after collection following transport and storage at ambient temperatures. Sample material was examined microscopically in order to obtain a general impression of the types and abundance of algae present. Approximately one gram of material was spread over the surface of agarised (1.5% w/v) Bold's basal medium (BBM) (Chantanachat and Bold, 1962) containing 10% v/v of an unfertilised garden soil extract. Moist plate enrichment cultures (Lund, 1945) were established. The sample was moistened with sterile distilled water and the cultures examined over a period of six weeks. Algae appearing on agarised media were used to innoculate stock cultures on BBM agar slopes.

Examination of algae. Cultures were examined at magnifications up to x1000 using illumination. Photographs were taken using Ilford Pan F film. Lugol's iodine was used to test for the presence of starch and occasionally to clarify the number of nuclei. Indian ink and toluidine blue helped reveal the presence of gelatinous matrices. The latter stain often helped in distinguishing sporangium wall remains. Chloroplast structure



Map. Localities from which samples were removed for analysis of the algal flora.

was elucidated using a dark blue filter. (Kodak Wratten Nr. 48) as suggested by Friedmann (1966).

SAMPLE LOCATIONS

The approximate locations of the 32 sample collections are shown on the map.

1. Green crust-like algal growth thinly coating the underside of a portion of lava.
2. Fine-grained moist ash in small depressions in lava, with a slight moss growth.
3. Well established cushions of moss up to 5 cm in diameter, on ash and dust collected in crevices and hollows in the lava.
4. Coarse-grained tephra around and below bird droppings.
5. Coarse-grained tephra a few metres distant from the droppings sampled in 4 above.

6. Fine-grained tephra in the centre of a well established growth of *Honkenya peploides* one metre wide.
7. Bare tephra a few metres from sample 6 above.
8. Moss from extensive cushion growths in a damp, dimly illuminated cave in the lava field.
9. Scrapings from green crusts of algae on damp lava surfaces in cave, as 8 above.
10. Fine-grained tephra, moist, lodged in crevices and depressions in lava.
11. Green crust of algae coating the bones of a dead bird, adjacent to 10 above.
12. Tephra in depressions in one of the last lava flows, only slight moss development.

13-15. Samples removed from a lava knoll the summit of which was used as a nesting site by black-backed gulls; bird droppings and bones in the immediate vincinty.

13. Rich growth of bright green filamentous algae on summit of knoll.
14. Moss from a large cushion 30 cm in diameter on the edge of the knoll.
15. Blackish felts of filamentous Cyanophyta.
16. Moss cushion cm. in diameter; an isolated growth on lava.
17. Fine-grained, moist tephra in depressions in lava, adjacent to 16 above.
18. Coarse-grained, loose tephra, distant from phanerogamic colonisers.
19. Coarse-grained tephra from within a *Honkenya peploides* stand.
20. Fine-grained moist tephra with a slight moss development, warmed by adjacent steam vent.
21. Adjacent and similar to 20 above.
22. Brown algal slime in water film on rock surface within the opening of „the Bell" fumarole.
23. Macroscopic growths of blue-green algae, adjacent to 22 above, but in a hotter region of the steam vent.
24. Fine-grained tephra with a greenish surface coloration, around „the Bell" fumarole but hardly warmed by steam emissions.
25. Slight moss growths in a region of steam emission.
26. Moss from extensive growths in the crater of Surtur II.
27. Moss growths warmed by steam, on the southern lip of Surtur II.
28. Loose tephra from the summit of the high ridge above and to the north-west of Surtur II.
29. Loose tephra from around steam bases in the most extensive stand of *Elymus arenarius,* the area spotted by many bird droppings.
30. Lower leaves, dead basal leaves and stems of *Honkenya peploides,* partially below loose tephra or just below the surface.
31. Fine-grained tephra with slight moss growth, from steam-warmed ground above a fumarole.
32. Fine-grained tephra in depressions in lava.

GENERAL NOTES REGARDING ALGAE RECOVERED

In the present study 59 forms of green and yellow-green algae were recovered. Of these over 20 are thought to be new records for Surtsey. However, certain isolates could correspond to the problematic algae noted by previous researchers. For instance, Behre and Schwabe (1972) recorded „*Chlorococcum* and related genera" in samples removed since 1969. These could have included *Bracteacoccus, Neochloris, Borodinella, Tetracystis* and *Myrmecia,* described here for the first time. Similary, the taxa described here as species of *Chlamydocapsa* and *Palmellopsis* could have been included as palmelloid stages of *Chlamydomonas* in previous studies.

Genera of terrestrial and freshwater algae recovered on Surtsey since 1967 are listed in Table 1. Comparisons between studies have shortcomings because of taxonomic problems and the varying extent of the individual surveys, for instance the differing number and locations of the samples removed by different workers. However, it appears that the number of algae that have reached the island as viable propagules is still increasing. The absence of forms found in previous studies is probably due to an insufficiency in sampling rather than to the absence of those algae. The number of genera recovered in the individual studies has risen from 8 in samples taken in 1967 (Maguire, 1968) to 37 in the present investigation. The total number of genera recovered since studies began now stands at about 52.

Macroscopially visible growths of Chlorophyta were present in only four of the samples. Green, powdery crusts of an unidentified chaetophoralean alga occasionally occurred in small fissures and depressions in the lava surfaces. These growths were only found where the lava surface was shaded and in moist surroundings (samples 1 and 9). Sample 9 was taken from within a small, damp cave in the lava field and it was here that this type of growth showed its greatest luxuriance. The influence of bird life on algal growth was readily apparent. Bones of dead birds, which were not infrequent in the lava field, were foci of enriched algal growth and often had a greenish coating of algae over their surfaces. Sample 11 consisted of a bone with a green crust of predominantly *Chlamydomonas augustae* associated with various other green and blue-green algae and diatoms. A prominent knoll in the lava field was used as a nesting site by a pair of black-backed gulls. In the nutrient-enriched area on the top of the knoll considerable growths of the filamentous *"Hormidium"* stage of *Prasiola crispa* were present (sample 13) together with a felt of *"Phormidium"* and moss cushions. The final sample with macroscopic green growths was taken from the steam moistended soil adjacent to "the Bell" fumarole (sample 24). The faint green coloration was due to the presence of abundant cells of *Chlorella vulgaris* var. *autotrophica.*

The macroscopic felts of blue-green algae, and brown slimes of diatoms in the warm, damp regions around the active steam fumaroles are well known from previous studies. Samples 22 and 23 consisted of such growths removed from within, and adjacent to, "the Bell" fumarole. They revealed an associated flora of green and yellow-green algae of respectively 9 and 10 forms. Samples 20, 21, 25, 26 and 31 were of bryophyte growths adjacent to steam emission and contained a mean number of 10 algae.

In general the greatest number of forms were recovered from well-established bryophyte cushions. Six samples (number 3, 8, 14, 16, 26 and 27) contained from 7 to 16 and a mean of 11 algae. Sample 16 contained 16 algae, the maximum number found in all samples. Where bryophyte growth was at an early stage of development without any cushion formation (samples 2, 12, 20, 21, 25 and 31) fewer algae were recovered, ranging from 6 to 13 and with a mean of 8 per sample.

Tephra completely devoid of bryophytes and phanerogamic colonisers (samples 4, 5, 7, 10, 17, 18, 28 and 32) contained fewer algae, with a mean of 4 and a range of 0 to 8. The four samples recovered from amongst well-established growths of the phanerogams *Honkenya peploides* (samples 6, 19 and 30) and *Elymus arenarius* (sample 29) produced similar numbers of algae to the bare tephra, a mean of 3.5 and a range of 0-7.

Only two samples failed to reveal the presence of any viable algae of any type (samples 4 and 29). Both of these were in areas covered by many bird droppings. It would appear that toxic material in the droppings killed even dormant cells transported into these areas.

It is likely that there was sufficient moisture for algal growth only amongst the bryophyte cushions, in small depressions in the lava where wind-blown tephra had accumulated, and in areas affected by steam emission. The bare unconsolidated tephra, which covers large areas of the island, and the similary loose tephra amongst the phanerogam stands, was probably too freely drained and too unstable for algal growth. The algae recovered from such samples were probably present in low numbers as dormant cells blown in from the limited areas of abundant algal growth or from regions outside the island.

Only five algae were recovered from more than ten samples. *Muriella terrestris* var. A was the most widespread and present in 15 samples. *Klebsormidium flaccidum, Chlorella vulgaris* var. *autotrophica, Bracteacoccus minor* and *Chlorella zofingensis* var. A were found in respectively 14, 13, 11 and 11 samples. Four algae occurred in 6 to 10 samples, namely *Chlamydomonas pseudintermedia, Oocystis minuta* var., *Borodinella polytetras* and an unidentified member of the Eustigmatophyceae, with respectively 9, 7, 7 and 7 occurrences. The large majority of algae were only occasionally recovered, in less than 6 samples, and 22 of these were present in only a single sample.

SYSTEMATICS

CHLOROPHYCEAE

The classification of Bold and Wynne (1978) is followed to the ordinal level. Genera are listed alphabetically within each order.

Volvocales

Chlamydomonas augustae Skuja
Fig. 1, 2
Ettl, 1976, p. 403, Taf. 63a
Samples; 2, 10, 11, 14, 32.

Cells ellipsoidal, 13-22 μm long by 7-17 μm wide; chloroplast axial with radiating arms spreading to form plates at cell wall (Fig. 2); pyrenoid slightly posterior, surrounded by small starch grain. 2, 4, 8 and 16 zoospores formed.

Previous records: Surtsey, Behre and Schwabe (1970).

Chlamydomonas foraminata Behre and Schwabe
Behre and Schwabe, 1970, p. 68-69, Taf. I
Fig. 1-6
Samples; 22, 27.

Previous records: Surtsey, Behre and Schwabe (1970).

Chlamydomonas perpusilla Gerloff
Fig. 5, 6
Ettl, 1976, p. 516, Taf. 100, Fig. 3
Samples; 25.

Cells narrowly ellipsoidal straight or curved, 8-12 µm long by 2.5 - 3 µm wide; chloroplast a parietal plate; pyrenoid lateral, surrounded by small starch grains; stigma slightly anterior to pyrenoid; nucleus posterior.

Previous records; Surtsey, *C.* sp. ad *perpusilla* (Korsh.) Gerloff, Behre and Schwabe (1970).

Chlamydomonas cf. *perpusilla* Gerloff
Fig. 8-10
Samples; 17.

Cells narrowly ellipsoidal, straight or slightly curved, 5-13 µm long by 2.5-5 µm wide; chloroplast a lobed parietal plate; pyrenoid lateral surrounded by an apparently complete starch sheath; nucleus posterior; stigma anterior.

Chlamydomonas pseudintermedia Behre and Schwabe
Fig. 143
Behre and Schwabe, 1970, p. 70-71, Taf. I,
Fig. 8-12.
Samples; 2, 3, 8, 10, 12, 21, 22, 25, 27.

Previous records: Surtsey, Behre and Schwabe (1970).

Chlamydomonas sp. A
Fig. 3, 4
Samples; 17, 27, 31.

Cells ellipsoidal, 5 - 8.5 µm long by 2.5 - 6 µm wide; chloroplast a perforated, parietal cup; pyrenoid lateral and somewhat posterior, surrounded by large starch plates; stigma anterior; nucleus anterior. 4, 8 and 16 gametes formed, these copulating immediately on relase; palmelloid stage formed.

The lateral pyrenoid and perforate chloroplast place this isolate in the *Chlamydella - perforata* group described by Ettl (1976).

Chlamydomonas sp. B
Fig. 7, 142
Samples; 25.

Cells broadly ellipsoidal, 12-15 µm long by 6-9 µm wide; chloroplast a perforate, parietal cup; pyrenoid lateral, surrounded by large starch plates; stigma slightly anterior of pyrenoid; nucleus approximately central. Palmelloid stage readily formed.

Similar to *C.* sp. A in the *Chlamydella - perforata* group of Ettl (1976).

Tetrasporales

Chlamydocapsa sp. A
Fig. 12-14, 140, 141
Samples; 12, 21, 24, 27.

Colonies mucilaginous with cells arranged in groups of 2,4 and 8 throughout (Fig. 140, 141); mucilage faintly stratified around cells and cell groups. Cells broadly ellipsoidal, 8-12 µm long by 5-10.5 µm wide; chloroplast a lobed, perforate, parietal plate (Fig. 12, 13); pyrenoid surrounded by large starch grains. 2, 4 and 8 zoospores formed, with posterior nucleus, anterior stigma (Fig. 14).

Following the scheme proposed by Fott (1972) the presence of lamellations in the mucilage places this alga in *Chlamydocapsa* rather than *Palmellopsis* in which lamellations are absent.

Previous records; Glerárdalur; Broady (1978) described two *Chlamydocapsa* isolates.

Chlamydocapsa sp. B
Fig. 17-19, 135, 136
Samples; 21, 24, 31.

Colonies mucilaginous with cells in groups of 2, 4, 8 and 16 surrounded by faint remains of dilated sporangium wall. Adult cells generally broadly ellipsoidal (Fig. 17), to 13 by 8.5 µm, some approaching spherical (Fig. 136); chloroplast axial with broad radiating arms joining to form a perforate parietal portion (Fig. 19); pyrenoid surrounded by numerous small starch grains. 2, 4, 8 and 16 (Fig. 135) zoospores released by gelatinization of sporangium wall; zoospores (Fig. 18) with an anterior nucleus and stigma.

Palmellopsis sp.
Fig. 15, 16, 137-139
Samples; 3, 21, 23, 24, 27.

Colonies mucilaginous with cells in groups of 2, 4, 8, 16 and 32; mucilage without distinct lamellations. Adult cells broadly ellipsoidal (Fig. 15), up to 19 by 17.5 µm; chloroplast an extensive, perforate cup (Fig. 138, 139); pyrenoid surrounded by numerous starch grains which are often arranged in rows (Fig. 16). 2, 4, 8, 16 and 32 zoospores released by gelatinization of sporangium wall, these are often released without the formation of flagella, as aplanospores, and remain in close groups (Fig. 137); zoospores with posterior nucleus and anterior stigma.

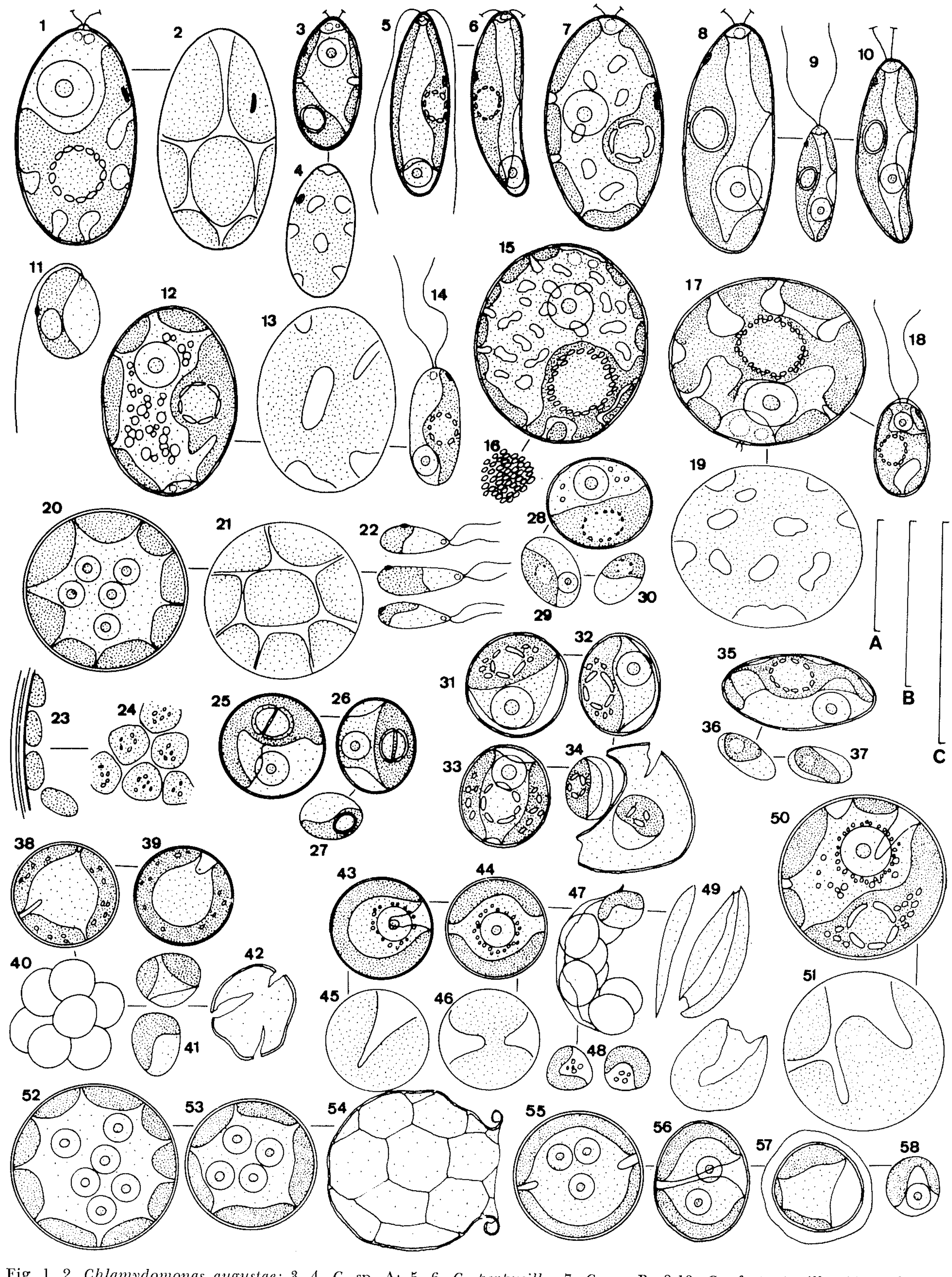


Fig. 1, 2, *Chlamydomonas augustae;* 3, 4, *C.* sp. A; 5, 6, *C. perpusilla;* 7, *C.* sp. B; 8-10, *C.* cf. *perpusilla;* 11, *Pedinomonas minor;* 12-14, *Chlamydocapsa* sp. A; 15, 16, *Palmellopsis* sp.; 17-19, *Chlamydocapsa* sp. B; 20-22, *Bracteacoccus minor;* 23, 24, *B. giganteus;* 25-27, *Chlorella vulgaris* var. *autotrophica;* 28-30, *C.* sp. B; 31-34, *C.* sp. A; 35-37, *C. saccharophila* var. *ellipsoidea;* 38-42, *C. zofingensis* var. A; 43-49, *C. zofingensis* var. B; 50, 51, *C.* sp. C(?); 52-54, *Muriella terrestris* var. A; 55-58, *M. terrestris* var. B. The scales represent 10 μm. A; Fig. 12, 13, 15-19, 20-22. B; Fig. 1-10, 14, 25-58. C; Fig. 11.

Chlorococcales

Bracteacoccus sf. *giganteus* Bischoff and Bold
Fig. 23, 24, 151, 152
Bischoff and Bold, 1963, p. 44-46, Fig. 70-72, 131-136
Samples; 14, 17, 18, 26.

Cells spherical, to 60 µm diameter; wall 1-2 µm thick (Fig. 23); chloroplasts parietal and internal, disc-like (Fig. 24, 151). Reproduction by numerous zoospores and aplanospores; aplanospores spherical 3.5 µm diameter; zoospore morphology not clearly observed.

Bracteacoccus minor (Chodat) Petrova
Fig. 20-22, 153, 154
Starr, 1955, p. 63-64, Fig. 153, 154
Samples; 2, 8, 9, 16-19, 25, 26, 30, 32.

Cells spherical to 15 µm diameter; chloroplasts parietal, discoid (Fig. 20, 21, 154). Zoospores and aplanospores produced in thin-walled sporangia up to 21 µm diameter and containing numerous spores; zoospores naked, stigma variably positioned (Fig. 22); aplanospores spherical, 3.5 µm diameter (Fig. 153).

Characium sp.
Fig. 147-150
Samples; 19, 22.

Adult cells approximately ellipsoidal (Fig. 148), up to 15.5 µm long by 8.5 µm wide, possessing a holdfast with a terminal button-like swelling; chloroplast parietal containing a distinct pyrenoid surrounded by two large starch plates. Reproduction by autospores (Fig. 149, 150), released by rupture of sporangium wall; zoosporangia observed but not the released zoospores.

Previous records: Glerárdalur; Broady (1978) recovered an unidentified *Characium* sp.

Chlorococcum sp.
Fig. 83-85, 144
Samples; 20, 21.

Adult cells broadly ellipsoidal (Fig. 85-144) occasionally spherical (Fig. 84), to 16 µm diameter; chloroplast cup-shaped, perforated and fissured; pyrenoid in basal thickened portion of chloroplast, surrounded by distinct starch plates; two contractile vacuoles situated opposite the pyrenoid and adjacent to the large nucleus. Sporangia contain 2, 4, 8 and 16 zoospores and aplanospores; zoospores 7-9 µm long by 3.5 - 5 µm wide, with a posterior nucleus and anterior stigma (Fig. 83).

Previous records: Surtsey, *Chlorococcum* spp. recovered by Maguire (1968), Schwabe and Behre (1972). Glerárdalur, unidentified *Chlorococcum* spp., Broady (1978).

Neochloris bilobata Vinatzer var.
Fig. 86-89, 145, 146
Vinatzer, 1975, p. 221-223, Abb. 5
Samples; 20, 31.

Cells spherical, to 25 µm, exceptionally 37 µm diameter; chloroplast bi-lobed (Fig. 86-88); pyrenoid large, between the chloroplast lobes, surrounded by numerous small starch grains; nucleus distinct. Numerous zoospores and aplanospores formed in thin-walled sporangia (Fig. 145); zoospores pyriform, naked, with a posterior stigma (Fig. 89).

Vinatzer (1975) described zoospores with an anterior stigma.

Chlorellales

Chorella saccharophila var. *ellipsoidea* (Gerneck) Fott and Nováková
Fig. 35-37, 163-165
Fott and Nováková, 1969, p. 39-41, Plates XI, XII
Samples; 9, 17.

Adult cells narrowly ellipsoidal (Fig. 35, 165), to 10.5 µm by 4.5 µm; chloroplast approximately saucer-shaped, often only partially adherent to the inner wall; pyrenoid surrounded by small starch grains. Sporangia containing 2 to 16 spores, one of the products of protoplast divison is usually larger than the remainder (Fig. 163, 164); spores narowly ellipsoidal (Fig. 36, 37), from 3.5 by 2 µm, released by rupture of the sporangium wall.

Previous records: Surtsey, *C. saccharophila,* Schwabe and Behre (1972).

Chlorella vulgaris var. *autotrophica* (Shihira and Krauss) Fott and Nováková
Fig. 25-27, 155, 156
Fott and Nováková, 1969, p. 25-26, Plate III f-o.
Samples; 2, 3, 6, 7, 10, 11, 20-25, 26, 30.

Adult cells spherical to 6 µm diameter; young cells ellipsoidal (Fig. 26, 27); chloroplast more or less a broad band; pyrenoid situated to one side of chloroplast (Fig. 25), surrounded by two large starch plates; nucleus readily visible. Sporangia releasing 2, 4, 8 and 16 ellipsoidal to sub-spherical spores by irregular rupture of the wall, remains of which are visible (Fig. 156) especially following staining with toluidine blue.

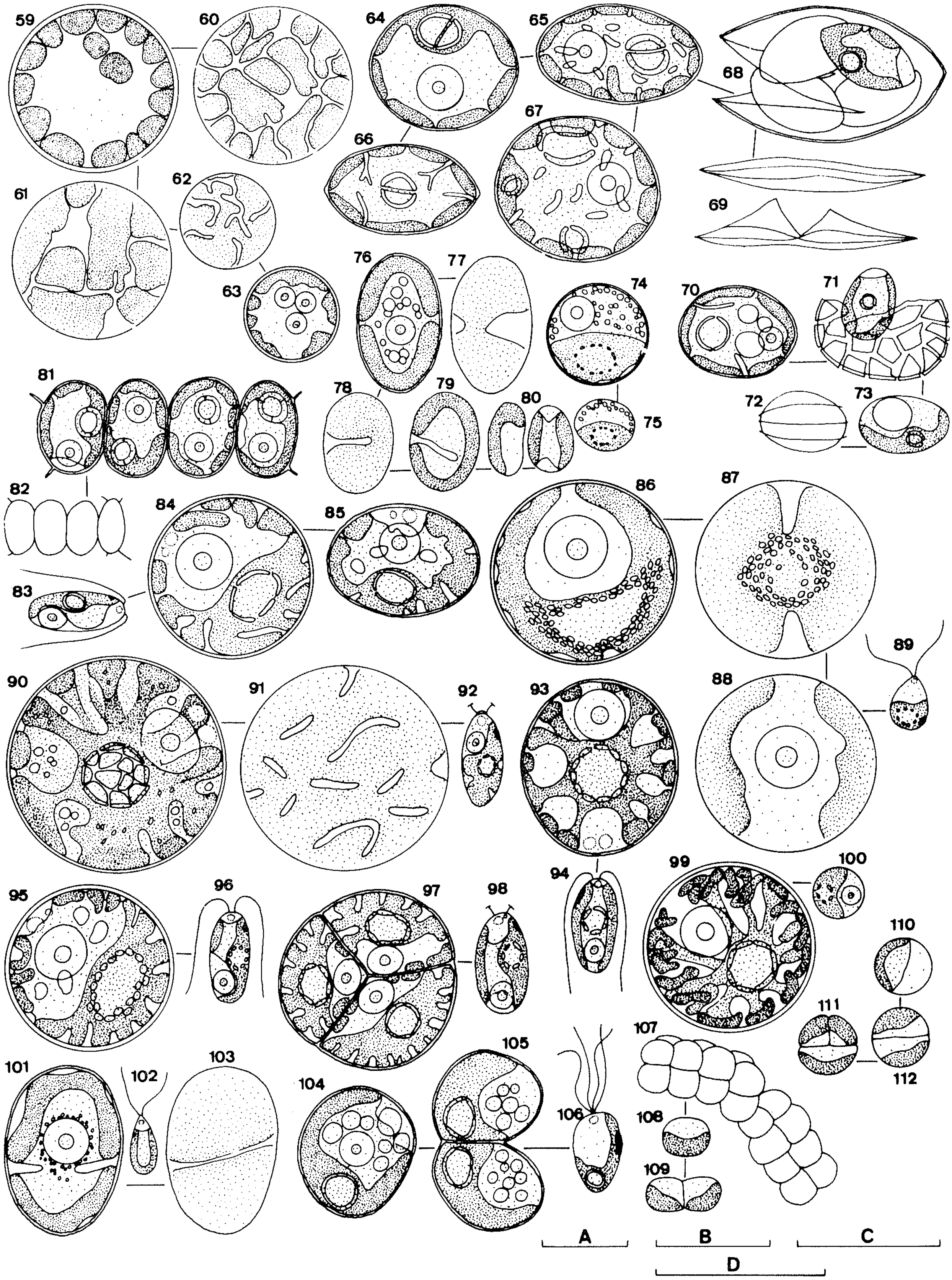


Fig. 59-63, *Muriella* sp. (?); 64-49, *Oocystis minuta* var.; 70-73, *Scotiellocystis* sp. (?); 74, 75, *Sphaerocystis* cf. *signiensis;* 70-80, *Coccomyxa gloeobotrydiformis;* 81, 82, *Scenedesmus microspina;* 83-85, *Chlorococcum* sp.; 86-89, *Neochloris bilobata;* 90-92, *Tetracystis* sp. A; 93, 94, *T.* sp. D; 95, 96, *T.* sp. B; 97, 98, *T.* sp. C; 99, 100, *Borodinella polytetras;* 101-103, *Myrmecia biatorellae* var.; 104-106, *Fernandinella alpina* var. *subglobosa;* 107-109, *Chlorosarcina* sp. A (?); 110-112, *Planophila* sp. (?). The scales represent 10 μm. A; Fig. 81, 82, 90-92, 95, 96, 100-103. B; 59-63, 83-89, 93, 94, 97-100, 104-112. C; 64-73, 76-80.

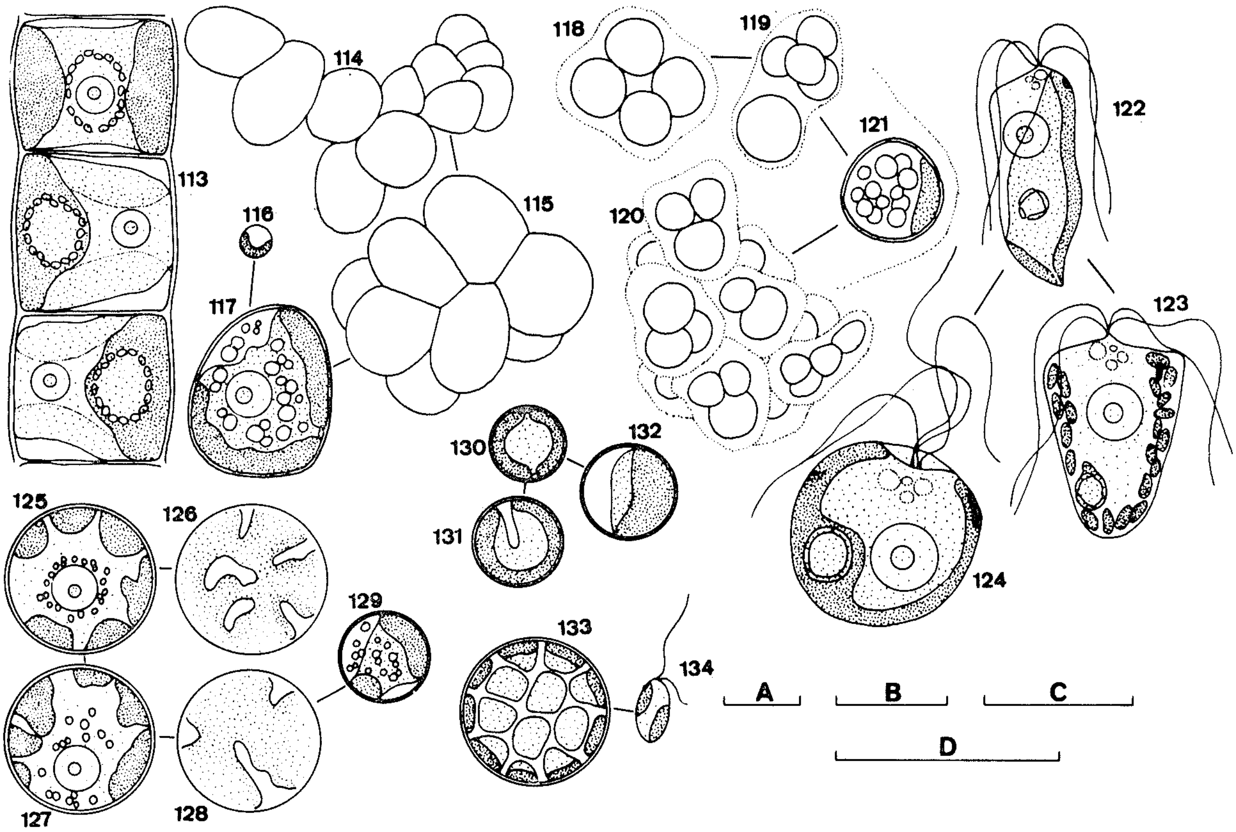


Fig. 113, *Ulothrix implexa;* 114-117, cf. *Apatococcus lobatus;* 118-121, unidentified chaetophoralean alga; 122-124, *Prasinochloris* sp. (?); 125-129, *Chloridella* sp. (?); 130-132, *C. minuta;* 133, 134, *Gloeobotrys* sp. (?). The scales represent 10 μm. A; Fig. 114, 115, 118-120. B; Fig. 116, 117, C; Fig. 113, 121, 125-129, 133, 134. D; Fig. 122-124, 130-132.

Previous records: Surtsey, *C. vulgaris,* Schwabe and Behre (1972). Glerárdalur, *C. vulgaris* var. A and B, Broady (1978).

Chlorella zofingensis Doenz var. A
Fig. 38-42, 160, 161
Fott and Nováková, 1969, p. 42-44, Plate XIII
Samples; 2, 14, 16-19, 23, 24, 28, 31, 32.

Adult cells spherical, to 6.5 μm diameter, young cells ellipsoidal, subspherical; chloroplast parietal, lobed plate covering most of the cell wall; starch grains observed in chloroplast. 2, 4 and 8 spores released by irregular rupture of sporangium wall, remains of which are visible (Fig. 161); spores tending to remain aggregated (Fig. 40, 160).

Previous records: Glerárdalur, *Chlorella* cf. *zofingensis,* Broady (1978).

Chlorella zofingensis Doenz. var. B.
Fig. 43-49, 166
Samples; 16.

Adult cells spherical, to 8 μm diameter; chloroplast often bi-lobed (Fig. 45, 46, 166) with small starch grains scattered throughout; nucleus distinct and often surrounded by small granules. Sporangia release 2, 4, 8 and 16 subspherical spores from 2.5 μm diameter (Fig. 48), these remain adherent to sporangium wall, often in an approximately saucer-shaped arrangement (Fig. 47).

Chlorella sp. A
Fig. 31-34
Samples; 6, 11.

Adult cells mostly ellipsoidal or sub-spherical, few spherical, to 6 by 5.5 μm; chloroplast a broad parietal band; pyrenoid surrounded by two to several starch grains of variable size; nucleus readily visible. Sporangia up to 10 μm diameter, contain 2, 4, 8, 16 and more (32?) spores released by irregular rupture of wall, remains of which are visible (Fig. 34).

Chlorella sp. B
Fig. 28-30, 157-159
Samples; 26, 31, 32.

Adult cells broadly ellipsoidal (Fig. 28, 159), to 7.5 by 6 μm; chloroplast saucer-shaped occupying about half of cell; pyrenoid indistinct, surrounded by small starch grains. Sporangia contain 2, 4 and 8 ellipsoidal spores, released by

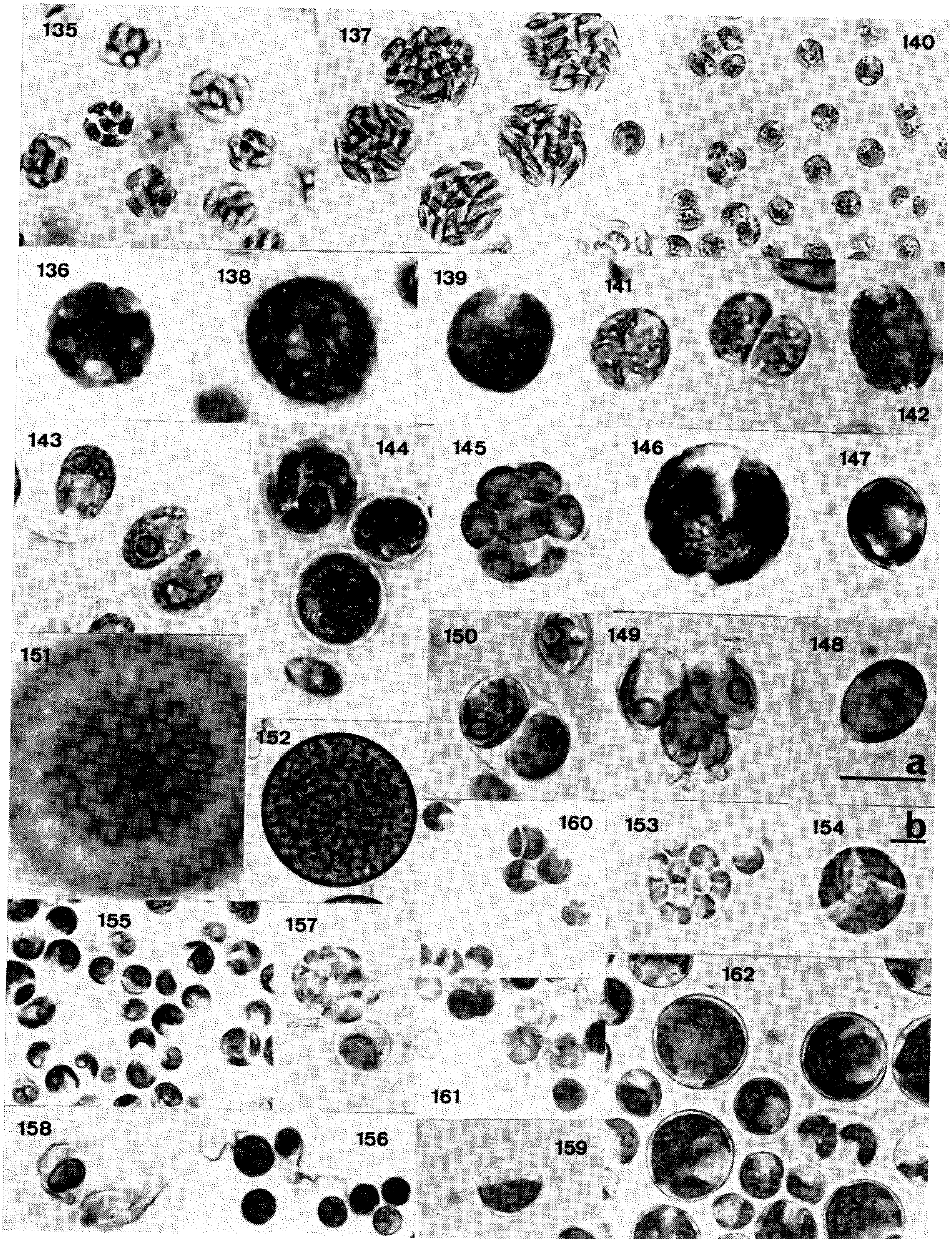


Fig. 135, 136, *Chlamydocapsa* sp. B; 137-139, *Palmellopsis* sp.; 140, 141, *Chlamydocapsa* sp. A; 142, *Chlamydomonas* sp. B; 143, *Chlamydomonas pseudintermedia;* 144, *Chlorococcum* sp.; 145, 146, *Neochloris bilobata;* 147-150, *Characium* sp.; 151, 152, *Bracteacoccus* cf. *giganteus;* 153, 154, *B. minor;* 155, 156, *Chlorella vulgaris* var. *autotrophica;* 157-159, *C.* sp. B; 160, 161, *C. zofingensis* var. A; 162, *C.* sp. C. The scale represents 10 μm. A; Fig. 136, 138, 139, 141-151, 153-162. B; 135, 137, 140, 152.

irregular rupture of sporangium wall (Fig. 157) which remains readily visible (Fig. 158).

Chlorella sp. C?
Fig. 50, 51, 162
Samples; 3, 12, 16, 25.

Adult cells spherical, to 12 μm diameter; chloroplast a broadly lobed cup (Fig. 50, 51); pyrenoid distinct, surrounded by several large starch grains; nucleus distinct. Sporangia contain 2, 4, 8 and 16 almost spherical spores (Fig. 162) released by irregular rupture of sporangium wall which remains readily visible.

Coccomyxa gloeobotrydiformis Reisigl var.
Fig. 76-80, 178
Reisigl, 1969, p. 498-499, Abb. 3
Samples; 6, 8, 9, 16, 19.

Colonies mucilaginous, containing irregulary distributed cells (Fig. 178) and temporary groups of 2, 4, 8 and 16 recently released spores. Adult cells ellipsoidal, to 13 by 9 μm but mostly 7 by 5 μm; chloroplast parietal, often bi-lobed, containing scattered starch grains; oil globules formed. Spores (Fig. 80) released by rupture and partial gelatinization of sporangium wall.

Reisigl (1969) described slightly smaller cells with the production of only 2 and 4 spores.

Previous records: Surtsey, *Coccomyxa* sp., Schwabe (1970).

Muriella terrestris Petersen var. A
Fig. 52-54, 167-169
Petersen, 1932, p. 403, Fig. 9
Samples; 2, 3, 6-9, 12, 16, 18, 19, 22, 24, 26, 30, 32.

Adult cells spherical, to 12 μm diameter; chloroplasts numerous, parietal, plate-like. Sporangia release 2, 4 and 8 spherical to ellipsoidal spores (Fig. 168) through an almost circular rupture of the sporangium wall. On staining with toluidine blue the inner surface of the empty sporangium wall can be seen to have internal slightly thickened ribs of wall material giving a reticulated appearance (Fig. 54, 169).

The cells of this isolate are larger than those described by Petersen (1932) and resemble those found by Reisigl (1964).

Previous records: Surtsey, *M. terrestris,* Behre and Schwabe (1970); *M. decolor,* Schwabe (1970); Glerárdalur, *M.* cf. *terrestris,* Broady (1978).

Muriella terrestris Petersen var. B.
Fig. 55-58, 172-174
Petersen, 1932, p. 403, Fig. 9
Samples; 7, 8, 18, 19, 23.

Adult cells spherical and broadly ellipsoidal, to 9 μm diameter; chloroplasts parietal plates, one to 4 per cell. Sporangia contain 2, 4 and 8 spores released by irregular rupture of sporangium wall (Fig. 172); young cells often surrounded by the remains of the sporangium wall (Fig. 57).

Muriella sp.?
Fig. 59-63, 179-182
Samples; 20, 23.

Adult cells spherical, to 16 μm diameter; chloroplasts numerous, parietal, irregulary shaped plates (Fig. 59-61, 179; in young cells the single chloroplast perforate and lobed (Fig. 62). Sporangia contain from (Fig. 181) to over 16 spores, spores themselves often undergo protoplast division before their release through the ruptured sporangium wall (Fig. 180); young cells occasionally surrounded by sporangium wall remains (Fig. 182).

The chloroplasts are unlike those of other *Muriella* spp. in their irregularity of shape.

Oocystis minuta Guillard, Bold and MacEntee var.
Fig. 64-69, 170
Guillard and others, 1975, p. 21-22, Fig 17-20; Watanabe, 1978, p. 15, Fig. 1-3
Samples; 10, 12, 13, 17, 18, 24, 31.

Adult cells broadly ellipsoidal, 6-13 μm by 4.5 - 11 μm; chloroplast parietal, extensive, often perforate (Fig. 65, 67); wall occasionally slightly thickened at each pole (Fig. 66); pyrenoid distinct, surrounded by two thick starch plates although occasionally several large grains present. Sporangia contain 2, 4, 8 and 16 spores, released after development of a wide polar split in the wall (Fig. 68, 170).

Previous records: Glerárdalur, cf. *Oocystis* sp. Broady (1978).

Scenedesmus microspina Chodat
Fig. 81, 82, 171
Uherkovich, 1973, p. 3, Fig. 24, 25
Samples; 23, 24.

Coenobia of 4 and 8 ellipsoidal cells; terminal cells often bearing two short spines; coenobia with 4 cells 14-31 μm long by 7-13 μm broad.

Previous records: Surtsey, Schwabe and Behre (1972).

Scotiellocystis sp.?
Fig. 70-73, 175
Samples; 20, 21, 23.

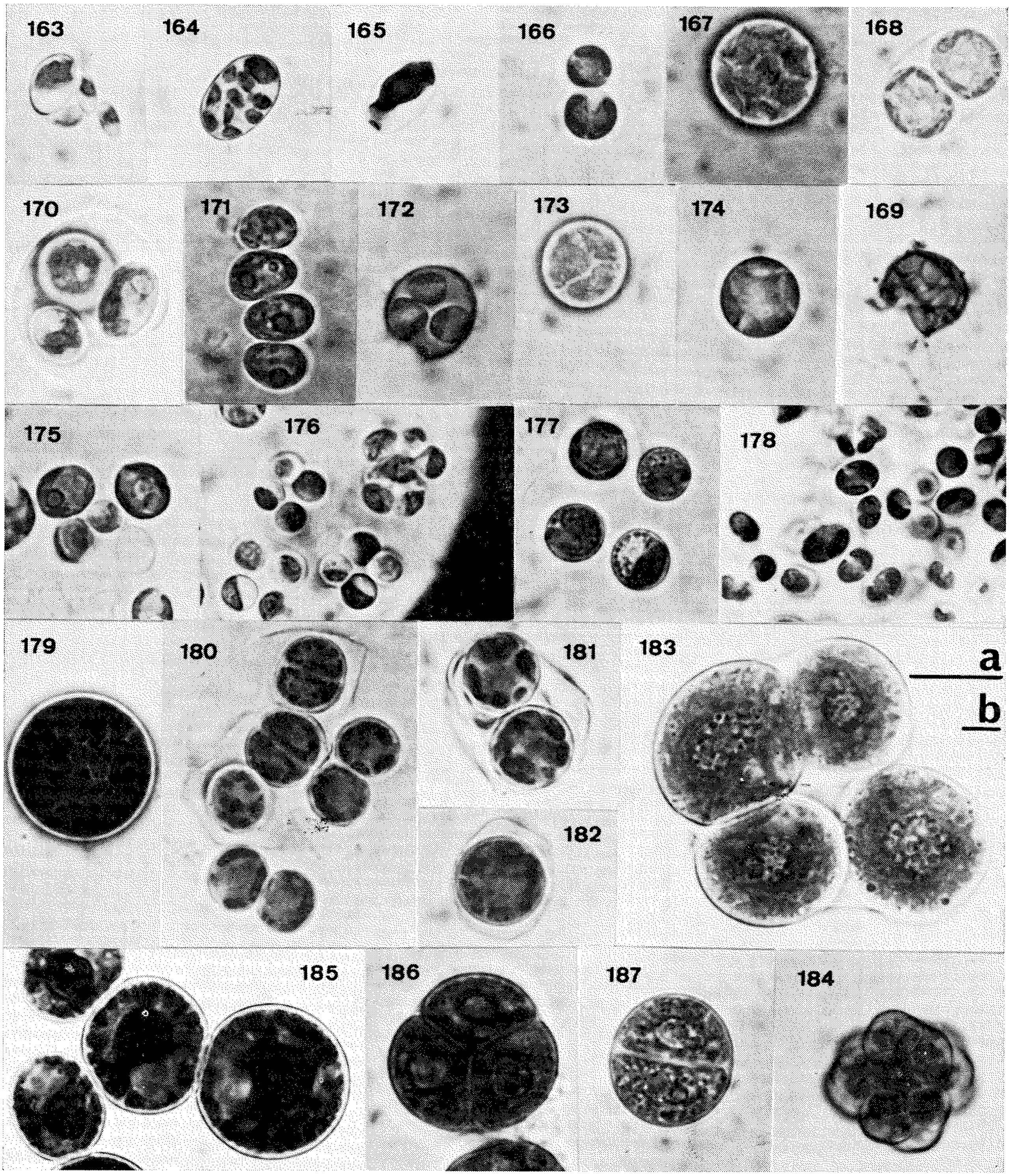


Fig. 163-165, *Chlorella saccharophila* var. *ellipsoidea;* 166, *C. zofingensis* var. B; 167-169, *Muriella terrestris* var. A; 170, *Oocystis minuta;* 171, *Scenedesmus microspina;* 172-174, *Muriella terrestris* var. B; 175, *Scotiellocystis* sp. (?); 176, 177, *Sphaerocystis* cf. *signiensis;* 178, *Coccomyxa gloeobotrydiformis;* 179-182, *Muriella* sp. (?); 183, 184, *Tetracystis* sp. B; 185-187, *T.* sp. D. The scales represent 10 μm. A; Fig. 163-183, 185-187. B; Fig. 184.

Adult cells ellipsoidal, 4-7 (-10) μm by 2.5 - 5 (-7) μm; chloroplast parietal, fissured, plate-like; pyrenoid distinct, surrounded by two large starch plates; cell contents vacuolate (Fig. 70); sporangia and adult cell walls occasionally covered by irregular plates of material (Fig. 71); recently released spores with faint parallel ridges across wall (Fig. 72, 73). Sporangia contain 2, 4, 8 and 16 spores released by irregular rupture of sporangium wall.

This isolate appears to belong in *Scotiellocystis* as defined by Fott (1976).

Sphaerocystis sf. *signiensis* Broady
Fig. 74, 75, 176, 177
Broady, 1976, p. 396-397, Fig 4
Samples; 3.

Colonies mucilaginous, containing groups of 2, 4 and 8 cells. Adult cells spherical to 7 µm diameter (Fig. 74, 177) and occasionally broadly ellipsoidal; chloroplast saucer-shaped occupying about half of wall surface and somewhat non-adherent; pyrenoid faint, surrounded by small starch granules. Partial gelatinization and rupture of sporangium wall releasing 2, 4, and 8 ellipsoidal spores from 3.5 by 3 µm (Fig. 75) in size.

Previous records: Glerárdalur, *S.* cf. *signiensis* with slightly larger cells, Broady (1978).

Chlorosarcinales

Borodinella polytetras Miller
Fig. 99, 100, 195-197
Bourrelly, 1966, p. 137, Pl. 20, Fig. 1; Fritsch and John, 1942, p. 377-378, Fig. 2, S-Y
Samples; 20, 22, 23, 24, 26, 27, 31.

Cells spherical, to 14 µm diameter; chloroplast axial with arms radiating from the slightly eccentric pyrenoid. Zoospores naked with a stigma and two equal flagella, becoming spherical on quiescence (Fig. 100). Desmoschisis resulting in the formation of diads (Fig. 195), tetrads and tedrad complexes (Fig. 197).

Chlorosarcina sp. A?
Fig. 107-109, 208
Samples; 26.

Cells usually single and in temporary pairs (Fig. 108, 109, 208) resulting from vegetative division, occasionally larger aggregates observed (Fig. 107) in which cells remain adherent after division in three planes; single cells slightly longer than wide (Fig. 108), 3-4 µm long.

Chlorosarcina sp. B?
Fig. 207
Samples; 19.

Cells 3.5 - 7 µm diameter, in cubical and more irregular aggregates formed by vegetative division in three planes.

Fernandinella alpina var. *semiglobosa* Fritsch and John fo.
Fig. 104-106, 206
Fritsch and John, 1942, p. 380, Fig. K-Q
Samples; 14.

Cells subspherical (Fig. 104), up to 12 µm diameter; chloroplast parietal, cup-like; pyrenoid distinct. Sporangia forming 4 zoospores; zoospores quadriflagellate, stigma large, median to posterior (Fig. 106). Desmoschsis results in diad (Fig. 105) and tetrad (Fig. 206) production.

In the description of *F. alpina* var. *subglobosa* given by Fritsch and John (1942) colonies of 4 to 32 cells are formed and the cells are often somewhat pyriform.

Myremecia biatorellae (Tschermak-Woess and Plessl) Petersen var.
Fig. 101-103, 198-205
Tschermak-Woess and Plessl, 1949, p. 203, Fig. 1-4; Andreyeva, 1978, p. 449, Fig. 3, 4
Samples; 3, 16.

Adult cells subspherical, pyriform and broadly ellipsoidal, to 26 by 20 µm (Fig. 101, 198, 199, 204); chloroplast extensive, bilobed, parietal (Fig. 101, 103, 200). Zoospores naked, pyriform (Fig. 102) formed in large numbers and released through apical rupture of sporangium wall; aplanospores spherical, 3-5 µm diameter (Fig. 205) also released in large numbers. Desmoschisis results in formation of diads (Fig. 201), tetrads (Fig. 202) and tetrad complexes (Fig. 203).

This genus is usually placed in the Chlorococcales, for instance by Bourrelly (1966) and Andreyeva (1978). However, the vegetative division (desmoschisis) of the cells into diads and tetrads, which dissociate slowly, indicates that this species has close affinities with the members of the Chlorosarcinales. The present isolate differs from *M. biatorellae* by the absence of a stigma from the zoospore.

Previous records: Iceland, *M. pyriformis* Petersen (1928a).

Planophila sp. ?
Fig. 110-112, 209
Samples; 18.

Cells single, in temporary pairs and occasionally in gropus of 3 (Fig. 111) or 4 resulting from vegetative division in one or two planes; single cells spherical, to 5 µm diameter; chloroplast saucer-shaped covering half of cell wall; pyrenoid occasionally indistinctly visible (Fig 209).

Tetracystis sp. A
Fig. 90-92, 191-194
Samples; 11, 14, 22, 31.

Adult cells spherical to 26 µm diameter (Fig. 191); young cells ellipsoidal (Fig. 192); chloroplast massive with axial portion surrounding an almost central pyrenoid (Fig. 90), and radiating arms joining with a perforate parietal portion (Fig. 91); perforations in chloroplast surface

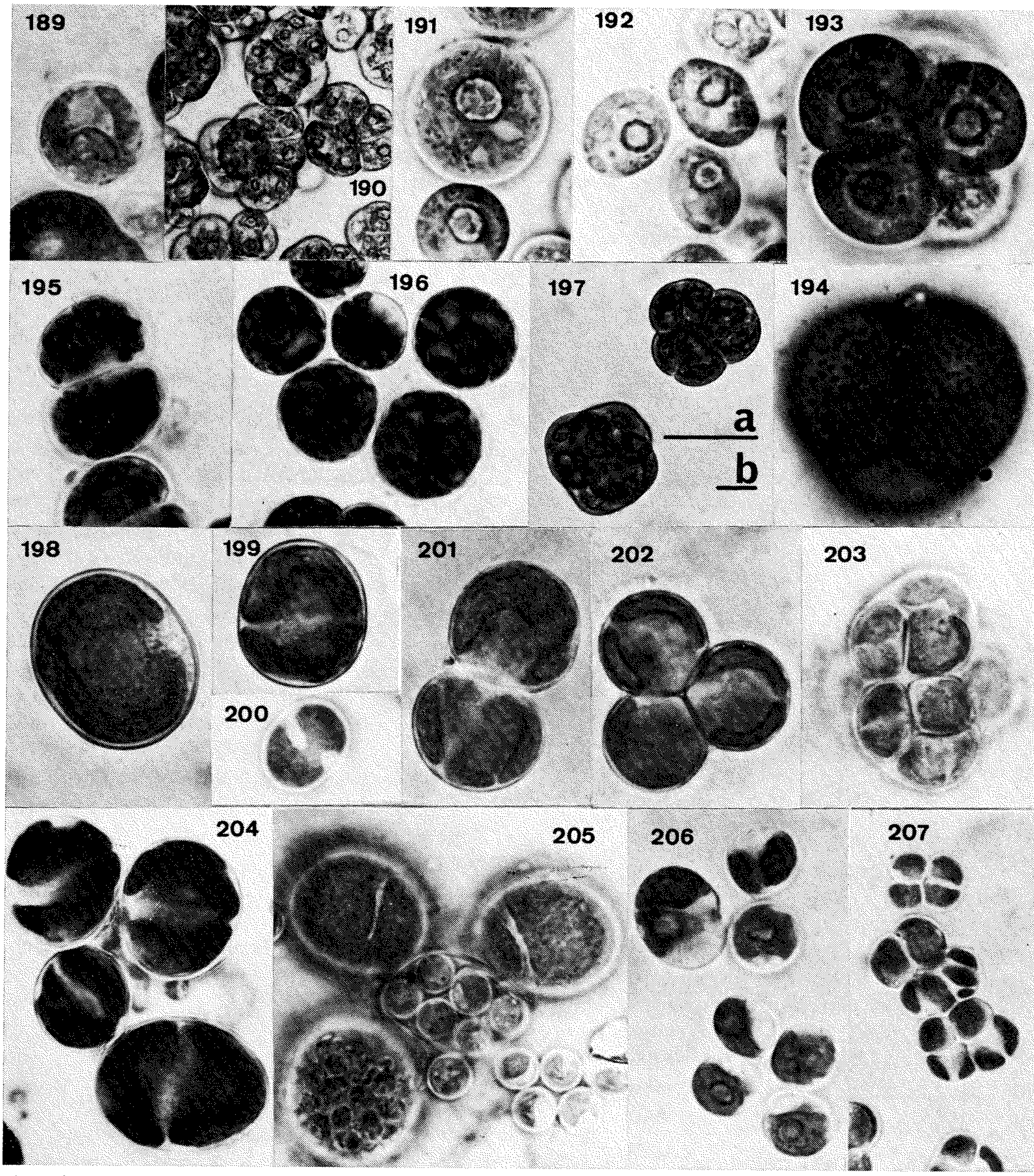


Fig. 189, 190 *Tetracystis* sp. C; 191-194, *T.* sp. A; 195-197, *Borodinella polytetras;* 198-205, *Myrmecia biatorellae var.;* 206, *Fernandinella alpina* var. *subglobosa;* 207, *Chlorosarcina* sp. B (?). The scales represent 10 µm. A; Fig. 189, 191-196, 198-207. B; Fig. 190, 197.

readily visible as dark areas after staining with toluidine blue (Fig. 194); pyrenoid surrounded by large starch grains; a pair of contractile vacuoles lie in an opening in chloroplast immediately above large nucleus. Sporangia release 16 and 32 (?) ellipsoidal zoospores, 11 µm by 5 µm, with anterior nucleus and stigma; aplanospores ellipsoidal; tetrads (Fig. 194), octads (Fig. 193) and tetrad complexes formed.

Neither this isolate nor the following three isolates could be identified to any of the species described by Brown and Bold (1964).

Previous records: Glerárdalur, unidentified *Tetracystis* spp. Broady (1978).

Tetracystis sp. B
Fig. 95, 96, 183, 184
Samples; 30.

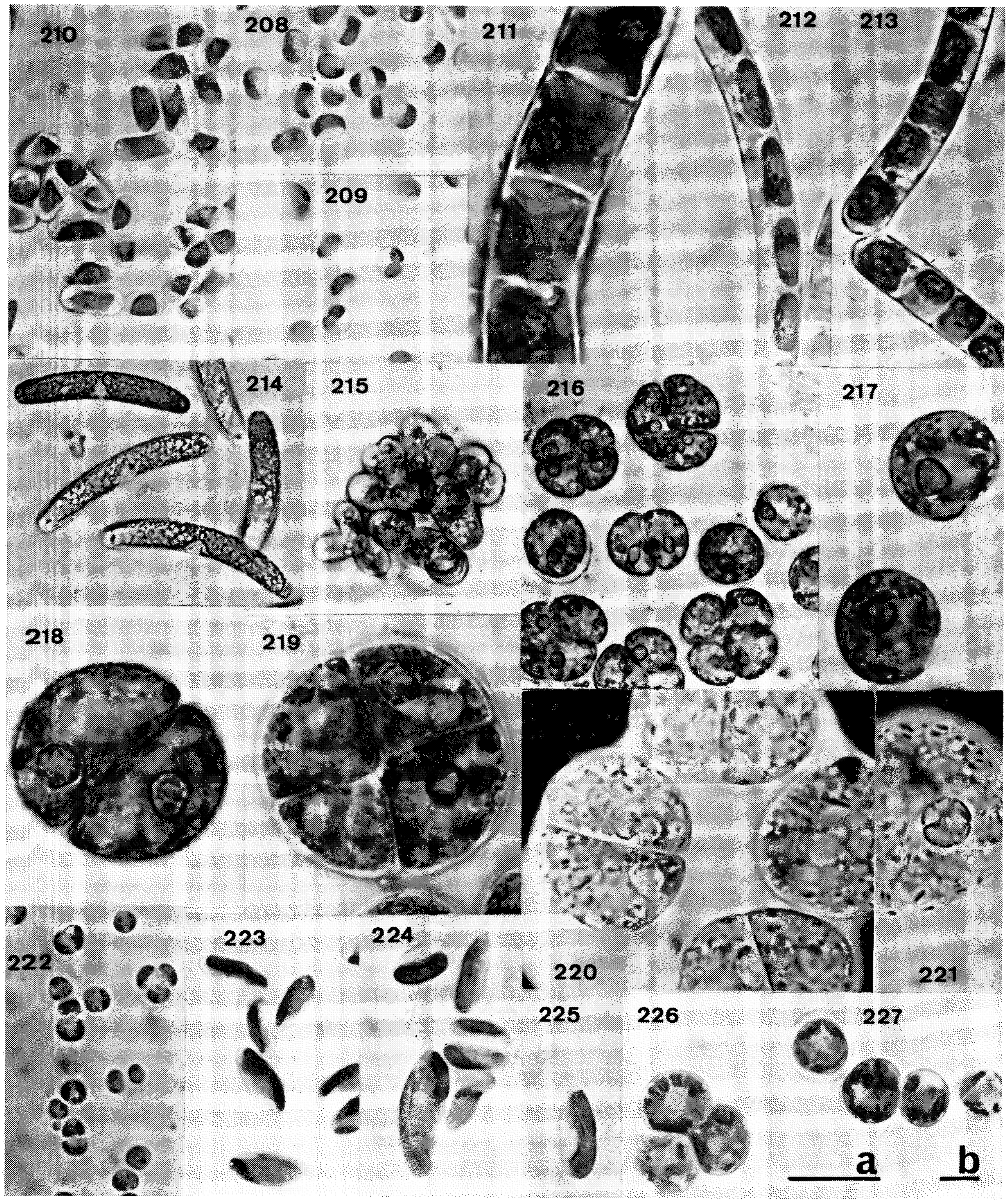


Fig. 208, *Chlorosarcina* sp. A (?); 209, *Planophila* sp. (?); 210, *Stichococcus bacillaris;* 211, *Ulothrix implexa;* 212, 213, *Klebsormidium flaccidum;* 214, *Closterium pusillum;* 215, cf. *Apatococcus lobatus;* 216-221, *Prasinochloris* sp. (?); 222, *Chloridella minuta;* 223, *Monodus subterraneus* var. A; 224, 225, *M. subterraneus* var. B; 226, 227, *Chloridella* sp. (?). The scales represent 10 µm. A; Fig. 208-213, 217-227. B; 214-216.

Adult cells spherical, 16-22 µm diameter; chloroplast cup-shaped, fissures in thick portion surrounding eccentric pyrenoid, perforations through thin portion above pyrenoid (Fig. 95); a pair of contractile vacuoles occupying opening in chloroplast, adjacent to nucleus; pyrenoid surrounded by numerous small starch grains. Zoospores ellipsoidal, 10-12 µm by 4-5 µm, with a posterior nucleus and anterior stigma. Desmoschisis results in tetrad (Fig. 183) and tetrad complex (Fig. 184) formation.

Tetracystis sp. C
Fig. 97, 98, 189, 190
Samples; 30.

Adult cells spherical when single (Fig. 189), to 13 µm diameter; chloroplast cup-shaped with basal, thickened, fissured portion containing a pyrenoid surrounded by large starch grains. Zoospores with posterior nucleus and anterior stigma (Fig. 98). Desmoschisis resulting in tetrad and tetrad complex (Fig. 190) formation.

Tetracystis sp. D
Fig. 93, 94, 185-187
Samples; 32.

Adult cells broadly ellipsoidal (Fig. 93) and spherical, to 17 µm diameter; chloroplast massive with axial portion, surrounding slightly eccentric pyrenoid, and radiating arms poining perforate parietal portion; a pair of contractile vacuoles situated at opposite pole to distinct nucleus; pyrenoid surrounded by small starch grains. Zoospores 9.5 - 13 µm by 5 µm, with large anterior stigma and posterior nucleus (Fig. 94). Desmoschisis results in formation of diads (Fig. 187) and tetrads (Fig. 186).

Ulotrichales

Klebsormidium flaccidum (Kuetz.) Silva, Mattox and Blackwell
Fig. 212, 213
Syn: *Hormidium flaccidum* Kuetz. in Mattox and Bold, 1962, p. 31, Fig. 33-42
Samples; 3, 9, 10, 12-14, 16, 17, 20, 23, 24, 26, 27, 31.

Filaments long, fragmenting in old cultures (Fig. 213), 4.5 - 8 µm wide. Cells 3.5 - 20 µm long, mostly about 6 µm long in active cultures; chloroplast occupying about half of wall; pyrenoid surrounded by several small starch grains.

Previous records: Surtsey, as *Chlorhormidium flaccidum,* Schwabe and Behre (1972); Glerárdalur, *C. flaccidum* (A. Br.) Fott, Broady (1978).

Stichococcus bacillaris Naegeli
Fig. 210
Mattox and Bold, 1962, p. 36-37, Fig. 45-49
Samples; 9, 26.

Filaments short, composed of no more than 4 cells, readily fragmenting. Cells 2.5 - 3.5 µm wide by 3.5 - 7.5 µm long; pyrenoid faintly visible.

An appearance of a similar faint pyrenoid is visible in Fig. 48 and 49 of Mattox and Bold (1962).

Previous records: Surtsey, *S. bacillaris* Naeg. s. ampl., Behre and Schwabe (1970); Iceland, Petersen (1928a); Glerárdalur, Broady (1978).

Ulothrix implexa Kuetzing
Fig. 113, 211
Printz, 1964, p. 14, Tab. I; 16, 17
Samples 27.

Filaments long, 10.5 - 14 µm wide, slightly constricted at transverse walls. Cells 7-16 µm long; chloroplast encircling about two-thirds of cell, containing a single pyrenoid.

Chaetophorales

cf. *Apatococcus lobatus* (Chodat) Petersen
Fig. 114-117, 215
Vischer, 1960, p. 337-338, Abb. 5
Samples, 3, 8.

Irregularly branching filaments and aggregates of cells. Cells to 20 µm diameter; cell contents not clearly observed due to large oil accumulations; chloroplast parietal; aplanospores (Fig. 116) spherical, 3 µm diameter, released in large numbers by rupture of sporangium wall.

Previous records: Surtsey, cf. *A. lobatus,* Schwabe (1970).

Unidentified
Fig. 118-121
Samples; 1, 9.

Only wild material examined, no growth in BBM. Cells spherical and subspherical, to 12 µm diameter, usually 6-8 µm, single, in tetrahedral groups and small branching aggregates (Fig. 118-120), embedded in mucilage; cell contents not clearly observed due to large quantities of oil globules; chloroplast parietal (Fig. 121).

Ulvales

Prasiola crispa (Lightf.) Meneghini
Printz, 1964, p. 104, Tab. XXIII, Fig. 2
Samples; 13, 14, 15.

Uniseriate filaments of the *"Hormidium"* stage observed.

Zygnematales

Actinotaenium cucurbita var. *attenuatum* Teiling
Teiling, 1954, p. 406, Fig. 67-69
Samples; 27.

Previous records: Surtsey, *Actinotaenium* sp., Schwabe and Behre (1972); Glerárdalur, Broady (1978).

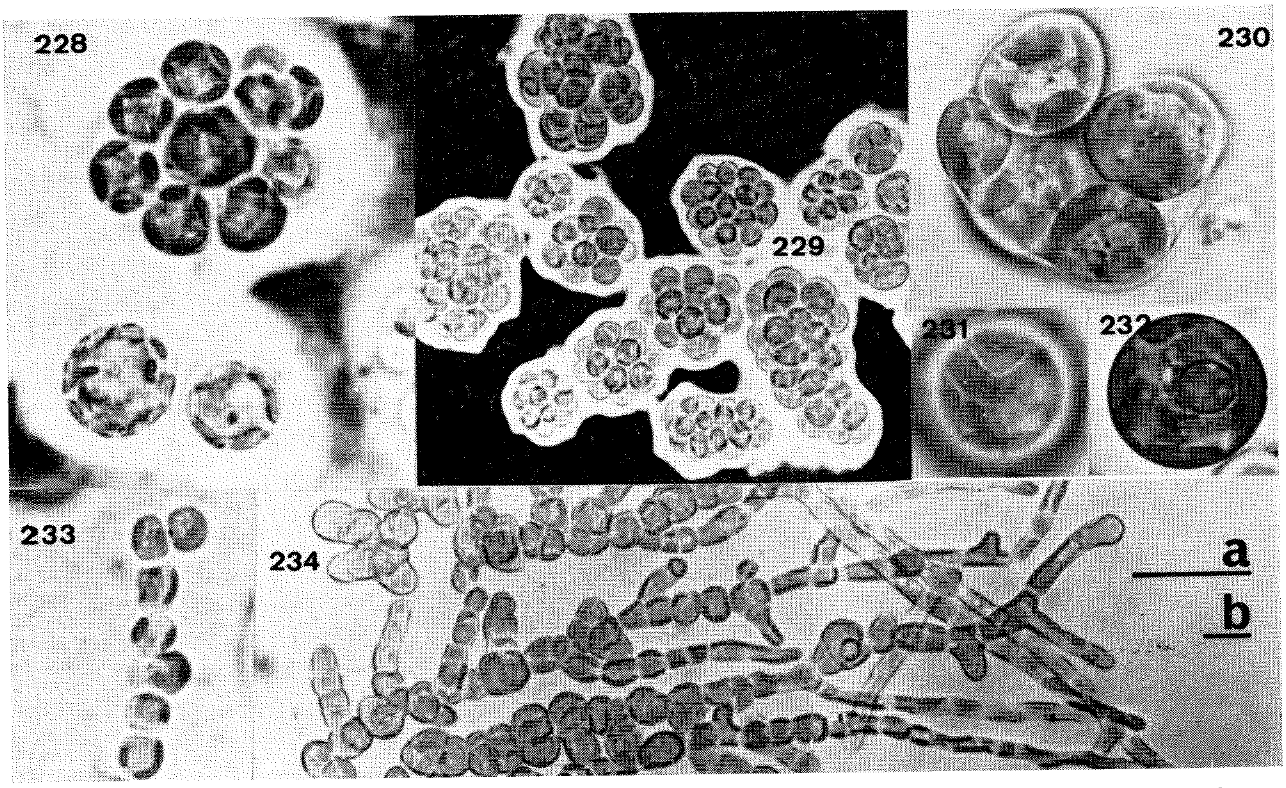


Fig. 228, 229, *Gloeobotrys* sp. (?); 230-232, unidentified eustigmatophycean alga; 233, 234, *Heterococcus* sp. The scales represent 10 μm. A; Fig. 228, 230-234. B; Fig. 229.

Closterium pusillum Hantzsch
Fig. 214
Krieger, 1937, p. 279, Taf. 14, Fig. 6
Samples; 26, 31.

Cells 31-55 μm long by 8-9 μm wide; each of the two chloroplasts containing one or two pyrenoids; a single crystal present in a vacuole at each pole.

Previous records: Surtsey, Schwabe and Behre (1972); Glerárdalur, *C. pusillum* var. *major* Racib., Broady (1978).

Cylindrocystis brebissonii (Ralfs) De Bary
Krieger, 1937, p. 207, Taf. 6, Fig. 4
Samples; 26, 27.

Previous records: Glerárdalur, Broady (1978).

PRASINOPHYCEAE

Prasinochloris sp.?
Fig. 122-124, 216-221
Samples, 20, 22, 23.

Mucilaginous, colonial stage dominant in culture (Fig. 16, 220) in which cells single, in pairs (Fig. 218), isobilateral tedras (Fig. 219) and octads; mucilage often lamellate, distinctly so on staining with toluidine blue. Cells spherical and subspherical due to mutual adpression, 7-30 μm diameter; chloroplast in young cultures cup-shaped, in older cultures becoming perforated and fragmented (Fig. 218, 219); pyrenoid single in small cells, often two or more in larger cells, surrounded by large starch plates (Fig. 221); small starch grains scattered throughout chloroplast; nucleus large, distinct; several contractile vacuoles occupy an opening in chloroplast and cell in this region is often slightly concave (Fig. 124, 217). Quadriflagellate, pleiomorphic zoospores formed on transfer of material from agar to aqueous medium, cells dividing into 2, 4 and 8 spores; chloroplast single (Fig. 122) or fragmented (Fig. 123); stigma anterior. On cessation of activity cells become approximately spherical (Fig. 124) with a depression where flagella emerge; long, branching pseudo-cilia observed on one occasion, prior to mucilage secretion.

This alga is similar to *P. sessilis* Belcher (1966) in the possession of a sedentary phase forming naked quadriflagellate zoospores but differs in the production of copious mucilage, the release of more than two zoospores and in zoospore morphology.

Pedinomonas minor Korschikoff
Fig. 11
Ettl, 1967, p. 3-4, Fig. 1:7, 2:6-8
Samples; 28.

Cells ellipsoidal in lateral view, flattened in dorsal view, 4-5 μm long by 2.5 - 3 μm wide; chloroplast a parietal plate; pyrenoid faint.

XANTHOPHYCEAE

Mischococcales

Chloridella minuta Gayral and Mazancourt var.
Fig. 130-132, 222
Gayral and Mazancourt, 1958, p. 347, Fig. II. 1
Samples; 16.

Cells spherical, 3 - 4.5 (-6) μm diameter; chloroplast parietal occupying more than half of wall. Sporangia releasing 2, 4 and 8 subspherical spores, ruptured sporangia walls only occasionally remaining visible.

The Surtsey isolate has slightly larger cells and a more extensive chloroplast than *C. minuta* Gay. and Maz.

Previous records: Glerárdalur, *C. minuta,* Broady (1978).

Chloridella sp.?
Fig. 125-129, 226, 227
Samples; 16, 23, 27.

Cells spherical and subspherical, to 13 μm diameter; chloraplast a perforate, lobed, parietal plate, fragmenting in largest cells into irregular plates. Sporangia releasing 2, 4, 8 and 16 spherical to subspherical spores (Fig. 129) by irregular rupture of wall; sporangium wall remains are often visible around single cells (Fig. 227).

Gloeobotrys sp.?
Fig. 133, 134, 228, 229
Samples; 16.

Cells embedded in mucilage in aggregates containing 4, 8 and larger numbers of cells (Fig. 228, 229); mucilage without lamellations. Adult cells spherical, to 18 μm diameter; chloroplasts numerous, parietal plates (Fig. 133). Sporangia release numerous zoospores (Fig. 134) and aplanospores by gelatinization of sporangium wall; zoospores with two chloroplasts.

The cells resemble those of *Botrydiopsis* in the possession of numerous parietal chloroplasts but the presence of mucilage secretions is a character of *Gloeobotrys.* Pascher (1937) describes the subgenus *Gloeobotrys* s. stricta for the forms with spherical cells. The isolate under examination here, however, possesses larger cells and has less extensive mucilage development than the single described species of that sub-genus.

Previous records: Glerárdalur, *G.* cf. *terrestris* Resigl of the sub-genus *Allantogloea,* Broady (1978).

Monodus subterraneus Petersen var. A
Fig. 223
Petersen, 1932, p. 406, Fig. 13
Samples; 9, 12, 26.

Cells 6.5 - 10.5 μm. Sporangia containing usually 2 and 4, rarely 8 spores.

Petersen (1932) described the production of only two spores in each sporangium.

Previous records: Surtsey, Schwabe and Behre (1972); Glerárdalur, Broady (1978).

Monodus subterraneus Petersen var. B
Fig. 224, 225
Samples; 3, 14, 21.

Cells 6.5 - 15 μm by 3-6 μm. Sporangia containing usually 8, infrequently 2 and 4 spores.

This isolate differed slightly in cell size and spore production from the previous isolate. The size range is greater than described by Petersen (1932).

Tribonematales

Heterococcus sp.
Fig. 223, 234
Samples; 28.

Filaments richly branched, 3-9 μm wide (Fig. 234). Zoosporangia produced (Fig. 233). Further study required.

Heterothrix exilis Pascher
Pascher, 1937, p. 921, Fig. 774, 777b
Samples; 6, 18.

Filaments often over 20 cells in length with little fragmentation. Cells 3.5 - 5 μm wide by 4.5 - 9 μm long, slightly inflated in central region; chloroplasts parietal, 2 to 4 in each cell.

EUSTIGMATOPHYCEAE

Unidentified genus
Fig. 230-232
Samples; 8, 12, 16, 21, 22, 25, 26.

Adult cells spherical, to 16 μm diameter; chloroplast parietal, perforated by narrow slits (Fig. 231); pyrenoid distinct with an angular outline, not embedded within chloroplast (Fig. 232). Aplanospore formation (Fig. 230).

Previous records: Glerárdalur, a similar, unidentified alga was recovered by Broady (1978).

TABLE I. Genera of green and yellow algae recovered from Surtsey 1967-1978.

Genus	Sampling date 1967[1]	1968[2,3]	1969-70[4]	1978[5]
Characiopsis	..	..	+	..
Chloridella	..	..	..	+
Gloeobotrys (?)	..	..	..	+
Monodus	..	..	+	+
Pleurochloris	..	+	..	..
Heterococcus	..	..	..	+
Heterothrix	..	..	+	+
Tribonema	..	..	+	..
Unident. Eustigmatophyceae	..	..	..	+
Euglena	..	+	+	..
Petalomonas	..	+	+	..
Pedinomonas	..	..	..	+
Prasinochloris (?)	..	..	..	+
Carteria	..	..	+	..
Chlamydomonas	+	+	+	+
Dunaliella	+	..	..	..
Chlamydocapsa	..	..	..	+
Palmellopsis	..	..	..	+
Chlorella - like	+	..	..	..
Chlorella	..	+	+	+
Coccomyxa (?)	..	+	..	..
Coccomyxa	..	..	..	+
Dictyosphaerium	..	..	+	..
Muriella	..	+	..	+
Nannochloris	+	..	..	..
Oocystis	..	..	..	+
Scenedesmus	..	..	+	+
Scotiellocystis	..	..	..	+
Sphaerocystis	..	..	..	+
Characium	..	..	..	+
Bracteacoccus	..	..	..	+
Chlorococcalean - like	+	+	+	..
Chlorococcum	+	..	+	+
Neochloris	..	..	..	+
Fasciculochloris	+	..	..	..
Borodinella	..	..	..	+
Chlorosarcina (?)	..	..	..	+
Fernandinella	..	..	..	+
Myrmecia	..	..	..	+
Planophila (?)	..	..	..	+
Tetracystis	..	..	..	+
Gloeotila	..	+	+	..
Klebsormidium	..	..	+	+
Stichococcus	+	+	+	+
Ulothrix	..	..	..	+
cf. *Apatococcus*	..	+	..	+
Unident. Chaetophorales	..	..	..	+
Prasiola	..	..	..	+
Actinotaenium	..	..	+	+
Closterium	..	..	+	+
Cylindrocystis	..	..	..	+
Mesotaenium	..	..	+	..
TOTAL	8	11	19	37

[1]Maguire (1968), [2]Schwabe (1970), [3]Behre and Schwabe (1970), [4]Schwabe and Behre (1972), [5]this study.

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Marine algal colonization at Surtsey

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INTRODUCTION

Observations on the marine algal settlement around Surtsey have been carried out, at fairly regular intervals, since the formation of rocky shores on the island in 1964 (Jónsson, 1966, 1967, 1968, 1970a, 1970b, 1972). The investigations have so far been of exploratory nature extending to different parts of the shore and the sublittoral zone depending on the accessibility and the changing development of the shoreline. The main objectives have been the identification, the order of arrival and the distribution of pioneer populations. Since the beginning of the settlement in 1964 the number of invading species has been steadily increasing. In 1970, the number of species reached 46, including 11 species of diatoms. How-

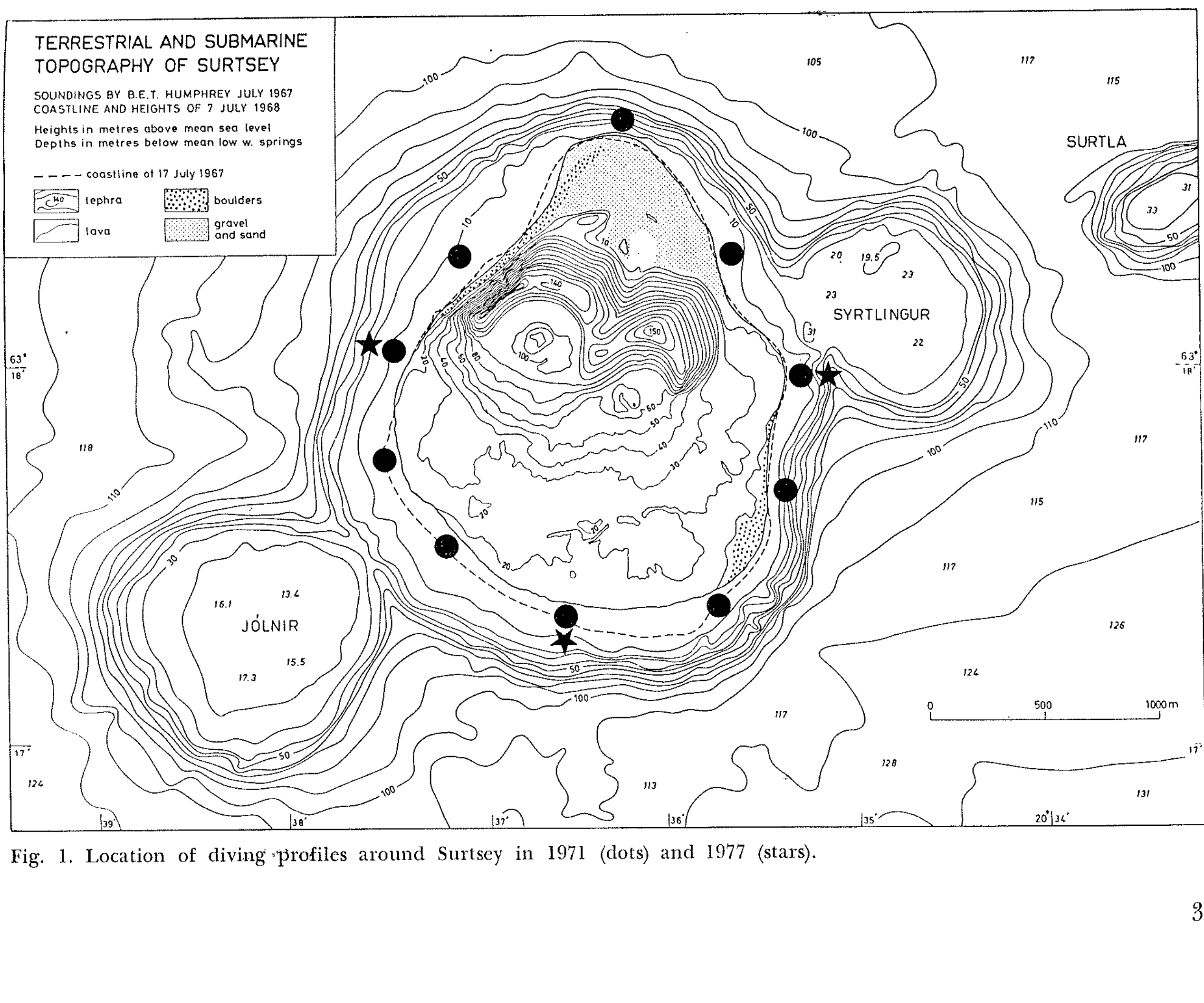


Fig. 1. Location of diving profiles around Surtsey in 1971 (dots) and 1977 (stars).

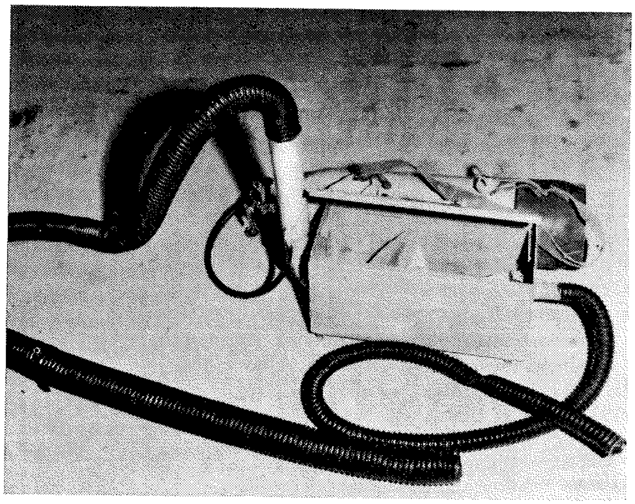


Fig. 2. Underwater suction sampler showing the filtering compartment with open lid, the inhalation tube to the right and the high pressure air tank connected with the exhalation tube. (Courtesy of Jóhannes Briem.)

ever, only a few species were of ecological importance. In the littoral zone two belts could be recognized, an upper one of *Urospora penicilliformis,* intermixed with various accompanying species, and a lower one of colonial naviculoid diatoms in a mucilaginous matrix. The sublittoral vegetation was dominated by *Alaria esculenta* populations. This situation, as compared to that known in mature algal communities of adjacent islands, indicated that the marine algal colonization of Surtsey was yet in its pioneer stage.

This paper deals with further observations on the marine algal settlement at Surtsey carried out in 1971 and 1977.

PROCEDURES OF INVESTIGATION

In 1971 the period of investigation extended from 20 to 30 August. Studies were carried out from the field station on Surtsey. The shore was explored at low tide by landing parties and the sublittoral zone by divers. The littoral zone was surveyed all around the island exept for the south coast which was quite inaccessible. In the sublittoral zone 10 transects were investigated from 0-30 m depth (Fig. 1). Dives were made at 5, 10, 20 and 30 m depth and specimens were handcollected into plastic pails with cross-cut lids. The depth was measured with a wrist gauge. The nature of the bottom and the general features of the algal vegetation were recorded after each dive. The identification of species was made on fresh material. The nomenclature is mainly according to Caram and Jónsson (1972). Herbarium specimens were prepared and species photographed for later reference.

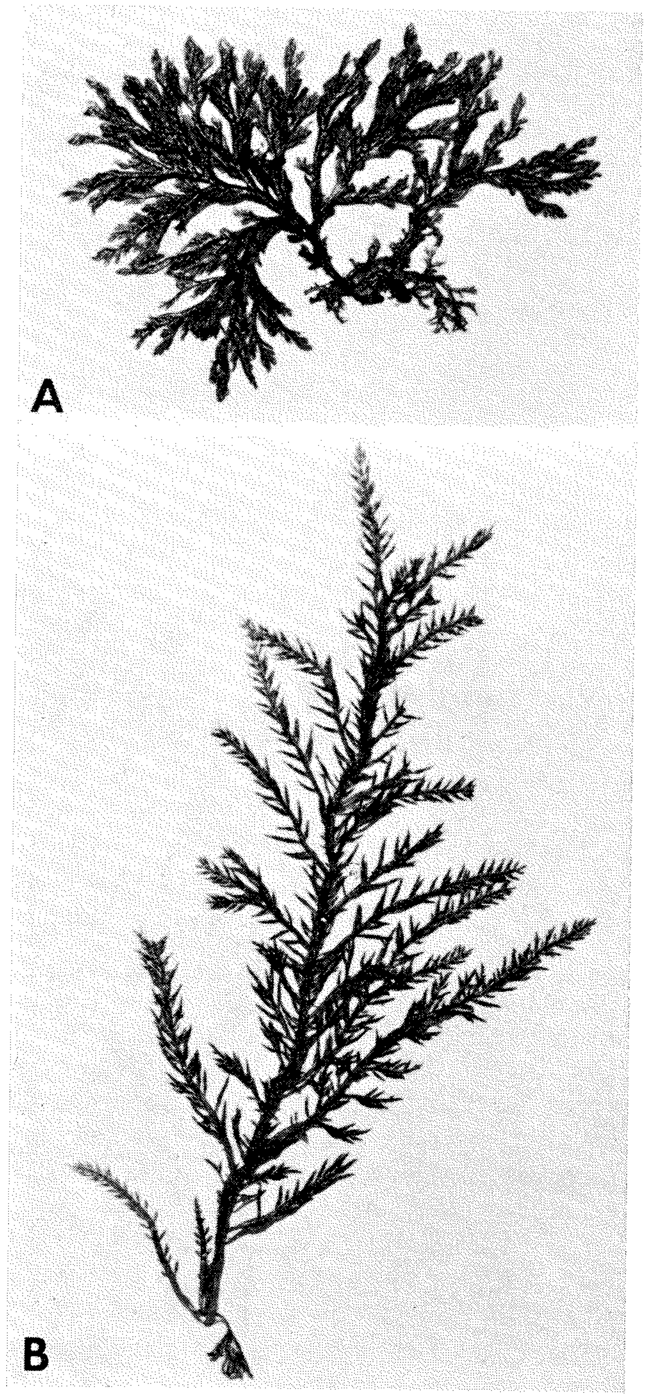


Fig. 3. A. *Plocamium cartilagineum.* Sterile plant from 10 m depth east of Surtsey, July 11 1977; nat. size 6 cm.
B. *Lomentaria clavellosa.* Plant from 20 m depth south of Surtsey, July 11 1977; nat. size 17 cm.

In 1977 the field work was performed from R/V Árni Fridriksson from 9 to 11 July in a similar way as described above. During this short survey investigations were limited to 3 subtidal transects, located off the east, west and the south coasts of the island (Fig. 1). Due to inaccessibility only the east and the west coasts could be explored by landing parties. Most of the material collected was fixed aboard the ship in 2% for-

TABLE I Vertical and horizontal distribution of marine algal species found in Surtsey waters in 1971 and 1977.

Species	Littoral	Sublittoral			1971			1977		
		0-10	15-20	30 m	E	S	W	E	S	W
RHODOPHYCEAE										
Rhodochorton purpureum	..	×	..	..	..	..	×	..	..	..
Plocamium cartilagineum	..	×	..	..	..	..	..	×	..	..
Rhodophysema elegans	..	×	..	..	..	..	..	..	×	..
Euthora cristata	..	×	..	..	..	..	..	×	..	..
Lomentaria clavellosa	..	×	..	..	..	..	..	×	×	..
Lomentaria orcadensis	..	×	×	..	..	..	×	×	×	×
Antithamnion floccosum	..	×	×	×	×	×	×	×	..	×
Antithamnion plumula	..	×	..	..	..	..	..	×	..	..
Delesseria sanguinea	..	×	×	×	..	..	×	×	×	×
Phycodrys rubens	..	×	×	..	×	×	×	×	×	×
Polysiphonia urceolata	..	×	×	..	×	×	×	×	×	×
Porphyra umbilicalis	×	..	..	..	×	..	×	×	..	×
Porphyra miniata	..	×	×	..	×	×	..	×	×	×
Conchocelis rosea	..	×	×	..	..	..	×	×	..	..
PHAEOPHYCEAE										
Ectocarpus siliculosus	×	..	..	..	..	..	..	×	×	..
Ectocarpus fasciculatus	×	..	×	..	×	..	×	×	..	×
Giffordia granulosa	..	..	×	..	×	..	..	..	..	..
Giffordia ovata	..	..	..	..	..	..	..	..	..	..
Giffordia recurvata	..	..	..	..	..	..	..	..	..	..
Giffordia secunda	..	×	..	..	..	..	..	×	..	..
Petalonia fascia	×	×	×	..	×	×	×	×	..	×
Petalonia zosterifolia	×	..	..	..	×	..	×	×	..	×
Scytosiphon lomentarius	×	..	..	..	..	..	..	×	..	×
Ralfsia sp.	×	..	..	..	..	..	×	..	..	..
Desmarestia aculeata	..	×	×	..	..	..	×	..	..	×
Desmarestia ligulata	..	×	×	..	×	×	×	..	×	..
Desmarestia viridis	..	×	×	..	×	×	×	×	×	×
Chorda filium	..	×	..	..	..	..	..	..	..	×
Chorda tomentosa	..	×	..	..	..	..	..	×	..	..
Laminaria hyperborea	..	×	×	..	×	×	×	×	..	×
Laminaria digitata	..	×	..	..	..	×	..	..	..	..
Alaria esculenta	×	×	×	..	×	×	×	×	×	×
CHLOROPHYCEAE										
Codiolum gregarium	×	..	..	..	×	..	×	×	..	×
Urospora penicilliformis	×	..	..	..	×	..	×	×	..	×
Ulothrix consociata	×	..	..	..	..	..	..	..	..	×
Ulothrix pseudoflacca	×	..	..	..	×	..	×	×	..	×
Ulothrix subflaccida	×	..	..	..	..	..	×	..	..	..
Enteromorpha prolifera	×	..	..	..	×	..	×	×	..	×
Enteromorpha compressa	×	..	..	..	×	..	..	..	..	..
Ulva lactuca	..	×	..	..	..	..	×	..	..	..
Monostroma grevillei	..	×	..	..	..	..	×	×	×	×
Acrosiphonia spinescens	..	..	..	..	..	..	..	..	..	×
Derbesia marina	..	×	..	..	..	..	×	..	×	×
Pseudentoclonium submarinum	×	..	..	..	×	..	..	..	..	..
CYANOPHYCEAE	×	..	..	..	×	..	..	×	..	..

malin seawater and analyzed ashore. In three instances plants and animals in the sublittoral zone were loosened from the bottom by a scraper and collected by an underwater suction sampler (Fig. 2) within quadrats measuring 25 x 25 cm (1/16 m^2). This sampling process proved to be successful but was too time-consuming.

RESULTS

1. *Species survey*

The species composition of the macroscopic marine flora off Surtsey in 1971 and 1977 and the distribution pattern of individual species are summarized in Table I.

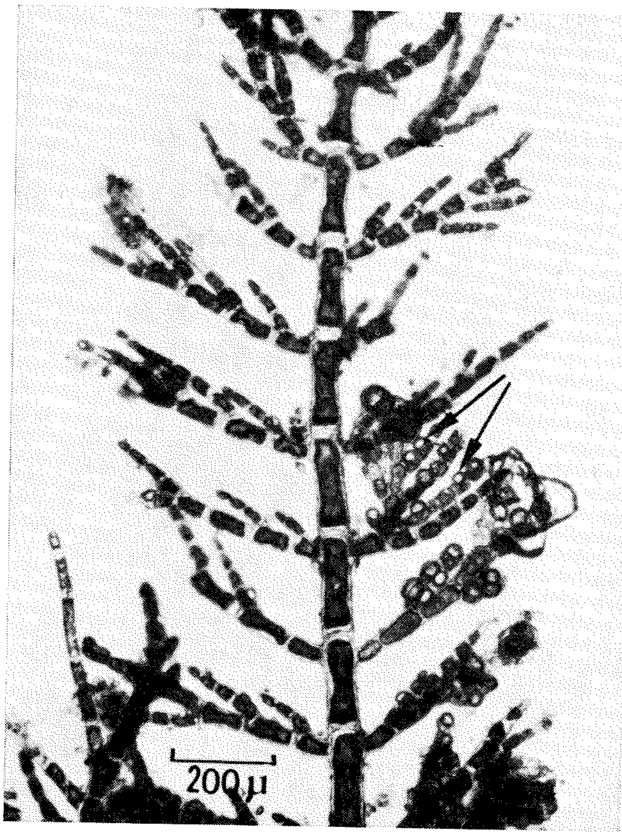


Fig. 4. *Antithamnion plumula* var. *boreale*. A part of sterile plant with gland cells (arrows); specimen from 10 m depth east of Surtsey, July 10 1977.

A total of 31 algal species were found growing in the coastal waters off Surtsey in 1971 and 34 species in 1977. The following 18 species were found for the first time, 8 species in 1971 and 10 in 1977:

Rhodochorton purpureum (Lightf.) Rosenv.
Two tetrasporiferous specimens were found in 1971 on *Desmarestia aculeata* collected at 8 m and 20 m depth off the west coast.

Plocamium cartilagineum (L.) Dixon
Some sterile specimens were found in 1977 growing at 12 m depth on rocks off the east coast (Fig. 3A).

Rhodophysema elegans (Crn. frat. ex J. Ag.) Dixon
Patches of this species were found in 1977 at 10 m depth off the south coast where they grew on bare rocks. The specimens were 1-5 cm in diameter and had tetraspores between sterile nemathesial filaments on the surface of the thallus.

Lomentaria clavellosa (Turn.) Gaill.
Several plants of this species were found in 1977 at 10 m depth off the east coast growing on rocks amongst Hydrozoa. The largest specimen measured 20 cm and bore tetraspores (Fig. 3B).

Antithamnion plumula (Ellis) Thur. var. *boreale* (Gobi) Kjellm.
A few sterile specimens with typical gland cells (Fig. 4) were found in 1977 growing on haptera of *Laminaria hyperborea*.

Delesseria sanguinea (Huds.) Lamouroux
One sterile specimen partly covered with Bryozoa was found in 1971 on rocks at 20 m depth off the west coast. In 1977 this species was redetected at 10-30 m depth at the same locality (Fig. 5B).

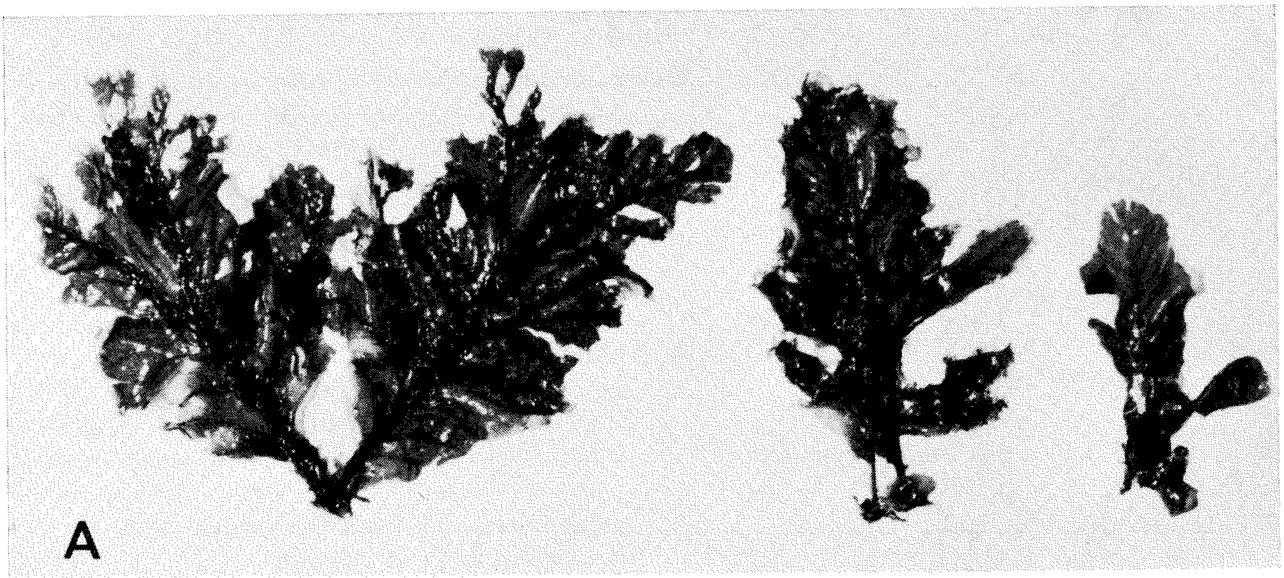
Conchocelis rosea
This alga which is the sporophyte in the life history of *Porphyra* or *Bangia* was found in 1977 off the east coast at 10-20 m depth growing on mussels and calcareous Polychaeta tubes. It was sterile when collected.

Ralfsia sp.
In 1971 a small crust of the genus *Ralfsia* was found growing on the shore at the west coast amongst *Ectocarpus* and *Petalonia*. On one occasion *Petalonia* was found growing on the crust. The specimens were sterile.

Desmarestia aculeata (L.) Lamouroux
In 1971 one sterile specimen, 75 cm in length, was found on rock at 20 m depth off the west coast (Fig. 6). Another specimen found five days later in the same locality measured 60 cm.

Giffordia secunda (Kütz.) Batt.
This species was first detected in 1971 in a collection from 3-19 m depth off the SW-coast. The plants grew on rocks and bore ovoid plurilocular sporangia.

Giffordia recurvata (Kuckuck) Cardinal
This species which was not previously known from Iceland grew up together with *Giffordia ovata* and *Giffordia granulosa* in stock culture of *Derbesia marina* collected in 1977 at 10 m depth off the east coast. Our specimens attained a length of about 4 cm, and developed plurilocular sporangia (Fig. 7A). They agree with Cardinal's description of this species (Cardinal, 1964).



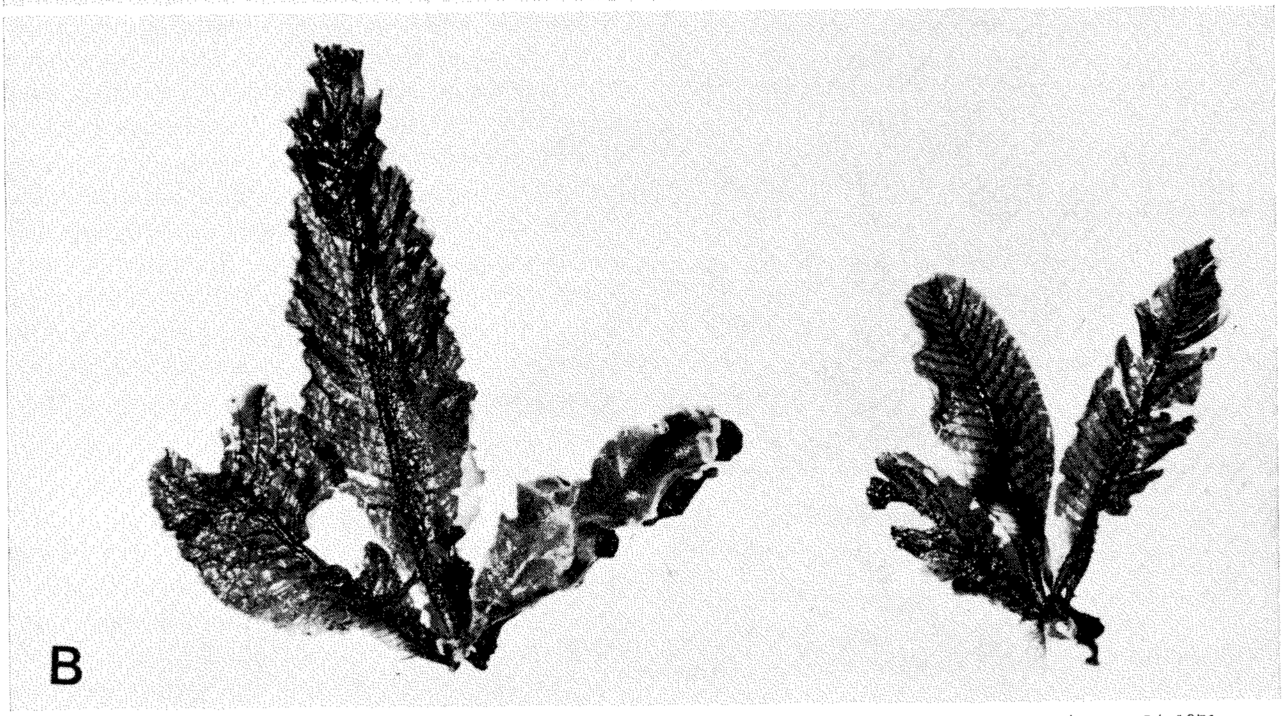


Fig. 5. A *Phycodrys rubens*. Different aspects of plants picked up from 20 m depth west of Surtsey, August 24 1971; max. nat. size 8 cm.
B. *Delesseria sanguinea*. Young (right) and old (left) specimens, the latter one covered partly by *Membranipora membranacea;* collected at 20 m depth west of Surtsey, August 24 1971; max. nat. size 7 cm.

Giffordia ovata (Kjellm.) Kylin

Typical specimens (Fig. 7B) bearing plurilocular sporangia grew up with the preceeding species in stock culture of *Derbesia marina*.

Chorda filum (L.) Stackh.

This species which grew on stones amongst *Alaria esculenta* at 10 m depth was found for the first time in 1977 off the west coast. The plants were 60-70 cm long but sterile. This species has not previously been found growing in the Westman Islands.

Chorda tomentosa Lyngb.

In 1977 several scattered individuals bearing unilocular sporangia were found at 5 m depth on stones off the east coast. As the previously mentioned species this one has not been recorded in the Westman Islands before (Fig. 8B).

Ulothrix subflaccida Wille

This species was first found in 1971 on stones at high tide level on the west coast growing amongst *Ulothrix pseudoflacca* and *Urospora penicilliformis*.

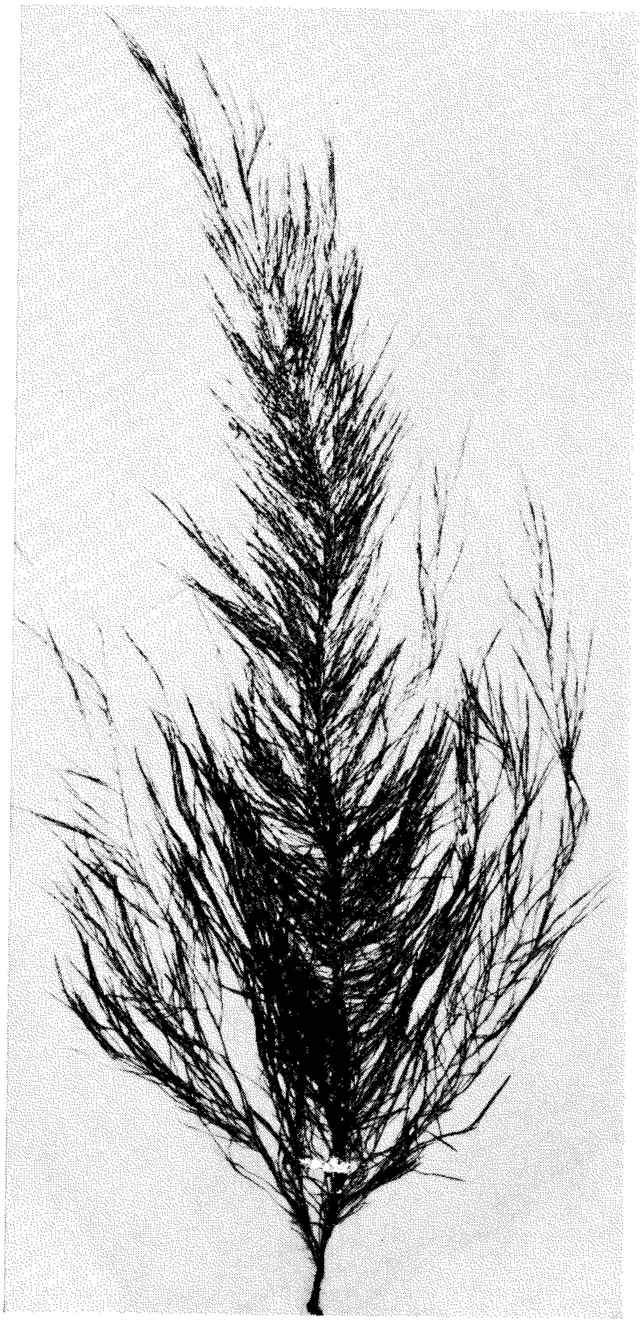


Fig. 6. *Desmarestia aculeata.* A fully grown plant from 20 m depth west of Surtsey, August 24 1971; nat. size 75 cm.

Derbesia marina (Lyngb.) Sol.

In 1971 some specimens were found growing on calcareous Polychaeta tubes at 6-10 m depth off the west coast. Some of these plants bore lateral sporangia (Caram and Jónsson, 1973).

Pseudentoclonium submarinum Wille

This species was found for the first time in 1971 growing on solid rocks above high tide level on the east coast.

Other species mentioned in Table I have been reported on previously (Jónsson, 1970a, 1972).

2. *The vegetation*

a. Littoral zone. The substratum of the littoral zone is mainly of three types: huge blocks bordering the lava cliffs of the west, south and east coasts with gravel and sand in between, the boulder terrace occupying the southeast and northwest coasts and sand forming the northern spit (Fig. 1).

In 1971 and 1977 there had been minor changes in the littoral vegetation from that reported in previous years, i.e. there were still two algal belts, a green one, located at high tide level, and a brown belt below. Between 1971 and 1977 *Alaria esculenta* was found to have extended its cover from the sublittoral zone into the brown belt of the tidal zone. The littoral vegetation appeared to be similar all along the rocky shore in both 1971 and 1977. No vegetation was found on the northern spit and a very scanty one on the boulder terraces. A total of 16 species have been found growing on the shore, the most conspicuous of these at present being *Enteromorpha prolifera.* Other common species are *Urospora penicilliformis, Ulothrix pseudoflacca, Petalonia fascia* (Fig. 9A), *P. zosterifolia* (Fig. 8A), *Porphyra umbilicalis* (Fig. 10A) and diatoms in mucilage threads. *Scytosiphon lomentarius* (Fig. 9B) is less common.

b. Sublittoral zone. The bottom from 0-30 m depth is of more or less uniform character around the island. It is mostly covered with big blocks of rock and boulders surrounded by gravel and sand. The rocky surfaces offer a suitable substrate for algal settlement. Around the northern spit the bottom is of sand and gravel with no visible vegetation.

In the sublittoral zone a total of 30 species were detected. Of these 19 were found in 1971 and 27 in 1977. In 1977 11 species were found growing in all transects and the most common of these were *Alaria esculenta* (Fig. 11), *Laminaria hyperborea* (Fig. 12) and *Desmarestia viridis* (Fig. 13). These species were associated with several species of red algae, i.e. *Phycodrys rubens* (Fig. 5A), *Delesseria sanguinea* (Fig. 5B), *Porphyra miniata* (Fig. 10B), *Lomentaria orcadensis* (Fig. 14A), *Polysiphonia urceolata* (Fig. 14B) and *Antithamnion floccosum.*

In 1971 *Desmarestia ligulata* (Fig. 15) was a conspicuous element of the submarine flora all around the island. In 1977, however, this species was found only off the south coast and represented by a few small individuals. On the other hand,

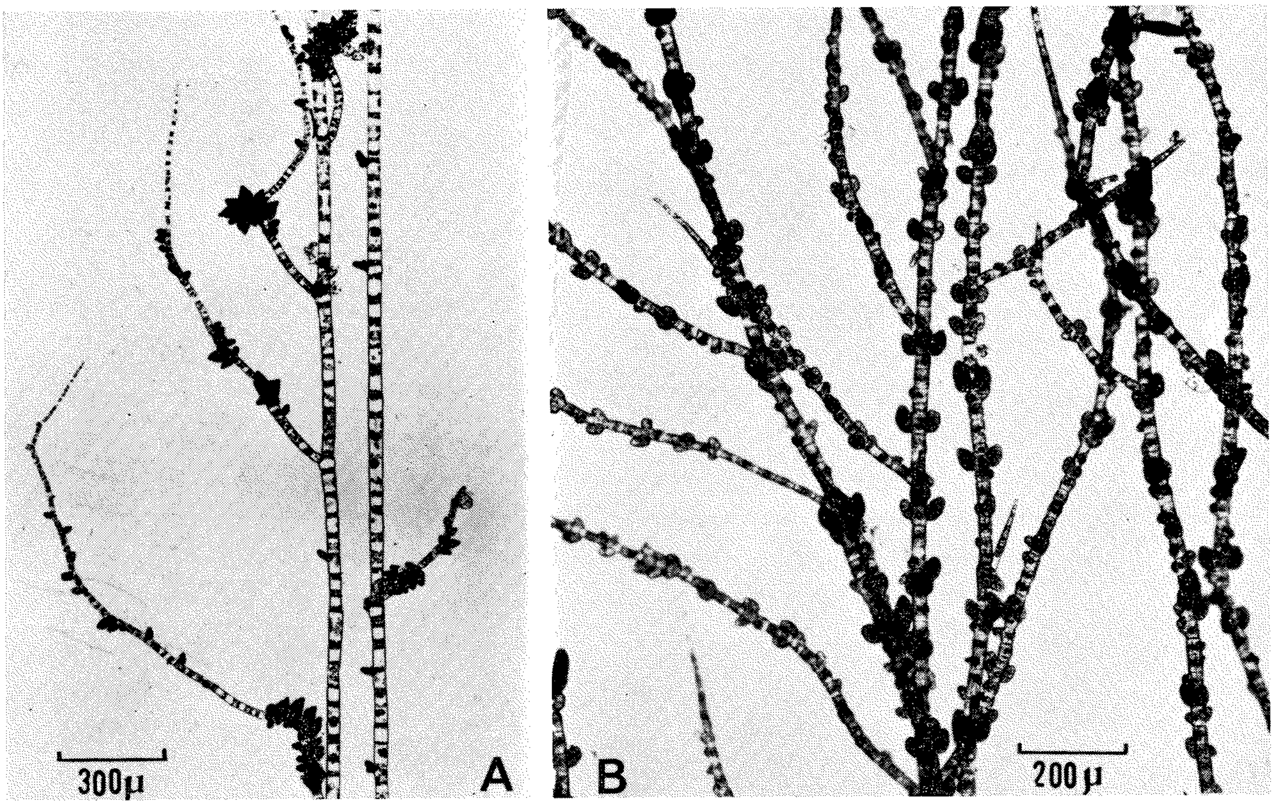


Fig. 7. A. *Giffordia recurvata.* A part of a plant with plurilocular sporangia; grew up in stock culture of algae collected at 10 m depth east of Surtsey, July 10 1977.
B. *Giffordia ovata:* part of a plant with plurilocular sporangia; grew up with preceeding species.

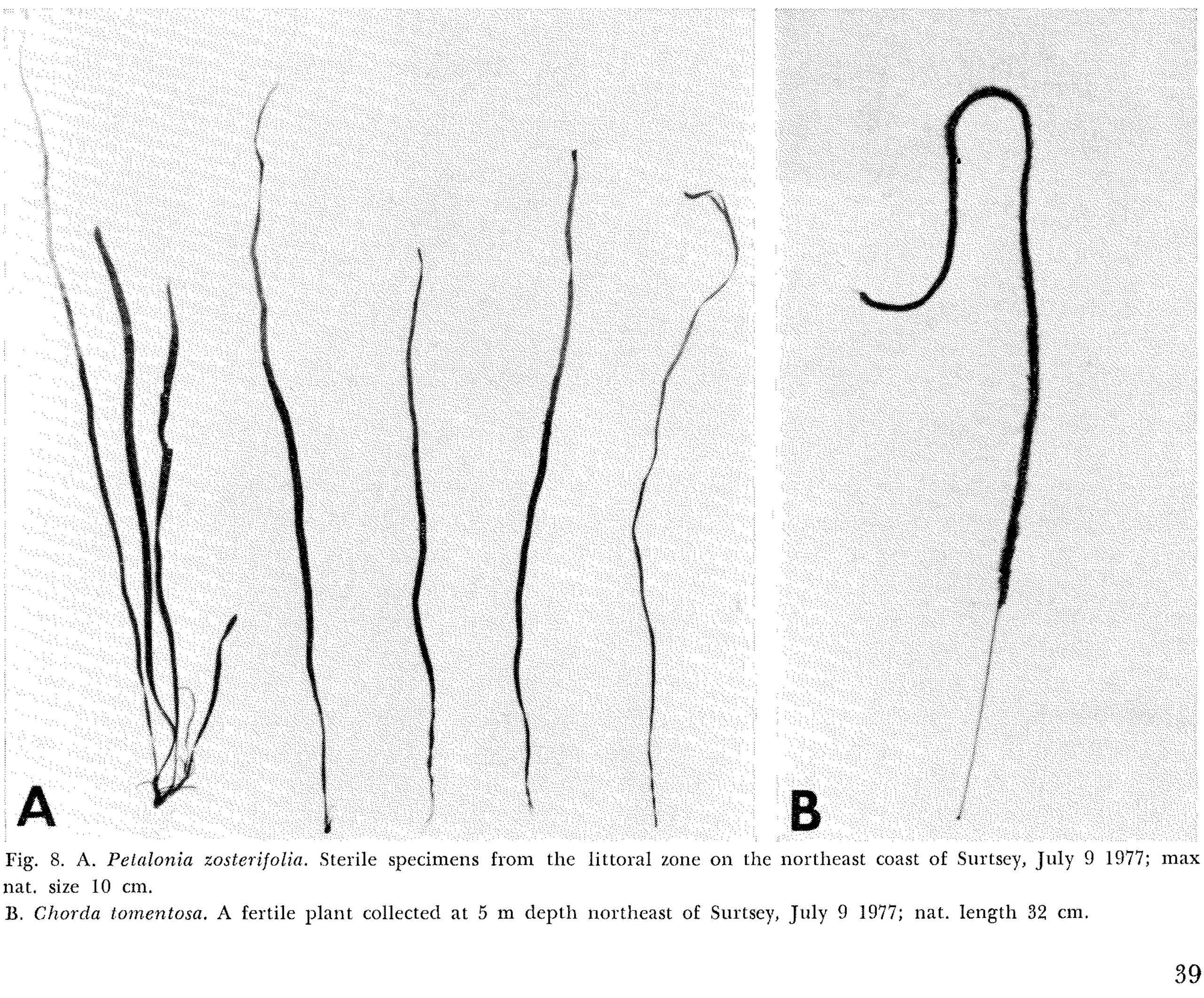


Fig. 8. A. *Petalonia zosterifolia.* Sterile specimens from the littoral zone on the northeast coast of Surtsey, July 9 1977; max nat. size 10 cm.
B. *Chorda tomentosa.* A fertile plant collected at 5 m depth northeast of Surtsey, July 9 1977; nat. length 32 cm.

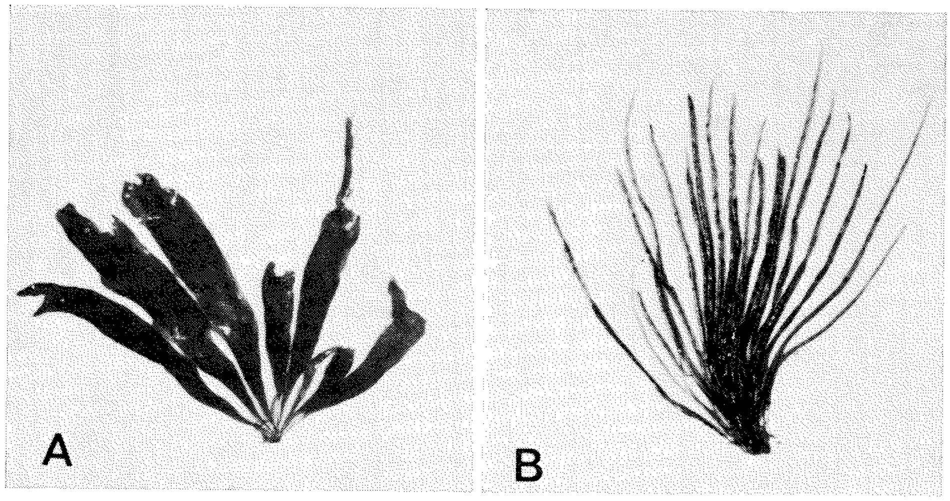


Fig. 9. A. *Petalonia fascia.* A cluster of broad specimens collected in the intertidal zone on the southeast coast of Surtsey, August 27 1971; max. nat. size 4,5 cm. B. *Scytosiphon lomentarius.* A tuft of typical specimens from the intertidal zone on the east coast of Surtsey, August 23 1971; max. nat. size 6,7 cm.

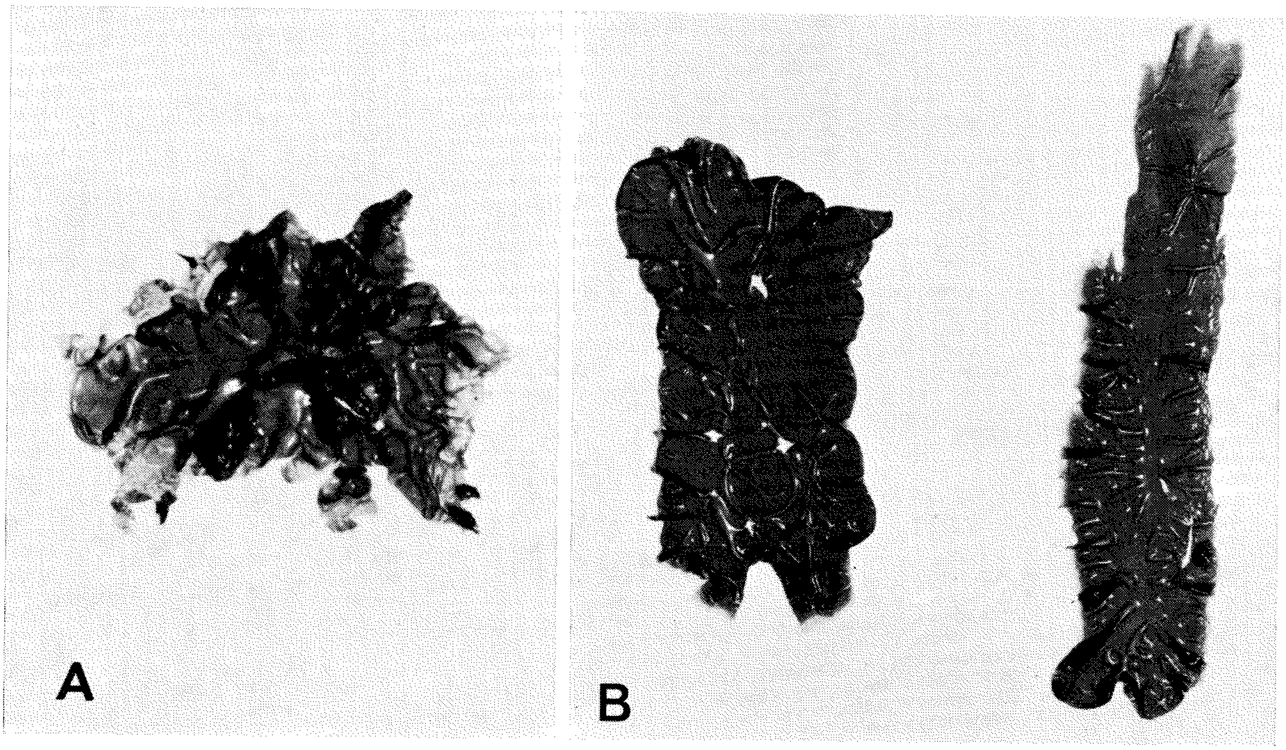


Fig. 10. A. *Porphyra umbilicalis.* A fertile plant from the intertidal zone on the east coast of Surtsey, August 23 1971; nat. size 4x7 cm.
B. *Porphyra miniata.* Fertile plants from 5-10 m depth south of Surtsey, August 28 1971; max. nat. size 17,5 cm.

Derbesia marina and *Lomentaria orcadensis* had expanded since 1971. The former species was restricted to the west coast, but is now also growing off the south coast. *L. orcadensis* was in 1971 only found on the south coast but in 1977 it occurred in all transects.

In the sublittoral zone the algae were randomly distributed on rock surfaces at a depth range from 0 m to the lower limits of the vegetation at about 20 m depth, although few individuals could be found down to the depth of 30 m. This applies to both periods of observation. It was noted, that the *Alaria esculenta* populations were moving upwards, now occupying the lowest part of the tidal zone in several places. *Laminaria hyperborea,* first detected on the island in 1967, was found to be most often growing together with *Desmarestia viridis.* In 1971 the largest plants brought up from the bottom had a stipe length of 8-10 cm and the blades were 25-30 cm long. Similarly, the largest plants collected in 1977 measured 63-64 cm in stipe length and 52-66 cm in blade length. They grew at 15 m depth and were 5-6 years old. Their stipes are frequently covered with a luxurious growth of epiphytes. In addition to Hydrozoa and Bryozoa the following algal epiphytes were found on stipes and haptera of *Laminaria hyper-*

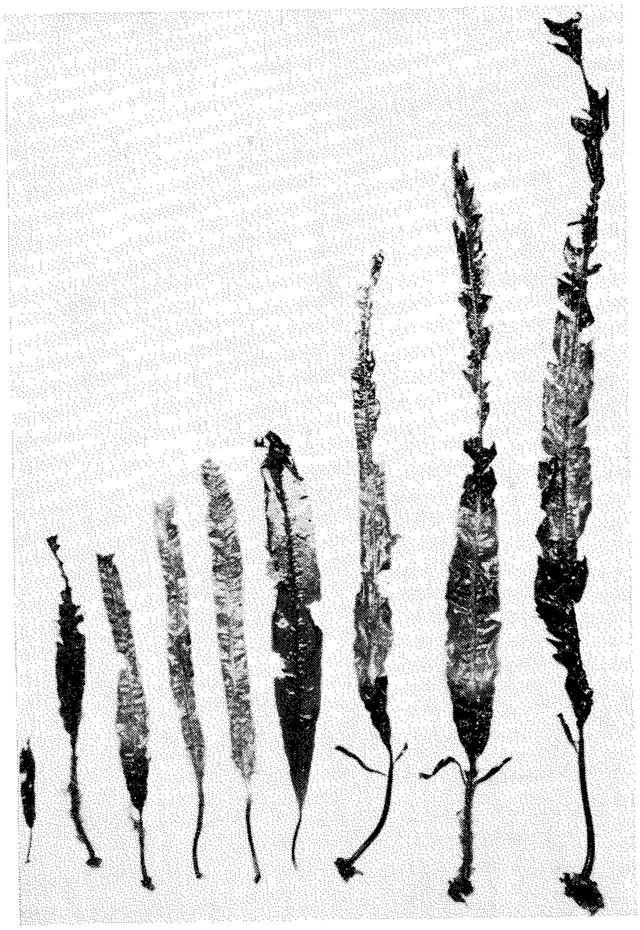


Fig. 11. *Alaria esculenta*. Growth variations in plants collected at 20 m depth west of Surtsey, August 24 1971; max. nat. size 62 cm.

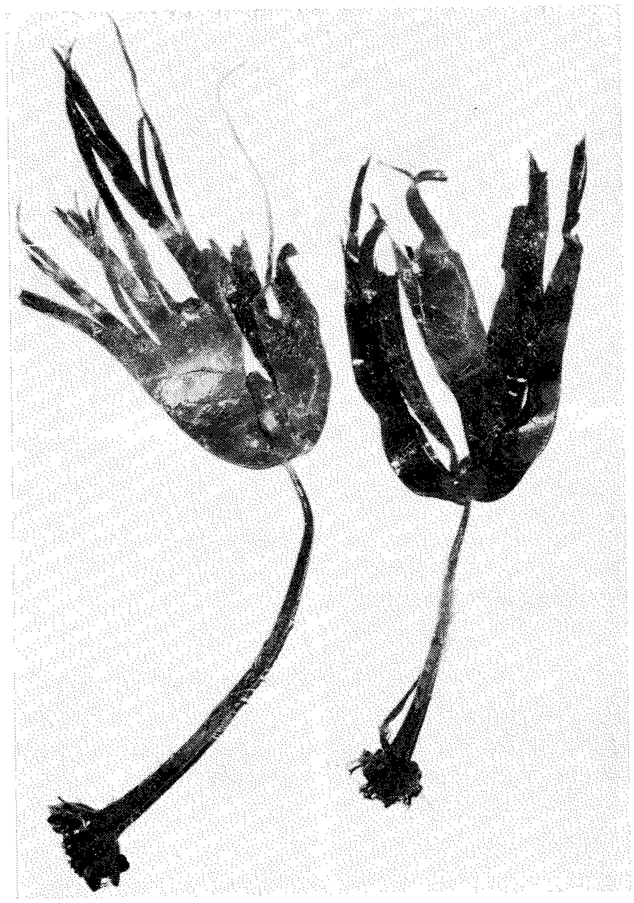


Fig. 12. *Laminaria hyperborea*. Well developed, typical specimens from 10 m depth east of Surtsey, August 28 1971; note epiphytes and epizoa on stipes and lamina; nat. size 85 cm.

borea: Polysiphonia urceolata, Antithamnion floccosum, Callophyllis cristata (=*Euthora cristata*), *Lomentaria orcadensis, Giffordia sp.* and *Alaria esculenta*. The blades are often covered with large patches of Bryozoa.

An estimate of the algal biomass at Surtsey could not be made during our short survey. However, samples taken with the underwater suction sampler within three quadrats at 10 m, 15 m and 20 m depth off the east coast revealed 7,9, 1,1 and 0,2 kg/m^2, algal biomass, respectively.

There are actually two major seaweed beds in Surtsey waters, located off the east and the west coasts of the island. In these two localities the eroding action appears to be somewhat less than elsewhere along the coast (Norrman et al. 1974).

DISCUSSION

All the new algal colonizers at Surtsey have been found in similar habitats on the coasts of Iceland with the exception of *Giffordia recurvata* which was not previously known from Iceland. This species is regarded as very rare in

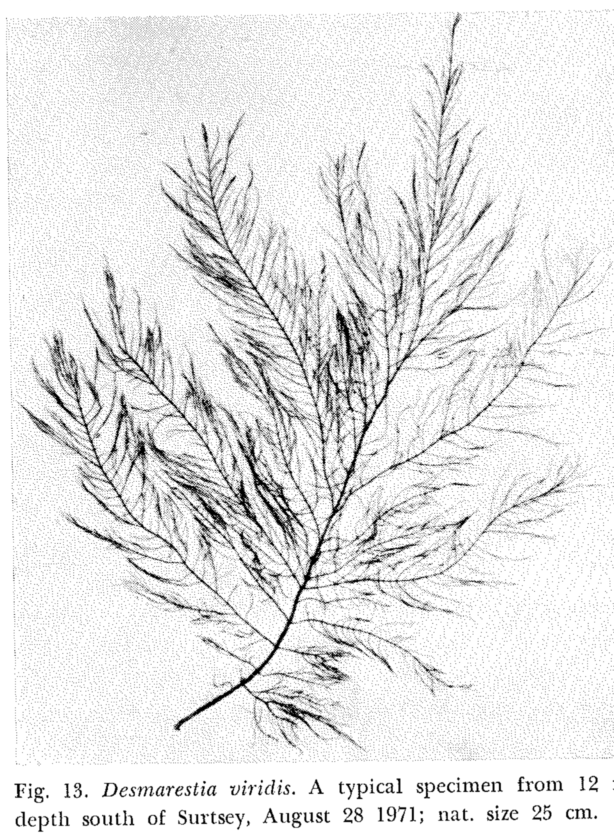


Fig. 13. *Desmarestia viridis*. A typical specimen from 12 m depth south of Surtsey, August 28 1971; nat. size 25 cm.

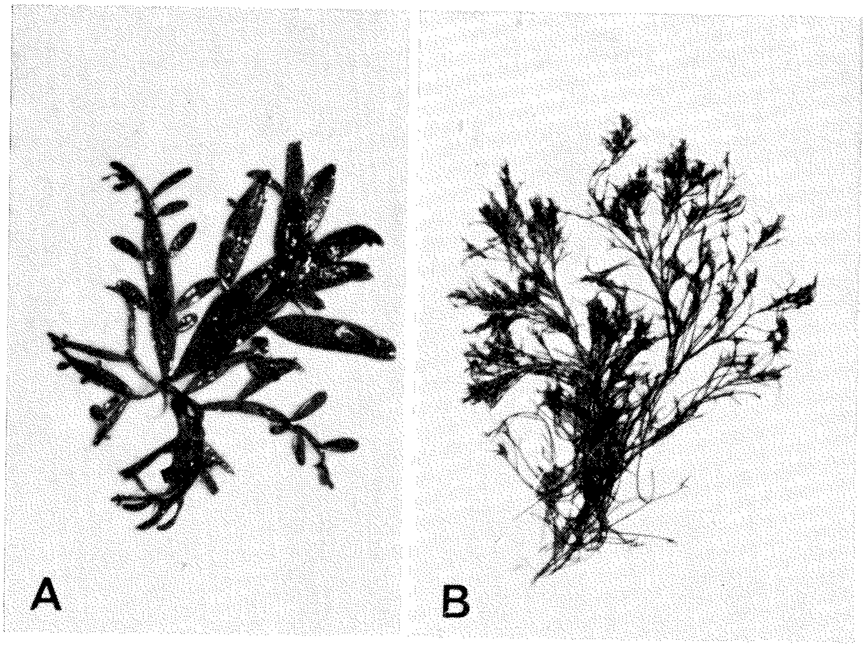


Fig. 14. A. *Lomentaria orcadensis.* A typical specimen from about 15 m depth southwest of Surtsey. August 28 1971; nat. size 4 cm.
B. *Polysiphonia urceolata.* A specimen collected at 10 m depth south of Surtsey, August 28 1971; nat. size 9 cm.

the North Atlantic (Cardinal, 1964). Of special interest is the occurrence of *Rhodophysema elegans,* found off the south coast of Surtsey. This species is the first one of the deep water crustose red algae found to colonize the island. Crustose coralline algae were not found in spite of thorough search. The presence of *Chorda filum* and *Chorda tomentosa* at Surtsey is rather unexpected as these species have not been found growing in the Westman Islands. The former is, however, a common driftweed on Surtsey and Heimaey. A similar unusual occurrence of *Chorda tomentosa* has been reported (as *Halosiphon tomentosum)* from new lava flows in Jan Mayen (Gulliksen 1974). Other species, such as *Plocamium cartilagineum* and *Lomentaria clavellosa,* are common deep water red algae in the area and were already presumed as likely colonizers (Jónsson, 1967).

A total of 50 species of macroscopic algae have been identified in the marine environment of Surtsey since the beginning of the colonization 13 years ago. This represents about 42% of the total number of macroscopic algal species found to grow in the Westman Islands. It appears that the marine algal colonization as a whole has been taking place by progressive immigration of species (Table II and Fig. 16). However, year-to-year variations in species composition have been observed during this period. This may be due to seasonal periodicity of short-lived algae and/or to the presence of opportunistic species. Also the possibility that individual species have been overlooked in the field should not be ruled out, especially in the subtidal region. The length of time spent collecting underwater is only 20-30 minutes for each dive. One must work quickly and there is little time to explore vast areas looking for rare species. In addition, dives are often extremely difficult and even dangerous owing to surge and heavy swell.

Among the algal species colonizing Surtsey, 23 were found in the littoral zone and 31 in the

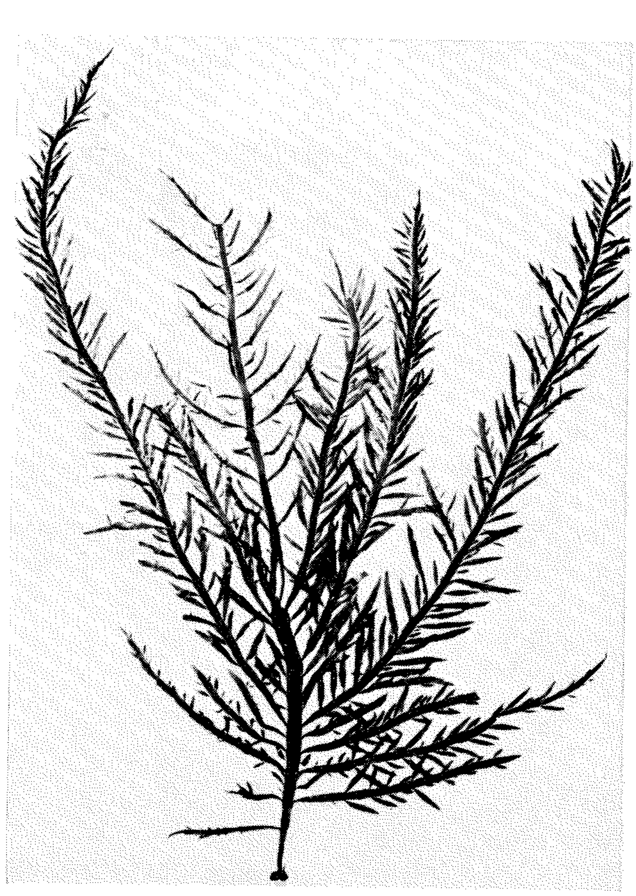


Fig. 15. *Desmarestia ligulata.* A typical specimen from 10 m depth east of Surtsey, August 25 1971; nat. size 70 cm.

TABLE II Marine algae and their order of arrival as recorded at Surtsey 1964-1977.

Species or groups	1964	1965	1966	1967	1968	1969	1970	1971	1977
Diatoms	+	+	+	+	+	+	+	+	+
Urospora penicilliformis	..	+	+	+	+	+	+	+	+
Ulothrix flacca	..	..	+	+	+	+	+	..	..
Ulothrix pseudoflacca	..	..	+	+	+	+	+	+	+
Enteromorpha flexuosa	..	..	+	..	..	..	..	..	..
Enteromorpha intestinalis	..	..	+	..	..	..	..	..	..
Pylaiella littoralis	..	..	+	..	..	..	..	..	..
Ectocarpus confervoides	..	..	+	+	+	+	+	+	+
Scytosiphon lomentarius	..	..	+	+	+	+	..	+	+
Petalonia fascia	..	..	+	+	+	+	+	+	+
Petalonia zosterifolia	..	..	+	+	+	+	+	+	+
Alaria esculenta	..	..	+	+	+	+	+	+	+
Porphyra umbilicalis	..	..	+	+	+	+	+	+	+
Codiolum gregarium	..	..	+	+	+	+	+	+	+
Enteromorpha linza	..	..	..	+	+	..	..	..	..
Enteromorpha compressa	..	..	..	+	+	+	+	+	..
Acrosiphonia arcta (= A. spinescens)	..	..	..	+	+	+	..	..	+
Giffordia hincksiae	..	..	..	+	+	+	+	..	..
Desmarestia viridis	..	..	..	+	+	+	+	+	+
Ulothrix consociata	..	..	..	..	+	+	+	..	+
Urospora wormskioldii	..	..	..	..	+	+	..	..	..
Enteromorpha prolifera	..	..	..	..	+	+	+	+	+
Monostroma grevillei	..	..	..	..	+	..	..	+	+
Laminaria hyperborea	..	..	..	..	+	+	+	+	+
Desmarestia ligulata	..	..	..	..	+	+	+	+	+
Desmarestia aculeata	..	..	..	..	+	..	..	+	+
Porphyra purpurea	..	..	..	..	+	..	..	..	..
Porphyra miniata	..	..	..	..	+	+	+	+	+
Lomentaria orcadensis	..	..	..	..	+	..	+	+	+
Antithamnion floccosum	..	..	..	..	+	+	+	+	+
Phycodrys rubens	..	..	..	..	+	+	+	+	+
Polysiphonia urceolata	..	..	..	..	+	+	+	+	+
Giffordia granulosa	..	..	..	..	..	+	..	+	+
Blue-Green Algae	..	..	..	..	..	..	+	..	+
Ulva lactuca	..	..	..	..	..	..	+	+	..
Laminaria digitata	..	..	..	..	..	..	+	+	..
Euthora cristata	..	..	..	..	..	..	+	..	+
Derbesia marina	..	..	..	..	..	..	..	+	+
Pseudendoclonium submarinum	..	..	..	..	..	..	..	+	..
Ulothrix subflaccida	..	..	..	..	..	..	..	+	..
Giffordia secunda	..	..	..	..	..	..	..	+	+
Ralfsia sp.	..	..	..	..	..	..	..	+	..
Rhodochorton purpureum	..	..	..	..	..	..	..	+	..
Delesseria sanguinea	..	..	..	..	..	..	..	+	+
Ectocarpus siliculosus	..	..	..	..	..	..	..	..	+
Giffordia ovata	..	..	..	..	..	..	..	..	+
Giffordia recurvata	..	..	..	..	..	..	..	..	+
Chorda filum	..	..	..	..	..	..	..	..	+
Chorda tomentosa	..	..	..	..	..	..	..	..	+
Plocamium cartilagineum	..	..	..	..	..	..	..	..	+
Rhodophysema elegans	..	..	..	..	..	..	..	..	+
Lomentaria clavellosa	..	..	..	..	..	..	..	..	+
Antithamnion plumula v. boreale	..	..	..	..	..	..	..	..	+
Conchocelis rosea	..	..	..	..	..	..	..	..	+

sublittoral zone. Of these, 4 species have settled in both zones. A striking fact is that the colonization in the littoral zone has not progressed markedly since the occupation by some pioneer species as early as 1966 (Fig. 16). A similar observation has been made for intertidal pioneer populations of algae on lava flows in the Hawaiian Islands (Doty, 1967). This situation may be ascribed to the harsh environmental conditions in the intertidal zone. The most important limiting

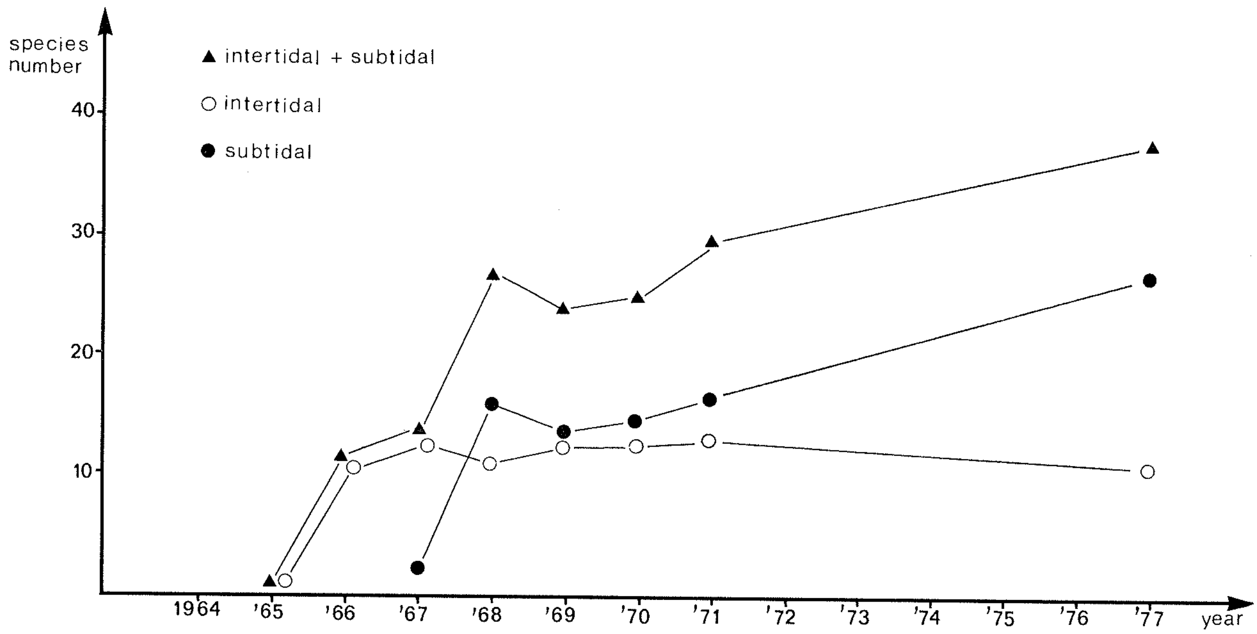


Fig. 16. The number of species of marine algae (diatoms not included) recorded from Surtsey since the beginning of the settlement; note the stationary situation in the intertidal zone contrasting with a progressive colonization in the subtidal zone.

factors are presumably the scouring action by sand and pumice, in addition to the mobility of the substrate due to wave abrasion along the lava cliffs and movement of abraded material. It may therefore be expected that the pioneer stage in the littoral zone of Surtsey will last until the stability of the substrate has been reached. As a contrast to this situation the algal colonization of the sublittoral zone has been progressing faster although starting later (Fig. 16). The difference may be attributed to a more stable environment.

As stated above, only a few subtidal species are actually of ecological importance. These are *Alaria esculenta, Laminaria hyperborea* and *Desmarestia viridis,* which were first recorded in 1966, 1967 and 1968, respectively. It is to be noted that the colonization by these species at Surtsey has not proceeded by seral stages of succession similar to those described for artificially or accidentally denuded plots in old floral areas (den Hartog, 1959, Norton and Burrows 1967). Probably, no competitive relations of species will set in as long as there are sufficient vacant places for the new colonizers and their descendants. This problem must be solved on a quantitative basis.

ACKNOWLEDGEMENTS

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ADDENDUM

Since the preparation of this paper the marine benthic diatoms collected in Surtsey during the survey in 1977 have been worked up by Marie-France Simon, Laboratoire de Biologie Végétale Marine, Paris University. The species identified are given in the following list. Many of these have been previously reported from Iceland (E. Østrup: Marine Diatoms from the coast of Iceland, Bot. Icel., *2*: 347-398, 1918). New records are printed in *italics.*

Amphipleura rutilans (Trentepohl) Cleve; littoral W.
Amphora turgida Greg.; littoral E.
Biddulphia obtusa (Kützing) Ralfs; littoral W.
Grammatophora marina (Lyngbye) Kützing: sublittoral W.
Grammatophora serpentina (Ralfs) Ehrenberg v. pusilla (Greville) Peragallo; sublittoral W.
Isthmia enervis Ehrenberg; sublittoral E.
Licmophora abbreviata Agardh; littoral E.

Licmophora communis (Heiberg) Grunow; littoral W.

Licmophora hyalina Kützing; littoral W.

Licmophora jurgensii Agardh (=L. oedipus (Kütz.) Grunow); littoral W.

Navicula gracilis Ehrenberg; littoral E.

Navicula grevillei (Agardh) Cleve; sublittoral W.

Navicula lanceolata (Agardh) Kützing; littoral E.

Navicula lanceolata v.phyllepta (Kützing) Cleve; littoral E.

Navicula ramosissima (Agardh) Cleve; littoral and sublittoral E and W.

Navicula tenuis (Agardh) A. Cleve; littoral E.

Nitzschia migrans Cleve; littoral W.

Rhabdonema adriaticum Kützing; littoral and sublittoral W.

Synedra investiens W. Smith; littoral E and W.

Synedra pulchella (Ralfs.) Kützing; littoral W and E.

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Vascular plants on Surtsey 1977–1980

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INTRODUCTION

The vascular plants of Surtsey have been investigated annually since 1965, when the first plant was observed on the island. Reports on these investigations have been published in the Surtsey Research Progress Reports. The last accounts covered the period 1971-1976 (Fridriksson, 1978). This paper deals with a study of Surtsey's flora of vascular plants during the following four year period 1977-1980.

The methods used in the study during the first two years were the same as described in previous reports. Attempts were made to count, mark and map individual plants and their location was plotted on a chart of the island. The map bore a grid with a coordinate system with quadrats of 100 square m. each, marked numerically and alphabetically. The location of plants and their mapping was done with the aid of an aerial photograph.

In the two latter years the method had to be changed when it came to the study of *Honkenya peploides* which had increased in number to the extent that counting individual plants was not feasible. Instead their frequency was measured by counts in quadrats or on transects.

A description was given of a number of individual plants regarding flowering and seed setting.

Photographs were taken to document appearance of plants and their associations.

DESCRIPTION OF POPULATION SIZE

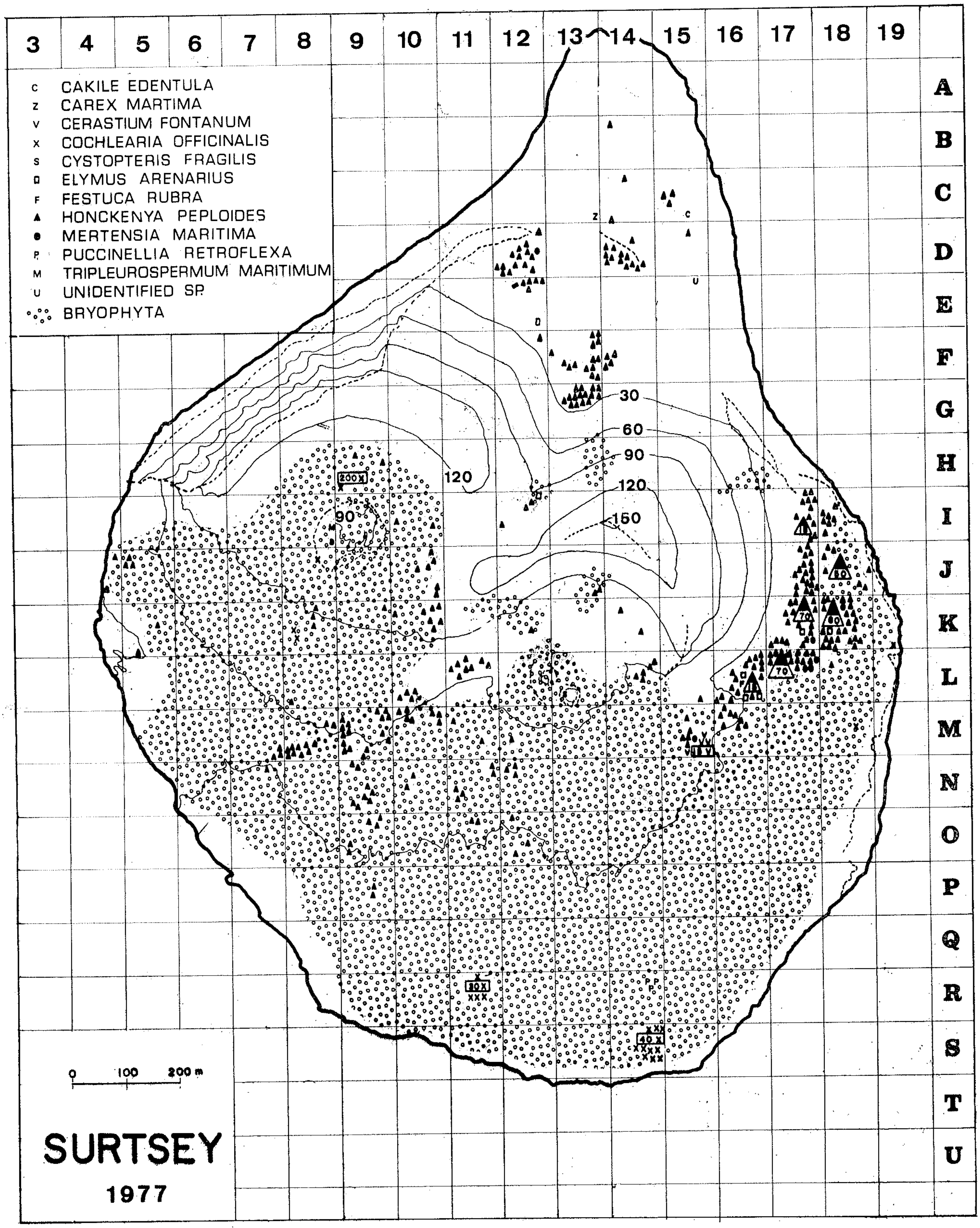
Eleven plant species were recorded on Surtsey in the summer of 1977. In addition to the 10 species which grew there in 1976, *Cakile arctica* (syn. *C. edentula* ssp. *islandica*) was once more rediscovered on the island. One plant was also found which may be of the species *Atriplex patula,* but because of its small size it was not possible to confirm the identification. If correctly identified this is the first time the species has been found on Surtsey.

Of the 1132 individuals of vascular plants which were recorded on Surtsey in the autumn of 1976, 489 were found living in the spring of 1977, 473 new plants were found in the summer of 1977, and 962 plants were registered on Surtsey in the autumn of 1977, or 170 fewer than in 1976. This decrease was primarily due to the fact that only 256 seedlings of *Cochlearia officinalis* coll. were recorded in 1977, while in 1976 there were 452 *Cochlearia officinalis* and *Cerastium fontanum* ssp. *scandicum* seedlings. Thus the number of mature *Cochlearia officinalis* and *Cerastium fontanum* plants decreased considerably since 1976. In spite of this the total number of mature plants increased from 680 in 1976 to 706 in 1977, which results from the continual spread of *Honkenya peploides.*

It is probable that a higher number of seedlings would have been found, both of *Cochlearia officinalis, Cerastium fontanum* and *Honkenya peploides* had the investigation been carried out later in the summer, but no field observations were made after August 4.

Two plant species flowered for the first time on Surtsey in 1977: *Mertensia maritima* and *Tripleurospermum maritimum.* Both species probably developed seed. Six plant species in all flowered on Surtsey in 1977. In addition to those named above, there were *Cakile artica, Cochlearia officinalis, Cerastium fontanum* and *Honkenya peploides* (Fig. 1).

Of the 962 plants that were recorded on Surtsey in the autumn of 1977, 698 plants were found living in the summer of 1978, or 72%. This was



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c CAKILE EDENTULA
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v CERASTIUM FONTANUM
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s CYSTOPTERIS FRAGILIS
ELYMUS ARENARIUS
F FESTUCA RUBRA
HONCKENYA PEPLOIDES
MERTENSIA MARITIMA
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M TRIPLEUROSPERMUM MARITIMUM
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SURTSEY
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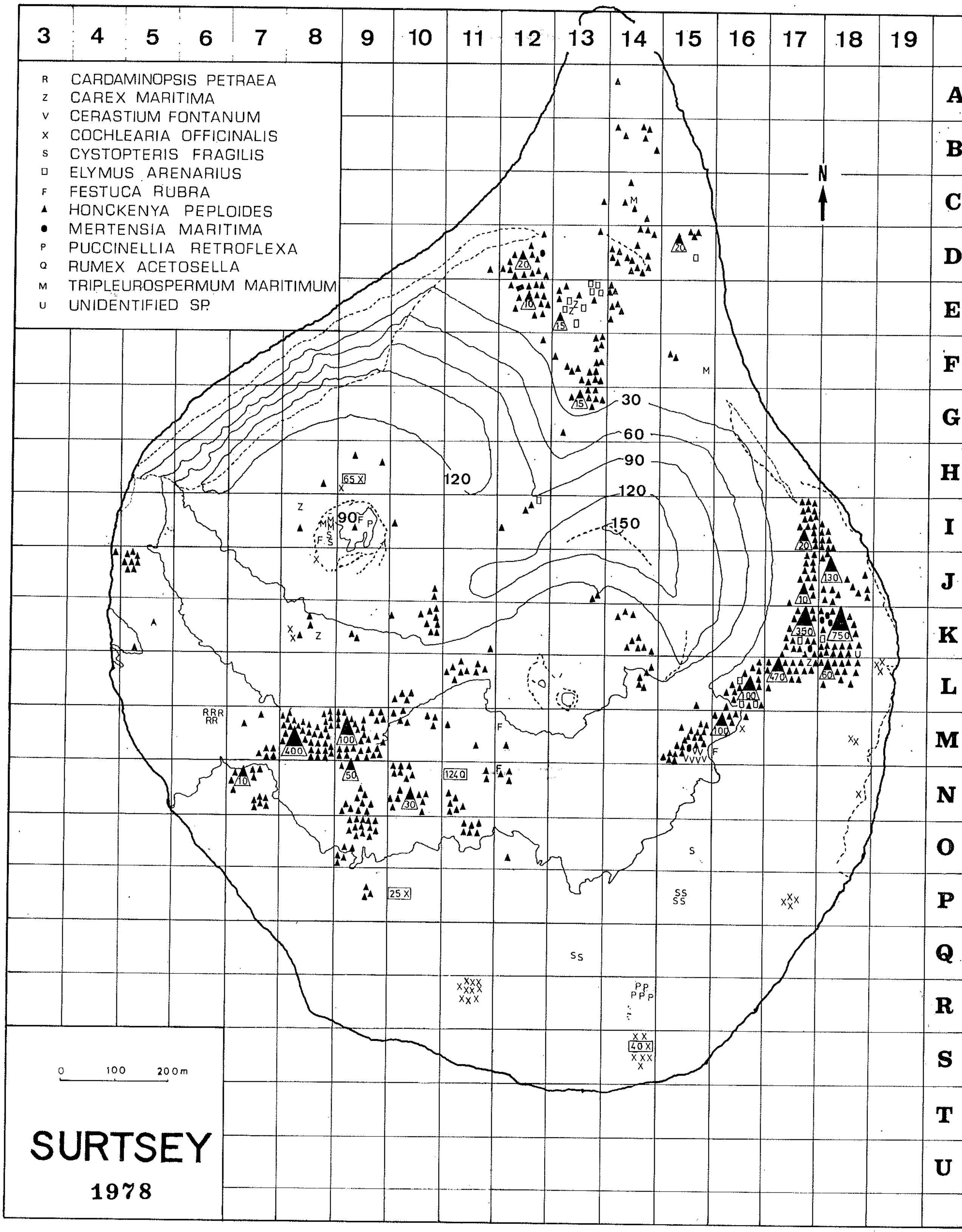
Fig. 1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S CYSTOPTERIS FRAGILIS
□ ELYMUS ARENARIUS
F FESTUCA RUBRA
▲ HONCKENYA PEPLOIDES
● MERTENSIA MARITIMA
P PUCCINELLIA RETROFLEXA
Q RUMEX ACETOSELLA
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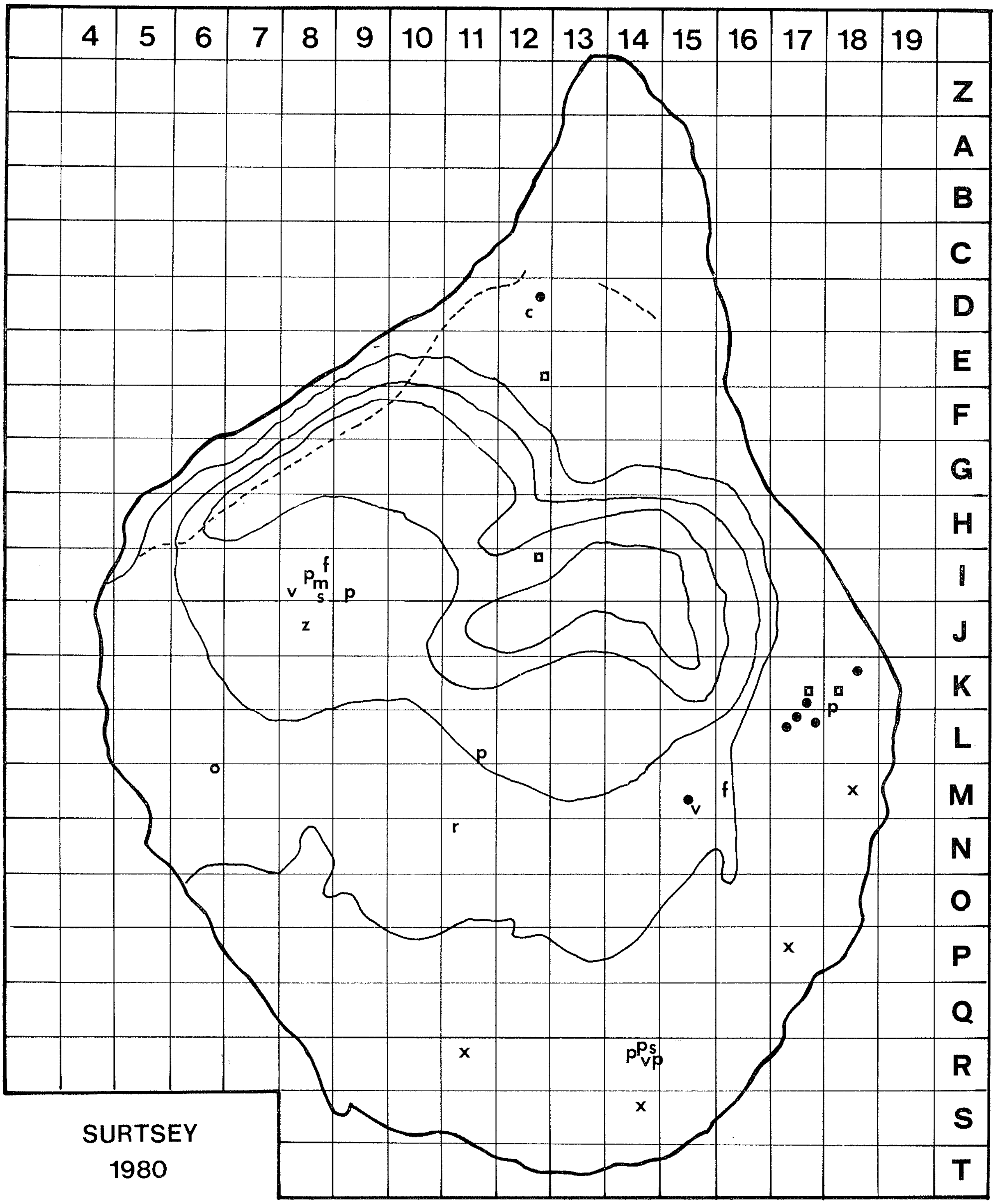
Fig. 2



DISTRIBUTION OF VASCULAR PLANTS

c	CAKILE EDENTULA	¤	ELYMUS ARENARIUS
o	CARDAMINOPSIS PETRAEA	f	FESTUCA RUBRA
z	CAREX MARITIMA	•	MERTENSIA MARITIMA
v	CERASTIUM FONTANUM	p	PUCCINELLIA RETROFLEXA
x	COCHLEARIA OFFICINALIS	r	RUMEX ACETOSELLA
s	CYSTOPTERIS FRAGILIS	m	TRIPLEUROSPERMUM MARITIMUM

Fig. 3

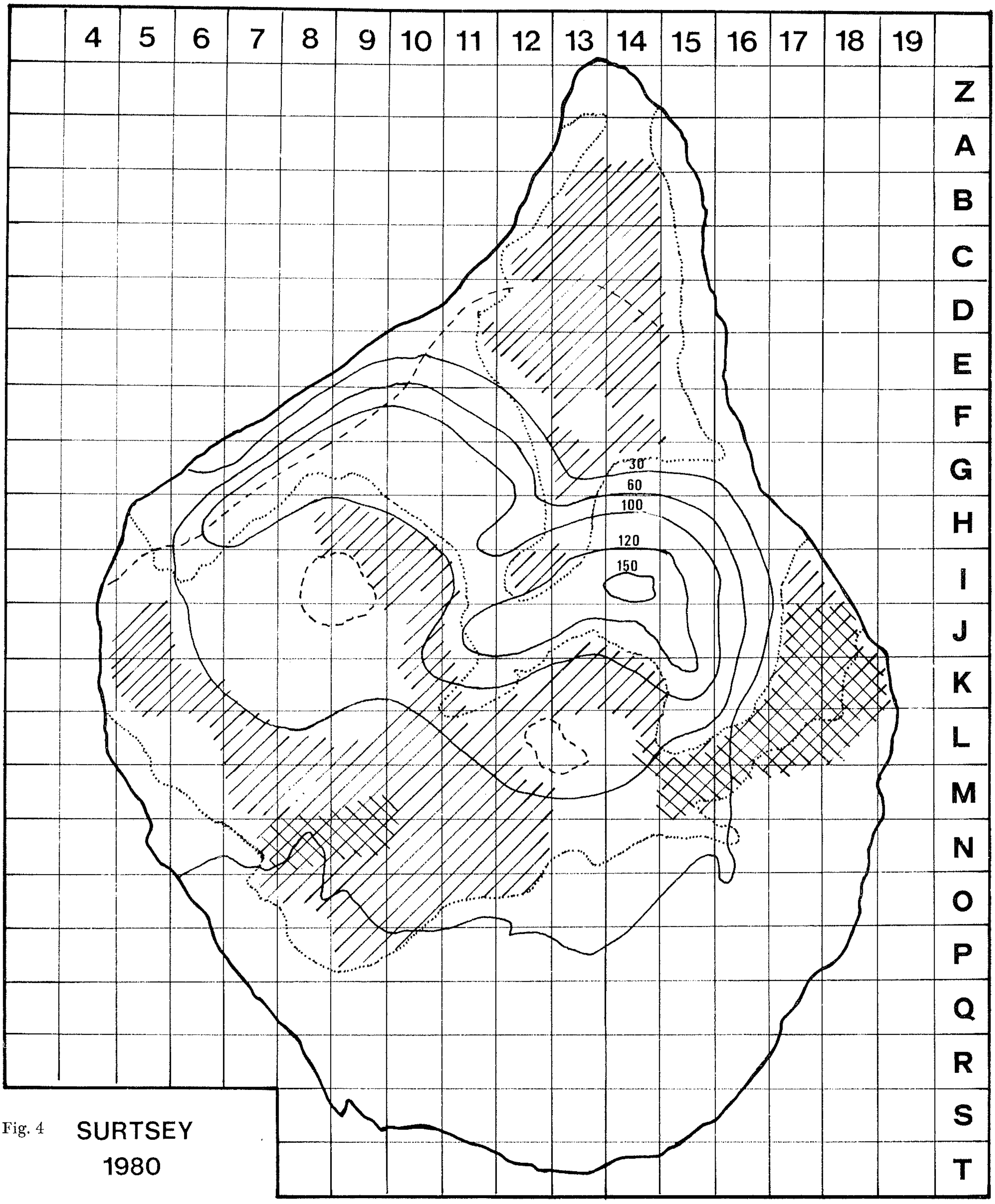


Fig. 4

DISTRIBUTION OF HONCKENYA PEPLOIDES

<100 PLANTS PER QUADRAT

100-5000 " " "

SANDY AREA

the highest percentage of plants that overwintered between years on Surtsey.

In the summer of 1978 the vascular plants began to thrive increasingly well on Surtsey. Two new species were found, *Rumex acetosella* and *Cardaminopsis petraea,* both of which have since borne seed and multiplied on the island. A few well developed individuals of *Festuca rubra* and *Carex maritima* were found, although both species have had difficulties in establishing themselves on Surtsey during the past years. Of the vascular plants on Surtsey in 1978, *Honkenya peploides* had the most marked increase with a total of 2.512 new individuals recorded. Of other species 218 new individuals were found, making the total number of new individuals 2.730 in addition to the 698 plants that overwintered. Thus, a total of 3.428 vascular plants were registered on Surtsey in the autumn of 1978 (Fig. 2). In the two following years, 1979 and 1980, there was a tremendous increase in the number of plants of *Honkenya peploides,* whereas there was no major change in the number of individuals of other species on the island (Fig. 3). The *Honkenya* plants were consequently no longer counted as individual plants, but estimated as having been 24.000 and 50.000 respectively those two years. A special chart was drawn in 1980 to show the distribution of *Honkenya peploides* (Fig. 4).

Thirteen species of vascular plants were recorded on Surtsey in the years 1978-1980: *Cakile arctica, Cardaminopsis petraea, Carex maritima, Cerastium fontanum* ssp. *scandicum, Cochlearia officinalis, Cystopteris fragilis, Elymus arenarius, Festuca rubra, Honkenya peploides, Mertensia maritima, Puccinellia retroflexa, Rumex acetosella* and *Tripleurospermum maritimum.* These will now be dealt with individually.

INDIVIDUAL SPECIES

Atriplex patula L.:

A plant was found in quadrat E-15, which is possibly of the species *Atriplex patula.* but the smallness of the plant prevented a firm identification. This plant grew together with some *Honkenya peploides* plants at the high tideline and there is no doubt that the seed from which it grew was carried to Surtsey by sea. *Atriplex patula* is a common shore plant in Iceland and grows on Heimaey.

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

One specimen of *Cakile arctica* was found on Surtsey in 1977. This plant was numbered 77-94 and was located in quadrat C-15. It consisted of one branch with 5 leaves, and bore 3 flowers on August 2, but no fruit.

In 1978 there was no specimen found of this species. However, in 1979 a new individual had occupied quadrat D-12 at the hightide line. It flowered and had set seed late in Jule. In 1980 this plant had disappeared but again another *Cakile* plant was found in the same quadrat.

Cakile arctica, being an annual, has not managed to find a firm foothold on Surtsey. It is conceivable that meager soil hinders the plant from achieving the level of development necessary to maintain the minimum seed production needed to establish itself firmly.

Most of the *Cakile arctica* plants which have been found on Surtsey have been very puny and seed production has been extremely small. Occasional plants have nevertheless come to maturity and achieved considerable seed production, but not sufficient to ensure the preservation of *Cakile arctica* on the island. The existence of *Cakile arctica* on Surtsey is almost totally dependent on seed from neighbour islands and there are distinct yearly changes in the number of plants on the island.

It would be interesting to investigate during the coming years what connection exists between seed production on Heimaey and the number of plants on Surtsey the following year. The prevailing wind following the fall of seed on Heimaey and on the southern coast of Iceland is also a deciding factor whether seed is dispersed in any quantity to Surtsey.

Cardaminopsis petraea (L) Hiit.:

In August 1978 five plants of this species were found in quadrat M-6, No. 78-136. They all grew together on a small spot. This species had not been observed on Surtsey before. The largest plant had 2 flowers and 2 fruits and was 7 cm long. The others did not flower and were from 1-4 cm in length. As with *Rumex acetosella,* it is likely that *Cardaminopsis* seed was brought to Surtsey the previous summer, and that a plant grew up and developed seed. This seed was most likely brought by a bird.

In 1979 six plants were found growing on that same spot, two of which were flowering. In 1980 the colony had increased very little.

Cardaminopsis petraea is a common plant all over Iceland and thrives well on sand flats. The conditions on Surtsey are probably favorable for this species and it is likely that it will continue to increase in number and spread and become a permanent settler on the island.

Carex maritima Gunn.:

Plant No. 70-72 in quadrat M-11, which in 1976 was disturbed and nearly destroyed by a pair of *Larus marinus* that used it for nesting material, had completely disappeared in 1977. Plant 75-10 in quadrat M-19, which vanished in August 1976, had not grown again and may be counted among the departed.

A new specimen was found on July 29 in quadrat C-13, and it was given the number 77-96. This tiny plant consisted of 1 culm with 3 small leaves. The location of this plant indicates that the seed from which it grew was carried to Surtsey by the sea. This plant was not destined to live long, for it was pulled up by *Rissa tridactyla* on August 2nd and destroyed. Thus birds destroyed all the specimens of *Carex* on Surtsey.

During the summer of 1978 four new plants were found, two of which were well developed and had 28 culms (No. 78-148 in J-8) and 23 culms (No. 78-161 in I-8). Neither, however, had developed flowers. The two remaining plants consisted of 4 and 1 culms. The locations of the larger plants indicates that they have grown from seed carried to the island by birds. The two smaller plants, No. 78-142 and 78-182, grew both by the shore indicating that the seed from which they grew was very likely brought to the island by sea.

In 1979 only two of the plants were alive, the small plant No. 78-182 in quadrat L-17 and the larger plant No. 78-148 in quadrat J-8, which had developed 35 culms and formed a tuft 50x 35 cm in area. In 1980 the species was only represented by the large plant in quadrat J-8.

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

There was a considerable decrease in the number of *Cerastium fontanum* ssp. *scandicum* plants from 1976 to 1977. In 1976, 38 mature plants were found, but the number was reduced to 19 plants in 1977. They developed on the average five shoots per plant, and during that summer thirteen plants flowered.

Of the 19 plants recorded on Surtsey in 1977, only 6 were found in 1978, five of which flowered. No new plants were found that year.

There were 27 mature plants of this species found on the island the following year. In quadrat R-14 there were 23 plants growing together on a 2x5 metre large area. All these plants were flowering, some of which had already set seed and had even produced 70 new seedlings that were growing along with the mature plants. Thus there were altogether 97 plants of this species found that year on Surtsey. In 1980 the colony had still increased in quadrat R-14. In puadrat M-15 and I-8 new plants had developed.

The species had managed to survive on the island since it was first observed in 1975. It has readily developed seed, but is not yet well established.

Cochlearia officinalis L.:

Cochlearia officinalis decreased considerably on Surtsey from 1976 to 1977. Of the 501 plants recorded in 1976, 391 were seedlings. In 1977 only 30 „large" plants were found, of which two were new, and there were 256 seedlings. The total number of *Cochlearia* plants in autumn 1977 was 286. Only three of these 30 „large" plants flowered, No. 71-71, 75-66 and 76-172, but near the last-named about 200 seedlings had developed at the beginning of August 1977. Seed had not germinated around the other two plants at that time. *Cochlearia* was found in 8 quadrats in 1977 and in 7 quadrats the previous year. A plant was now found in quadrat K-19, where there was none in 1976.

In 1978 *Cochlearia officinalis* decreased to 160 plants and only 50 seedlings were found. The „large" plants increased in number from 30 in 1977 to 110 in 1978, and were found in 6 new locations. Only five plants flowered in 1978, and it is likely that all developed seed. Seedlings were observed alongside three plants.

In 1979 there were only 91 specimens of *Cochlearia* counted on the island of which 13 had overwintered, mostly in quadrat R-11. The rest of the plants were seedlings, most of which were found in that same quadrat. In 1980 the species was still found to be occupying four quadrats in the south and southeastern parts of the lava. The majority of the *Cochlearia* plants were, as in previous years, rather undeveloped and it is obvious that conditions are not yet as favourable for the species as on the rocks of the neighbouring islands.

Cystopteris fragilis (L) Bernh.:

In 1977 one plant, No. 72-113 in I-8, survived the winter, but another plant, No. 73-599, disappeared. A new plant was found during the summer of 1977, No. 77-89, which grew in a moss tuft on a vertical lava face in quadrat L-16.

This plant consisted only of 1 frond of about 1 cm in length. Plant No. 72-113 thrived during the year. It had 5 fronds and 2-3 buds at the end of July. The longest frond was about 15 cm. It was unfertile. Plant No. 72-113 survived the following winter but plant No. 77-89 disappeared. Eight additional *Cystopteris* plants were found in 1978, making a total of nine plants recorded. Plant No. 72-113 had grown considerably and had 6 fronds and two buds on July 27. The longest frond was 20 cm in length. For the first time the plant formed spores on 5 fronds. Two of the new plants were found in a small mossy cavity where the species has been observed before, No. 73-113 in Q-13. These may be older plants and, therefore, the previous number was kept. Each plant had two fronds.

A new plant was found in a crevice in the westernmost lava crater in I-8. It had 3 fronds on July 27, the longest being 6 cm. Five tiny plants, with one frond each, were found in two mossy cavities in quadrats O-15 and P-15. In 1979 there were five plants of this species growing on the island and the same number of plants in 1980.

All *Cystopteris fragilis* plants on Surtsey grow in moss tufts, which seem to offer requisite conditions. It is possible that the plants find the necessary moisture in the moss colonies not otherwise obtained on the island.

Elymus arenarius L.:

Out of ten *Elymus arenarius* plants in 1976, eight survived the winter. No new plants were found in 1977. Plant 74-51 in quadrat K-18 was, as before, the largest *Elymus arenarius* plant on Surtsey, and it increased markedly in size over the summer but did not flower. On August 1, 1977, the plant had 24 culms with 96 leaves; the longest leaves were 50 cm. There were about 160 cm between the most distant stolons. In 1976 this plant had 6 stolons ad 28 leaves. Plant 74-55 did also well, having 14 culms and 42 leaves on August 1, 1977, with 55 cm between stolons. In 1976 it had 4 culms and 14 leaves. Plant 74-78, in L-16, has also become large; on August 1, 1977, there were 12 culms and 27 leaves, while in 1976 it had 7 culms and 21 leaves. Other *Elymus arenarius* specimens had 1-5 culms and 3-17 leaves.

Although *Elymus arenarius* plants decreased in number on Surtsey in 1977, it is clear that the conditions there are favourable. The main cause of its scarcity is probably the limit of seed dispersal or lack of germination rather than the growing conditions on the island. The plants that have achieved a certain development on Surtsey propagated only by stolons and had not flowered.

Of the eight *Elymus arenarius* plants recorded in 1977, six overwintered and eight new plants were observed, making a total of 14 plants recorded in 1978.

All the new plants were located on the northern point of the island and it is, therefore, rather certain that they were dispersed to Surtsey by sea from other islands or from the mainland.

Older plants matured although none of them flowered. The largest plant, No. 74-51, in quadrat K-18, had 65 culms at the end of July 1978 and had increased by 41 stolons in one year. There were about 2 meters between the far ends of the stolons. A pair of *Larus marinus* nested close to the plant, resulting in abundance of droppings and food-leavings. Two youngs were raised in the nest and they sought shelter in plant No. 74-51.

Other old plants developed 1-15 culms, making them considerably smaller than the two mentioned above. Of the new plants found, eight were growing quite far from the sea, in quadrat E-13.

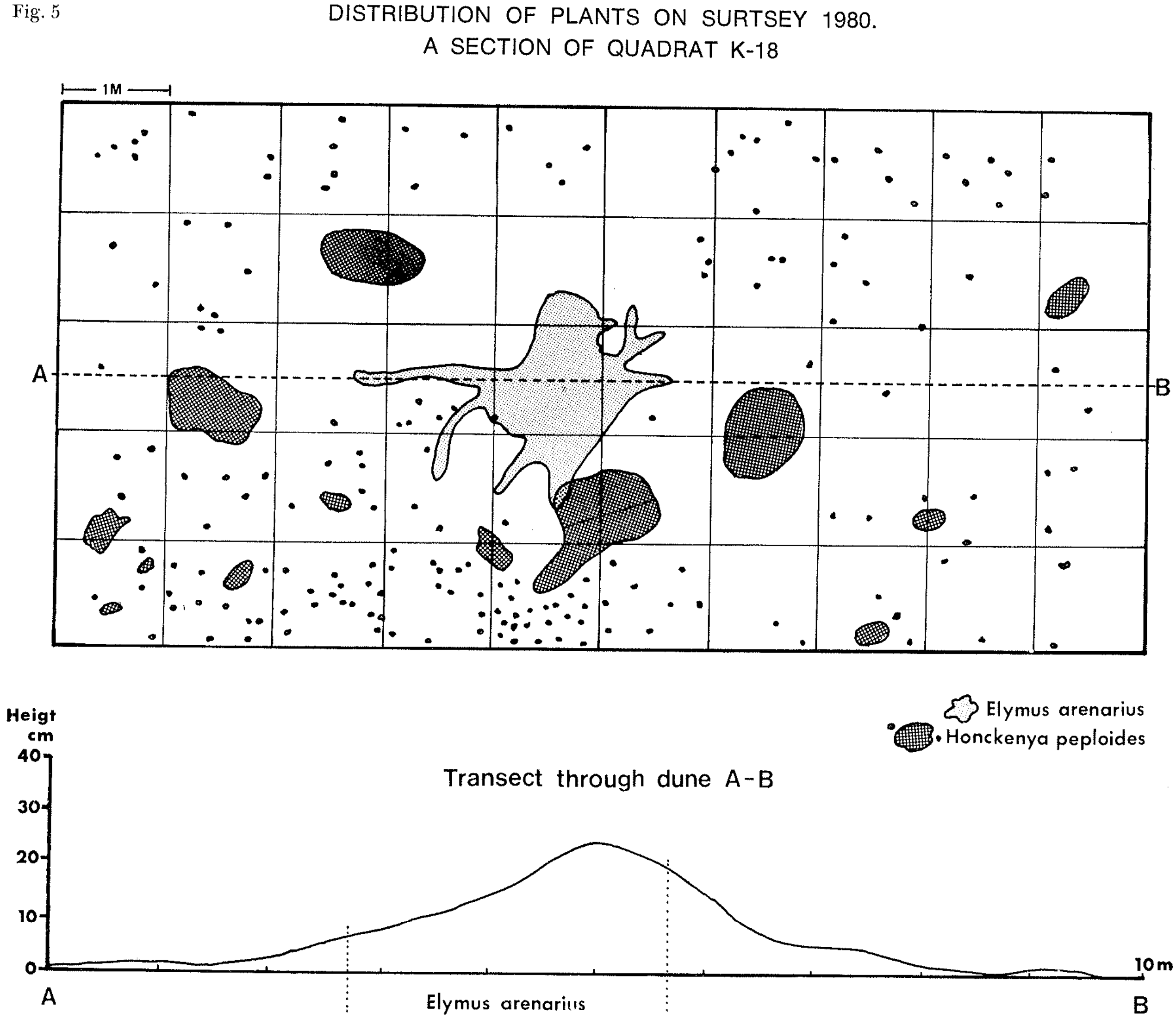
There were five plants found of the species on Surtsey in 1979 whereas all the new plants from previous years had disappeared. This year the large, well developed plant No. 74-51 in K-18 flowered, bearing eight spikes. The number of culms had increased to 121 and it now occupied an area of 155x290 cm. As in previous years a pair of *Larus marinus* frequently visited the spot and the young used the plant as a shelter. The plant consequently continued to benefit from the birds' droppings. As the plant increased in size, sand started to drift towards it forming a small dune.

Plant No. 74-51 was flowering again in 1980 with over fifty spikes and had still increased in size and more sand had been accumulated towards the developing dune. The spot was also occupied by *Honkenya peploides* plants which together with *Elymus* were forming a sand-dune association. The location of various plants in this dune association was plotted on a chart as shown in Fig. 5.

Festuca rubra L.:

The *Festuca rubra* plant in quadrat, L-12 which a pair of *Larus marinus* used as material for nestbuilding in 1976, did not appear in 1977 and was most likely wiped out. An extremely

Fig. 5



small plant of *Festuca rubra* was found in quadrat L-16 and numbered 77-90. This plant had only 1 culm with 2 leaves but it did not survive the following winter. However, in 1978 five plants were found, most of which were well developed. Two of the plants flowered, the first time this species flowered on the island. It is not known whether these plants managed to bear seed in 1978. They were given the following numbers: 78-32 in M-16, which had 45 culms and 4 panicles, and 78-18 in I-9, with 15 culms and 2 panicles. Other plants are No. 78-133 in N-12, 78-160 in M-12, and 78-176 in I-8.

It is interesting to note that so many well developed plants are observed on the island at the same time. Their locations indicate that the seed was brought to the island by birds during the fall 1977.

In 1979 three of these plants were alive. Plant No. 78-32 in quadrat M-16 flowered with 50 panicles and plant No. 78-18 in quadrat I-9 had 11 panicles. The third plant in I-8 did not flower. In 1980 all these plants were alive and flowering.

It is likely that *Festuca rubra* has firmly established itself on Surtsey where it grows on a sandy substrate, sheltered by the lava.

Honkenya peploides (L) Ehrh.:

There was little increase in the number of *Honkenya peploides* plants from 1976 to 1977. Of the 500 plants which grew on Surtsey in 1976 422 were alive in 1974, or 84%. This may be the highest percentage to have survived between years. In all 210 new plants were found in the summer of 1977 and there were thus 632 *Honkenya* plants recorded on Surtsey in the autumn of 1977.

A large number of these plants, or 166, flowered and 108 plants were recorded as bearing fruit. It is probable that this great rise in seed production led to the considerable increase of *Honkenya peploides* plants on Surtsey in the following years. The largest specimens covered over one square meter. The plants which achieved this size were Nos. 70-37 (95x110 cm), 70-39 (100x120 cm) and 71-43 (90-120 cm).

A breeding pair of *Larus marinus* used plant No. 71-69 as a nesting site and laid 3 eggs there in the spring of 1977. Three youngs broke through the eggs between June 18-20. At that time the plant was 40x50 cm in size with about 30 flowers. The nest formed approximately a 20x30 cm depression in which growth was badly disturbed (Fig. 6). The abundant droppings of the birds, however, caused a great burst of growth in the plant. By the end of July it had become the largest and most luxuriant plant mat on the island, with a little more than 100 flowers. At the end of the summer the nest basin was again overgrown with shoots. The plant had sixfolded in area from approximately 2,000 square cm (40x50 cm) to approximately 12.000 square cm (100x120 cm) in 6 weeks. Other *Honkenya peploides* plants which had been of similar size and grew under ordinary conditions by and large did not even attain twice their area by the end of July. This indicates the influence which the droppings had on the growth of plant No. 71-69. Many other *Honkenya* plants were in contrast to this injured by *Larus marinus* which bred on Surtsey. The birds tore branches from some of the plants for their nests. Traces of this could be seen on 40 plants.

Of the 632 *Honkenya peploides* plants recorded in 1977, 568 overwintered, or 89%. A very large number of new individuals were found, or 2.512, making a total of 3.080 plants recorded on Surtsey in 1978. This was a tremendous increase compared to previous years, and can only be attributed to the large seed production by the plants on Surtsey in the fall of 1977. If seed production and the increase in *Honkenya* plants on Surtsey are viewed from the beginning (Table 1) it is found that local seed production begins in 1971 when the first plant matured seed on the island; from then on the number of specimens increased gradually. In 1975 seed bearing plants were 17, in 1976 they were 36, and in 1977 108 plants were recorded maturing seed. Another increase occurs in the fall of 1978 when 190 plants were recorded with matured seed.

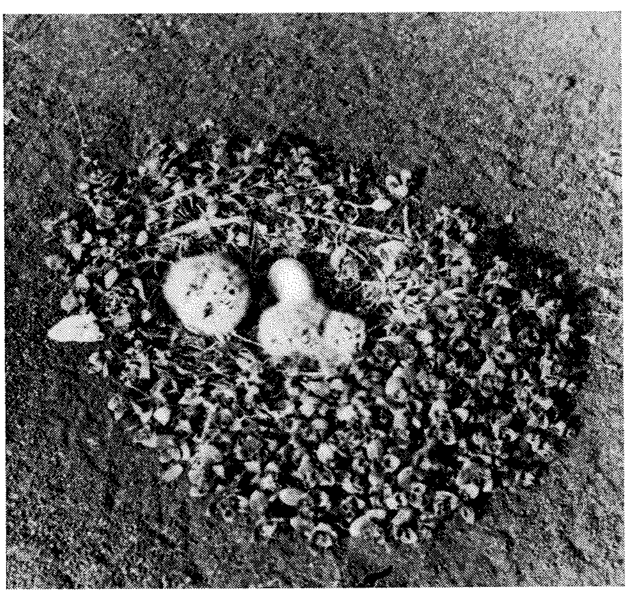


Fig. 6. A nest of *Larus marinus* in a patch of *Honkenya peploides* plant No. 71-69 in 1977.

Until 1971, when seed production started on Surtsey, the increase of *Honkenya* plants was completely dependent on dispersal of seed to the island. During the summers of 1967 to 1972 few new plants were found compared to what came later. The increase in the number of new plants recorded in 1973 and 1974 may, to some extent, be due to an extensive dispersal as an unusually large number of individuals of the species *Elymus arenarius* and *Mertensia maritima* were also recorded and neither one had begun seed production on the island.

The great increase of *Honkenya* plants on Surtsey is no longer as dependent on seed dispersal from outside as it was early in the island's existence. The species has now achieved a secure foothold on the island and its annual increase derives mainly from local seed production. Seed import to Surtsey, however, is bound to continue and although it has a much lesser effect than before on the increase of *Honkenya* plants, it plays an important role in adding to the gene pool of the plants of that species on the island.

In spite of the large increase in 1978, there was little change in the location of *Honkenya* plants. The increase occurred usually in quadrats where *Honkenya* plants grew already. In 1978 *Honkenya* plants were recorded in only 5 new quadrats.

The largest *Honkenya peploides* plant observed in 1978, No. 70-39, was in quadrat G-13 and measured in area 1.95 square m. Five other plants measured over 1 square m that same year.

The rapid increase in specimens of *Honkenya* on Surtsey continued in 1979. It then became necessary to change the methods of recording the plant's progress. It was no longer feasible to record each individual plant that survived the winter and then plot the additional plants that appeared during the summer. Instead plants were counted in quadrats representing either low or high densities of *Honkenya* stands. From that the total number of plants was estimated. The individual plants were recorded in three age groups: As seedlings, one year old plants and older plants. In 1979 the total number of plants in the low density quadrats were 350 seedlings, 575 yearlings and 131 old plants, whereas in the high density quadrats the plants numbered approximately 21.000 seedlings, 1.400 yearlings as well as 383 old plants. Thus, the total number of *Honkenya peploides* plants in 1979 were between 23.000 and 24.000 individuals.

It was noteworthy in 1979 that the distribution of the plants had increased from the year before. The drifting sand continues to be blown from the shore into the lava where it fills up the depressions and the plants follow in its wake gradually spreading into new lava territories. Near old and highly fertile plants the number of new seedlings is found to be several hundred per square meter.

In 1980 the number of *Honkenya* plants had still multiplied. This time the spread of the species was recorded and the density per quadrat measured in two magnitude classes, i.e. low density with less than 100 plants per quadrat and high density with 100-5.000 plants per quadrat. The areas occupied with *Honkenya* in 1980 were plotted on a map in these two classes as shown on the chart (Fig. 4). To facilitate the measurements of plants in the dense area, plants were counted along three fixed transects on the western side of the island, running from the shore up to the old crater, and again through the depression south of the lava crater. In these two sheltered areas there is a great abundance of *Honkenya* plants. The third transect runs up through the lava west of the crater where the plants are more scattered.

Mertensia maritima (L) S.F. Gray:

All the six plants of *Mertensia maritima* from 1976 survived the winter. In 1977 two new plants were also found. Two plants flowered in 1977. This had never occurred before. Plant No. 74-53, on quadrat K-18, bore 4 clusters of flowers with 28 blossoms in all. On August 1, 1977, about 10 seeds had dropped, which lay nearby the plant. Plant No. 75-6 flowered as well and bore 4 clusters of flowers, but birds destroyed it during the summer and it did not bear seed.

Six of these eight plants survived the winter and were observed again in 1978 along with 3 new individuals of *Mertensia*. Two new plants were found next to plant No. 74-53, proving that *Mertensia* has managed to propagate on the island, thereby making its expansion less dependent on long distance seed dispersal. In 1978

Table 1
Total number of plants on Surtsey pr. year, 1965-1980.

Year: Species:	'65	'66	'67	'68	'69	'70	'71	'72	'73	'74	'75	'76	'77	'78	'79	'80
Cakile arctica	23	1	22	..	2	..	..	1	33	3	5	..	1	..	1	1
Elymus arenarius	..	4	4	6	5	4	3	..	66	26	12	10	8	14	5	5
Honkenya peploides	..	..	24	103	52	63	52	71	548	857	428	500	632	3080	24000	50000
Mertensia maritima	..	..	1	4	..	..	..	15	25	44	11	6	8	9	8	7
Cochlearia officinalis	..	..	..	..	4	30	21	98	586	372	863	501	286	160	91	75
Stellaria media	..	..	..	..	..	4	2	2	1	..	..	..	..	..	..	..
Cystopteris fragilis	..	..	..	..	..	..	3	4	3	3	2	2	2	9	5	5
Angelica archangelica	..	..	..	..	..	..	..	2	2	..	..	..	..	..	..	..
Carex maritima	..	..	..	..	..	..	..	1	1	1	3	2	1	5	2	1
Puccinellia retroflexa	..	..	..	..	..	..	..	2	1	9	8	8	2	6	40	7
Tripleurospermum maritimum	..	..	..	..	..	..	..	1	5	2	2	2	1	4	1	1
Festuca rubra	..	..	..	..	..	..	..	..	1	1	2	1	1	5	3	3
Cerastium fontanum	..	..	..	..	..	..	..	..	..	..	106	99	19	6	97	150
Equisetum arvensis	..	..	..	..	..	..	..	..	..	..	2	..	..	..	..	..
Silene vulgaris	..	..	..	..	..	..	..	..	..	..	1	..	..	..	..	..
Sagina sp.	..	..	..	..	..	..	..	..	..	..	1	..	..	..	..	..
Juncus sp.	..	..	..	..	..	..	..	..	..	..	1	..	..	..	..	..
Atriplex patula (?)	..	..	..	..	..	..	..	..	..	..	..	..	1	..	..	..
Rumex acetosella	..	..	..	..	..	..	..	..	..	..	..	..	..	124	31	40
Cardaminopsis petraea	..	..	..	..	..	..	..	..	..	..	..	..	..	5	6	8
Unidentified plants	..	..	..	1	..	..	4	2	1	1	2	1	..	1	..	..
Total	23	5	51	114	63	101	85	199	1273	1319	1449	1132	962	3428	24000+	50000+

two plants dropped seed, no. 74-68 and 77-89.

In 1979 eight plants were rediscovered and all but one was found to bear flowers and mature seed. Again in 1980, there were seven plants flowering of this species.

Puccinellia retroflexa (Curt.) Holmb.:

Out of eight *Puccinellia* plants which were on Surtsey in 1976, only two lived through the winter. No new plant was found in 1977. The two plants were No. 74-89, which had 6 culms and 27 leaves, and No. 76-142, which had 1 culm and 4 leaves. Neither plant flowered in 1977, but both survived the winter. In 1978 four additional plants were recorded, making a total of six plants recorded in August 1978. Plant No. 74-89 had 1 panicle. Two new plants were adjacent to it, but neither flowered. A small non-flowering specimen was found by stake No. 72-90, but no plant was there in 1977.

A new plant was found in the westernmost crater in quadrat I-9. It had 14 culms and 7 panicles on August 1. This is the most well developed *Puccinellia* plant which has been observed on the island. It is likely that its propagation has been due to special conditions in the crater, which appear to be much more favourable than those of the plant's other habitat on Surtsey. In 1979, there were 40 plants growing on the island of which only four were mature and flowering. The remaining 36 were seedlings and young plants. In 1980, however, only seven large plants of this species were found growing on Surtsey.

Rumex acetosella L.:

In 1978 there were 124 plants of *Rumex acetosella* found in an area of about one square m in quadrat N-11, No. 78-128. This species had not been observed on Surtsey before. Most of the plants were very tiny, with 5-10 leaves, the red colour of the leaves indicating a lack of sufficient phosphate in the soil. Ten plants looked relatively well developed, and three of them flowered.

In 1979 the large plants had increased to 31 and were occupying an area of 1x2 m. The seedlings had not survived the winter. In 1980 the colony was still developing with about 40 plants.

It is likely that *Rumex* seed was brought to Surtsey during the summer or autumn of 1977 and that a plant grew up from it and managed to develop seed the same year. The location indicates that the seed was dispersed to the island by birds. If it was brought by sea, it must have been blown over a long distance filled with obstacles to reach its location.

The rapid increase of *Rumex acetosella* on Surtsey in its first year indicates that the species can thrive there in the future, propagate and increase its area.

In Iceland *Rumex acetosella* is common on the lowlands, especially near populated areas. It thrives best in a gravelly or sandy soil and should therefore be able to do well on Surtsey.

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

There were two plants of this species living on Surtsey in 1976. Plant No. 72-40, in quadrat S-14, had vanished in 1977, but the plant No. 76-171 which was found in the westernmost lava crater in 1976, was doing well the following year. It bore about 40 leaves and reached a diameter of about 15 cm. In July that summer it flowered and produced two heads on the same stalk. This was the first time that *Tripleurospermum maritimum* had flowered on Surtsey. Conditions in the lower part of the crater seemed to be promising for the plant where it had some moisture and a good shelter. That old plant was alive in 1978, alongside two tiny seedlings. This was the first time that the species propagated on Surtsey. The motherplant, however, did not flower in 1978 and was not doing well. A new tiny, unflowering plant was also found that summer in quadrat F-15.

In the two following years of 1979 and 1980 only the old plant in the crater survived, but bore no flowers, whereas the young plants had died.

Although *Tripleurospermum maritimum* has managed to propagate on Surtsey, its future does not look very promising. It is obvious from the present state of the plant's development that the conditions on Surtsey are not too well suited for this species and that it may have difficulties in further colonization.

UNIDENTIFIED SPECIES

In quadrat K-18 a lone plant was found. It consisted only of 2 coytledons, and could not be identified. It was assigned number 78-83.

SAND DUNE ASSOCIATION

The Surtsey ecosystem has up till now been so immature that only pioneer organisms are present. In 1978, a tendency was observed toward

Fig. 7. A plant of *Elymus arenarius* in flower, and *Honkenya peploides* in the background, together forming a sand dune vegetation.

formation of an association of two species of vascular plants, i.e. *Elymus arenarius* and *Honkenya peploides* in a certain area of the island (Fig. 7). This has developed further throughout the period. Even the *Larus marinus* fledglings have used this area for shelter, so that one would expect an increased growth due to fertilization. This may be the first place for a succession stage beyond the colonization stage to occur on Surtsey. The area was investigated, measured, and mapped (Fig. 5). These two species are also found on the mainland where they form unstable sand dunes and are succeeded by *Festuca rubra* and other grasses. Such ecosystems would be valuable for further study. The sand binding abilities of the two pioneer species are well known and *Elymus arenarius* is used in Iceland in erosion control.

There is an immense struggle for survival for the vascular plants in the island's harsh habitat, where individuals often encounter lack of foothold, nutrition, water and shelter, and have to withstand high winds, droughts, frost, salt spray, floods, sulphuric fumes and sand abrasion, as well as some competition from others. Thus only highly specialized and tolerant species succeed in colonizing the island. Some of these conditions are similar to those faced by individuals of species used in erosion control of the devastated areas on the mainland. Thus, much can be learned about rehabilitation methods from the struggle of these pioneers to survive the conditions on Surtsey.

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A survey of the subtidal fauna of Surtsey in 1974

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ABSTRACT

Investigations on the subtidal fauna of Surtsey were continued in the summer of 1974. Marine benthic invertebrates were collected with use of SCUBA-diving. The aim of these investigations is to study the progression of the colonization by marine animals, of the hard substrates which formed during and after the eruption in 1963, and to follow the development and succession of the epifauna associations.

INTRODUCTION

Investigations on the subtidal fauna of Surtsey were continued in the summer of 1974. These investigations were initiated shortly after the formation of the volcanic island in 1963 (Nicolaisen 1967 and 1968 and Sigurdsson 1968, 1970, 1972 and 1974). The purpose is to study the colonization by marine animals, of the hard substrates which formed during and after the eruption, and to follow the succession of the epifauna associations, which have developed.

This paper describes the preliminary results of the survey in 1974. So far, only species of the following animal-groups have been identified; Prosobrancia, Nudibranchia, Lamellibranchiata, Cirripedia, Isopoda, Decapoda, Asteroidea, Ophiuroidea, Ascidiacea and Pisces. Hydrozoans have partly been worked by the author, but not fully enough for publication. Much indentification work remains to be done, on Polychaeta, Amphipoda, Bryozoa, Nemertinea, Porifera and some other groups.

SAMPLING

Animals were collected by SCUBA-diving on July 11-13 1974, on the same transects and depths as in 1971. Transects I, II and III are at the west coast, V at the east coast and VIII at the south coast (see Sigurdsson 1974, Fig. I).

RESULTS AND DISSCUSSION

Table 1 shows the observed distribution of marine animals, that were collected at the coast of Surtsey in 1974, and so far have been identified. The most common species was the wrinkled rock-borer *Hiatella arctica* (L.). It was found on 15 out of 17 sampling sites, at all depths except the shallowest one. It occured both on bare rock as well as on *Laminaria* holdfasts. The crabs *Hyas coarctatus* Leach and *Galathea nexa* Embleton, the barnacle *Balanus balanus* (L.) and the common mussel *Mytilus edulis* (L.), were also common. *M. edulis* was locally abundant, especially on hard bottom between 10 and 30 m depth, where it occasionally formed dense colonies. On these colonies the star-fish *Asterias rubens* L. was frequently found. A rich epifauna was usually observed on the shells of *M. edulis,* especially the larger ones. The barnacles *B. balanus* and *Verruca stroemia* (O. Fr. Müller) were quite common, but hydroids and bryozoans were most dominating in this epifauna association. A rich epifauna was also found on kelps *(Laminaria* spp. and *Alaria* sp.), the most common being *V. stroemia,* hydroids, bryozoans and the banded chink snail *Lacuna divaricata* (Fabr.). Many animals were found hiding between the branches of *Laminaria* holdfasts e.g. the brittle-star *Ophiopholis aculeata* (O. Fr. Müller) and numerous polychaets and nemerteans.

The east-transect seems to be the richest in number of species observed. Some species seemed to be restricted to this transect, e.g. the clam *Chlamys distorta* (Da Costa), the saddle-oyster *Heteranomia squamula* (L.) and the fish *Liparis montagui* (Donovan). Some species were more abundant here than elsewhere, e.g. "dead men's fingers" (*Alcyonium digitatum* L.), the isopods *Janiropsis breviremis* Sars and *Munna kröyeri* Goodsir, the brittle-star *O. aculeata* and the sea-

TABLE 1
Distribution of marine benthic animals at the coast of Surtsey in 1974

Transects	West coast							East coast						South coast				Frequency
	I					II	III	V						VIII				
Depth (m)	5	10	15	20	30	10-18	10-17	5	10	15	20	30	40	12-15	20	30	40	
OCTACORALLIA:																		
Alcyonium digitatum L.	..	..	..	..	×	..	..	..	..	..	×	×	×	..	..	..	..	4
PROSOBRANCHIA:																		
Buccinum undatum (L.)	..	..	..	..	..	×	..	..	..	..	..	..	..	..	..	..	..	1
Lacuna divaricata (Fabr.)	×	×	..	..	..	×	×	..	×	..	×	×	..	×	..	..	..	8
Odostomia unidentata (Mont.)	..	..	..	..	..	..	..	..	..	..	..	×	..	..	..	..	..	1
Velutina velutina (Möller)	..	..	..	..	..	..	..	..	..	..	..	..	×	..	..	..	..	1
NUDIBRANCHIA:*																		
Aeolidia papilosa (L.)	..	..	..	×	×	..	..	..	..	..	..	..	..	..	..	..	..	2
Acanthodoris pilosa (Müller)	..	×	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	1
Dendronotus frondosus (Ascanius)	..	×	..	×	..	..	..	..	×	..	..	..	..	×	..	..	..	4
Doto coronata (Gmelin)	..	..	×	×	..	..	..	..	×	..	..	×	..	×	×	..	..	6
Tergipes tergipes (Forskål)	..	×	×	×	×	..	..	..	..	..	..	..	..	×	..	..	..	5
LAMELLIBRANCHIATA:																		
Chlamys distorta (Da Costa)	..	..	..	..	..	..	..	..	..	×	×	×	×	..	..	..	..	4
Heteranomia squamula (L.)	..	..	..	..	..	..	..	..	..	..	..	×	×	..	..	..	..	2
Hiatella arctica (L.)	..	×	×	×	×	×	×	..	×	×	×	×	×	×	×	×	×	15
Mytilus edulis (L.)	..	..	×	..	×	×	×	×	×	×	×	×	..	..	×	..	..	10
CIRRIPEDIA:																		
Verruca stroemia (O. Fr. Müller)	..	..	×	..	..	..	..	..	×	×	×	×	..	..	×	..	..	6
Balanus balanus (L.)	..	..	..	..	×	..	×	..	×	×	×	×	×	..	×	×	×	10
ISOPODA:																		
Janiropsis breviremis Sars	..	..	×	..	..	..	..	..	×	×	×	×	..	×	×	..	..	7
Munna kröyeri Goodsir	..	..	×	..	..	..	..	..	×	×	×	×	×	..	×	..	..	7
DECAPODA:																		
Eualus pusiolus (Krøyer)	..	×	..	×	..	..	..	..	..	..	..	×	×	..	×	×	×	7
Galathea nexa Embleton	×	×	..	..	×	×	..	..	..	..	×	×	×	×	×	×	×	11
Hyas coarctatus Leach	×	×	×	×	×	..	×	..	..	×	×	×	×	..	×	×	×	13
Pandalus montagui Leach (juvenile)	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	×	1
ASTEROIDEA:																		
Asterias rubens L.	..	..	×	×	..	..	×	..	..	..	×	×	..	..	..	..	..	5
OPHIUROIDEA:																		
Ophiopholis aculeata (O. Fr. Müller)	..	..	..	..	..	..	..	..	×	×	×	..	×	..	×	..	..	5
Ophiura sp. (juvenile)	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	×	1
ASCIDIACEA:																		
Ascidia callosa Stimpson	..	..	×	..	..	..	..	..	..	..	..	..	..	..	..	×	..	2
Styela rustica L.	..	..	..	×	..	..	..	..	×	..	..	×	×	..	..	..	..	4
PISCES:																		
Liparis montagui (Donovan)	..	..	..	..	..	..	..	×	..	..	..	..	..	..	..	..	..	1

* also a few unidentifiable speciments

squirt *Styela rustica* L. Nudibranchs are an exception to this, as they were more common on the transects at the west and south coasts.

Several species were collected in 1974, which have not been recorded from Surtsey earlier. These are the common welk *Buccinum undatum* (L.), the prosobranch *Velutina velutina* (Möller) and the brittle-star *O. aculeata.*

Identification of the 1974 material has not been completed yet. Further analyses of the data are therefore premature. Thus the results of the sampling in 1974 cannot be compared with results from earlier samplings, at this stage. Treatment of the data in order to evaluate species association, faunal similarity, community structure, progression of the colonization and successional stages, will have to wait for the time being.

The aim of the investigations at Surtsey has been to obtain information on the qualitative, as well as the quantitative aspects of colonization of subtidal substrates, but because of lack of suitable quantitative sampling methods for sublittoral fauna and flora on hard bottoms, most emphasis has been laid on the former aspect. At this stage of the investigations, a quantitative approach to the problem is highly needed, because of growing species diversity and complexity of the epifauna associations. Therefore, the aim of the marine biological research group is to fulfill this need by using a new quantiative photogrammetric method, described by Lundälv (1971).

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The Collembola of Surtsey, Iceland

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INTRODUCTION

The history of the Collembola of Surtsey is treated at length in Lindroth et al. (1973). In general , the account of this work is based on material collected up to the year 1970, but as for the Collembola, some material collected as late as 1972 is included. The account of the present paper is based partly on Lindroth et al. (1973), partly on material collected after 1972 and partly on older material not included in Lindroth et al. (1973). The material used in this paper has been collected by the present author and by Icelandic biologists working on Surtsey (Erling Ólafsson, Jón Eldon and Hálfdán Björnsson).

GENERAL CONSIDERATIONS

Table 1 gives a survey of all Collembola known from Surtsey up to the year 1978. The table shows the number of specimens found of each species from each year of collection. The species are arranged in the table so that those found at the earliest date come above those found at a later date. No collecting was done in the years 1973, 1975 and 1977. All species found on Surtsey since the publication of Lindroth et al. (1973) are treated in this paper. Reference may therefore be made to Lindroth et al. (1973) as to distribution and general ecology within Iceland.

It is seen from Table 1 that 16 species of Collembola have been found on Surtsey up to the year 1978. Of these, 9 species (56%) have been found in two of the years in question or more. The 4 uppermost species in the table have been found on by far the most numerous occasions. These species must be considered as permanent inhabitants of Surtsey (cf Lindroth et al. (1973), p. 267). As to the 5 species found during two or (in one case) three years only, this is of course

TABLE 1. The Collembola of Surtsey 1967-1978. The table shows the years of collecting and the total number of specimens collected each year. The species are arranged so that those found at the earliest date come above those found at a later date.

Year of collecting	67	68	69	70	71	72	74	76	78
No 1. *Archisotoma besselsi* Pack.	2	..	123	392	284	678	718	669	262
– 2. *Onychiurus duplopunctatus* Strenzke	..	1	..	..	..	7	5	8	1
– 3. *Isotoma maritima* Tullb.	..	15	..	18	18	44	13	28	..
– 4. *Hypogastrura assimilis* Krausb.	..	..	..	8	2	4	38	69	64
– 5. *Vertagopus arborea* L.	..	..	..	36	..	23	..	..	..
– 6. *Folsomia fimetaria* L.	..	..	..	..	..	3	1	..	..
– 7. *Proisotoma minuta* Tullb.	..	..	..	..	..	6	11	..	..
– 8. *Onychiurus armatus* Tullb.	..	..	..	..	..	6	217	9	..
– 9. *Anurida granaria* Nic.	..	..	..	..	..	1	..	..	..
– 10. *Folsomia quadrioculata* Tullb.	..	..	..	..	..	..	1	..	..
– 11. *Hypogastrura denticulata* Bagn.	..	..	..	..	..	..	2	..	..
– 12. *Friesea mirabilis* Tullb.	..	..	..	..	..	..	7	..	1
– 13. *Tullbergia krausbaueri* Börn.	..	..	..	..	..	..	..	6	..
– 14. *Isotoma notabilis* Schäff.	..	..	..	..	..	..	..	59	..
– 15. *Isotoma violacea* Tullb.	..	..	..	..	..	..	..	24	..
– 16. *Megalothorax minimus* Will.	..	..	..	..	..	..	..	37	..

more doubtful. One species (*Vertagopus arborea*) has not been found since 1972, two species not during the last two years of collection and one species not during the last year of collection. One specimen of *Friesea mirabilis* was found in 1978, whereas 7 specimens had been found in 1974, but under very special circumstances (in tuft of grass driven ashore from some other island (Ólafsson, 1978).

As to the remaining 7 species found during one year of collection only, permanent colonization is as yet extremely doubtful. Reservations must of course be made regarding imperfect collections. The collections have, however, been made in the same way and with similar intensity on each occasion. On the sandy northern part of the island, collecting has been made partly by turning stones, pieces of driftwood etc., and catching the animals observed by the naked eye or a magnifying glass with a brush dipped in alcohol, and partly by establishing traps in the form of petri-dishes three quarters filled with alcohol and buried in the sand up to the lip. Since 1972, when the mosses began developing to a certain extent in the southern lava areas, samples of the mossy vegetation have been collected, brought home and treated in Berlese-funnels.

THE DISTRIBUTION OF COLLEMBOLA WITHIN SURTSEY

Species of the shores. All the species of Table 1 down to no. 12 (*F. mirabilis*),i.e. 75% of all species, have been found on or near the shores. (*Proisotoma minuta* has as yet not been found on the shore itself but half-way between the shore and the house). Of these species, *Archisotoma besselsi, Onychiurus duplopunctatus* and *Isotoma maritima* are decidedly halobiontic, occurring almost exclusively on ocean shores. The remainder, with the exception of *V. arborea* and eventually *Hypogastrura assimilis* and *Anurida granaria,* are rather ubiquitous species, occurring in many different soil types and occasionally on ocean shores. The species *A. granaria, Folsomia quadrioculata, Hypogastrura denticulata* and *F. mirabilis* were all found in tufts of grass that were washed ashore. Of these, only *F. mirabilis* has been found again, i.e. in 1978, as a single specimen close to the shore. The case of *V. arborea* is extremely curious. The species is not found on the mainland of Iceland, but on the island of Bjarnarey. On the continent of Europe the species is most often found on the trunks of trees.

TABLE 2.
Species of the inner parts of the northern sandy plain.

Archisotoma besselsi
Onychiurus duplopunctatus
Isotoma maritima
Hypogastrura assimilis
Vertagopus arborea
Proisotoma minuta
Onychiurus armatus

Species of the inner parts of the northern sandy plain. Table 2 shows the species that have been found in the inner parts of the northern sandy plain, i.e. at least 50 metres from the shore and inwards. The innermost and highest point at which Collembola have been found in this area lies in the slope ca. 100 metres to the W of the house at a height of ca. 24 m above sea level in sub-area E3 (cf Lindroth et al. (1973), p. 149, Fig. 1). *A besselsi* has been found in many places all over the sandy plain up to the highest point mentioned above. On the sandy plain between the shore and the beginning of the slopes, it was found up to the uppermost fringes of driftwood and debris thrown up by the heaviest winter-storms at a height of ca. 5 m a.s.l. which practically includes the whole plain (Fig. 1) Above these fringes no Collembola were found. This indicates that the species can only live where sea-water has deposited salt in the ground. The chronology of advance for *Archisotoma* is as follows.. Up to 1972 only on the shore. In 1974 up to the uppermost fringes of driftwood and debris at the beginning of the hill-slopes to the SW. In 1976 up to the above-mentioned point ca. 100 metres W of the house. In 1978 no Collembola were found higher up than along the fringes of driftwood etc. along the beginnings of the hill-slopes. This retreat as compared with 1976 may be the result of the unusually dry weather in this summer (see later in this paper).

O. duplopunctatus was already found in 1972 in sub-area E3, i.e. well inside the sandy plain. In 1976 it had advanced up to the fringes of driftwood etc. at the beginnings of the hill-slopes to the SW. *I. maritima* was found up to 1974 exclusively on or close to the shore. In 1976 it was found in the fringes of driftwood etc. at the beginnings of the hill-slopes to the SW.

H. assimilis was found exclusively on the shores up to 1970. In 1972 it was found under pieces of wood and on the sand half-way between the house and the shore. In 1976 it was found only

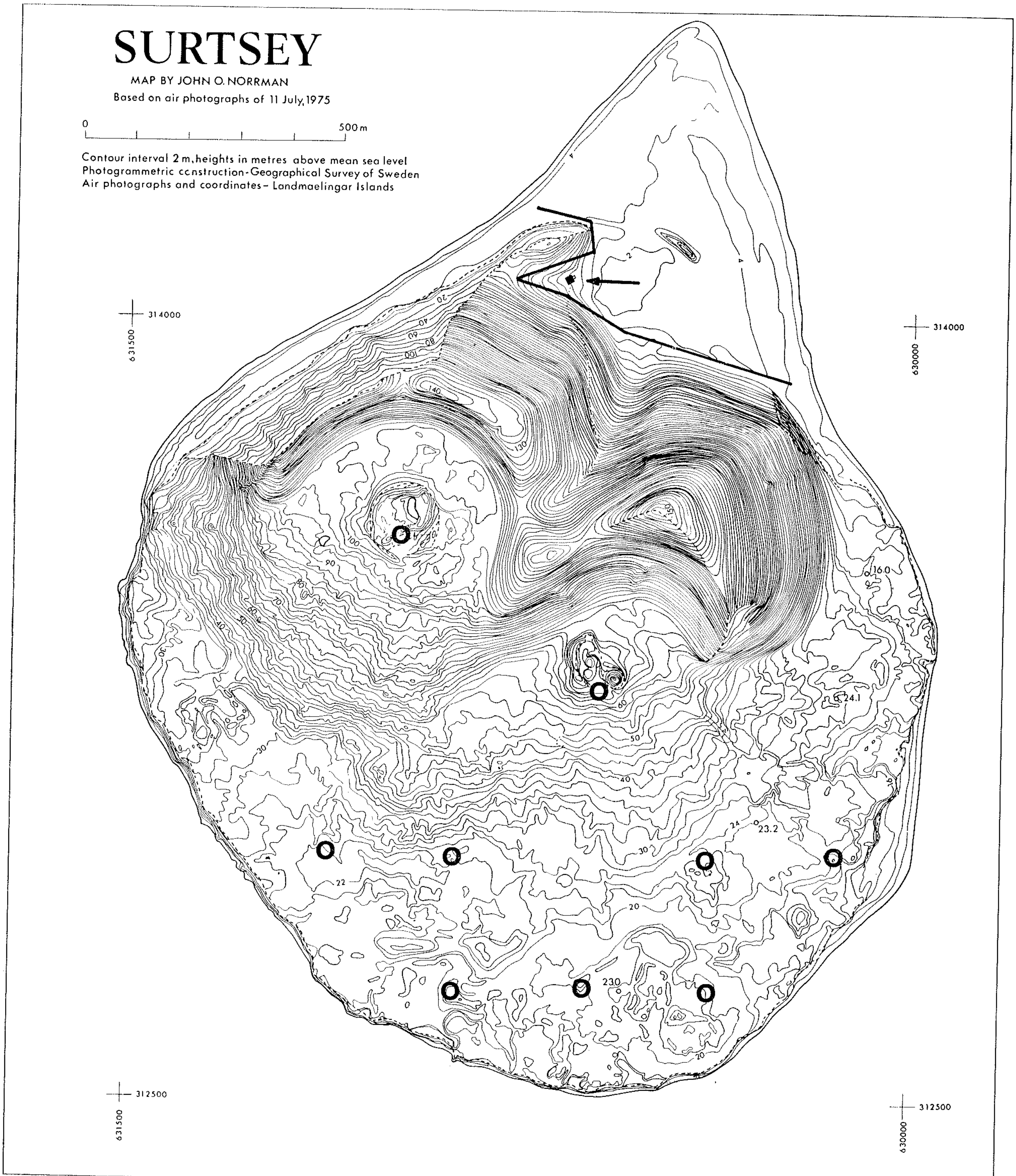

Fig. 1. Distribution of the Collembola of Surtsey. Thick line in the north: Limits of the distribution of Collembola on the northern sandy plain. Arrow: House. Black rings: Localities of Collembola of the lava mosses.

on the shore, but in 1978 it was found in the fringes of driftwood etc. at the beginning of the hill-slopes to the SW.

V. arborea was found on the shore only up to 1970, but in 1972 the species was found both on the shore and in the house. Since 1972 the species has not been found again and as stated above, its occurrence on Surtsey is extremely curious.

P. minuta was found in 1972 and 1974 halfway between the house and the shore and under pieces of wood near the house. Up to now it has never been found on the shore proper.

Onychiurus armatus was found in sub-area E3 in 1972 and in a similar place in 1974. In 1976 it was found in the fringes of driftwood etc. at the beginnings of the hill-slopes to the SW.

Species of the mossy vegetation of the southern lava fields. As stated above samples of the mossy vegetation of the lava fields have been collected since 1972 and treated in Berlese-funnels. In 1972 and 1974 these yielded no Collembola, but in 1976 4 species, 126 specimens in all, emerged from the samples (30 samples were collected each year). The species and their total numbers are seen from Table 1, nos. 13-16. All the species are very common soil animals on the mainland of Iceland and also found on Heimaey. All, with the exception of *Megalothorax minimus,* are also found on one or more of the nearby small islands. The numbers and distribution of the species is as follows (Fig. 1):

Tullbergia krausbaueri was found in 3 samples in the following sub-areas: E6 (1 ex.) in the eastern crater. D5 (1 ex.) in the western crater. D7 (4 exx.) in the lava.

Isotoma notabilis was found in 10 samples in the following sub-areas: E6 (10 exx.) in the eastern crater. D5 (6 exx.) in the western crater. C7 (16 exx.) in the lava. E8 (5 exx.) in the lava. F7 (20 exx.) in the lava. F8 (1 ex.) in the lava. G7 (1 ex.) in the lava.

Isotoma violacea was found in 3 samples in the following sub-areas: C7 (2 exx.) in the lava. D7 (21 exx.) in the lava. F8 (1 ex.) in the lava.

Megalothorax minimus was found in 5 samples in the following sub-areas: D7 (1 ex.) in the lava. D8 (7 exx.) in the lava. E6 (25 exx.) in the eastern crater. E8 (2 exx.) in the lava. F8 (2 exx.) in the lava.

In 1978 parallel collections were made and the same number of samples was taken. *No Collembola at all were found in the samples.* This result must be regarded as very remarkable since the catches of the previous collections were so rich. The only conclusion to be drawn is that an initial community of soil animals in a primitive, developing plant community as that of Surtsey is extremely vulnerable and may easily be eradicated (e.g. by extreme drought or by covering of sand or both in combination). When the members of the community are dead, there are no adjacent communities to furnish new individuals to the plant community when the circumstances become more favourable. The plant community must therefore wait for new "deliveries" of animals from outside the island (cf Lindroth et al. (1973), p. 262).

In 1978 the collecting of Collembola was made at the end of July and the beginning of August. According to the Bulletin of the Icelandic Meteorological Institute (Veðráttan 1978), precipitation in July 1978 was less than half the mean precipitation for that month in SW-Iceland. The three nearest weather-stations on the coast, for which measurements are available, show the following precipitation as per cent of normal: Vík 41; Vestmannaeyjar 64; Eyrarbakki 31. According to personal communication from people working over long periods on Surtsey in the summer 1978, the weather was occasionally so dry, that the mosses in the lava looked "burned". This seems to corroborate the theory that the Collembola of the mosses died of drought during July 1978, or some other period since 1976, probably not so long before 1978.

MODES OF DISPERSAL

The halobiontic species *A. besselsi* and *I. maritima* have often been observed in considerable numbers floating on the ocean surface along the shores. This indicates that these species may be transported from the other islands or from the mainland of Iceland floating directly on the surface. Two experiments have been made to corroborate this theory. These are accounted for on pp. 249-251 (the "Bottle-message" experiment) and on p. 260 (seawater exposure of *Archisotoma* and *Isotoma maritima*) in Lindroth et al. (1973). These experiments show clearly that halobiontic Collembola may easily drift by ocean currents over the distances in question here.

The fact that Collembola, both halobiontic and non-halobiontic, may be extracted from tussocks of grass washed ashore on Surtsey (see above) shows that this kind of transport has also occurred.

The occurrence in 1976 of considerable numbers of non-halobiontic soil Collembola in the mossy vegetation of the lava-fields in the inner parts of Surtsey strongly indicates aerial dispersal of these species. Zoochorous dispersal (with birds) and/or anthropochorous dispersal seems very unlikely for these animals.

ACKNOWLEDGEMENTS

The author is indebted to Dr. L. E. Henriksson, Uppsala, and Dr. Erling Ólafsson, Reykjavik, for valuable cooperation. The fieldwork was sponsored by the Swedish National Science Council and by the Surtsey Research Society.

ABSTRACT

Sixteen species of Collembola have been found on Surtsey up to the year 1978. Four species, *Archisotoma besselsi, Onychiurus duplopunctatus, Isotoma maritima* and *Hypogastrura assimilis* must be considered as permanent inhabitants of Surtsey in 1978. 75 per cent of all species have been found on or near the shores. Of these, *A. besselsi, O. duplopunctatus* and *I. maritima* are decidedly halobiontic. 7 species have been found in the inner parts of the northern sandy plain, the innermost and highest point, at which Collembola have been found, being ca 100 metres W of the house. Otherwise, Collembola occur over the whole plain up to the beginning of the hill-slopes to the SW. In 1976 4 species of Collembola, 126 specimens in all, were found in the mossy vegetation of the southern lava fields. These had, however, completely vanished in 1978, very probably owing to extremely dry weather during July 1978. Three modes of dispersal of Collembola have been demonstrated or can be inferred from the present studies: 1. Drifting by ocean currents (halobiontic species). 2. Transport with tussocks of grass drifting from other islands or the mainland (halobiontic and non-halobiontic species). 3. Aerial dispersal of non-halobiontic soil-living species.

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Vedráttan, 1978: Meteorological Bulletin, Reykjavik.

The status of the land-arthropod fauna on Surtsey, Iceland, in summer 1981

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INTRODUCTION

Since the volcanic island Surtsey emerged from the sea the dispersal of organisms to the island and the development of biotic communities there have been studied by a number of biologists.

Lindroth et al. (1973) gave a full report of the land-arthropod fauna on Surtsey up to 1970. This was followed by Ólafsson (1978) reporting on the situation during 1971-1976, and by Bödvarsson (1982), dealing with Collembola on Surtsey from the beginning of research on the island up to 1978.

Since 1976 the present author has not had the opportunity to visit Surtsey until in July 1981. This is a report on the status of the land- arthropod fauna on the island as distinguished during that visit, with notes on the principal changes which have occurred since 1976.

In Ólafsson (1978) some of the Hymenoptera from 1971, 1972 and 1974 were excluded as they had not been identified. They have been included in the present paper.

THE FIELD-WORK

In 1981 field-work took place on July 10-16. The weather was generally unsettled. Only on July 10 the weather was favourable for collecting flying insects, warm south-easterly gentle breeze and sunshine. The remaining days the wind was fresher, sometimes too strong for field-work, mostly rainy but sandstorms when dry. These days were used for collecting in caves and searching for life under driftwood.

Thirteen pit-fall traps, made of petri-discs with a formaldehyde solution and soap, were stationed on the northern spit and on the north-eastern part of the lava-field, 10 and 3 in each locality, respectively. Because of the generally adverse weather they were operated for 64 hours only from July 13 to 15. Moss samples were collected from the lava fields for treatment in Berlese-funnels. Most of them have been sent to Dr. H. Bödvarsson, Uppsala, for further examination.

THE MATERIAL

The material collected in 1981 consists of 1244 specimens of land-arthropods and 2 oligochaetes. Collembola dominate with 723 exx. They will be reported upon later by H. Bödvarsson thus only vaguely referred to in the present paper.

The Collembola that are mentioned, were identified by H. Bödvarsson, the Aphidina by R. Danielsson, Lund, and the Araneae by Árni Einarsson, Reykjavík. The remaining material was identified by the author.

THE SPECIES LIST

The number of specimens of each species collected in 1981 is given in brackets after each species name. Species not previously recorded from Surtsey are marked with an asterisk. All Collembola are excluded.

HEMIPTERA

Aphidina

**Acyrthosiphon auctus* Walk. (33).

LEPIDOPTERA

Fam. Yponomeutidae

Plutella maculipennis Curt. (4).

COLEOPTERA

Fam. Carabidae

Amara quenseli Schnh. (1).

Fam. Staphylinidae

Atheta atramentaria Gyll. (3).

**A. excellens* Kr. (1).

A. sp. (2 larvae).

DIPTERA

Fam. Chironomidae

Cricotopus variabilis Staeg. (8).

Orthocladiinae indet. (1).

Diamesa bertrami Edw. (1).

D. zernyi Edw./*bohemani* Gtgh. (7).

Fam. Ceratopogonidae

Gen. sp. (1).

Fam. Phoridae

Megaselia sordida Zett. (1).

Fam. Piophilidae

Piophila vulgaris Fall. (7).

Fam. Coelopidae

Coelopa frigida F. (9).

Fam. Heleomyzidae

Heleomyza borealis Boh. (81).

Fam. Ephydridae

Philygria vittipennis Zett. (4).

Fam. Sphaeroceridae

**Limosina rufilabris* Stenh. (1).

Fam. Drosophilidae

Drosophila funebris F. (1).

Fam. Carnidae

**Meoneura lamellata* Coll. (52).

Fam. Scatophagidae

Scatophaga furcata Say (1).

Chaetosa punctipes Meig. (1).

Fam. Muscidae

Musca domestica L. (2).

Hydrotaea dentipes F. (2).

Myospila meditabunda F. (1).

**Limnophora orbitalis* Stein (1).

Fam. Anthomyiidae

Fucellia fucorum Fall. (7).

Hydrophoria teate Walk. (1).

Pegohylemyia fugax Meig. (2).

Nupedia infirma Meig. (7).

Delia platura Meig. (3).

Delia sp. (*platura* Meig./*echinata* Ség.) (3 ♀).

Fam. Calliphoridae

Protophormia terraenovae R.-D. (2).

Calliphora uralensis Vill. (2).

Cynomyia mortuorum L. (1).

Indet. larva (1).

Cyclorrhapha

Indet. larvae (6).

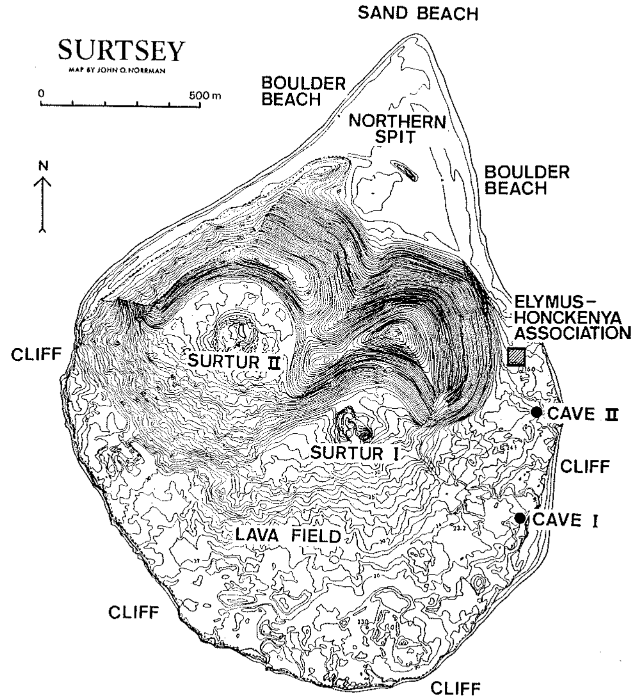

Fig. 1. Topographic map of Surtsey, based on air photographs of 11 July, 1975. Adapted from Norrman (1978).

ARANEAE

Fam. Linyphiidae

Erigone arctica White (43).

Cf. *Erigone* sp. (9 juv.).

Meioneta nigripes Simon (1).

Lephtyphantes mengei Kulcz. (2).

L. cf. *mengei* Kulcz. (3 juv.).

ACARI

Neomolgus sp. (71).

Indet. spp. (131).

OLIGOCHAETA

Fam. Enchytraeidae

Gen. sp(p.) (2).

BIOTOPES AND COMMUNITIES

In the following discussion the development of some biotopes and their faunas will be outlined. For the location of the different biotopes see Fig. 1.

It is obvious that some of the species listed above have found a suitable habitat on Surtsey and have settled permanently on the island. As shown by Bödvarsson (1982) the island may sometimes be rather inhospitable to some of the smaller organisms. For instance certain species of Collembola were quite common in 1976 but missing in 1978, presumably because of exceptionally dry weather that year. Nonetheless some other species have obviously settled on the island for good, viz. some species of collemboles (see Bödvarsson 1982) and acarids, a single aphid species, some species of Diptera, some spiders, and perhaps also one or two staphylinid beetles.

Carcasses

The first opportunities insects were offered to survive and multiply on the island were probably connected with carcasses drifted ashore and birds dying on the island. A certain amount of competition for carcasses is likely to occur between gulls and the saprophagous insects. In 1981 a number of carcasses were found that had been covered by tephra, thus inaccessible to gulls. These were inhabited by *Heleomyza borealis* larvae, a species that proved to be very common on the island in 1981.

The shores

The shores of Surtsey offer three main kinds of conditions, all of them being rather inhospitable.

The tip of the island's northern spit is formed of a very unstable sandy beach, constantly moving depending on the wind direction and force. In a few hours only the sand spit may totally alter the form. This of course means that a firm fauna has difficulty in establishing itself on this beach. Yet the collembole species *Archisotoma besselsi* Pack. is usually to be found there. No doubt this halobiontic species is simply moved along with the sand, as it is often observed floating on the surface of the sea. Many other species of Collembola have been found on the shore (see Bödvarsson 1982), but *A. besselsi* seems to be the only one never missing, being found under drifted seaweed and other drifted objects, as well as unprotected on the open sand. One life macropterous specimen of the carabid beetle *Amara quenseli* was found under a small piece of wood on this beach.

The extreme tip excluded, the shores of the northern spit are built up by boulders of varying size. These boulders are frequently moved by heavy surf so most algal vegetation is excluded from this beach, which thus looks quite sterile. Only one land-arthropod species was found here, viz. the predatory mite *Neomolgus* sp., which was surprisingly common. A predator must have a prey. These may have been collemboles that were not detected, although cannibalism may also occur.

The third shore type is found under the high cliffs on the east, south and west side of the island. These shores are much more stable, compared with the northern spit, but are nonetheless drastically altered during winter storms. During the summer drastic changes only take place when the surf is exceptionally heavy. These semipermanent rocks manage to get covered by green algae during the summer time. As on the boulder beach the mite *Neomolgus* sp. was common on these coasts. The salt water rockpools were not studied this time, but they are known to provide niche for the chironomid *Cricotopus variabilis* and the collemboles *Archisotoma besselsi* and *Isotoma maritima* Tullb. (Lindroth et al. 1973; Ólafsson 1978).

The inner parts of the northern spit

This area can be described as a sandy plain with boulders buried to greater or lesser extent in the sand. Occasionally the sea flows over this plain, especially in winter, forming a line of driftwood and variety of debris below the slopes. Scattered plants of *Honkenya peploides* (L.) Ehrh. grow in this area, some of them infested by the aphid *Acyrthosiphon auctus*. On the humid underside of the driftwood fungi grow. This habitat developed early in the history of Surtsey and soon attracted several species of collemboles and acarids, even spiders and enchytraeids. This habitat and its fauna has scarcely changed the last years. Bödvarsson (1982) gives further information on this area.

The lava-field

In the lava the vegetation has made great progress compared with the situation in 1976 (see Fridriksson 1978). The moss cover is increasing steadily, especially in the Surtur II crater and in the lava flow from Surtur I. In some areas, for instance the Surtur I crater, where mosses were well developed in previous years, by 1981 the vegetation had been mostly covered by tephra and thus destroyed. As outlined by Bödvarsson (1982) the moss was inhabited by a variety of soil animals in 1976. This fauna appears to have been destroyed by the drought of summer 1978. In 1981 a poor soil fauna had been reestablished. Moss samples were collected for treatment in Berlese-funnels. They were all sent to H. Bödvarsson for study and are not dealt with further in this paper except details of a few samples retained by the author. Acarids were found in all of them and two species of Collembola in one of the samples, viz. *Onychiurus duplopunctatus* Strenzke and *Sminthurides malmgreni* Tullb., the latter species new to Surtsey.

Most land-arthropods seemed to be confined to well sheltered damp places like collapsed caves. Only acarids were found in the more exposed places. A certain collapsed cave on the south-east part of the island was studied thoroughly (cave I, Fig. 1). The moss flora is well developed in this cave. *Onychiurus duplopunctatus* (4 exx.) and *Sminthurides malmgreni* (13 exx.) were extracted from a moss sample collected there and two juvenile spiders (cf. *Erigone* sp.) as well. Six additional specimens of spiders were collected here, *Erigone arctica* (ad. ♀), cf. *Erigone* sp. (1 juv.), *Lepthyphantes mengei* (ad. ♀ with egg cocoon) and *L.* cf. *mengei* (3 juv.). In another cave (cave II, Fig. 1), which had only a small opening in the ceiling four spiders were collected on a big stone below the opening. *Erigone arctica* (ad. ♂), cf. *Erigone* sp. (2 juv.) and *Meioneta nigripes* (ad. ♂). Some acarids were found there as well. In 1976 2 specimens of *E. arctica* were collected on exactly the same spot (Ólafsson 1978). The silky threads of spiders were commonly observed on the lava.

The north-eastern part of the lava-field has been partly covered by tephra. In that area a simple plant community has developed, composed of a few plant species. The most important species is *Honkenya peploides,* which has been the most prominent species on Surtsey since early in the history of the island (Fridriksson 1970, 1978). In last years the species has increased explosively, represented by thousands of individuals in 1981, distributed all over the island.

A subsection of this area was studied specifically. There were two well developed *Elymus arenarius* L. tufts, covering about 2 m² each, a few plants of *Mertensia maritima* (L.) S.F. Gray and *Cochlearia officinalis* L., also undeveloped grasses, probably *Festuca rubra* L., growing among the *Honkenya* plants.

Obviously only few species of arthropods feed solely on this vegetation. The aphid *Acyrthosiphon auctus* turned out to be abundant on some of the *Honkenya* plants, both winged and apterous individuals. In the larger *Honkenya* tufts, some of which may cover 1 m² or more, branches were rottening and covered by fungi. There the collembole *Hypogastrura denticulata* Bagn. was found to be common.

Bird nests

A pair of Great Black-backed Gulls *Larus marinus* L. nested on the island for the first time in 1974. Ever since a few pairs have nested there annually. The gulls were suspected to have negative influence on the development of plant succession by tearing up plants for use as nest material. It has now become obvious, that the gulls have proved to be very important components in the simple life community now established on Surtsey. In 1981 five pairs of Great Black-backed Gulls were found to have produced young on the island. Also a pair of Herring/Glaucous Gull hybrids *Larus argentatus* Pont. / *hyperboreus* Gunn. (cf. Ingólfsson 1970). Their nest was located in a small collapsed cave. A single young was found nearby. The nest was built primarily of *Racomitrium* moss. Nest materials were collected and treated in Berlese-funnels, but only a single acarid was found.

One of the nests of the Black-backed Gulls was located on one of the *Elymus* tufts. The other nests were not found as the young had left well before this field-work took place. The nest materials consisted of branches and leaves of *Elymus* and *Honkenya.* The nest was mostly covered by tephra under which the nest materials were decaying. Here Diptera larvae abounded. The majority of them belonged to the species *Heleomyza borealis,* a single larva of the family Calliphoridae was also found and larvae of two or three other unidentified species. Two staphylinid species were also found in the nest, *Atheta atramentaria* (3 exx.) and *A. excellens* (1 ex.), the latter being new to the island. Two *Atheta* sp. larvae were extracted from nest materials treated in Berlese-funnels, also the collembole *Hypogastrura denticulata* (9 exx.) and acarids (12 exx.).

Obviously the importance of the gulls was not just confined to the nest. The gulls or their young seek shelter in the *Elymus* tufts leaving droppings and food remains behind, enriching the soil. Of course this benefits the plants, also giving saprophagous and coprophagous Diptera species like *Piophila vulgaris* and *Meoneura lamellata* excellent opportunities. The latter, which was known to be rare in Iceland, (Andersson 1967; Lindroth et al. 1973) proved to be surprisingly common in these droppings. The species had not been observed on Surtsey before. Of course a community needs predators for its completion. The spider *Erigone arctica* was found to be common in that community, 41 ad. were collected and 3 juv. cf. *Erigone* sp., also a single *Lepthyphantes mengei* (ad. ♀).

To summarize, a simple but apparently self-sufficient ecosystem has now been established on Surtsey, composed of a few species of vascular plants, fungi, various invertebrates with different demands, birds, and no doubt different micro-organisms, (which are beyond the scope of this study). This ecosystem is of course simple and probably unstable, but it is obviously the beginning of a more complicated ecosystem to be developed in the future.

NOTES ON OLDER HYMENOPTERA MATERIAL

When preparing my previous publication on the land-arthropods of Surtsey (Ólafsson 1978) some specimens of Hymenoptera had not been identified. These specimens have now been studied by specialists in the field. The 6 specimens in question belong to 5 species:

Fam. Braconidae

Meteorus rubens Nees *(leviventris* Wesm.) 11. VIII.1971, 2 exx., leg. E. Ólafsson (det. T. Huddleston).

Fam. Ichneumonidae

**Pimpla instigator* F. 1.VII.1971, 1 ex., leg. E. Ólafsson (det. G. J. Kerrich).

**Promenthes pulchellus* Hlgr. 22.VIII.1972, 1 ex., leg. J. Eldon (det. G. J. Kerrich).

Meloboris collector Thunb. 3.VIII.1974, 1 ex., leg. E. Ólafsson (det. R. Hinz).

**Diadegma boreale* Horstm. 10.VIII.1972, 1 ex., leg. J. Eldon. HOLOTYPUS (see Horstmann 1980).

Of these 5 species 3 are new to Surtsey, 2 are new to the Icelandic fauna, viz. *P. instigator* and *D. boreale,* and the last mentioned turned out to be new to science, described by Horstmann (1980).

ACKNOWLEDGEMENTS

First of all I thank Prof. J. Norrman who invited me to participate in this Surtsey expedition, and paying all expences. Him and Mr. M. Norrman and Mr. L.-E. Henriksson I thank for their company and help on Surtsey. Also sincere thanks to all those who assisted with the identification of the material, Högni Bödvarsson, Árni Einarsson, R. Danielsson, R. Hinz, K. Horstmann, T. Huddleston and G. J. Kerrich. Aevar Petersen gave valuable comments on the manuscript.

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Report on the sampling of the benthic fauna of Surtsey 1977 and 1980

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In the years 1977 and 1980 the bentic fauna at Surtsey was sampled by SCUBA-divers. Both years the sampling was carried out from the research vessel Árni Friðriksson.

In 1977 the three main traverses off the E-, S- and W-coasts of Surtsey were worked at 5 to 40, 9 to 20 and 10 to 30 meters respectively. Many underwater photographs were taken. Further sampling was prevented by bad weather.

Most of the 1977 samples have been worked up.

In 1980 the same three main traverses were worked. Due to surf at the S-coast the divers could not work in shallower water than 15 m. Some extra stations were taken at the W- and SW-coast.

Besides the sampling of benthos a quantitative underwater photogrammetric method, described by Lundälv (1971), was used.

The 1980 samples of benthos are being analysed.

The littoral zone of Surtsey is still so unstable that the invertebrates have not been able to colonize it. In 1977 and 1980 the only animals found living there were 0-group barnacles, *Balanus balanoides* (L.) Bruguière. As yet the barnacles have been unable to survive the violent changes in the tidal zone caused by the enormous oceanic waves in the wintertime.

ACKNOWLEDGEMENTS

This research has been a part of the Surtsey Research Society's program and has been sponsored by The Icelandic Science Foundation, The Marine Research Institute, Reykjavík and The Surtsey Research Society. This is highly appreciated.

Thanks are also due to all those who have assisted in carrying out the research program.

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GEOLOGY AND GEOPHYSICS

The Surtsey Research Drilling Project of 1979

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INTRODUCTION

The scientific value of a Surtsey drilling program was first conceived shortly after the eruption ceased (Proceed. Surtsey Res. Conf., Reykjavík, June 1967, p. 73), because of the exceptional opportunity to study the development of a historic, well-studied, oceanic volcano from its inception on the seafloor, through the formation of a volcanic island, to the modification of the volcanic edifice by hydrothermal processes.

However, mainly because of problems concerning funding, the project was not realized before 1979. In January 1979, a drilling proposal was approved as a cooperative scientific effort by the Geothermal Research Program of the U.S. Geological Survey and the Icelandic Museum of Natural History.

The purpose of the drilling was mainly to provide constraints on 1) the nature of basaltic submarine volcanic activity from vents in the depth range from about 130 m to sealevel, and the composition of rocks erupted during the course of the submarine eruption; and 2) hydrothermal processes, including the nature of palagonitization of the basaltic hyaloclastites and formation of secondary minerals, and, 3) the thermal history both above and below sea level as indicated by thermal logging and character of alteration.

The drilling was performed by the Icelandic State Drilling Contractors from June 29 to August 22, 1979, during 34 days of active drilling. Frequent storms made the drilling conditions arduous with high winds, producing sand storms, and heavy seas causing frequent disruption of the seawater intake pipe and difficulties in landing men and equipment on the beach in a rubber dinghy. However, on the whole the drilling operation was successful and core recovery was excellent. The scientific party, consisting of Sveinn P. Jakobsson, James G. Moore, Ólafur Ingólfsson and Bjarni Kristinsson, monitored drilling progress, logged core, and made detailed studies of surface geology. The drilling costs, excluding post-drilling science, amounted to $119,000, of which 24 percent were transport costs. This was about 8 percent above the projected expenditure.

THE GEOLOGY OF SURTSEY

Eruption history

The eruption history of Surtsey and the two adjacent temporary islands is well known through the work of Thorarinsson et al. (1964) and Thorarinsson (1965, 1968), and has been outlined previously along with preliminary drilling results (Jakobsson & Moore 1980). However, since the history of the Surtsey eruption is of vital importance in understanding the drilling results, the main events are listed below, and further summarized in Table I.

The visible eruption started with phreatic explosions from a 300-400 m long fissure trending 035° on November 14, 1963. Presumably the eruption broke through the sea floor a few days before it became visible. The most recent pre-eruption soundings in the Surtsey area were made in 1901 by the Royal Danish Hydrographic Office (Copenhagen 1931), and the closest measure-

TABLE I
History of the Surtsey eruptions.

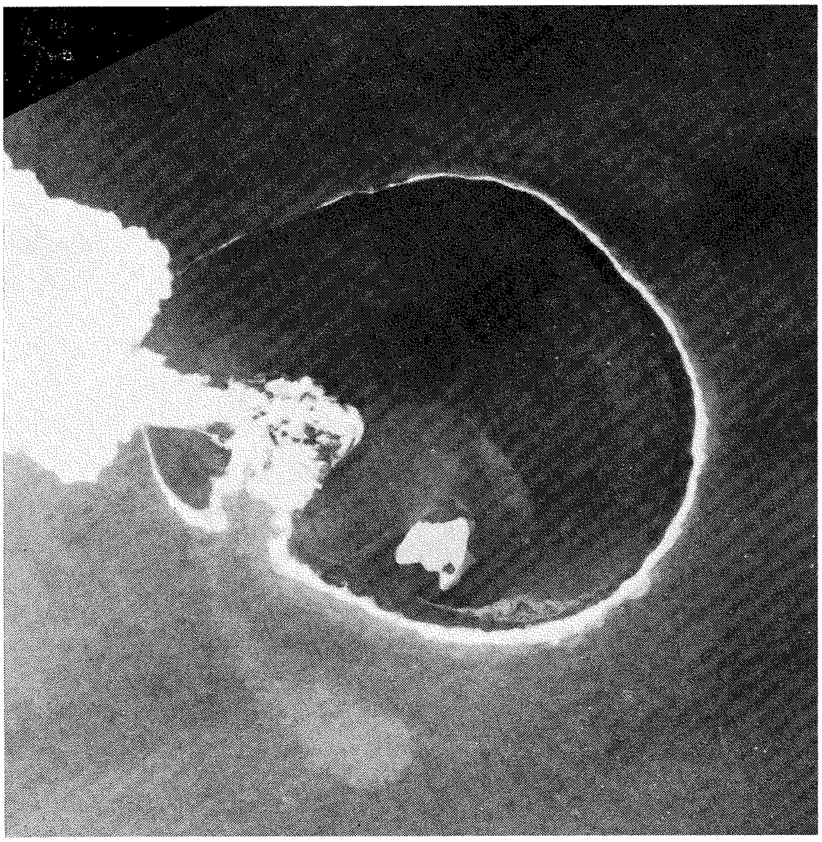
Year	Mo	Date	
1963	Nov.	8—12	Approximate beginning of eruption on sea floor?
	Nov.	14	First visible explosive activity broke sea surface in vicinity of eastern vent.
	Nov.	15	First appearance of island of Surtsey.
	Dec.	28	Submarine activity (Surtla) became visible 2.5 km eastnortheast of Surtsey.
1964	Jan.	6	Submarine activity (Surtla) ceased 2.5 km eastnortheast of Surtsey after building a submarine ridge more than 100 m high.
	Jan.	31	Activity ceased at eastern Surtsey vent.
	Feb.	1	Explosive (phreatic) activity began at site of western Surtsey vent.
	Mar.	19- Apr. 1	Surtsey northern lagoon formed.
	Apr.	4	Surtsey western vent ceased explosive activity and began effusive phase.
	Apr.	29	Effusion of lava ceases from western Surtsey vent.
	May-July		Probably some lava extruded (submarine) on the seafloor southwest of Surtsey.
	July	9	Effusion (visible) of lava resumes from western Surtsey vent.
1965	May	11?	Submarine activity at site of Syrtlingur may have begun.
	May	17	Effusion of lava ceases from western Surtsey vent.
	May	22	Explosive activity begins visibly at site of Syrtlingur 0.6 km eastnortheast of Surtsey.
	Oct.	17	Explosive activity of Syrtlingur has ceased.
	Oct.	24	Syrtlingur completly washed away.
	Oct.	end?	Submarine eruptive activity probably began on ridge 1 km southwest of Surtsey (site of later-appearing Jólnir).
	Dec.	26	Visible explosive activity southwest of Surtsey.
	Dec.	28	First appearance of the island of Jólnir.
1966	May	late	Fault-bounded lagoon appears on north side of Jólnir.
	Aug.	10	Phreatic activity of Jólnir ceases.
	Aug.	19	Effusive activity started from Surtsey eastern vent.
	Oct.	31	Jólnir completely washed away.
	Dec.	12-17	Vent on inner northwest wall of eastern tephra cone erupted small lava flow.
1967	Jan.	1-4	Vent on outer north slope of eastern tephra cone erupted lava which flowed into north lagoon.
	Jan.	1-8	Vent on inner north wall on eastern tephra cone erupted lava which flowed south past drillhole site.
	Jan.	2	Vent on outer northeast slope of eastern tephra cone erupted tiny lava flow.
	Jan.	2-7	Two curved faults formed on inner east wall of eastern tephra cone and the lower one erupted small lava flow.
	June	5	Effusive activity ceased at Surtsey eastern vent.

ments to the drill site show a water depth of 128 m 1.5 km east. From the general bathymetric configuration we estimate preeruption water depth at the drill hole site to be 130 ± 5 m. The island was born on Nov. 15, and grew rapidly in size. On January 31, 1964, the eruption ceased in the eastern vent (Surtur I) which had been active until then, but broke out the following day in a northeast trending fissure on the northwest side of the crater (Fig. 1A). On April 4, 1964, the eruption in the western crater (Surtur II) changed over to an effusive phase, as the island was then obviously large enough to isolate the vent from the inflow of seawater. Between December 28, 1963, and January 6, 1964, submarine activity was visible about 2.0 km eastnortheast of Surtsey. A submarine ridge, called Surtla, was built up to more than 100 m in height but did not reach the sea surface.

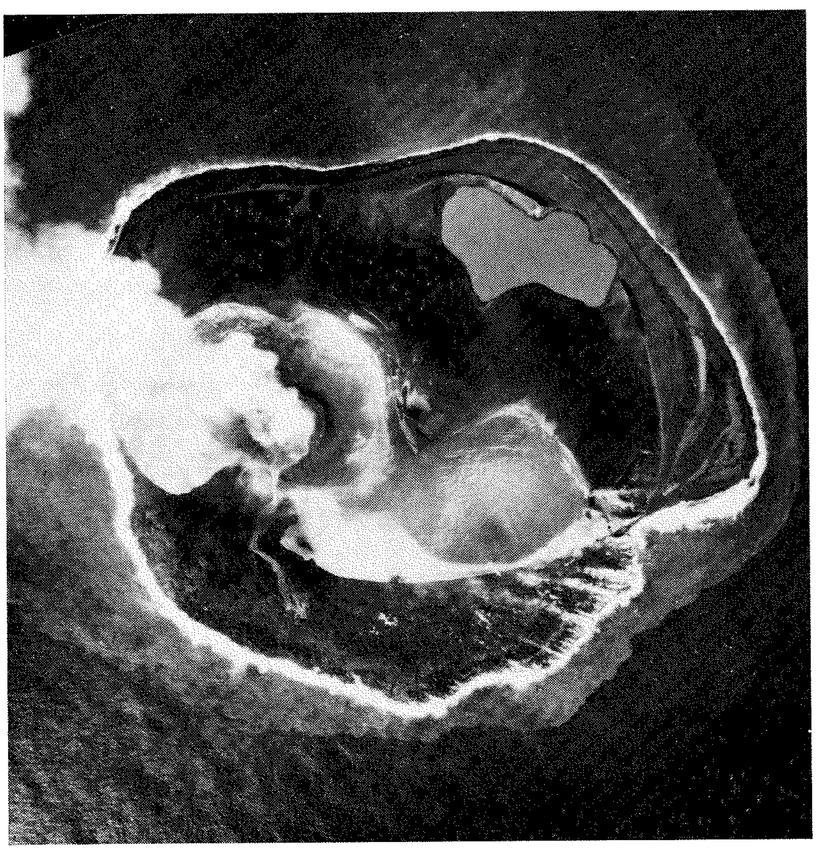
Effusive Hawaiian-type activity continued in the western crater (Fig. 1B and Fig. 2) until May 17, 1965 and gradually built up a flat lava plain towards the south, while foreset-bedded (flow-foot) breccia formed at the front below sea level at the same time.

Explosive activity appeared on May 22, 1965, at a site about 600 m eastnortheast of Surtsey. A small island, Syrtlingur, was formed and reached a height of 70 m. This island was washed away by wave action a few days after the eruption ceased about October 17, 1965. Another island, Jólnir, was created by submarine activity some 800 m southwest of Surtsey on December 26, 1965. Eruptions continued until August 10, 1966, and the island disappeared in late October of that year.

On Surtsey, new eruptions started on August 19, 1966, when a ca. 220 m long fissure opened up on the floor of the eastern crater (Surtur I), which had been inactive since the end of January 1964. From this fissure (Fig. 1C), lava flowed incessantly during late 1966 and early 1967, and was last seen to flow on June 5, 1967. Between December 12-17, 1966, another fissure



A



B

Fig. 1. Air photographs of Surtsey, taken by the Icelandic Geodetic Survey. In all photographs north is toward the top. A) February 17, 1964; phreatic eruptions issue from the western tephra crater; the eastern crater which ceased activity on January 31, is partly filled with lake. B) April 11, 1964; activity in the western crater became effusive on April 4, and lava flows

C

Scale

0 400 m

D

enlarged the island southward; the eastern crater has been covered with a blanket of tephra from the western crater. C) October 2, 1966; effusive activity from vents within the eastern tephra crater. D) July 20, 1979, 12 years after eruptions ceased. The location of the drill site is indicated with a black arrow. Published with the permission of the Icelandic Geodetic Survey.

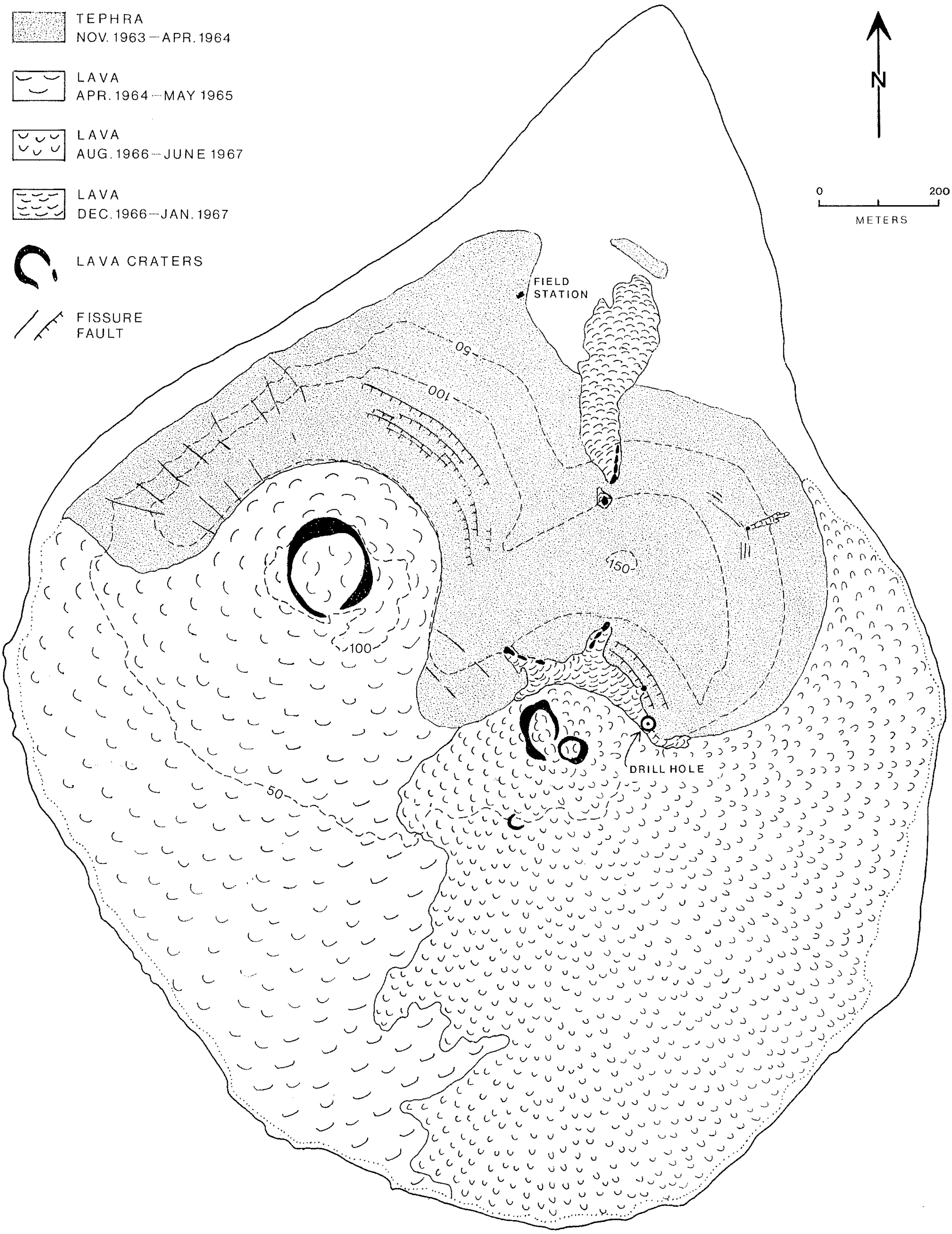


Fig. 2. Geologic map of Surtsey, based on topography of 1975 by Norrman (1978). The extensive western vent lava flows of April 1964 – May 1965 and east vent lava flows of August 1966 – June 1967 are shown by pattern. The small flows of December 1966 – January 1967 within and on the flanks of the east vent are shown separately. Known fissures and faults (teeth on downthrown side) are indicated. Elevation contours in meters are shown by dashed lines.

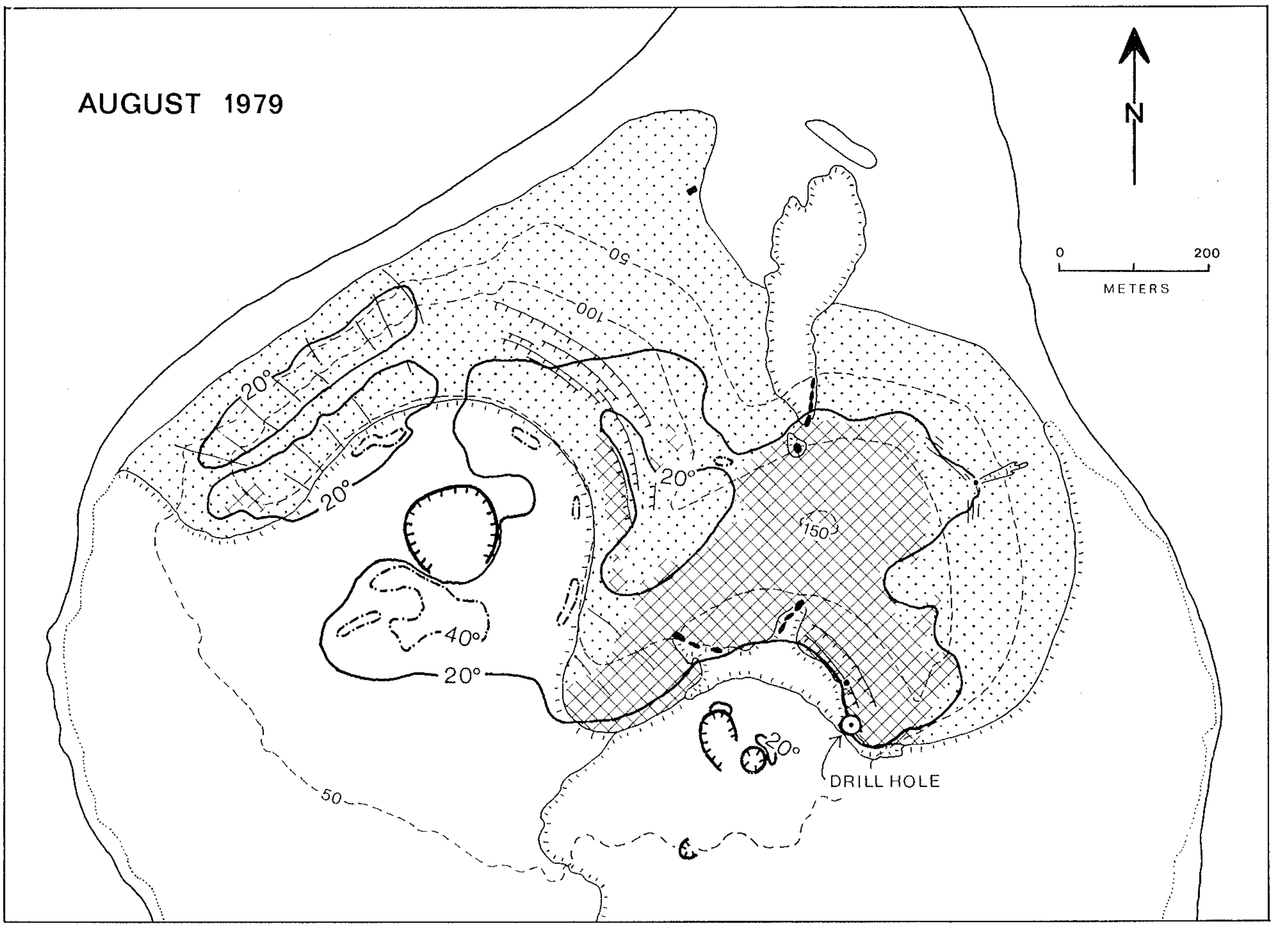


Fig. 3. Map of the central part of Surtsey; compare with Figs. 2 and 1D. The area of primary tephra is dotted. The hydrothermal area is indicated by the 20°C and 40°C isotherms (as measured at a depth of 20 cm), of August, 1979. Surface exposures of palagonitized tephra are cross-hatched.

was active in the western inside wall of the eastern tephra crater producing a small lava flow, and between January 1-8 1967 lava broke through the eastern tephra ring at four additional sites (Fig. 2 and Table I). The southernmost eruption site (now covered by sand drift) is situated only 60 m from the drill site.

At the end of the eruptions in 1967 Surtsey had reached a size of 2.8 km^2, and the total amount of material erupted was estimated to be 1.1-1.2 km^3, about 60-70 percent of which was tephra.

Drill site events.

Probably by November 16, 1963 and definitely by November 22 (Thorarinsson et. al. 1964, Fig. 6), the area of the drill site location was above sea level. As far as the record goes, the drill site area has been above sea level since that time.

Examination of unpublished photographs, mainly those of Sigurdur Thorarinsson, reveal that the part of the eastern tephra ring where the drill site is located, was largely built up during November 1963, and was fully developed late in December 1963. However, during the phreatic activity in the western tephra crater between February 1 — April 3, 1964, a blanket of tephra (about 10-15 m thick) was desposited on the eastern crater. Eolian erosion (Ingólfsson 1982) later removed a substantial part of this blanket from the drill site area.

Eyewitness and photographic evidence indicates that no major disturbances of the tephra layers occurred at the drill hole site. However, the drill site may have subsided about 4 m from 1964 to the time of drilling in 1979 (Moore 1982).

The tephra: Mode of emplacement and composition

The tephra above sea level was deposited as bedded air fall tephra and base surge flows, cf. Thorarinsson et al. 1964, Figs. 5,7 and 11, and Moore 1967. Two types of phreatic explosive activity dominated, intermittent „cocks-tail" explosions and continuous uprush of tephra (Thorarinsson 1965). Information from the recent drill hole (Fig. 7) indicates that subaerially deposited tephra extends at least to a depth of 14 m below

A

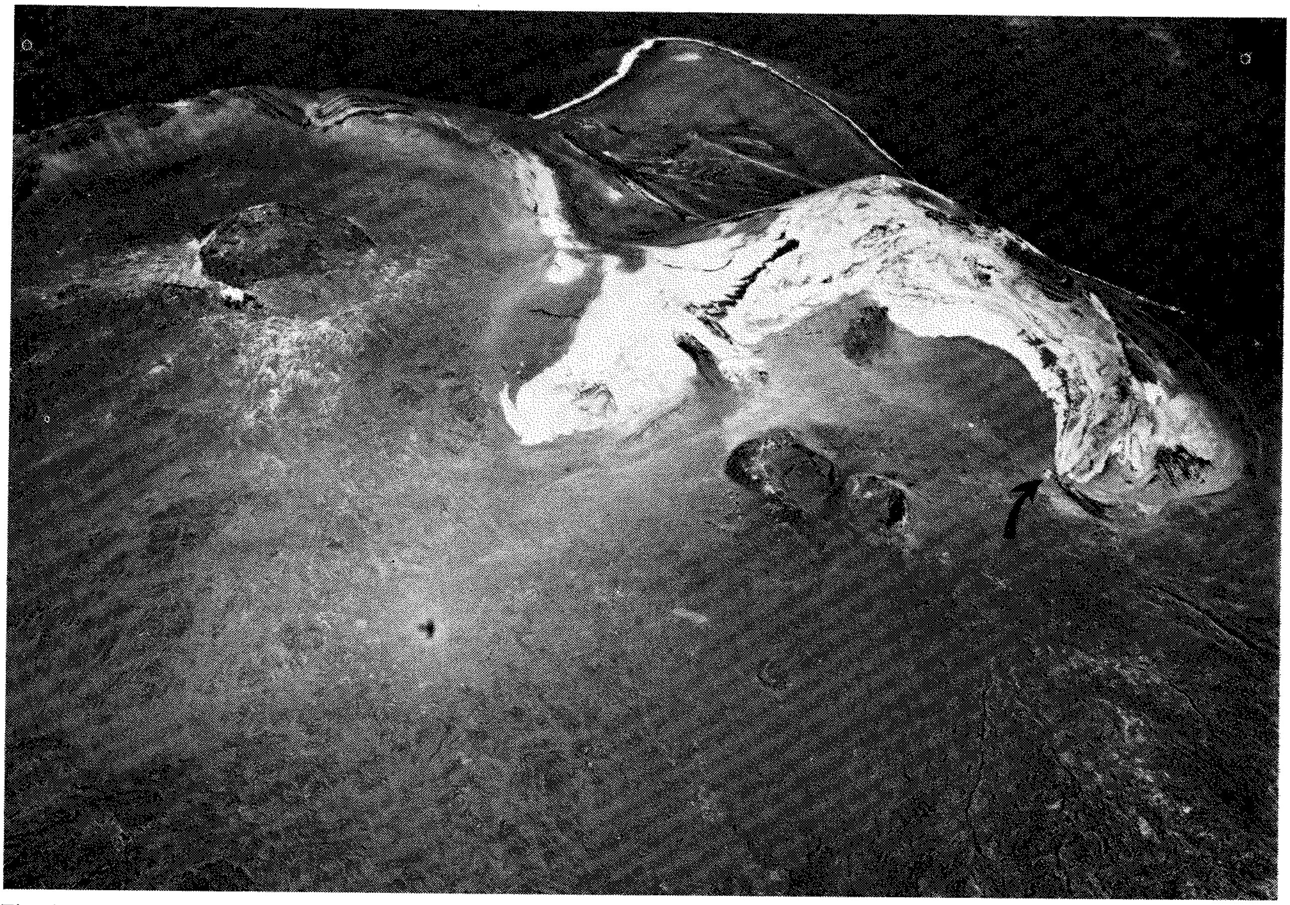


Fig. 4. Oblique air photographs of Surtsey, taken on July 20, 1979, by the Icelandic Geodetic Survey. A) Central part of Surtsey, looking NNE; The drill site is indicated with a black arrow at the SE rim of the eastern tuff ring. Light areas are consolidated palagonitized tuff.

sea level and possibly deeper, indicating a considerable subsidence. Whether deeper layers are formed by submarine or subaerial activity is difficult to determine.

The original unaltered tephra is generally poorly sorted with some 60-70 percent in the coarse ash (0.06-2 mm) fraction. Exceptions are the reworked sedimentary layers (p. 92), and the sand/tephra below ~176.5 m depth (Fig. 7). Surtsey is *locus typicus* of „surtseyan" tephra and the reader is referred to Walker & Croasdale (1972) for descriptions of pyroclast shape and size sorting.

About 80-90 percent of the alkali olivine basalt tephra is made up of fracture-bounded clasts of basaltic glass (sideromelane n: 1.605± 0.002). The remainder is composed of phenocrysts and glassy basalt fragments of varying crystallinity. The phenocrysts are Cr-spinel (picotite), olivine (Fo 84-86) and plagioclase of two generations, a large (An 63-65), and a small (An 70-75). Melting experiments at one atmosphere pressure (dry conditions), made on the first Surtsey lava of April 1964 (Tilley et al. 1967), showed that olivine crystallized at 1220°C, plagioclase at 1180°C and clinopyroxene at 1155°C. Since clinopyroxene is not observed in the Surtsey tephra, the magma was apparently quenched during contact with seawater at 1155°-1180° C. This temperature range is in harmony with measurements in March 1965, when temperatures of 1151° and 1162° C were obtained from molten lava in the lava crater (Sigurgeirsson 1966). About 15-20 percent of the glass is tachylite, i.e. opaque black glass, with chemical composition and density similar to that of the sideromelane. The chief difference is that the tachylite is strongly magnetic.

Hydrothermal and palagonitized areas.

Since the formation of Surtsey the area of primary tephra has been inspected frequently (Jakobsson 1972, 1978). In 1969 the first signs of palagonitization of the basaltic glass were observed. The process was clearly related to the formation of a hydrothermal anomaly established after the period of effusive and intrusive activity in the eastern crater during August 1966 – June 1967, and probably mainly due to intrusive activity in December 1966 – January 1967

B

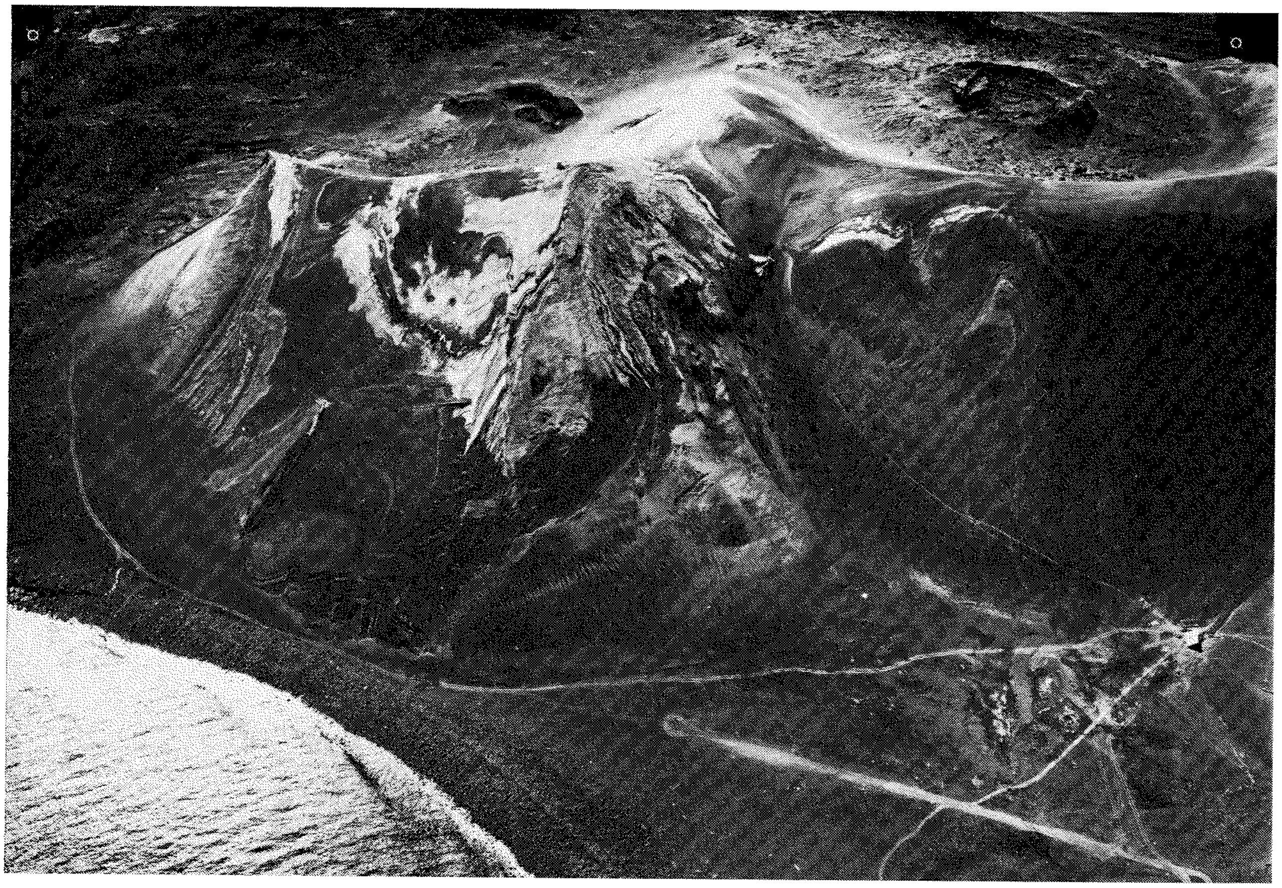


Fig. 4. B) Northern part of Surtsey, looking SW; trails radiate from Pálsbaer, the field station at lower right. The air strip at bottom is 280 m long. Published with the permission of the Icelandic Geodetic Survey.

(Table I, Fig. 2). Heat transfer in the tephra has been inferred to occur by upward convection of steam produced by vaporization of ground water of both marine and meteoric origin, the heat source being feeder dikes and shallow intrusions related to the 1966-67 effusive activity (Jakobsson 1978). This is confirmed by the recent study of Axelsson et al. (1982) who conclude that the heat content of the Surtsey tuff can originate from intrusions, and that the heat transfer in Surtsey is dominated by hydrothermal convection, both above and below sea level.

The extent of the hydrothermal area as measured at a depth of 20 cm in August 1979, is shown in Fig. 3. The size and near-surface temperature of the hydrothermal area in 1976 (Jakobsson 1978, Fig. 8) and 1979 (Fig. 3) is similar, and small changes, especially in the western crater, probably result largely from erosion. The highest temperature measured within the tephra pile in August 1979 was 100° C. The highest temperature measured in the lava at the surface was 153° C, just south of the western lava crater, where the lava pile is approximately 100 m thick.

In August 1979, the surface exposures of palagonitized tuff (Fig. 3), were somewhat larger than in 1976, due mainly to wind erosion, as the thin cover of unconsolidated tephra is continuously blown off the underlying palagonitized tuff. The volume of palagonitized tephra is much larger than would appear from surface exposures and is estimated to include 70-80 percent of the tephra pile above sea level.

THE DRILLING OPERATION

The drill hole is located at an elevation of 58.39 ± 0.15 m above sea level, just inside the eastern tephra crater, approximately 100 m southeast of the fissure vent active between November 1963 – February 1964 (Figs. 2-4). In order to achieve the main objectives of the project, the drilling was sited within the hydrothermal area, and outside the main lava field. Proximity to the lava craters of August 1966 – January 1967, was avoided because of the possibility of transecting extensive subvertical feeder dikes. Moreover the site had to be accessible by tractor, and reasonably close in elevation and distance to the sea, since seawater was the only feasible drilling fluid, and had to be pumped to the site through plastic pipe.

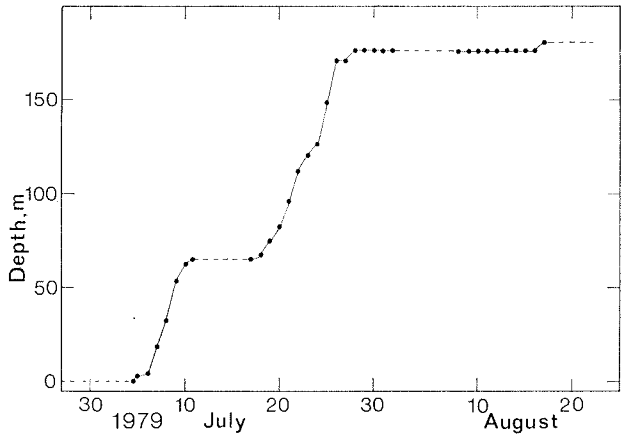


Fig. 5. The progress of drilling as indicated by daily hole depth in 1979. Unconsolidated tephra (sand?) at a depth of 171 m caused repeated drilling problems because of both loss of water circulation and hole collapse. Dashed lines indicate no drilling during preparation and completion periods, and drilling recesses.

On June 29, 1979, the Icelandic Coast Guard ship *Ódinn* transported about 39 tons of drilling equipment, food and fresh water, besides the drilling crew and scientists, to Surtsey. An Icelandic Coast Guard helicopter ferried all equipment lighter than 0.4 ton from the ship to the island in about 80 round trips. A larger U.S. Air Force helicopter, from the U.S. military base at Keflavík, carried the heavier equipment including the drill rig, drill pumps, drilling shelter and tractor, in 6 round trips.

The 3-man drill crew from the Icelandic State Drilling Contractors was headed by Sigurdur Sveinsson; other members were Jón Stefánsson, Helgi Ársaelsson and Eiríkur Stígsson. Gudmundur Sigurdsson managed the drilling operation from Reykjavík. The crew and the scientists stayed in Pálsbaer, the field station which was built in 1966 (Fig. 4B). After five days of preparations, drilling started on June 5, 1979. The drill rig was of the type Craelius — 2 (P-1000), which allowed raising the core barrel by wire-line without pulling the drill rods. Core diameter is 4.7 cm.

Drilling was comparatively easy down to a depth of 138 m (Fig. 5), with a core recovery of 97.9 percent. Below 138 m core recovery was variable because of the occurrence of unconsolidated layers of tephra or sand (Fig. 7). On July 26, at a depth of 171 m, drilling became very difficult after drilling through 13 m of loose tephra where repeated grouting with cement proved unsuccessful. During this period the pumping of seawater used as the drilling fluid was frequently disrupted by damage to the seawater intake pipe and the seashore pump during heavy storms and high surf. On July 29 the NCQ drilling rod (outside diameter 6.99 cm) became stuck at a depth of 176.5 m. Drilling was continued with BQ rods inside the NCQ rod. At a depth of 180.6 m when the BQ rod (outside diameter 5.56 cm) became stuck (but was subsequently freed), the decision was made to stop drilling. Between July 28 and August 18 (when drilling was discontinued), only 10 additional meters had been acquired.

Core recovery below 138 m depth was 33 percent; only drill cuttings were obtained between 140.0 — 143.8, 148.5 — 150.6, 157.5 — 168.7 and 170.5 — 180.1 m depths; and no samples were obtained between 138.1 — 140.0, 171.0 — 171.4, 172.6 — 174.9 and 180.1 — 180.8 m depths (Fig. 7). Total core recovery from the drill hole was 148.4 m, or 82.0 percent of the hole depth.

Precise leveling and water-level measurements in a dug pit on the north side of Surtsey (Moore 1982) show that the elevation of the drill hole collar (top of the outer casing, Fig. 6) is at 58.3± 0.15 m above mean sea level. The drill hole collar was capped and sealed in September 1980, to protect it from corrosion. The present reference point is the top of the NCQ casing, at 58.9±0.2 m above mean sea level. An exact measurement of the height difference between the two reference points was lost with other data when the transport boat „Bravó" was lost in the surf of Surtsey, September 12, 1980.

DRILL HOLE LOG

The complete core log is compared in Fig. 7 with information on dip of primary layering and slumping planes, wet specific gravity and temperature profiles. Furthermore, Oddsson (1982, Table I) has measured the dry density, the specific density and the total porosity, of 22 samples from the core. The reference level is the top of the outer casing 1979 reference of Fig. 6, at 58.39 ±0.15 m above sea level.

Lithology.

0 — 1.0 m

Wind-blown (eolian) sand; with sand dunes at the surface, composed of grains in the coarse and very coarse sand range (cf. Ingólfsson 1982). The sand has been deposited and reworked since December 1966; its source is the unconsolidated tephra of the two tephra cones. Irregular layering resulting from size sorting is conspicuous in this layer: the sand grains are composed of the same constituents as the tephra/tuff as described below.

Slight palagonitization of sideromelane sand grains is evident and increases downwards.

1.0 – 2.7 m

Alkali olivine basalt lava; which flowed and solidified during January 1 – 8 1967 (Thorarinsson 1968, Fig. 8). The lava is vesicular and unaltered (except for some high-temperature oxidation), and contains phenocrysts of Cr-spinel, olivine and plagioclase. It is petrographically indistinguishable from the dikes at 71.9–84.8 m depth.

Below 2.7 m

Below 2.7 m depth the entire section is made of tuff/tephra, with the exception of the basaltic dikes at 71.9–84.8 m depth. The original material was unconsolidated tephra which was deposited in air or water, during November 1963 – April 3, 1964, and mainly during November-December 1963, as stated above. Generally, unless otherwise stated below, the tuff/tephra is of „ordinary" coarseness (i.e. mainly in the coarse ash fraction) and is poorly layered. Small basalt blocks and bombs about 8-12 cm in size are not uncommon, and xenoliths of sediment (some containing shell fragments) and crystalline basalt are present.

The material below 2.7 m depth was originally quite uniform, however, different degrees of alteration and compaction have produced variations in rock chemistry, mineralogy, density and porosity. No pillow lava is present in the drill core.

2.7 – 8.2 m

Tuff; finely layered, porous and altered, color mostly dusky yellow with dark grayish-green layers, (Fig. 8A).

8.2 – 17.3 m

Tuff; poorly layered, dense and altered, mostly dark grayish-brown.

17.3 – 19.1 m

Tuff; coarse to very coarse, porous to very porous (open-textured) and altered, many scoraceous fragments, a few bombs, – color mostly dark grayish brown.

19.1 – 32.4 m

Tuff; dense and altered, dark grayish brown, with scattered bombs, (Fig. 8B).

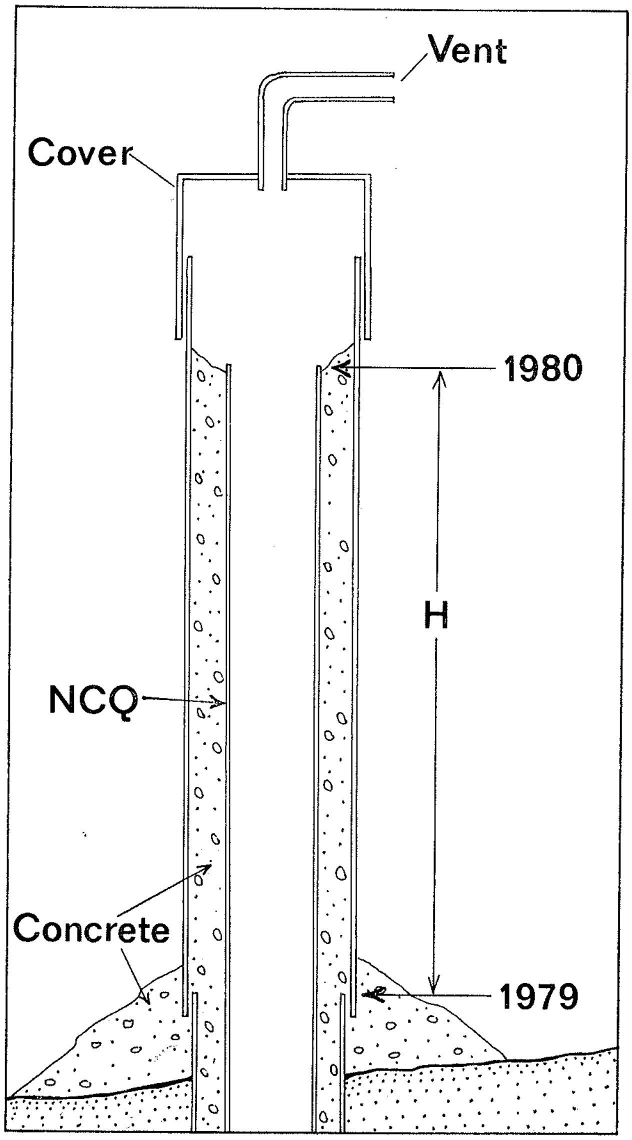


Fig. 6. Drillhead as completed in 1980. Reference level during 1979 drilling program was top of outer steel casing (58.39± 0.15 m above sea level which is now covered by cement). New reference level (1980) is 58.9±0.2 m above the 1979 level, but the exact measurement (H) was lost at sea.

32.4 – 35.7 m

Tuff; coarse to very coarse, porous to very porous, slightly altered, color dark grayish brown.

35.7 – 40.4 m

Tuff; slightly porous and slightly altered, dark grayish brown, (Fig. 8C).

40.0 – 52.5 m

Tuff; very coarse and porous, containing many pumiceous fragments and a few bombs, dark grayish brown.

52.5 – 71.9 m

Tuff; slightly porous to dense. Above 53.8 m depth the tuff is only slightly altered and is dark

SURTSEY 1979 DRILL HOLE

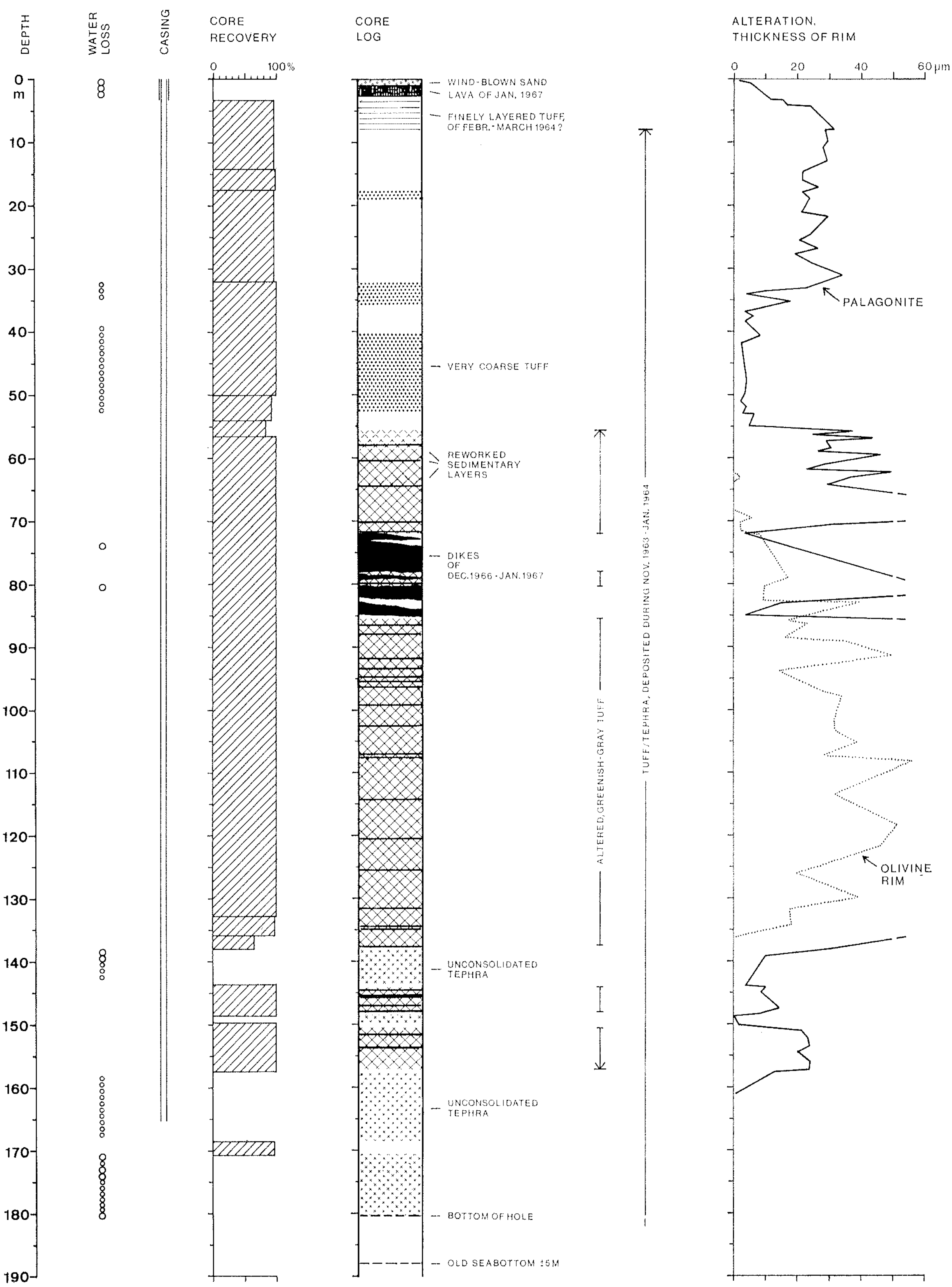
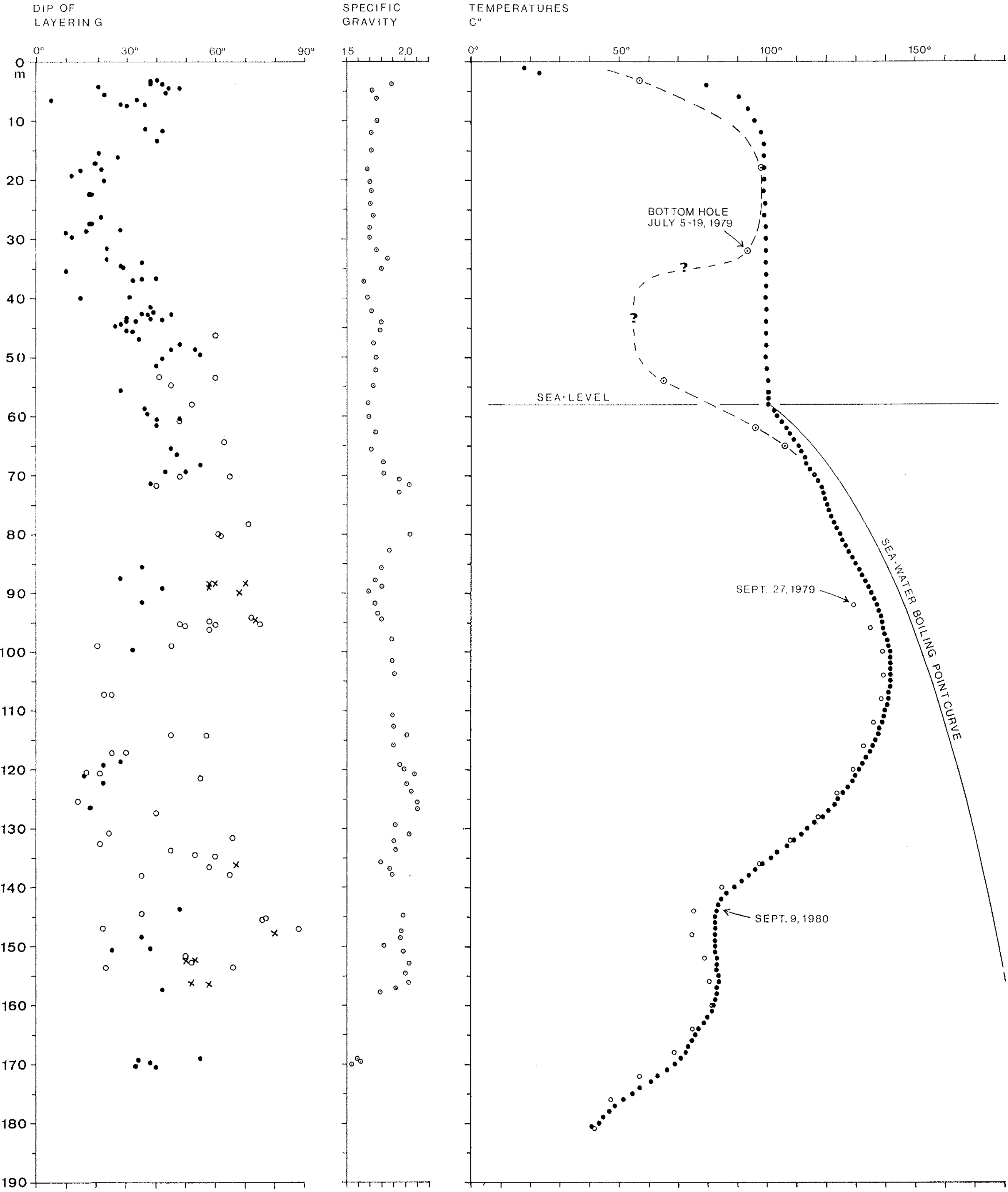


Fig. 7. Graphic core log. Water loss is indicated by large circles (complete loss of drilling fluid), and small circles (partial to heavy loss). Alteration is shown by thickness of alteration rims on sideromelane and olivine grains; above 50 µm measurements are inaccurate. Distinction is made between two types of layering: primary bedding (black dots), presolidification slumping planes (open circles); postsolidification shear planes are also indicated (crosses). Also shown is wet specific gravity of solid core, along with temperature measurements of July 1979, September 1979 and September 1980.


DIP OF LAYERING
SPECIFIC GRAVITY
TEMPERATURES C°
0°
30°
60°
90°
1.5
2.0
0°
50°
100°
150°
0 m
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
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190
BOTTOM HOLE JULY 5-19, 1979
SEA-LEVEL
SEPT. 27, 1979
SEPT. 9, 1980
SEA-WATER BOILING POINT CURVE

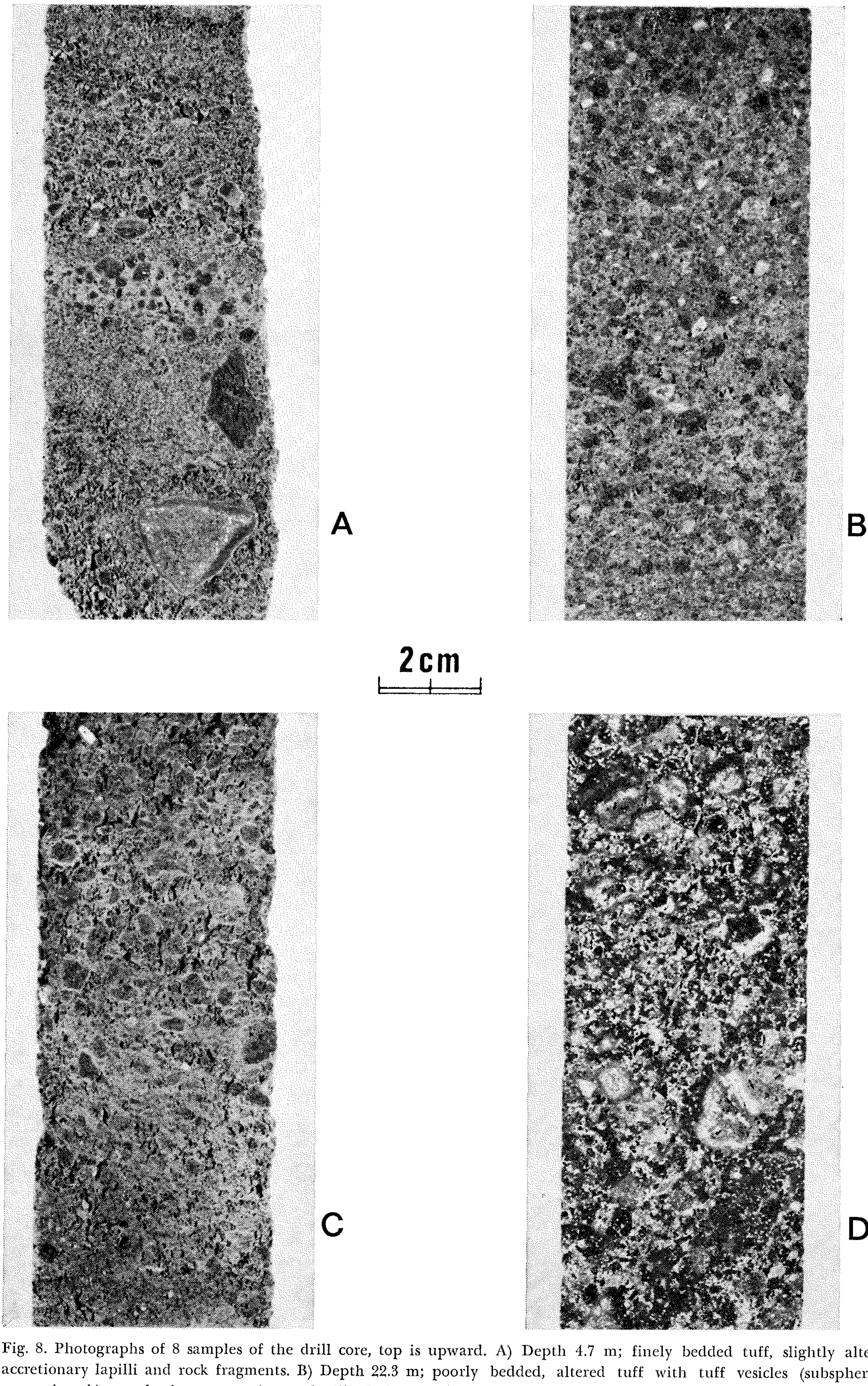
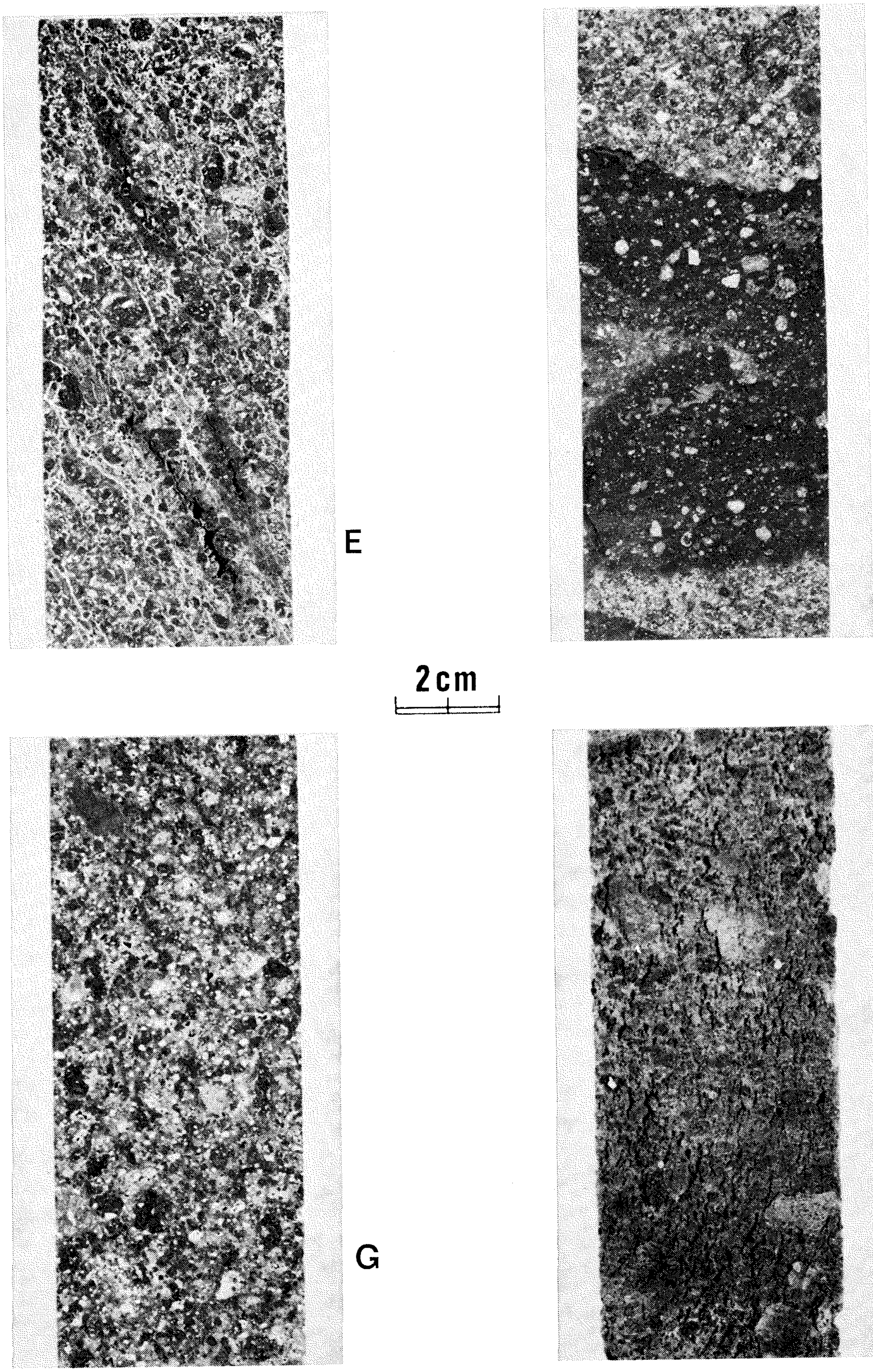


Fig. 8. Photographs of 8 samples of the drill core, top is upward. A) Depth 4.7 m; finely bedded tuff, slightly altered, with accretionary lapilli and rock fragments. B) Depth 22.3 m; poorly bedded, altered tuff with tuff vesicles (subspherical open spaces in ash), poorly shown accretionary lapilli. C) Depth 37.0 m; crudely bedded, coarse tuff, slightly altered with accretionary lapilli. D) Depth 59.3 m; tuff, much altered with white secondary mminerals in cavities, and no primary bedding visible.



E) Depth 88.4 m; much altered tuff, with shear planes; white zones and specks are generally zeolites and tobermorite. F) Depth 95.3 m; much altered tuff with reworked sedimentary layer cut parallel to strike; presolidification slumping has occurred at the top of the layer. G) Depth 107.5; much altered tuff, with no visible layering. H) Depth 150.2 m; tuff slightly altered, unlayered and compact. Photographs by Hjálmar R. Bárdarson.

grayish brown. Below 53.8 m traces of white secondary minerals appear, and at 58.5 m they make up more than 1 volume percent, and rapidly increase downwards. Below about 57.4 m the tuff is highly altered and assumes a greenish hue, and at 59.5 m the rock is distinctly greenish gray, cf. Fig. 8D. The uppermost reworked sedimentary layer occurs at 58.0 m depth, but between 53.1 and 58.0 m a few „muddy" layers occur. The shallowest distinct slumping plane occurs at 53.3 m, however, there is possibly one at 46.4 m depth. An apparent transition occurs at about 72 m depth below which the tephra may be deposited as „slush" in water.

71.9 – 84.8 m

Dikes, irregular; dipping about 60°-80°; the tuff is intercalated between the dikes at 72.6 – 73.0 m, 78.4 – 78.8 m, 79.2 – 80.4 and 82.1 – 82.8 m, and is mostly brownish black and only slightly altered (Fig. 7). The dikes are unaltered alkali olivine basalt, with phenocrysts of Cr-spinel, olivine and plagioclase and are petrographically indistinquishable from the lava at 1.0 – 2.7 m depth. The dikes show quenched glassy margins against the tuff.

84.8 – 138.1 m

Tuff; poorly layered, dense, much altered, greenish gray with white specks (cf. Fig. 8 E,F,G). A few blocks and pumiceous fragments occur. Many reworked sedimentary layers (Fig. 8F) and slumping planes are present. This unit grades into brownish unaltered tuff at the bottom.

138.1 – 143.8 m

Tephra (sand?); unconsolidated and unaltered; no sample was collected between 138.1 – 140.0 m, as all the drilling fluid was lost, and only cuttings were obtained between 140.0 – 143.8 m. More resistant layers may be present in this unit, as indicated by variations in the drilling rate.

143.8 – 148.5 m

Tuff; poorly layered, dense, much altered, greenish gray. Brownish and unaltered at contacts with units above and below.

148.5 – 149.7 m

Tephra (sand?); unconsolidated and unaltered; only drill cuttings are available.

149.7 – 150.4 m

Tuff; poorly layered and porous, unaltered and brownish (Fig. 8H).

150.4 – 157.4 m

Tuff; poorly layered and dense, much altered, greenish gray. Brownish and unaltered at the contact with the unit below.

157.4 – 168.6 m

Tephra (sand?); unconsolidated and unaltered; only drill cuttings are available.

168.6 – 170.0 m

Tuff; layered, porous, slightly altered and brownish.

170.5 – ~176.5 m

Tephra (sand?); unconsolidated, unaltered; only drill cuttings are available, expect at 171.0 – 171.4 m and 172.6 – 174.9 m, where no samples were collected.

~176.5 – 180.6 m

Sand or tephra; unconsolidated and unaltered, no samples below 180.1 m as all the drilling fluid was lost; only coarse sand, no fines came up with the drilling fluid.

Accretionary lapilli and vesiculated tuff.

Accretionary lapilli or mud balls (Moore & Peck 1962) are common in the Surtsey tephra, especially in the inner slopes of the tephra rings (Lorenz 1974a). They are also common in the core at depths between 2.7 – 17.3 m and 32.4 – ~57.0 m (Fig. 8A and C). Between 57.0 – ~72 m depth accretionary lapilli are less common, and below about 72 m they are apparently scarce. However, alteration and compaction at deeper levels makes positive identification of accretionary lapilli difficult. The accretionary lapilli generally contains a core of a single grain of glass or basalt around which is an accreted layer of very fine ash, commonly about 0.10—0.25 mm thick, but on a few larger lapilli up to 0.6—2 mm thick. The fine accreted layers are believed to have formed when wet lapilli nucleii were thrown into an ash cloud containing abundant steam. It is noteworthy that accretionary lapilli do not seem to occur in tuff layers with dip less than about 22° (Fig. 7). The rather abrupt change in the occurence at about 72 m depth may indicate the transition from tephra deposited subaerially to tephra deposited as „slush" in water.

Vesiculated tuff is commonly found in surface layers on Surtsey (Lorenz 1974a), and is common at depths between 2.7 – 32.4 m (Fig. 8B).

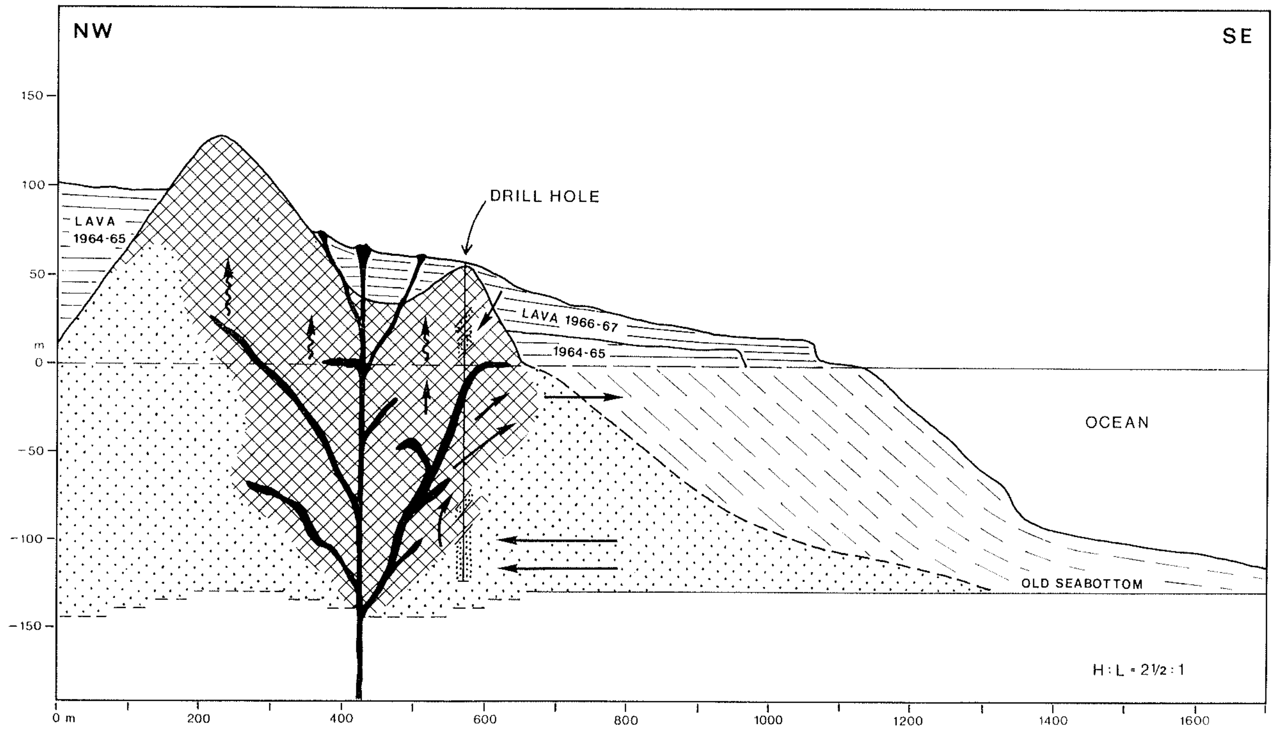


Fig. 9. Profile through the eastern tephra and lava craters, and the drill hole, from NW to SE. The pyroclastic material formed between November 14, 1963 and April 4, 1964 and is dotted, and the estimated distribution of consolidated rock is cross hatched. The coarse permeable tephra layers encountered in the hole are shown by fine stippling and feeder dikes and other instrusions of 1966-1967 are black. Arrows indicate suggested flow direction of water (straight arrows) and steam (undulating arrows) in the southeasternmost part of the island. See text p. 92 for discussion.

The vesicles are most conspicuous at 17.3 – 32.4 m depth, i.e. where the tephra layers dip less than 30°, and where there are no accretionary lapilli. Vesiculated tuff is considered an indicator of phreatomagmatically formed base surges (Lorenz 1974b). The vesicles are up to several mm in size and are commonly rounded, though irregular in shape and are moulded against the margins of larger pyroclasts. They are apparently produced by steam and other gases included in wet ash.

Planar structures

Distinction is made between three types of planar structures: primary layering or bedding (defined by crude size sorting), slumping planes, and faults formed after partial or complete consolidation of the layers. Dip measurements on all easily recognized layers are plotted in Fig. 7. Plotted dips assume the hole is vertical; direction of dip is unknown in the unoriented core.

The dips of the primary bedded layers range from 5°-55° (89 measurements), and average 33°. Primary layering is less common below about 72 m depth (Fig. 7). Above this level the average dip decreases regularly from about 45° at 72 m depth to about 18° at 20-25 m depth, where it rises again to an average of 40° at the surface.

Secondary planes, which clearly indicate slumping in soft, wet layers occur below 40 m depth, and are especially common below 94 m depth. These slump planes are commonly associated with reworked sedimentary layers (Fig. 8F). The dip of these planes are usually considerably steeper than that of the primary layers (Fig. 7). The dip ranges from 14° to 89° (50 measurements), and average 48°.

In 13 places, between 88-157 m depth, secondary planes occur which are indicative of shearing (faulting) in semiconsolidated material (Fig. 8E). These shears occur in zones, commonly with open fractures, partly filled with secondary minerals. The faulting appears to have occurred before most of the secondary minerals were formed and before complete alteration and compaction of the tuff.

Density and porosity measurements

Specific gravity of the drill core was determined by weighing and measuring the volume of sections of the drill core and determining the loss of weight when immersed in water. Since it was not possible to entirely dry much of the core, all of the reported values are the specific gravity of wet core. The specific gravity generally compares directly with the degree of alteration of the core (compare Fig. 7). Down to about 70 m it averages 1.7–1.8. From 70–160 m depth it averages about 1.9. The short segment of relatively unaltered core at 170 m depth averages about 1.7.

Reworked sedimentary layers

About 40 silty layers were encountered between 58.0 and 153.6 m depth (Fig. 7). The thickness of these layers varies between 0.3 and 3.6 cm for all but two layers, which measure 10.5 and 22 cm. The average thickness of the layers is 1.9 cm, and the total vertical thickness is 76 cm. The layers are commonly associated with slump planes which have an average dip of 48°.

These layers (Fig. 8F), which are made up of the same consituents as the primary tephra, show considerable sorting; the finest and coarsest-grained fractions have disappeared leaving silty material. Rarely, single large grains or parts of unsorted tephra layers are present in the layers. At 53.4–57.7 m depth there are several „muddy" layers. These have no sharp contacts and are often vesicular. The layers may be interpreted as mud spatter from the tephra crater.

The reworked sedimentary layers may have formed when slumping of the water-saturated tephra pile occurred at the time of deposition. These layers tend to be regularly spaced (Fig. 7). Many of the layers are 4.5 – 6.5 m apart, although a spacing of <1 m between layers is not uncommon. Slumping apparently occurred rythmically as the pile gradually built up. Perhaps the periodic slumping was triggered by tidal currents.

THE HYDROTHERMAL SYSTEM

A general idea of the geometry of the hydrothermal system in the eastern part of Surtsey is based on observations during the eruption, surface geology, sea floor topography, and drill hole data (Fig. 9). The direction of dip of the tephra layers encountered in the hole is not known. The flatter dips near the surface may represent strata near the crest of the crater rim. Steeper dips at greater depth may represent strata deposited either within the crater or on the outer flanks. The close proximity of the drill hole to the eastern vent lava crater (140 m, Fig. 2) suggests that the strata dips southwest and hence was deposited within the crater on the inner crater walls. Likewise the dikes presumably also have a westerly dip so as to connect the main volcanic conduit beneath the vent center with the small flank eruptive vents active in 1966-67.

Porous unaltered tephra or sand layers were encountered at depths of 138.1 – 143.8 m, 148.5 – 149.7 m, 157.4 – 168.6 m, and 170.5 – 180.6 m (Fig. 7). In the bottom layer temperatures of 40°-60° C were recorded in 1979 and 1980, and since the other porous layers show only minor signs of alteration, similar temperatures may have prevailed in them. It is likely that cold sea water has entered the hydrothermal system through these deep porous layers, as also suggested by the high transmissivity observed at the bottom of the drill hole (Tómasson and Snorrason, 1982).

The zone of highly altered tuff below sea level corresponds closely with the zone of highest temperature measured in the hole (Fig. 7). Because of the growth of abundant secondary minerals in this heated environment, this rock has the lowest estimated permiability of any part of the hole (2.5×10^{-13} m^2) while the less altered tuff above sea level has a considerably higher permiability (1.4×10^{-10} m^2) (Axelsson et al., 1982).

Ground water, largely marine in origin, heated by contact with dikes and intrusions, produced this alteration and then rose and flowed probably eastsoutheast back to the sea near sea level. It is replaced by cold sea water flowing in from the bottom probably also largely from the east side of the island.

The temperature within the drillhole in a zone extending from sea level down for 40 m is only slightly lower than the boiling point curve (Fig. 7). Hence in this hot zone the ground water is no doubt boiling at certain favourable places and times depending on the state of the tide, the downflow of cool meteoric water, and other factors. Consequently a steam phase will rise through the tephra above sea level and will be concentrated in fractures and other favourable zones where it will heat the tephra to about 100° C.

During wet weather cold meteoric water from above will seep down especially through permeable layers. Perhaps the coarse tephra layers at 32.4 – 35.7 m and 40.4 – 52.5 m are only slightly altered because they served as channels for such descending cool, meteoric water.

Acknowledgements

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Rock quality designation and drilling rate correlated with lithology and degree of alteration in volcanic rocks from the 1979 Surtsey drill hole

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ABSTRACT

The Surtsey hyaloclastite was examined to see if geotechnical parameters depend on lithology. Measurements of rock quality designation (RQD) and rate of drilling are compared to degree of alteration, lithology and porosity. The RQD correlates well to alteration. It is shown how this result can contribute to the interpretation of the alteration process in Surtsey. Although drilling rate depends on many factors the main features may be explained by lithological and porosity differences. Results of density and porosity measurements on 22 core samples and 2 samples of incoherent tephra are presented together with quantiative determinations of the authigenic calcite content.

INTRODUCTION

In the course of research project in engineering geology including petrographical influence on rock strength and other geotechnical parameters, the author was able to obtain rock cores from a drilling investigation in Surtsey. Since the main part of this work is restricted to Icelandic volcanics in subaquatic facies, the availability of cores of similiar rocks from the Surtsey drill hole is used to extend the investigation over a wider range of petrological types.

One of the most obvious but rather surprising features of the Surtsey core is the mechanical consistency of what was originally loose hyaloclastic material. This is believed to be a result of a still active alteration process known as palagonitization (Jakobsson 1972, 1978). The rocks are monogenetic and known to have originated from the tephra eruption in Surtsey during November 1963 through March 1964. The variable degree of alteration together with variations in primary lithology must influence geotechnical parameters and it seemed worthwhile to study this relationship as it seemed likely that it has some practical value.

As a first attempt to examine this problem for the core as a whole, rock quality designation (abbr. RQD) and drilling rate are appropriate. The porosity was also evaluated during preparation for rock mechanics experiments. The results should be regarded as an extension to the drill log described in this volume (Jakobsson & Moore 1982) and are published here as they may be of interest to other scientists working on the palagonitization process.

METHODS

The RQD was introduced by Deere for the purpose of increasing information on in situ rock properties from boreholes (Deere 1968, Deere et al. 1969). It is defined as a percentage of core bits longer than 10 centimeters in the total well length in some specific part of a borehole. In other words this can be calculated from the core recovery by deleting all cores shorter than 10 centimeters. Clearly this parameter can only be a limited measure of rock quality, but it does give some idea of joint frequency and rock hardness. To reach a more realistic idea of the properties of rock mass more advanced methods including other important features have been developed (e.g. Barton et al. 1974). Since these methods are often based on RQD it is often preferred over other measures of joint frequency and has become a routine technique in geotechnical core logging. The measurement of RQD for this paper is according to the above definition.

Drilling rate is defined as a rate of advance of the core bit during drilling (Moore 1963). It is usually expressed as the time required to drill a certain standard length of a hole, or as prefered here as the real velocity of the drill hole advance. Several factors of different origin may affect drilling rate. Some of these relate to properties of the rocks encountered, others depend on mechanical factors of the drilling process and human ability and endeavor (Wirth GmbH 1979). Only in controlled and reproduceable conditions can it therefore be a measure of absolute hardness or abrasivity.

Observation of drilling rate is especially useful in rotary drilling as it is the first encountered data which is available even while boring before the hole is completed. Another advantage of this technique is that the log can be recorded over the entire length of the well as other methods of data logging e.g. some geophysical procedures may be incomplete or unfeasible.

In Surtsey the drilling rate was measured with a stop clock and all breaks caused by technical problems were noted and eliminated from the effective drilling time (National Energy Authority, drilling report, geological observations, Surtsey I, 1979).

Lithology and degree of alteration were used a basis of comparison (Jakobsson and Moore 1982). They used the thickness of the palagonite rim in large grains of sideromelan and the alteration rim on olivine phenocrysts as determined under the microscope as a value of alteration. According to this definition the alteration grade does not necessarily need to be identical with the state of rock hardness.

Porosity and alteration are often interconnected and in fact porosity may govern the process of alteration (Furnes 1974, Jakobsson 1978). Porosity of rocks was measured according to DIN 52102 (Deutsche Normen, 1965). This is based on measure of volume from core dimensions (length = 2 x diameter), dry core weight and specific density of pulverised rock determined in a pyknometer. The densities of incoherent materials sampled for soil mechanics testing were measured in situ by sand cone method (ASTM standards 1976).

It should be emphasized that all porosities mentioned here are total porosities, containing both intergranular porosities and vesicles within individual grains. As yet no attempt has been made to evaluate the proportions of initial porosity attributable to overburden load consolidation and authigenic minerals precipitating during palagonitization.

RESULTS AND DISCUSSION

In Fig. 1 RQD and drilling rate are compared with lithology and degree of alteration. The RQD was measured at 3 meter intervals. The drilling rate was also calculated over the same well lengths, although in some shifts where drilling was interrupted by technical problems shorter lengths were employed. Drilling sections where measurements were inobtainable are indicated by gaps in the drilling rate curve. In the analysis of the data it was found that 6 meter intervals could be used for the graphical representation without loosing the main information.

Figure 1 shows that RQD correlates with alteration grade, as RQD is usually high where palagonite rims are thick. This correlation is further emphasized in the lithology log. The low values between 72 and 84 meters are not only due to somewhat highly jointed basaltic dikes but also to the development of irregular contacts and to the rather loose nature of the hyaloclastite in this section. Extremely low values towards the bottom of the hole are due to two thick sections consisting nearly entirely of incoherent tephra.

TABLE I.

Dry density, specific density and total porosity of the Surtsey hyaloclastite.

Sample no	Depth (m)	Dry density (g/cm3)	Specific density (g/cm3)	Porosity (%)
1	4.2	1.39 ±0.02	2.78 ±0.01	49.9 ±0.5
3	8.2	1.46	2.78	47.4
5	12.1	1.49	2.79	46.8
7	19.0	1.39	2.77	50.0
8	21.0	1.61	2.78	42.2
10	24.9	1.39	2.78	50.1
12	33.4	1.66	2.78	40.3
14	41.1	1.51	2.80	46.0
15	52.1	1.52	2.79	45.7
20	58.2	1.54	2.78	44.6
22	68.3	1.55	2.77	43.9
25*	74.0	2.82	3.08	8.5
26*	77.6	2.81	3.08	8.8
27	88.3	1.59	2.78	42.6
30	98.0	1.73	2.77	37.5
33	108.7	1.71	2.76	38.0
34	110.5	1.68	2.76	39.2
35	125.3	1.88	2.77	32.2
37	132.7	1.75	2.78	37.0
38	147.5	1.74	2.79	37.8
40	150.0	1.52	2.78	45.2
43	155.3	1.89	2.77	31.9
SB 1**		1.4 ±0.05	2.84	49.5 ±1.0
SB 2**		1.5	2.85	46.8

* Basaltic dike.

** Measurements made on incoherent hyaloclastite in natural openings.

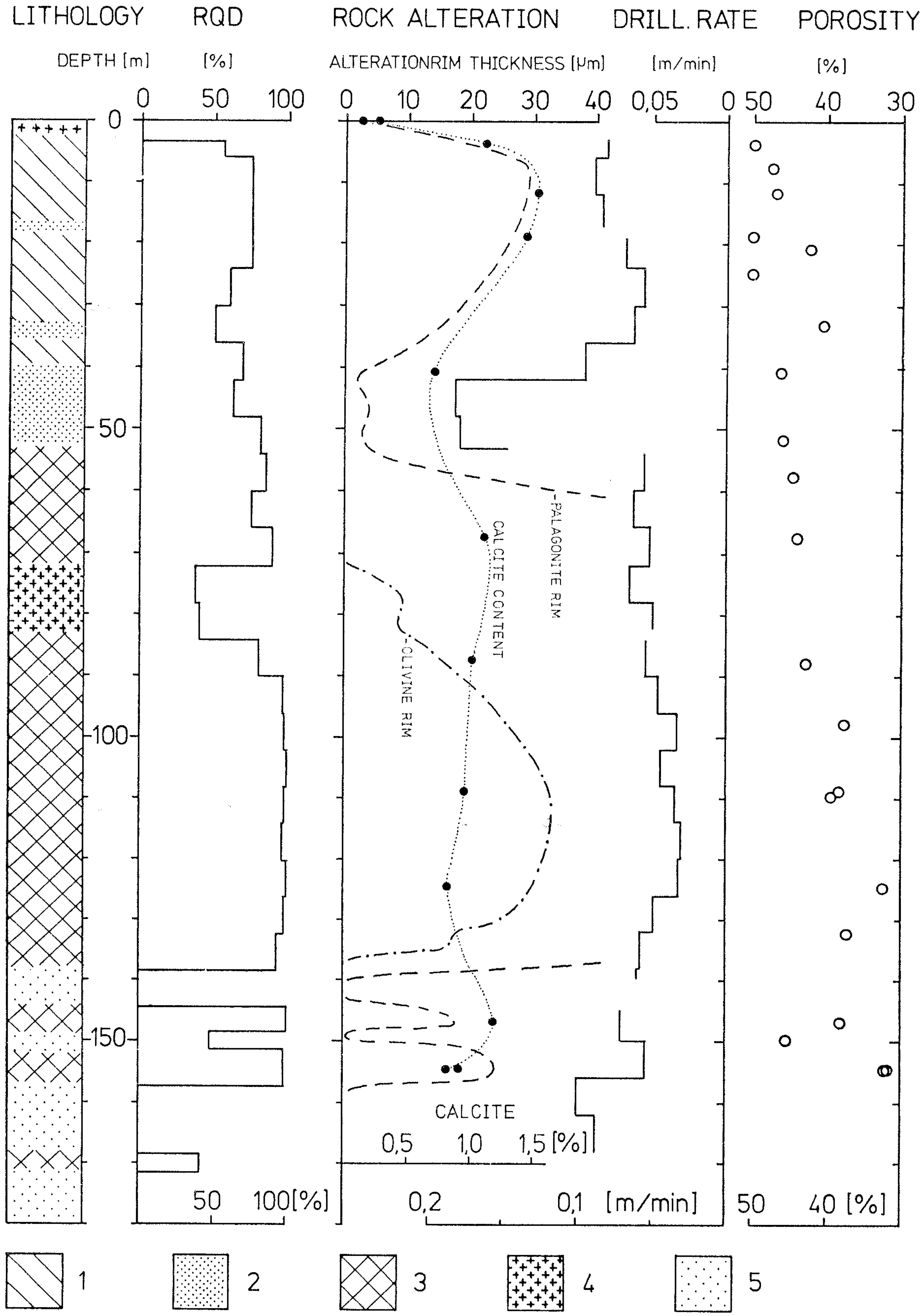

Fig. 1. Lithology and alteration rim curves, average values, pers. comm. Jakobsson and Moore, 1982. Explanation to lithology: 1) brown-black, poorly altered hyalocastite. 2) black, coarse and poorly graded hyaloclastite. 3) grayish-green sound hyaloclastite. 4) basaltic dikes and lava flow at top. 5) incoherent tephra.

The significance of these conclusions is further strengthened by the fact that the different measurements were made by different investigators, eliminating observational subjectivity.

As low RQD value correlates with either highly jointed rock or the presence of incoherent rock material such as the hyaloclastite initially was at the time of deposition, it can be concluded that the material was subsequently cemented and that discontinuities are healed during alteration processes. The hardening effect seems at least to some extent to be caused by growth of authigenic minerals during palagonitization. The non-linearity of changes of RQD with alteration indicates implicitly that the alteration system is in a part open as chemical constitutents of authigenic minerals may move within the rock mass prior to precipitation. This deduction is in good agreement with Jakobsson's theory of an alteration mechanism whereby cold seawater seeps under the island where it becomes heated and move upwards through the overlying rocks (Jakobsson 1978 and Jakobsson & Moore 1982). It is clear that petrographical examination could provide a solution to this problem. First results of high accuracy coulometric measurements of the amount of authigenic calcite (method described by Sixta 1977) show this feature directly (see Fig. 1).

The drilling rate curve shows one main peak in the upper part and another less obvious peak further down (Fig. 1). A comparision of drilling rate with palagonite thickness does not reveal obvious relationship of the details. The drilling rate peaks correlate however very closely with lithology and the curve also seems to follow the porosity trend. The main peak coincides with a rather coarse and poorly graded hyaloclastite which, in spite of the presence of large intergranular voids, has not an abnormally high porosity (see also Table I). The second high drilling rate section is most probably related to incoherent sand and tephra. It is though emphasized that there are many unkown mechanical factors which influence drilling rate in addition to lithology and porosity differences.

In the section of sound basalt an expected negative drilling rate anomaly was not found. This was probably caused by a compensation effect arising from the presence of rather incoherent and porous hyaloclastite of low alteration grade at the contacts of dykes which were thinner than the interval chosen to record the rate. It seems likely that a mechanical drilling time recorder would have greatly improved the reliability of the results.

Direct comparision of RQD with drilling rate is not suggested. High drilling rates can be caused by low RQD only in very fissile or incoherent rocks.

The results of this paper suggest that the more advanced rock mechanic experiments will add useful information on how rock hardening is related to palagonitization. Work is continuing along these lines and the author hopes to present more detail on this in a later paper.

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Tidal and leveling measurements on Surtsey July-August, 1979

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INTRODUCTION

During July and August, 1979, a 181 m deep hole was drilled on the eastern crater rim of the eastern vent on Surtsey (station SDH—1, Fig. 1). In order to establish the elevation of the top of the hole, a program of precise leveling and water-level measurements was undertaken. Leveling employed existing bench marks (Tryggvason, 1968, 1970, 1972), where practical, and utilized newly established bench marks where necessary. Water-level measurements were made in a pit east of the hut (station WP, Fig. 1), in the open ocean on the northeast coast, and within the drill hole.

WATER-LEVEL MEASUREMENTS

Water-level measurements were made in a newly dug pit (2 m deep, and about 2 m square) 100 m east of the hut at the northern base of the west vent. Measurements of the level of the brackish water within the pit were made relative to an arbitrary datum every hour for five 24-hour periods. The dates of record and 24-hour average water level above the datum are as follows: July 18 (64.43 cm), July 19 (64.32 cm), July 26 (55.48 cm), July 27 (54.34 cm), August 11 (67.26 cm. Fig. 2). The average of these averages which represents 120 measurements is 61.17 cm, and this is taken as the assumed average water level in the pit and the assumed *datum for the entire leveling survey*.

The tidal cycle is clearly shown in the water-level measurements and ranges in height 1.5 to 5 cm between adjacent high- and low-water (Fig. 2). The time of high water in the pit is clearly out of phase with that in the open ocean. It ranges from 5.1 to 6.5 (average 5.82) hours after the last preceding high tide in the Vestmannaeyjar (Westman Islands) as determined from tide tables.

The damping of the tidal flux and retardation of the tidal cycle is the result of limited permeability of the loose tephra, sand, and gravel which separates the dug pit from the open ocean which is 260 m distant at the closest point to the northwest and 340 m to the east. The determination of mean sea level in the open ocean cannot be accurately made without installation of a suitable tide gage on the island and maintaining it for a period of months or years. Hence only a rough approximation can be made of the elevation of the brackish water in the pit above mean sea level.

On July 27, 1979, a remarkably calm day, a tide staff was established on the beach on the northeast side of the northern cape and was tied in elevation to the dug pit by a level line. The staff was maintained from 1400 to 1900 (Icelandic standard time) during a period of rising tide which, unfortunately, did not include the trough of a low tide or crest of a high tide. During this period, the level of the ocean ranged from 126 cm below to 50 cm above the average level in the dug pit. Comparison with tide tables suggests that the average water level in the dug pit was 25±15 cm above mean sea level in the open ocean. However, the day of measurement was one in which the pit water level was 6.8 cm below the assumed average. Hence the best approximation available is that the dug pit average water level is 32±15 cm above mean sea level and all leveling measurements of bench marks would have to be increased by that amount to

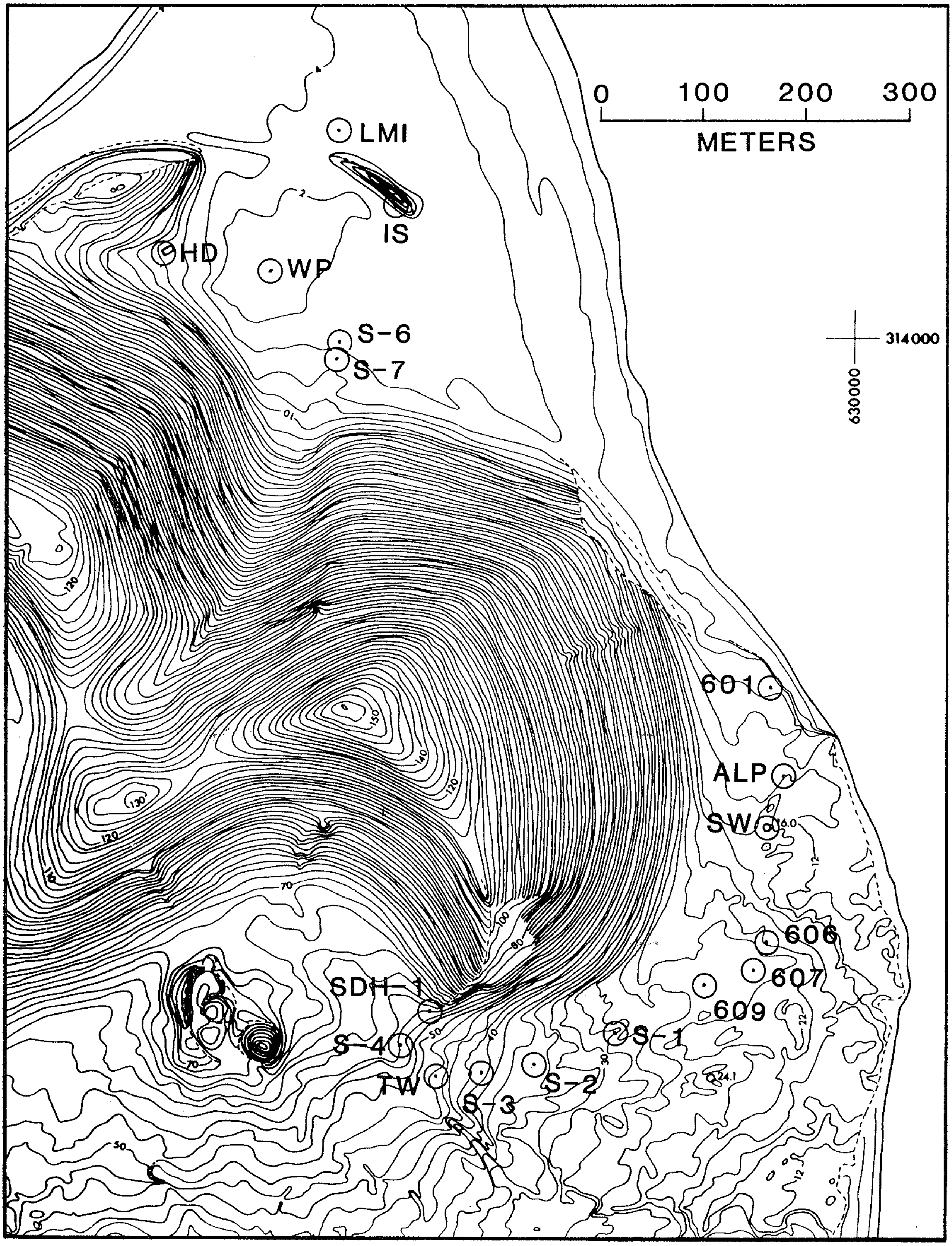

Fig. 1. Map of northeast Surtsey showing the location of bench marks occupied in the 1979 leveling survey. Drill hole is at station SDH–1. Map prepared by John Norrman from air photographs taken July 11, 1975. Contour intervals is 2 m.

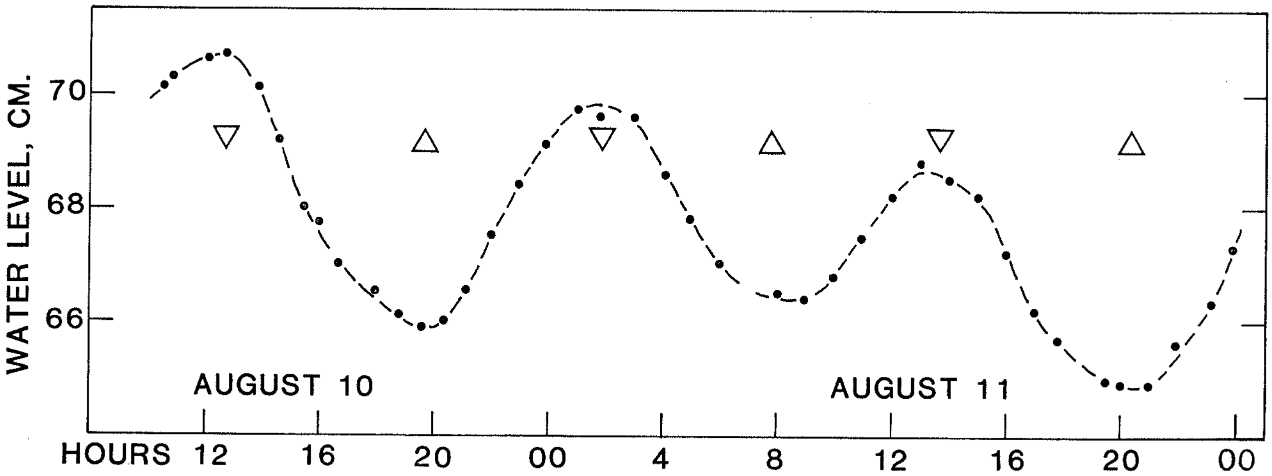

Fig. 2. Height of water level in dug pit August 10-11, 1979. Triangles show times of high tide, and inverted triangles, times of low tide at Westman Islands as determined from tide tables.

represent elevation above sea level. Also, of course, is the fact that water level in the dug pit is variable, and the five-day average may be a poor record of it considering variation due to rainfall, onshore wind, barometric pressure, and other local factors.

LEVELING

Precise leveling was carried out between the dug pit and the collar of the drill hole (Table I). Leveling was done with a Zeiss self-leveling level, and most of the lines were double-run and generally agreed within a few millimeters. Several new bench marks were established (Table I, Fig. 1) near the drill hole as well as on the northern cape of the island to serve as reference points for future water-level measurements near the dug pit. The elevation of all bench marks is shown relative to the five-day average water level in the dug pit which is arbitrarily assumed to be 0.00 m elevation (Table I).

The elevation of the drill hole collar (station SDH-1, Fig. 1, Table I) measured on the top of the outer casing (which is also the reference point for all depths measured within the hole) is 58.066 m above the average water level in the dug pit. The elevation of the drill hole collar above mean sea level in the open ocean is 58.39±0.15 m.

Measurements were made on the depth of water in the drill hole after it reached the depth of sea level on July 12, 1979. Measurements were made by lowering a weight on a monofilament fishline and listening for the splash or by lowering a float. The accuracy of both methods is reduced by stretch in the line, friction of the line on the walls of the casing, and the difficulty of

TABLE I

Elevation of stations above average water level in dug pit, July—August 1979

Station	Elev., M	Notes
SDH—1	58.066	Top of outer, large diameter steel casing of drill hole.
S—4	57.339	Concrete nail driven into lava flow with numbered aluminum tag.
TW	49.442	Center of white triangle painted on smooth lava.
S—3	41.183	Concrete nail driven into lava flow with numbered aluminum tag.
S—2	34.827	Concrete nail driven into lava flow with numbered aluminum tag.
S—1	27.157	Concrete nail driven into lava flow with numbered aluminum tag.
609	23.509	Brass bench mark (Tryggvason, 1972).
607	22.892	Brass bench mark (Tryggvason, 1972).
606	20.316	Brass bench mark (Tryggvason, 1972).
SW	15.905	White square with yellow, inner circle painted on smooth lava.
ALP	10.381	Base of bent aluminum peg.
601	8.295	Brass bench mark (Tryggvason, 1972) with last digit obscured.
LMI	3.387	Top of bent pipe north of small tuff hill (Tryggvason, 1970).
WP	0.00	Assumed datum. Five-day average of water level in dug pit (100 m east of hut) measured hourly.
HD	7.057	Threshold in doorway of hut.
IS	8.730	Top of iron stake on bench, southeast slope of small tuff hill, 3.75 m below summit of hill.
S—6	3.341	Concrete nail in lava flow about 200 m east-southeast of hut.
S—7	4.166	Concrete nail in lava flow about 200 m east-southeast of hut.

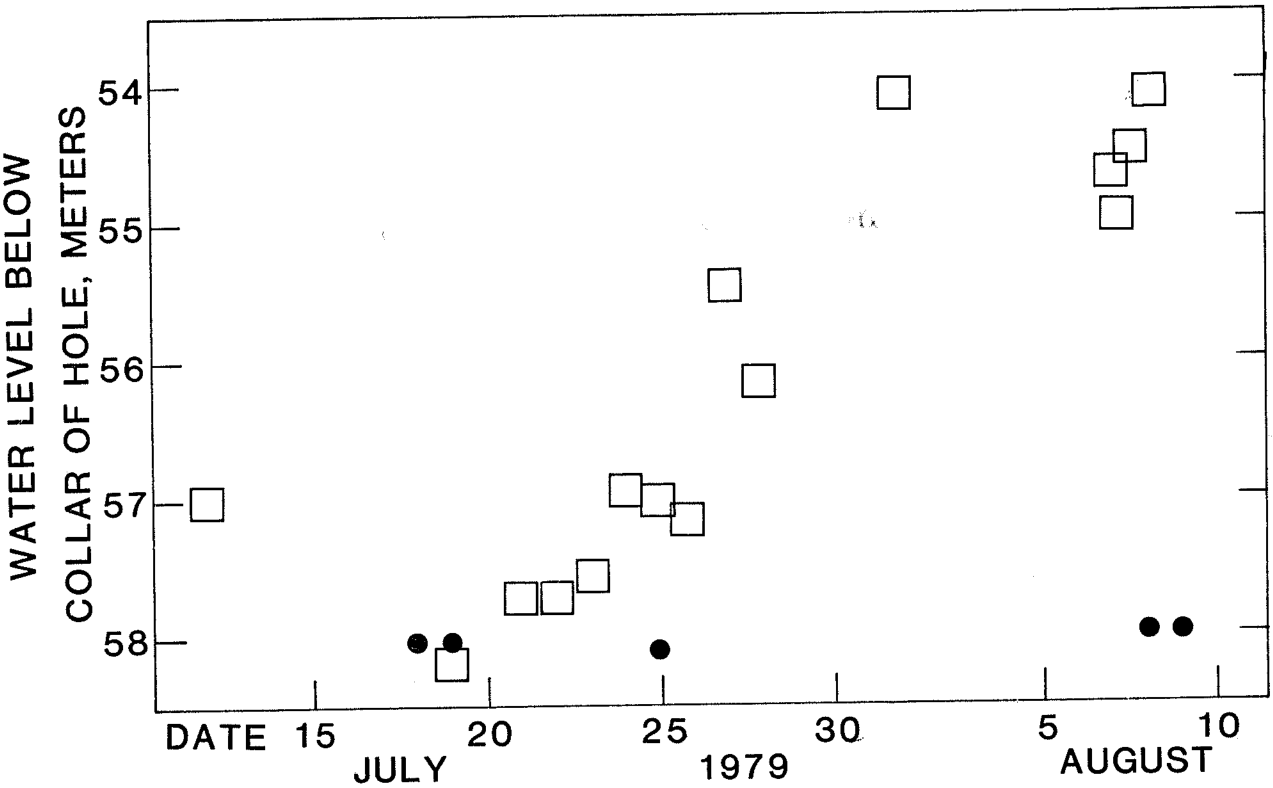

Fig. 3. Vertical distance of water level below collar of drill hole (station SDH–1) for water within drill hole (squares) and for water in dug pit (station WP, solid circles).

detecting the water level when the water is boiling. They show, however, that the lowest water level in the hole is close in elevation to that in the dug pit, and that as drilling progressed and large quantities of sea-water were pumped down the hole, the water level steadily rose to about 4 m above that in the dug pit (Fig. 3). Presumably in time, the drilling-induced saturation of tephra around the drill hole will return to normal, and the water level will fall to its predrilling level. However, other factors no doubt affect the measured water level within the drill hole. Free convection of hot water within the hole may have elevated the average temperature of the water column causing it to rise. Also, tides no doubt affect the water level in the hole.

SUBSIDENCE OF DRILL HOLE SITE

Tryggvason (1972) has shown that BM 601 had subsided 30-40 cm between 1967 and 1970 relative to the water level in preexisting lakes and in dug pits on the north cape of the island. The rate of subsidence decreased by about a factor of 2 each year during this measurement period. We find an additional subsidence of about 20 cm making a total of 50-60 cm from 1967 to 1979. In addition, Tryggvason (1972) has shown that all bench marks in his line crossing the middle of the island have subsided varying amounts relative to BM 601. Benchmark 616 which is closest to the drill hole site, subsided (relative to BM 601) about 12 cm from 1967 to 1970. Hence the drill hole site has probably subsided about 70-80 cm since 1967.

The amount that the strata within the drill hole has subsided relative to sea level since the island grew above sea level November 14, 1963, or since activity at the eastern vent ceased January 31, 1964, is unknown. Extrapolating backwards using the same rate of decrease of subsidence suggests that the drill hole site subsided about 3 m prior to 1967 or a total of about 3.8 m from 1964 to the time of drilling in 1979. The amount of subsidence which occurred contemporaneous with volcanic construction of the eastern tephra cone is unknown but may have been considerable. In any event, the passage zone in the drill hole, separating submarine-deposited tephra from subaerially-deposited tephra, is probably deeper than 3.8 m below water level (61.9 m depth) and may be considerably deeper.

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Thermal condition of Surtsey

By

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ABSTRACT

The results of temperature measurements performed in a borehole drilled on Surtsey in 1979 are presented. These results are used as the basis for a discussion of the thermal condition of Surtsey. The hypothesis that intrusions rather than pillow lavas are responsible for the excess heat content of Surtsey is favored, but it is concluded that the 13 meter thick dike complex found in the drill core is not sufficient to explain the thermal condition of the island. An average thickness of intrusions of at least 20 meters is needed. It is demonstrated that the heat transfer in Surtsey has been dominated by hydrothermal convection and that the system is vapor dominated above sea level. The permeability of the altered tuff in a 40 meter thick section below sea level is estimated to be 2.5×10^{-13} m^2. The permeability of the unaltered tuff above sea level is estimated to be about 1.4×10^{-10} m^2.

INTRODUCTION

During the summer of 1979 a 181 m deep, continuously cored, borehole was drilled on the newly formed island of Surtsey (Jakobsson & Moore 1980). The drill site is located about 150 m east of the center of the tephra crater Surtur I, as shown on Figure 1, at 58 m above sea level. The drilling was a joint project of the Icelandic Museum of Natural History and the United States Geological Survey. The drilling was performed by the Icelandic State Drilling Contractors. It is assumed that the hole bottom is within a few meters of the old sea floor, but the drilling had to be terminated at a depth of 181 m because of very loose material encountered at that depth.

The purpose of the drilling was to obtain a continous core (4.7 cm diameter) for the investigation of the structure of the island and the hydrothermal alteration of the tuff formed during the initial phase of the Surtsey eruption. The core has been described by Jakobsson & Moore (1982) and a simplified presentation of the lithology observed in the core is given in Fig. 2.

The drill hole makes it possible to study the thermal conditions within the island. The results of temperature logging performed by the Icelandic National Energy Authority (NEA) in

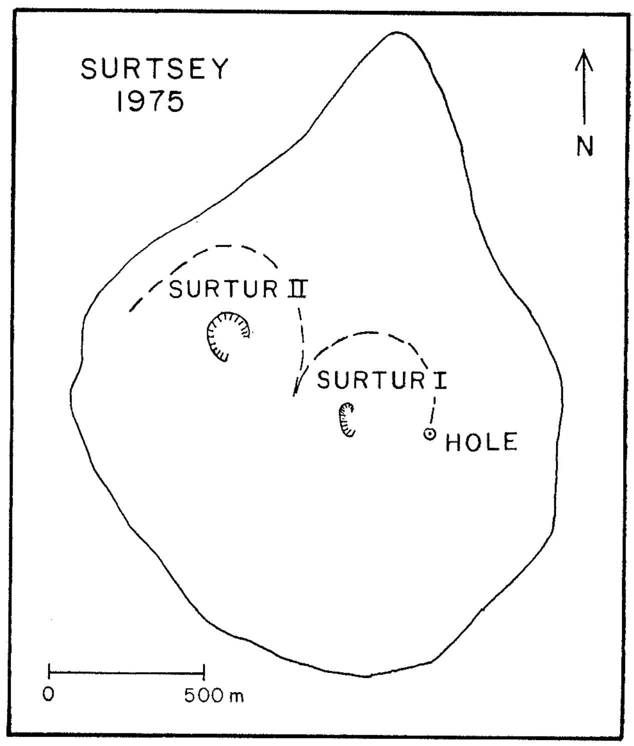

Fig. 1. A map of Surtsey showing the location of the borehole.

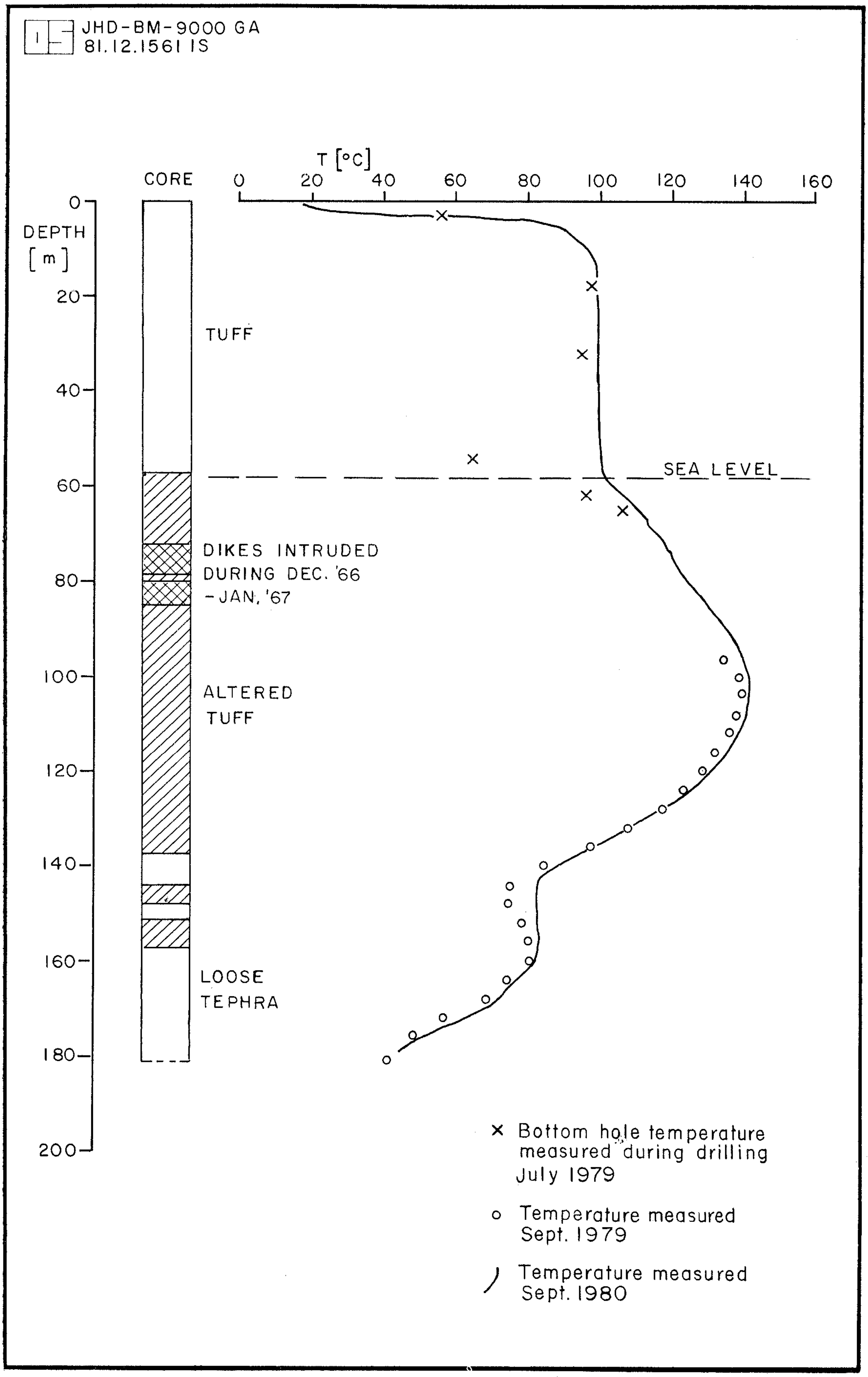

Fig. 2. The results of the temperature measurements of July and September 1979 and of September 1980, along with a simplified representation of the core lithology.

1979 and 1980 are reported in this paper along with attempts at interpretation.

MEASUREMENTS

Temperature logging was performed in the Surtsey borehole, by the NEA, at two different periods.

On the 26th of September 1979, 40 days after the drilling was completed, two temperature measurements were attempted. The first measurement, which was done with a thermistor mounted on an electrical cable, has been disregarded due to technical difficulties during the measurement. The second measurement of September 1979 was done by using a Kuster temperature gauge, and the temperature was measured every 4 m below 90 m depth. The results are shown in Figure 2.

A later temperature measurement was run on the 9th of September 1980. This measurement was performed with a platinum sensor mounted on a logging cable with a TEFZEL insulation. The resistivity of the platinum sensor was measured with a high impedance ohmmeter (Fluke 8022A Multimeter). The accuracy of the measurement is within ±0.5°C, and uncertainties in the calibration are less than 0.02°C. The temperature profile of September 1980 is shown in Fig. 2. Most of the following interpreations are based on this profile.

INTERPRETATION

General aspects

The temperature profile from the Surtsey borehole immediately shows several interesting features.

- The temperature is relatively high, having a mean value of 105°C.
- The absolute temperature and the temperature gradient vary substantially between different intervals in the hole.
- The maximum temperature, 141.3°C, is observed at 105 m depth, well below sea level, whereas the temperature decreases from that depth to the bottom of the hole, where the temperature is 40°C.

In the interpretation of the temperature profile observed in the hole the shape of the profile as well as the absolute temperature can be utilized.

An almost constant temperature of 100°C is measured between 15 m depth in the hole and mean sea level at 58 m. This results from boiling conditions at sea level. Since the observed temperature might only reflect the temperature inside the borehole it can not be concluded, from the temperature log alone, whether 100°C is the characteristic temperature of the tuff formation in this interval (Stefánsson & Steingrímsson 1980). However, bottom hole temperatures were measured (with a thermistor) intermittently during drilling. These measurements indicate a steep increase in temperature from the surface down to 15-20 m depth (Fig. 2), where a temperature of approximately 100°C is observed. Furthermore the temperature at 1 m depth at a site approximately 100 m from the site of the drillhole was 100°C in August 1970 according to Jóhannesson (1972). The above observations indicate that the interval between 15 m and 58 m is characterized by boiling. Thus the heat transport in that interval is dominated by one-dimensional convection, where the steam phase is rising and the condensate moving downwards. Convective heat transfer has previously been suggested by Jakobsson (1972 and 1978).

A zero temperature gradient is also observed in the interval between 142 and 159 m depths. As the thermal gradient is negative in adjacent regions, a convective zone is not possible. It is considered likely that this results from heat advection through a highly permeable layer in connection with the ocean.

Furthermore, the temperature decreases from 160 m depth down to the contact between the island and the old sea floor. It seems likely that there is another highly permeable layer at the

TABLE I

Estimates of the changes in temperature with depth, for various intervals in the borehole.

Interval	ΔT/ /ΔZ	Comments
0—20 m	5—15°C/m	Bottom hole temperature during drilling
0—58	1.5	Temperature log of September 1980
15—58	0.06	Temperature log of September 1980, constant gradient
58—72	1.4	Temperature log of September 1980, constant gradient
130—140	—2.6	Temperature log of September 1980, constant gradient
170—180	—2.8	Temperature log of September 1980, constant gradient

contact cooling Surtsey from below. This hypothesis is supported by the loose material encountered when drilling below 176 m depth. At the present the maximum temperature in the Surtsey borehole is observed at 105 m depth which is near the center of the tuff/tephra pile.

Two measurements of the thermal conductivity of the Surtsey tuff have been performed yielding values of about 1 J/ms °C for the wet tuff (Lachenbruch, personal communication). Based on the fact that the conductivity of steam is more than an order of magnitude lower than that of water we will assume a value of 0.5 J/ms °C for the material above sea level, whereas the value 1 J/ms°C will be used below sea level. Oddsson (1982) estimates the porosity of the Surtsey tuff and obtains values between 30 and 50% and an average value of 40%. Oddsson also estimates the dry density of the tuff to be 1600 kg/m^3 on the average.

The heat source

Since it is virtually impossible that the present heat content of Surtsey is the heat leftover from the phreatic phase of the Surtsey eruption, stored in the tephra created during that phase, two hypotheses on the heat source of Surtsey have been proposed:

A. The surface thermal anomaly (Friedman & Williams 1970, Jakobsson 1972, Jóhannesson 1972) observed in Surtsey is the result of considerable amounts of pillow lava, from the initial phase of the Surtsey eruption, at the base of the island (Sigvaldason 1968, Jóhannesson 1978).
B. The thermal evolution of Surtsey results from intrusive activity during a late stage of the volcanic activity (December 1966 to January 1967) of the island (Jakobsson 1978, Jakobsson & Moore 1980).

No pillow lavas were cored in the borehole. However, a 13 m thick discontinuous dike complex was found at about 80 m depth (see Fig. 2).

We cannot exclude the possible presence of pillow lava in Surtsey on the basis of either the drill hole core or the temperature log, but the highly conspicuous cooling at the base of the island and the lack of pillow lava in the core indicate that a large body of pillow lava, on the old sea floor, is highly unlikely.

Based on these considerations we are tempted to propose intrusions as the main source of heat for the present temperature distribution in the vicinity of the Surtsey borehole. These intrusions were probably formed during the period of effusive activity of the crater Surtur I, from August 19th, 1966 to June 5th, 1967. During December 1966 to January 1967 several fissures opened inside and north of the crater Surtur I, a few of them erupting small amounts of lava (Thorarinsson 1968). It is believed that the intrusive activity occurred at the same time. In late 1968 heat was observed in the tephra north of Surtur I (Friedman & Williams 1970), and this heat flow has continued up to the present (Friedman et al. 1976, Jakobsson 1978, Jóhannesson 1978).

We can introduce a very simple one dimensional model to estimate the effects of the intrusions found in the core. In this model the following parameters are used:

h_t = the thickness of the tuff = 170 m
h_i = the thickness of the intrusions = 10 m
T_i = the initial temperature of the intrusions = 1100°C
C_i = the heat capacity of the intrusions = 1000 J/kg°C
ϱ_i = the density of the intrusions = 3000 kg/m^3
Φ = the average water content of the tuff 0.3 m^3/m^3
C_t = the average heat capacity of the tuff = $4200\Phi + 800(1-\Phi) = 1800$ J/kg°C
ϱ_t = the density of the tuff = 1900 kg/m^3

If we assume the system to be closed (no heat loss) we can estimate the equilibrium temperature change of the tuff by

$$\Delta T = \frac{h_i C_i \varrho_i T_i}{h_t C_t \varrho_t} \quad (1)$$

This equation gives a temperature change of approximately 60°C, an upper limit since all heat loss is neglected. The fact that this estimate is much lower than the present average temperature of the tuff, indicates that a greater total thickness of intrusive material is needed to explain the heat content of the island, in the vicinity of the borehole, or that the initial temperature of the tuff was at least 45°C.

We can use the same simple approach to estimate the volume of intrusions needed to explain the average temperature, assuming the initial temperature to have been 5°C. Before we do that the heat lost from the island (in the vicinity of the hole) should be estimated. This can be done by the equation for heat conduction

$$Q = k\,dT/dz \quad (2)$$

where

Q = heat flow per unit area, per unit time
k = thermal conductivity
dT/dz = temperature gradient

and by utilizing the data in Table I.

We estimate the heat loss through the surface by assuming the near surface heat transport to be mainly conductive, even though convection is clearly important at other depths as can be seen later, and by using the temperature gradient of the uppermost 20 m (Table I) measured during drilling.

$$dT/dz = 15°C/m$$

and

$$k = 0.5 \ J/ms°C$$

We obtain the present value

$$Q = 7.5 \ W/m^2$$

Several observation (Friedman et.al. 1976, Jakobsson 1978, Jóhannesson 1978) inticate that this heat flow has been decreasing for the last 9 years. We will therefore assume the average conductive heat flux to have been twice this value, or 15 W/m^2, for the last 13 years.

The above assumption of pure conduction in the uppermost meters may not be valid since the annual precipitation in the Vestmannaeyjar area amounts to 1400 mm (Einarsson 1978). Less than 700 mm of the precipitation will evaporate (Einarsson 1972) and some of it will flow to the ocean. If we assume that 25% of the annual rainfall in the vicinity of the hole is vaporized we can account for this in the energy balance by raising the above heat flow estimate to about 30W/m^2. The present estimate of 7.5 W/m^2 is however an approximate lower limit which will be used later. It is noteworthy that the deuterium content of four samples of water vapor from Surtsey (Jakobsson 1978) is indicative of both sea water and meteoric origin. We estimate the heat lost by advection between 140 and 160 m by using

$$dT/dz = -2.6°C/m \text{ (Table I, 130–140m)}$$

and

$$k = 1.0 \ J/ms°C$$

and obtain

$$Q = 2.6 \ W/m^2$$

And the heat lost at the base of the island is similarily estimated to be

$$Q = 2.8 \ W/m^2$$

Consequently we estimate the total heat loss to have been

$$Q \simeq 35 \ W/m^2$$

on the average for the last 13 years, in the vicinity of the borehole. Or a total heat loss of

$$35 \ W/m^2 \cdot 13 \text{ years} = 1.4 \times 10^{10} \ J/m^2.$$

This value is only about 25% of the present heat stored in the tuff formation. This paradoxical result indicates that the considerable heat flow of 35 W/m^2 has not significantly influenced the thermal conditions of the formation around the hole.

Taking this heat loss into account we can now estimate approximately the volume fraction (χ) of intrusions needed to explain the average temperature observed in the hole. We obtain

$$\chi \simeq \frac{C_t \Delta T \varrho_t + Qt/h_t}{C_i T_i \varrho_i + C_t \Delta T \varrho_t} \qquad (3)$$

with the same notations as before and

$$\Delta T = 100°C$$

$$t = 13 \text{ years}$$

Equation (3) gives $\chi = 0.12$, or $h_i = 21$ m compared with the 10 m observed in the borehole. Since the heat loss estimated is only about 25% of the heat content, χ is not very sensitive to uncertainties in Q.

Thus the results of the above estimate are that the excess heat content of Surtsey can be explained if about 12% of the volume of the formation, in the vicinity of the borehole, is intrusive material. Or in other words intrusions having a mean total thickness of about 20 m. If we take the area of the surface thermal anomaly around Surtur I in 1976 (0.2 km^2 based on Jakobsson 1978) to be the surface area of the intrusions we obtain a volume of very roughly 0.004 km^3.

So far the results have been based only on the observed mean temperature. The location of the temperature maximum is also of interest. It is located about 25 m below the intrusions found in the hole. This could result if the temperature is constant in time at the top and the bottom of the system. In Surtsey the temperature is constant at 58 m depth (sea level) and most likely at 144 m depth (see Fig. 2 and p. 104).

Consider a simple heat conduction model (for the theory of heat conduction see (Carslaw &

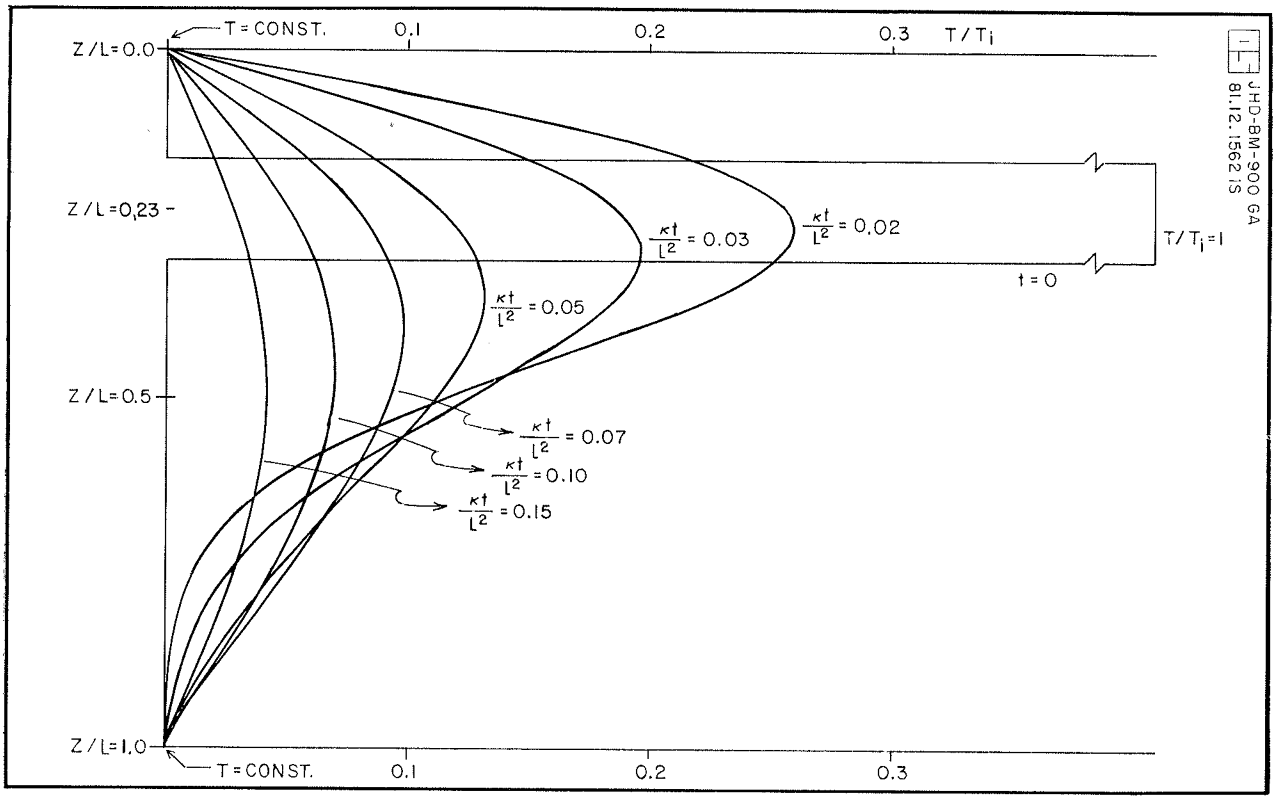

Fig. 3. The temperature distribution around an intrusion according to a simple heat conduction model.

Jaeger 1947) where a 1100°C hot intrusion of thickness d is emplaced asymmetrically in a layer of cold tuff of thickness l, at the time $t = 0$. The temperature is kept constant at the upper and lower boundaries of the tuff. Figure 3 shows the time evolution of the temperature distribution. It can be seen that the temperature maximum will migrate, by thermal conduction, to the center of the interval, regardless of the distribution of intrusions.

According to this model the temperature maximum in Surtsey should end up at 101 m depth. In 1979 and 1980 it is actually observed at 105 m depth. If the distribution of intrusions with depth in the formation near the hole is irregular the temperature distribution observed should be obtained when

$$\frac{\varkappa t}{l^2} \simeq 0.15 \qquad (4)$$

where

$\varkappa$ = thermal diffusivity = $k/\varrho c$
t = time since intrusive activity
l = thickness of tuff,

according to the above heat conduction model (Fig. 3).

Equation (4) can be used to estimate the effective diffusivity for the heat transport from the intrusions to the tuff formation. Using $t = 13.5$ years and $l = 90$ m we obtain $\varkappa_{eff} \simeq 3 \times 10^{-6}$ m^2/s. In the case of pure heat conduction the diffusivity for the tuff equals $\varkappa_{cond} = 3 \times 10^{-7}$ m^2/s. This indicates that conduction has not been the only mode of heat transfer below sea level in Surtsey, but that convection has been far more important.

Mode of heat transfer

The so-called Nusselt number is often employed in discussions of heat transfer. It is defined as the ratio between the total heat flux and the heat transferred by conduction alone (Elíasson 1973), that is

$$Nu = \frac{Q_{total}}{Q_{conduction}} \qquad (5)$$

We can now use the above estimate of the effective diffusivity (p. 106) to estimate roughly the average Nu number over the last 13½ years, for the interval between 58 and 144 m. As an approximation.

$$Nu \simeq \frac{\varkappa_{eff}}{\varkappa_{cond}} = 10.$$

We estimated previously that the minimum heat flux to the surface, in the vicinity of the Surtsey borehole, was presently of the order 7.5 W/m^2. Using the temperature gradient between 58 and

72 m in Table I, k = 1.0 J/ms°C and equation (2) we estimate the heat flux by conduction to be 1.4 W/m² in that interval. Assuming the heat flux in this interval to be the same as through the surface we can estimate the corresponding Nusselt number to be

$$\mathrm{Nu} \simeq \frac{7.5\ \mathrm{W/m^2}}{1.4\ \mathrm{W/m^2}} = 5$$

at the present. This present value is in good agreement with the value of 10 obtained above, as that value represents an average for the 13.5 year thermal history, whereas the value Nu = 5 is valid for the present thermal conditions in the interval just below sea level. In a similar way we can use the estimated heat flux through the surface of 7.5 W/m² to estimate the Nusselt number in the zone above sea level, by estimating the conductive heat flux in the interval 0—58 m to be

$$Q = k\Delta T/\Delta Z$$

with

$$k = 0.5\ \mathrm{J/ms°C}$$

and

$\Delta T/\Delta Z$ from Table I

we obtain

$$\mathrm{Nu} \simeq 10$$

This value should represent the present thermal conditions above sea level and corresponds to the value Nu ≃ 5 for the interval 58—72 m below sea level. Note that the thermal conductivity is assumed higher below sea level than above by a factor of 2.

The surface heat flux estimate was raised earlier to 30 W/m² in an attept to account for the energy lost in heating and vaporizing some of the precipitation. If we use this value instead of the minimum value of 7.5 W/m² we obtain Nu = 40 for the interval 0—58 m. This value is very high compared to most values presented elsewhere (Elder 1966, Elíasson 1973, Sondergeld & Turcotte 1977, Garg and Kassoy 1981) and not in agreement with the Nusselt number obtained from the effective diffusivity above. This seems to indicate that the precipitation does not influence the vertical heat transfer in the vicinity of the Surtsey borehole significantly.

Permeability of the Surtsey tuff

It has been argued above that convection is the most important mode of heat transfer in Surtsey. Thermal convenction in a water saturated porous layer is initiated when a critical Rayleigh number is exceeded. In a horizontal layer of thickness h and with a temperature difference ΔT, the Rayleigh number is given by

$$\mathrm{Ra} = \frac{\alpha g\ \Delta T\ h\varrho^2\ C_p\ K}{\mu k} \qquad (6)$$

where

α = coefficient of thermal expansion of fluid
g = acceleration of gravity
ϱ = fluid density
C_p = specific heat of the fluid at constant pressure
K = permeability of the rock
μ = dynamic viscosity of the fluid
k = thermal conductivity of the saturated rock

The critical value for a layer containing a single phase fluid having constant thermal properties equals $4\pi^2$. However, it has been shown that the critical Rayleigh number ($\mathrm{Ra_c}$) is lowered substantially when the variations of the thermal properties of water with temperature are taken into account (Straus & Schubert 1977). Figure 4 shows the results of Straus & Schubert (1977) on the relationship between $\mathrm{Ra_c}$ and the relative temperature difference, as presented by Garg & Kassoy (1981).

A relationship, for liquid water, between the Rayleigh and Nusselt numbers has been found empirically (Combarnous 1978) as well as theoretically (Garg & Kassoy 1981). Combining these results, the relationship can be expressed approximately

$$\mathrm{Ra} \simeq \mathrm{Nu} \cdot \mathrm{Ra_c} \qquad (7)$$

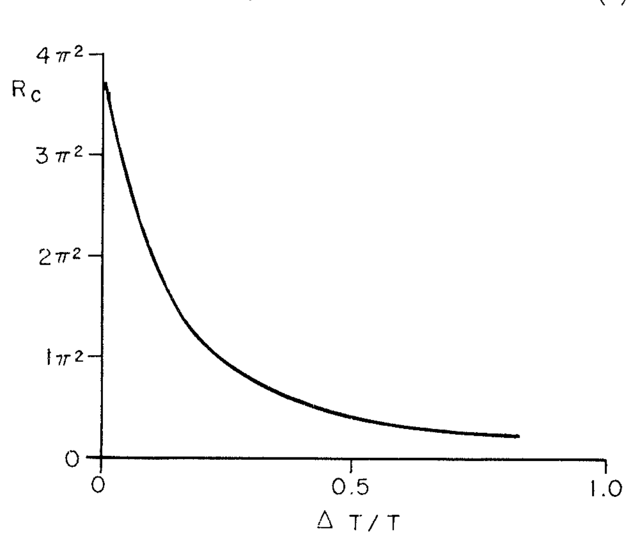

Fig. 4. The critical Rayleigh number as a function of the relative temperature difference (Garg & Kassoy 1981).

By using the previous estimate of the Nusselt number (p. 108), Fig. 4 and equations (6) and (7) we can estimate the permeability of the altered Surtsey tuff. Between the sea level at 58 m and 100 m depth, where we have estimated Nu $\simeq$ 5, there is a temperature difference of 40°C. By using Figure 4 we obtain $Ra_c \simeq 10$ and by equation (7) we estimate the Rayleigh number to be approximately 50. Using the following parameters

$\alpha = 8 \times 10^{-4} °C^{-1}$
$\varrho = 940$ kg/m³
$C_p = 4200$ J/kg°C
$\mu = 2.4 \times 10^{-4}$ kg/ms
$k = 1.0$ J/ms°C

and equation (6) we obtain

$K \simeq 2.5 \times 10^{-13}$ m² = 250 milli darcy as an estimate for the permeability between 58 and 100 m depths in 1980.

This method can not be employed to estimate the permeability above sea level in Surtsey, since a relationship between the Ra and Nu numbers for two phase convenction is not known to us. If the interval between 15 and 58 m contained liquid water instead of a steam-water mixture we would expect (based on different temperature gradients and Nu numbers) the permeability there to be about 100 times higher (i.e. 25 darcy) than below sea level. However, the results of Schubert & Straus (1977) indicate that porous layers with steam water mixtures are more susceptible to convection than are those containing only liquid water.

An alternative method to estimate the permeability above sea level is to assume the convection to be purely one-dimensional. We assume that the heat flux to the surface is carried by rising steam which condenses near the surface, where a liquid cap is formed (Schubert & Straus 1979, Sheu et.al. 1979, Straus & Schubert 1981). By using the minimum heat flux estimate $Q = 7.5$ W/m² we can estimate the mean vertical velocity of the steam

$$V_s = \frac{Q}{l\,\varrho_s} \simeq 5.5 \times 10^{-6} \text{ m/s}$$

where

l = latent heat of vaporization of water = 2.26×10^6 J/kg
ϱ = density of the steam = 0.6 kg/m³

According to Darcy's law the velocity of the rising steam equals

$$V_s = \frac{\chi K}{\mu_s}\left(\frac{dp}{dz} - \varrho_s g\right) \quad (8)$$

where

χ = relative permeability of rising steam $\simeq 1$
K = permeability
μ_s = dynamic viscosity of steam
p = pressure

If we assume the pressure to be controlled by the steam phase we have

$$p = \varrho_s g z$$

and

$$\frac{dp}{dz} \simeq \varrho_s g - g\varrho_s\alpha_s\Delta T$$

And using equation (8) we can derive

$$K = \frac{V_s\,\mu_s}{\chi g \varrho_s \alpha_s \Delta T} \quad (9)$$

Now using

$V_s = 5.5 \times 10^{-6}$ m/s
$\mu_s = 1.2 \times 10^{-5}$ kg/ms
$g = 9.8$ m/s²
$\varrho_s = 0.6$ kg/m³
$\alpha_s = 3.3 \times 10^{-2}$ °C⁻¹
$\Delta T = 2.5$ °C

we obtain

$K = 1.4 \times 10^{-10}$ m² = 140 darcy

for the permeability of the unaltered tuff above sea level in Surtsey. Whether the difference estimated between the permeabilities of the altered and unaltered tuff, by a factor of more than 500, is the cause for the different degree of alteration or the result thereof can not be confirmed at this point.

CONCLUSIONS

1. The fact that no pillow lava was found in the drill core of the Surtsey borehole and that substantial cooling is taking place at the base of the island favor the hypothesis that intrusions are responsible for the excess heat content of the formation around the hole rather than the hypothesis that the heat is the remainder of the initial heat in a hypothetical pillow lava.
2. The present heat content of the Surtsey tuff, in the vicinity of the borehole, can originate from intrusions with an average total thickness of roughly 20 m, compared to the 10 m of intrusions cored in the hole.

3. The heat transfer in Surtsey is dominated by hydrothermal convection, both above and below sea level. The interval above sea level is in fact considered to be a vapour dominated hydrothermal system. The heat transfer by convection is estimated to be up to ten times the heat flow by thermal conduction. The island is presumably cooled from below by advection.
4. The permeability of the altered Surtsey tuff between 58 and 100 m is estimated to be about 2.5×10^{-13} m^2 whereas the permeability of the unaltered tuff above sea level is estimated to be 1.4×10^{-10} m^2.
5. The observation that a large part of the original heat content of about 20 m of intrusions is still available in Surtsey, 13 years after the intrusive activity, puts a favorable perspective on the utilization of magmatic heat on Heimaey (Björnsson and Sigurgeirsson 1979) and elsewhere.

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Origin of natural remanent magnetization of tephra from the 1979 Surtsey drill hole, Iceland

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ABSTRACT

Magnetic properties of three tephra samples were studied in detail and one dike sample was also examined. The magnetic oxide grains in the dike have a minimum Curie temperature around 80° C. The tephra samples have somewhat higher Curie temperatures, and they have accurately recorded the geomagnetic inclination even though some were deposited below sea level. The mechanism of acquisition of the magnetic remanence in the tephra is probably oxidation of titanomagnetite to titanomaghemite, evidently in a hydrothermal environment. As oxidation and cooling proceed, the net magnetization of Surtsey volcano is expected to increase.

INTRODUCTION

The new volcano Surtsey, located southwest of Vestmannaeyjar (Westman Islands), Iceland, first broke the surface of the sea in late 1963, and eruptive activity ceased in mid-1967. The island is composed mainly of basaltic tephra but is covered by a carapace of lava on the southern and southwestern part (Thorarinsson 1967). In the summer of 1979, a cored hole was drilled on the east margin of the eastern vent and reached a depth of 181 m, which is 123 m below sea level and within a few meters of the pre-eruption sea floor. Almost all of the material penetrated by the hole is vesicular glassy basalt tuff (herein referred to as tephra); a 2-m-thick lava flow was found near the top, and a sub-vertical dike complex was encountered between 72 m and 85 m (Jakobsson & Moore 1980, 1982). Above sea level and below 150 m the tephra is fresh or only slightly altered, but there is a thick altered zone of palagonitized glass between about 80 m and 125 m. The extent of development of palagonite corresponds to a zone of elevated temperature that was measured in the hole after completion of drilling; the maximum temperature was 141° C at a depth of 105 m (Jakobsson & Moore 1982).

The objectives of this study were to estimate the content of magnetic minerals in the tephra (if any), to determine their composition and physical state, and to find out if the Surtsey tephra retained an accurate memory of the geomagnetic field.

EXPERIMENTAL RESULTS

Three core samples of basaltic tephra were analyzed. Recovery depths below ground surface and recovery temperatures are given in Table I. The samples are designated by their recovery depths. Samples 53.3 and 107.5 were well indurated, but sample 150.2 had to be partly impregnated with plastic. One oriented specimen (a core 2.5 cm in diameter) and several very small cores (300 to 400 mg) were cut from each sample. Saturation magnetization and thermomagnetic experiments were done on the small cores. Natural remanent magnetization measurements and conventional alternating-field demagnetizations were done on the oriented specimens.

Thermomagnetic curves for samples 53.3 and 107.5 are shown in Fig. 1. (Because of the plastic impregnation, no thermomagnetic curve could be obtained for sample 150.2.) Most of the iron in these tephra specimens is in paramagnetic form (in glass and silicate minerals), and in order to get

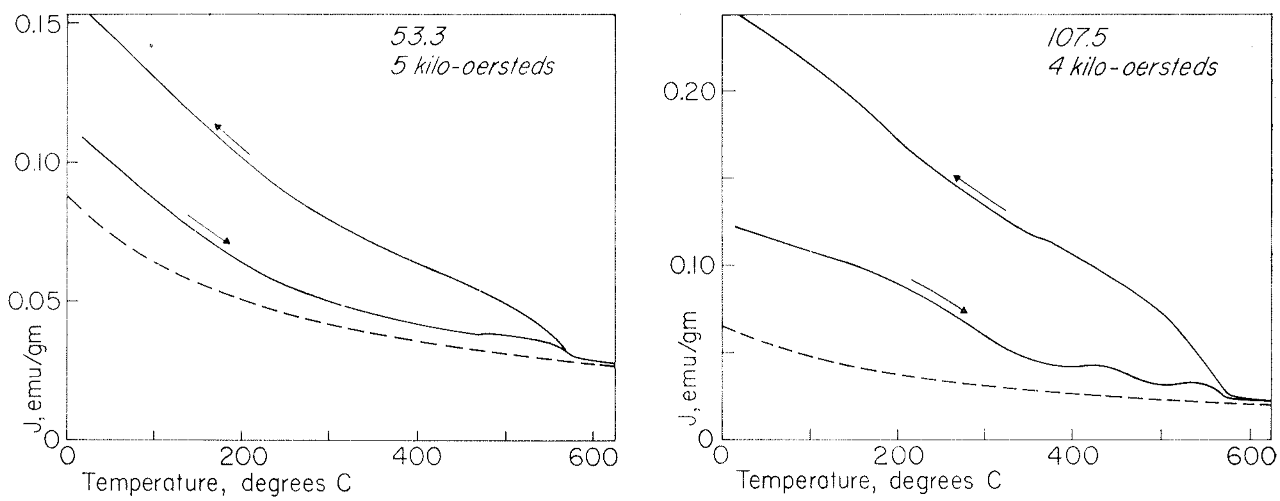

Fig. 1. Strong-field thermomagnetic curves for two tephra samples. Original recovery depths (m) and magnetizing fields are shown; J is specific magnetization. Heating and cooling curves are indicated by arrows. Experiments were done in nitrogen. Each dashed curve is the paramagnetic susceptibility, calculated using the simple Curie law and assuming that at 600°C nearly all the paramagnetism is due to iron in silicates and glass. Thus the ferrimagnetism in oxide minerals below the Curie temperature is the vertical difference between the dashed curve and the observed curve (not dashed).

an adequate signal from the small amounts of ferrimagnetic oxide present, very large inducing fields (5000 and 4000 oersteds) had to be used. The paramagnetic contributions to the thermomagnetic curves are shown in Fig. 1. These are obtained by assuming that the contribution to total magnetization of the iron in oxides at 600° C is very small and by using the simple Curie law to extrapolate the silicate paramagnetism down to room temperature. This extrapolation was confirmed by another experiment described below.

The two tephra specimens show markedly irreversible behavior. Large amounts of pure magnetite were produced during heating, commencing at about 350°–400° C. This irreversibility could arise in two ways: (1) oxidation of titanomagnetite to magnetite during heating, or (2) breakdown of cation-deficient titanomaghemite to magnetite plus other oxides during heating (Ozima and Ozima 1971). Owing to the large amounts of bound water present in the specimens, it was not possible to do the heating experiments in vacuum (which has been shown to supress oxidation effectively); instead, a nitrogen atmosphere was used. Because the tephra samples are so young and because formation of cation-deficient metastable titanomaghemite from stoichiometric titanomagnetite is evidently a process requiring long times and low temperatures (Gromme et al., 1979), oxidation during the experiment might seem to be a sufficient explanation for the irreversibility. Weight loss after heating was 3.2 percent for sample 53.3 and 7.7 percent for sample 107.5, so that oxidation could have been caused by water expelled from the palagonite. The apparent two-stage alteration in specimen 107.5, evinced by the two maxima on the heating curve (430° and 540° C), is quite unusual. The Curie temperatures of the original oxides are difficult to identify because alteration began at lower temperatures, but they are estimated as 250°±50° C for specimen 53.3 and 350°±50° C for specimen 107.5.

If we assume that these oxide minerals are stoichiometric titanomagnetite, then the corresponding mol fractions of ulvospinel in solid solution are roughly 0.45 and 0.35 for specimens 53.3 and 107.5, respectively. These values are significantly lower than the mol fraction 0.76 to 0.8 reported by Steinthórsson (1972) from a microprobe analysis of titanomagnetite in a sample of dolerite from Surtsey. Alternatively, we may assume that the original titanomagnetite in the tephra had the same composition as that in the dolerite. In this case the original Curie temperatures would have been approximately 0° C, and the fact that much higher ones are observed would be the result of natural low-temperature oxidation of titanomagnetite to titanomaghemite (Readman and O'Reilly 1972). Irving (1970) has suggested that such a process may be accelerated by moderate hydrothermal activity. If this interpretation is correct, then the extent of oxidation in specimen 53.3 is 80 percent, and in specimen 107.5 it is almost 100 percent (Gromme et al. 1979).

An attempt to resolve the question was made by examining some of the magnetic properties of a specimen of the dike rock retrieved from a depth of 74.1 m. The rock is well crystallized and contains approximately ten percent opaque minerals, but it is only moderately magnetic, having roughly three times the saturation magnetization (0.18 emu/gm) at room temperature as the average (0.054 emu/gm) of the tephra samples discussed below. The thermomagnetic curve for the dike rock is shown in Fig. 2. The starting temperature was close to that of liquid nitrogen, and the experiment was done in an argon atmosphere. Two magnetic phases are present, and the curve is similar to ones obtained from samples of Hawaiian lava-lake basalt (Gromme et al. 1969). The lower Curie temperature is approximately -140° C and represents a ferrian ilmenite. The higher Curie temperature is difficult to estimate; its minimum value is 80° C on the heating curve and 60° C on the cooling curve. This corresponds to a stoichiometric titanomagnetite containing roughly 70 mol percent of ulvospinel. Hence the unusually low Curie temperatures predicted by the chemical analyses published by Steinthórsson (1972) are partly confirmed, and it seems likely that the magnetic oxide in the tephra samples had the same or nearly the same original composition, but has subsequently been oxidized to titanomaghemite. Carmichael (1974) has reported Curie temperatures of 200° and 500° C for one specimen of Surtsey lava and a single Curie temperature of 550° C for a second, more oxidized specimen. These high Curie temperatures (500° C and above) are the result of high-temperature oxidation (Carmichael 1974, Gromme et al. 1969).

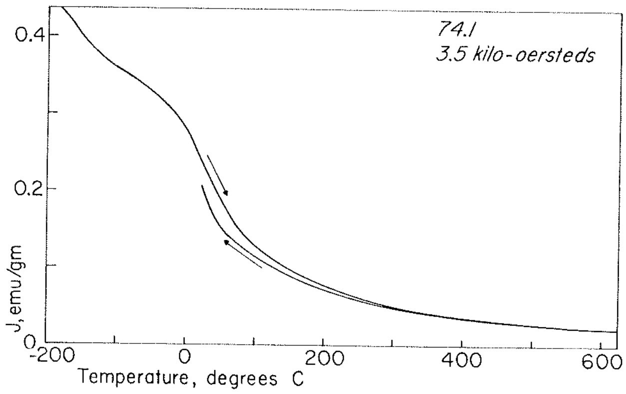

Fig. 2. Strong-field thermomagnetic curves for dike sample. Original recovery depth (m) and magnetizing field are shown; J is specific magnetization. Heating and cooling curves are indicated by arrows. Experiment was done in argon.

Strong-field isothermal magnetization data for all three tephra samples are shown in Fig. 3, representing the sum of both remanent and induced magnetizations. Magnetic saturation occurs at 3000 oersteds for sample 53.3, 4000 oersteds for sample 107.5, and 1500 oersteds for sample 150.2. Straight lines were fitted by least-squares to the collinear points in Fig. 3. The intercepts of the

TABLE I.
Magnetic and other properties

	Surtsey samples			Dredged pillow basalt
Depth, meters	53.3	107.5	150.2	
X_p, gm-1	1.7x10-5	1.7x10-5	1.8x10-5	n.d.
J_s, emu/gm	4.4x10-2	9.2x10-2	2.6x10-2	2.7x10-1
J_{rs}, emu/gm	2.5x10-2	4.7x10-2	1.4x10-2	1.2x10-1
J_{rs}/J_s	0.56	0.51	0.53	0.44
NRM, emu/gm	4.1x10-4	4.1x10-4	6.1x10-4	3.4x10-3
NRM/J_{rs}	0.02	0.01	0.04	0.03
MDF, oersteds	600	600	530	70—285
Inclination of NRM	81.5°	76.5°	83.0°	n.d.
T_c, degress C	250±50	350±50	n.d.	150—250
T(recovery), degrees C	50	140	65	4
Palagonite thickness, mm	0.06	0.5 (approx.)	<0.01	

Explanation: X_p is paramagnetic susceptibility.
J_s is saturation magnetization at room temperature.
J_{rs} is remanence after magnetization at room temperature in 9 kilo-oersteds.
NRM is natural remanent magnetization.
MDF is median destructive field.
T_c is Curie temperature.
Data for dredged pillow basalt are averages for six L-type fragments obtained near active spreading centers (Gromme et al. 1979), except for MDF which is the range observed in very young pillow basalt obtained from the median valley of the Mid-Atlantic Ridge (Ade-Hall et al. 1973, Johnson and Atwater 1977).
The geomagnetic inclination at Surtsey calculated from the 1965 I.G.R.F. coefficients is 75.5°.

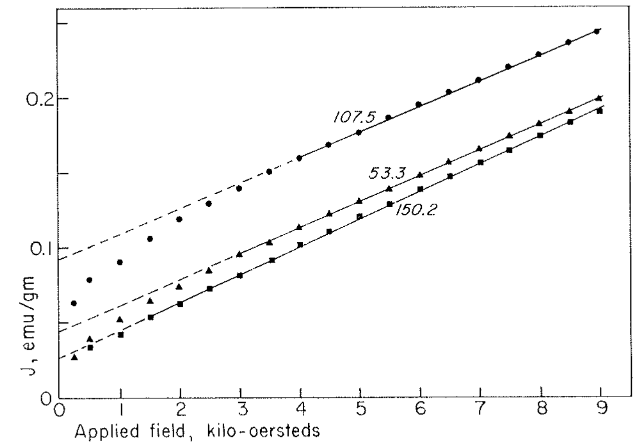

Fig. 3. Strong-field magnetization curves for three tephra samples. Recovery depths (m) of samples are shown; J is specific magnetization (remanent plus induced). The data were taken while reducing the applied field from 9000 oersteds to zero; thus they represent part of a hysteresis loop. Solid lines are least-squares fits to the points they encompass, and dashed lines are extrapolations to the zero-field ordinate.

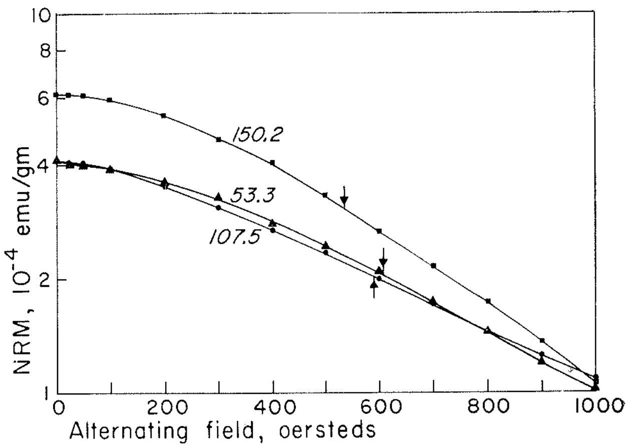

Fig. 4. Alternating-field demagnetization of natural remanent magnetization (NRM) in three tephra samples. Original recovery depths (m) are shown, and median destructive field (MDF) values are indicated by short arrows. Note the logarithmic scale used for NRM.

extrapolated least-squares lines on the magnetization axis are the values of saturation magnetization (J_s) of the ferrimagnetic oxide minerals in the samples (Table 1). The slope of the straight line at fields above saturation is the paramagnetic susceptibility of the iron-bearing silicate minerals and glass. The values of paramagnetic susceptibility (X_p) are essentially the same for all three samples (Table 1), and they are identical to the values obtained by extrapolating the Curie function from 600° C down to room temperature on the thermomagnetic diagram.

After the specimens were magnetized in 9000 oersteds, their saturation remanences were measured, and the values are given as J_{rs} in Table I. The ratio J_{rs}/J_s is a good indicator of the magnetic domain state of the oxides. For titanomagnetite, ratios below about 0.1 indicate multi-domain grains. For single-domain grains whose coercivities are controlled by uniaxial magnetostatic anisotropy (i.e., shape anisotropy of a randomly oriented assemblage of elongate grains), the ideal ratio is 0.50. For single-domain grains of magnetite or titanomagnetite whose coercivities are controlled by magnetocrystalline anisotropy (i.e., magnetization along [111] easy directions of a randomly oriented assemblage of equant grains), the ideal ratio is 0.87. Values between 0.1 and 0.5 represent either mixtures or pseudosingle-domain grains. For all three of the Surtsey samples the ratios are between 0.51 and 0.56. Such values are unusually high for basalts (except for some submarine pillows) and demonstrate that all of the titanomagnetite in the samples is within the single-domain size range. Depending on exact composition, this size range in titanomagnetite is certainly less than 1.0 micron and probably is between 0.6 and 0.1 microns (Dunlop 1981). Hence the oxide particle are probably virtually unobservable using a visible-light microscope.

The natural remanent magnetization (NRM) values and alternating field demagnetization curves of the oriented specimens are shown in Fig. 4. The specimens are magnetically hard, unusually so for basaltic rocks; the median destructive field (MDF) values are approximately 500 to 600 oersteds, and 10 percent of the NRM survives demagnetization at 1000 oersteds. These high values are in keeping with the observation that all the magnetic grains are single-domain. The specific intensities of NRM range from approximately $4x10^{-4}$ to $6x10^{-4}$ emu/gm. Considering the nature and mode of emplacement of these rocks, they carry an unexpectedly large NRM.

Table I is a summary of the magnetic properties of these specimens. For comparison, averages for selected dredged fragments of submarine basalt (L-type, most representative of new seafloor) are also given. J_s in the Surtsey specimens is much more variable than the paramagnetic susceptibility discussed above, and this reflects variations in both amount and composition of titanomagnetite or titanomaghemite. The uniformity of the paramagnetic susceptibility means that nearly all the iron is in paramagnetic form and that total iron content and its oxidation state are essentially the same in all three samples. There is roughly from one-third to one-tenth as much ferrimagnetic oxide in the Surtsey tephra as there is in unweathered dredged pillow basalt, and the amount in each tephra sample is definitely related to the extent of formation of palagonite (Table I).

A crude measure of the relative efficiency of acquisition of NRM is the ratio NRM/J_{rs} (assuming that the intensity of the geomagnetic field that produced the NRM was the same for all samples being compared). For the Surtsey samples this ratio ranges from 0.01 to 0.04, and for comparison the average value for the submarine pillows is 0.03. In other words, the mechanism of production of NRM in the Surtsey tephra was nearly as efficient, on the average, as the acquisition of thermoremanent magnetization (TRM) in submarine pillow basalt. The Surtsey tephra apparently recorded the geomagnetic field direction accurately as well. When probable orientation errors are considered, the measured inclinations (Table I) do not differ significantly from the present geomagnetic inclination at Surtsey. Moreover, the NRM directions did not change during demagnetization. The NRM of the tephra is sufficiently strong for a magnetic anomaly to be visible in a low altitude aeromagnetic survey, although magnetic effects of the overlying and underlying lavas would make such an anomaly difficult to distinguish.

DISCUSSION

The origin of the NRM in the tephra is something of a puzzle, in part because the thermal history of the samples is incompletely known. For example, dikes were encountered in the interval 72 to 85 m, and it is not known how close these or other dikes may be to other parts of the drill hole. We might suppose that both the maximum in the temperature profile at 105 m and the greater degree of induration of the upper two samples result from proximity of the dikes. Then if the NRM were TRM we would expect the lowest sample to be the least efficiently magnetized, but the opposite is true. Except in the immediate vicinity of dikes, the maximum temperature that any sample could have reached in situ is shown by the sea-water boiling curve (Jakobsson and Moore 1982). The measured Curie temperatures of the tephra samples are well above this curve, so that only a small fraction of the NRM in the tephra can be partial TRM. Depositional remanent magnetization (DRM) can be ruled out as well for several reasons. Many of the clasts are too large to have been oriented by the geomagnetic field as they settled through the sea water (or through air only in the case of sample 53.3). Even under optimal conditions of particle size, DRM is a very inefficient process compared to TRM. Finally, considering the turbulent state of an ash or tephra cloud during an eruption, it is improbable that the particles could have acquired coherent TRM's between the moment of eruption and the moment of deposition.

The NRM must have originated through an isothermal low-temperature processs, at least in the part of the volcano that is below sea level. The deepest specimen (150.2) has the most intense NRM and also shows the highest efficiency of NRM acquisition (Table I). Moreover, this specimen is virtually unaltered; the palagonite rinds are barely resolvable in an optical microscope (J.G. Moore, oral communication, 1982). It follows that the titanomagnetite responsible for the NRM must have formed in situ, evidently by precipitation from the basaltic glass (partial devitrification). The observation that the grain size of the titanomagnetite is less than 1 micron is supporting evidence for the plausibility of such a process. Under the circumstances the NRM would be a chemical or crystallization remanent magnetization (CRM). Although CRM has never been produced in titanomagnetite at low temperature in the laboratory, at higher temperatures (300° C—400° C) the efficiency of the mechanism of acquisition of CRM has been shown to be comparable to that of ordinary TRM under some circumstances (Kellogg et al. 1970).

Acquisition of NRM must have preceded the onset of the hydrothermal activity that caused extensive palagonitization higher in the tephra cone. The process of hydration of glass seems to have produced additional magnetic material, but it did not change the NRM appreciably. Note that sample 107.5 is almost completely altered whereas sample 53.3 is only moderately altered, yet they have identical NRM's. Low-temperature oxidation of titanomagnetite to titanomaghemite accompained the palagonitization of the glass, and the Curie temperature increased concomitantly. Arguing from the evidence of the dike sample, the Curie temperature of the original unoxidized titanomagnetite would have been high enough for the CRM to exist, and therefore the low-temperature oxidation would not have produced additional NRM, but would rather have diminished it somewhat (Gromme et al. 1979).

It is interesting that the Curie temperature of the dike sample (at 74.1 m) is lower than the temperature measured in the drill hole at that depth in late 1979. Hence at that time the dikes were essentially nonmagnetic. The abrupt increase that was observed in the magnetic field intensity just south of the summit (station Surtsey III) between 1968 and 1970 (Sigurgeirsson 1974) was probably due to cooling of the lava quite close beneath the observation station. The implication is that the net magnetization of Surtsey volcano has increased since that time owing to slow cooling of dikes, and it may still be increasing. The amount of increase would depend on the relative volume of such dikes.

ACKNOWLEDGEMENTS

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The geomorphology of Surtsey island in 1980

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INTRODUCTION

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

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

A GEOMORPHOLOGICAL MAP OF SURTSEY

General

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

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

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

The geomorphology of Surtsey

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

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

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

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

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

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

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

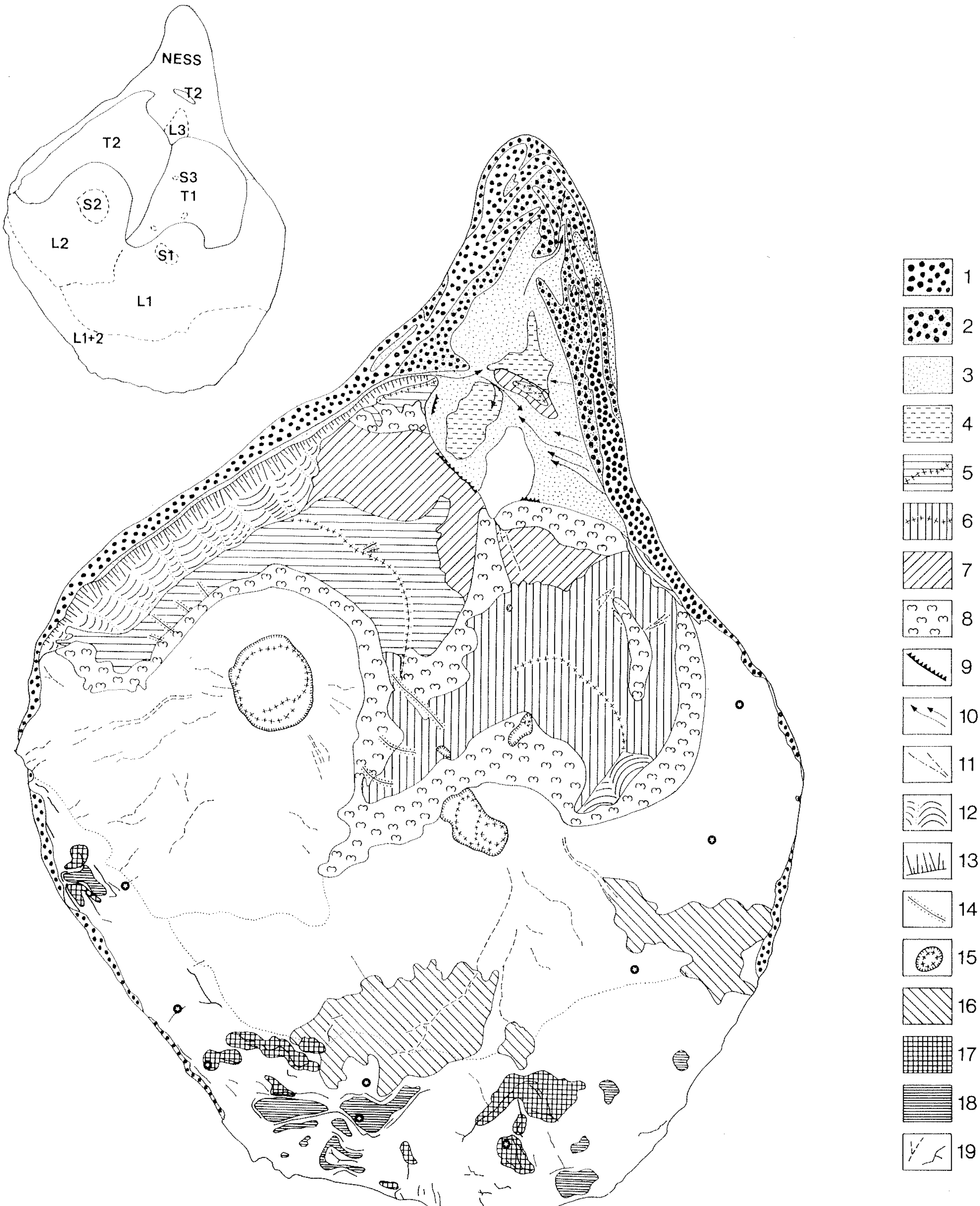

Fig. 2. Geomorphological map of Surtsey. Legend of inset map: S 1—3: the three main crater areas, L 1—3 the lava deposits of the three eruption sites, T 1—2 : tephra deposits.
Legend of main map: 1) Boulders deposited by wave action, 2) Boulders deposited by wave action, partly sand covered, 3) Sand,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

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

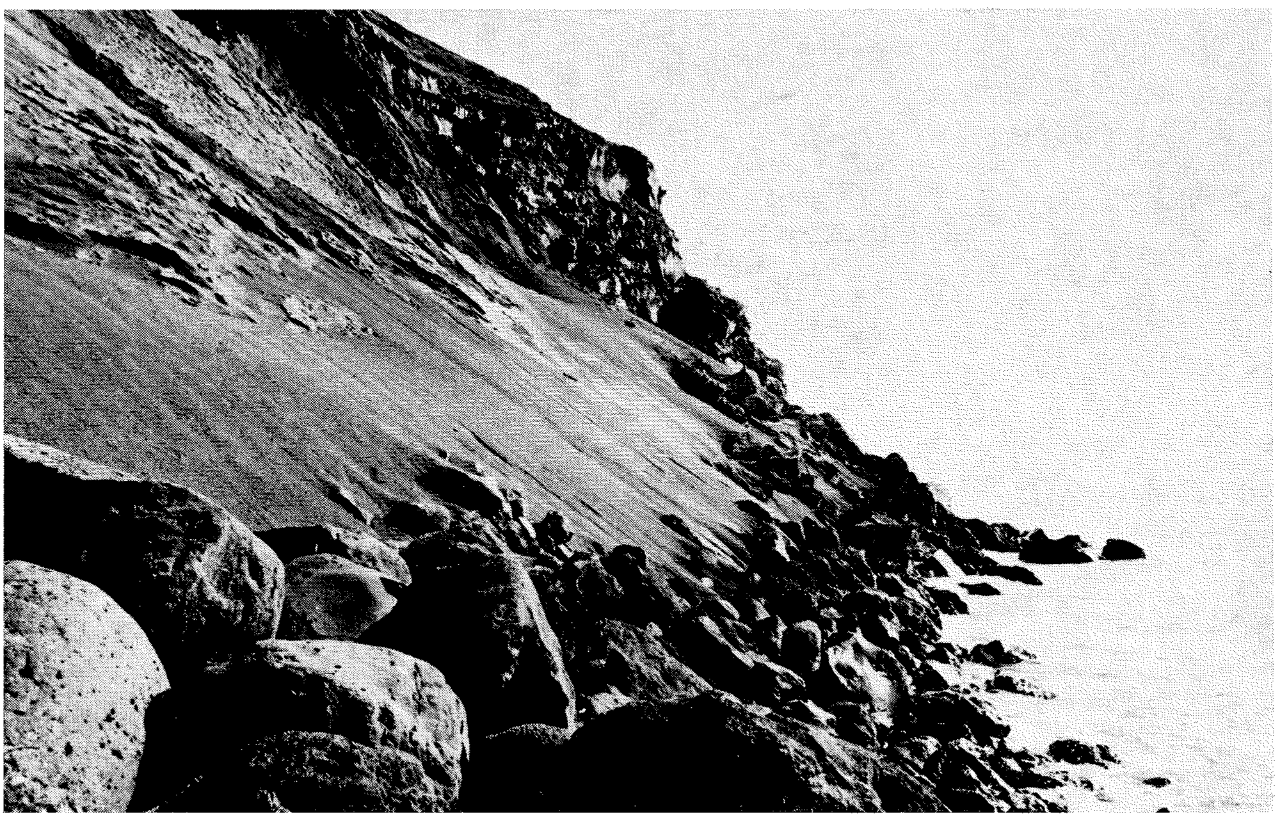

Fig. 4. The southern end of the western tephra cliff with a steep lava cliff in the background. Most of the shore terrace has been eroded by north-bound longshore drift and the talus material is gradually slipping into the sea. Note the angularity of the lava boulders abraded from the nearby cliff. Photograph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

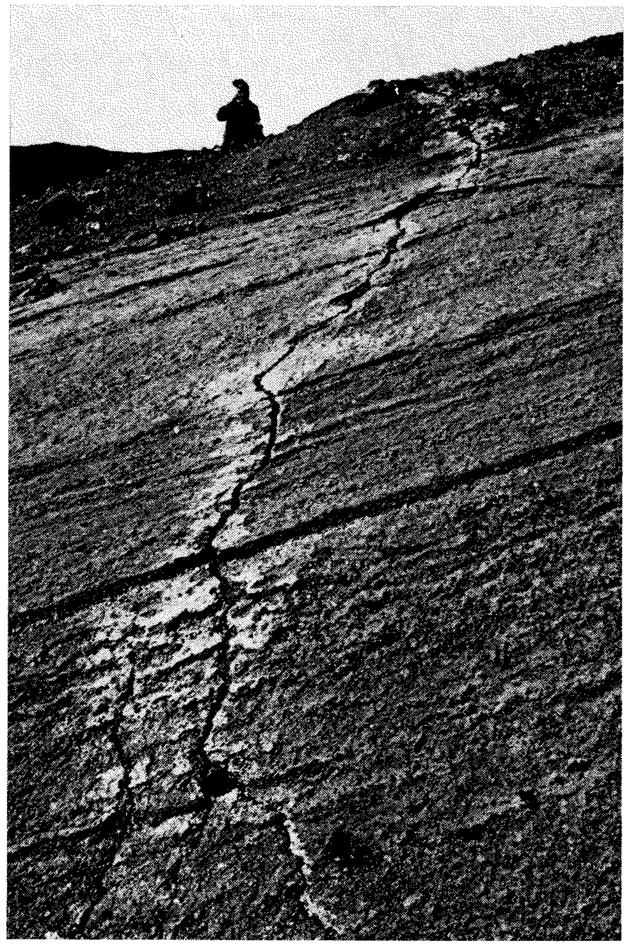

Fig. 5. Thermal fissure in palagonitized tephra (tuff) in the eastern cone. Photograph by B. Calles, June 1980.

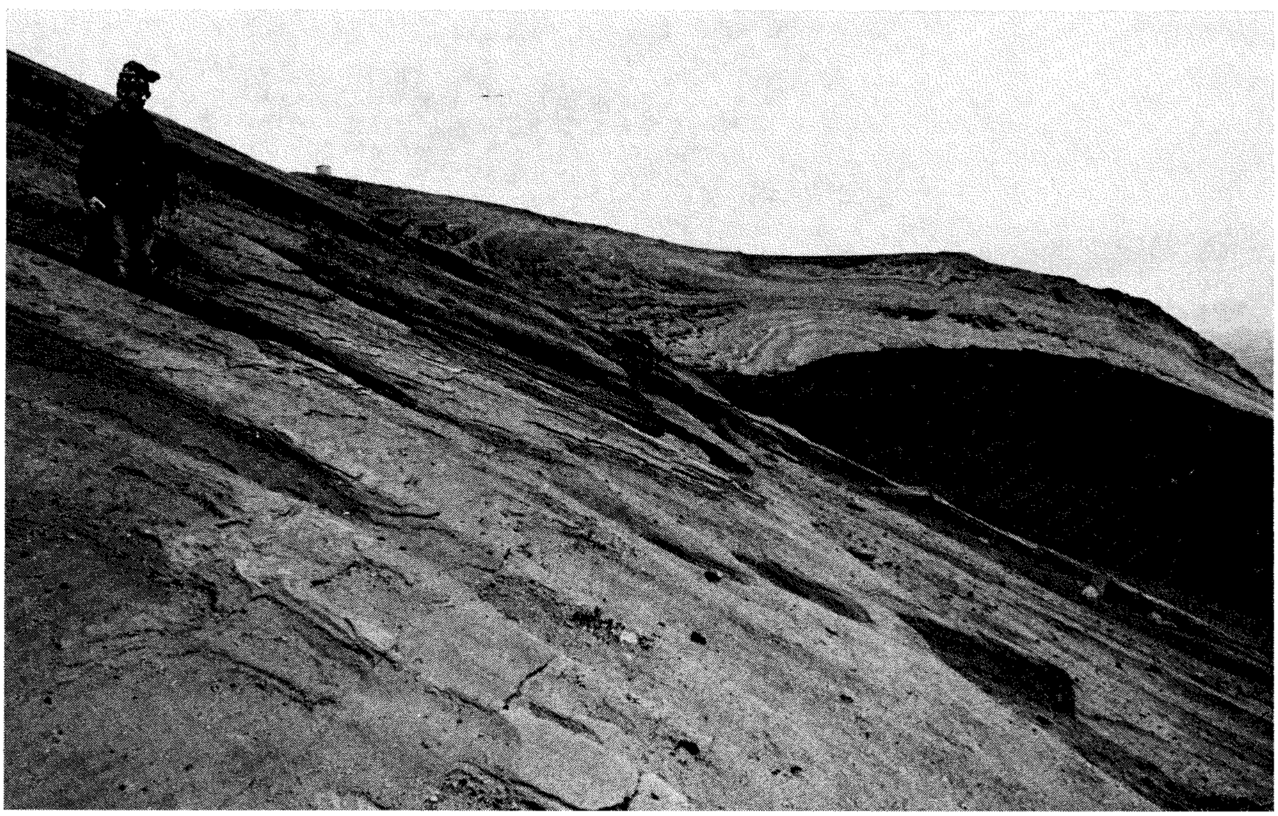

Fig. 6. Wind deflation of palagonitized tephra (tuff) in the eastern cone. Photograph by B. Calles, June 1980.

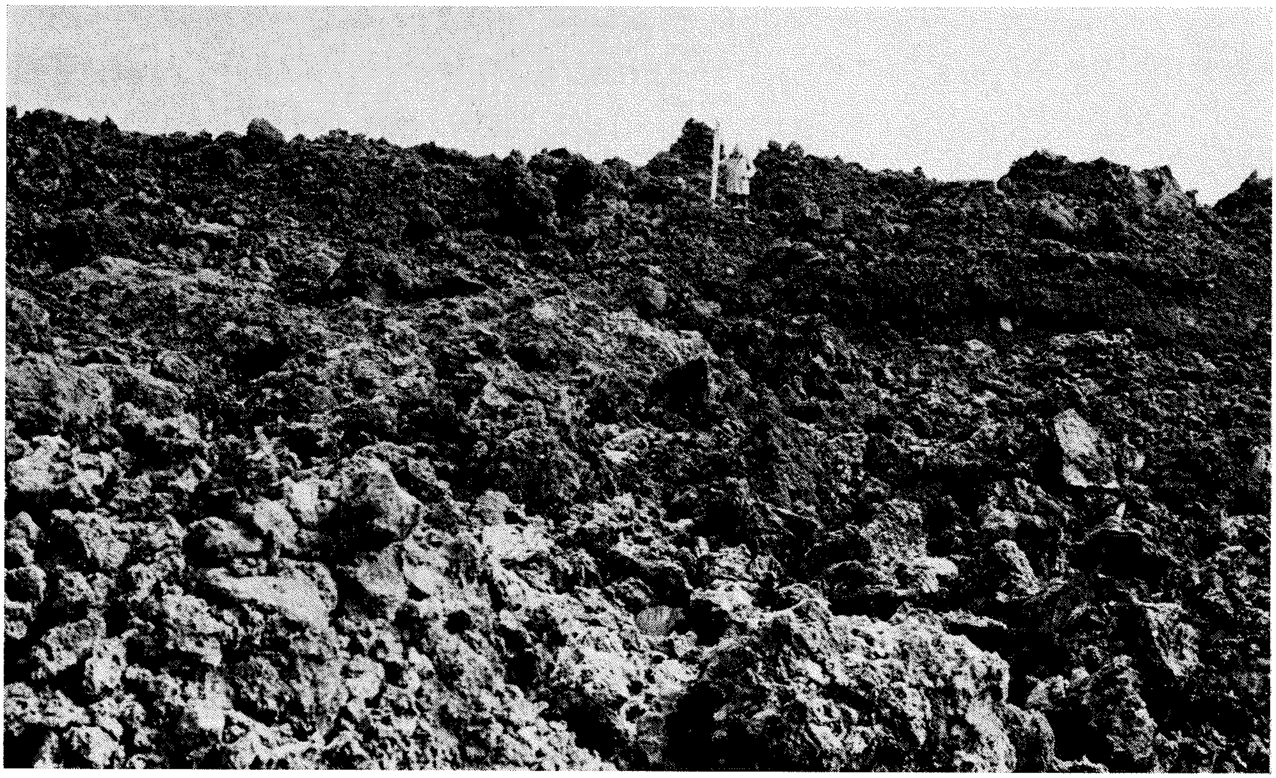

Fig. 7. Aa lava to the south of the eastern cone. Photograph by K. Lindé, June 1980.

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

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

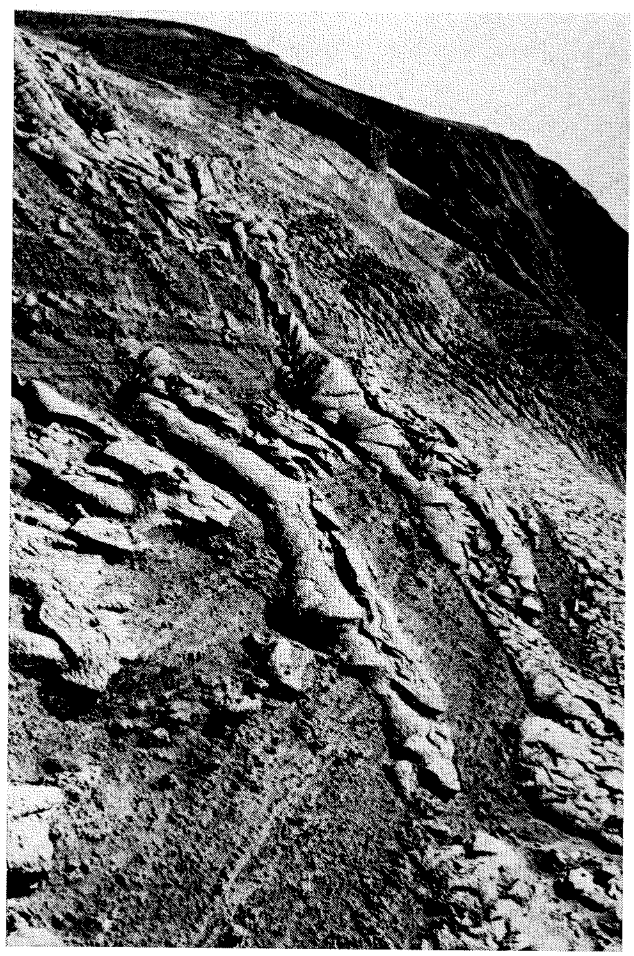

Fig. 10. Structures formed by wind action on a wet and silty material along the tephra wall of the western shore. The primary tephra structure is visible between the silt patches. Photograph by B. Calles, June 1980.

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

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

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

Mapping equipment

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

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

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

The resulting map

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

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

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

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

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

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

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

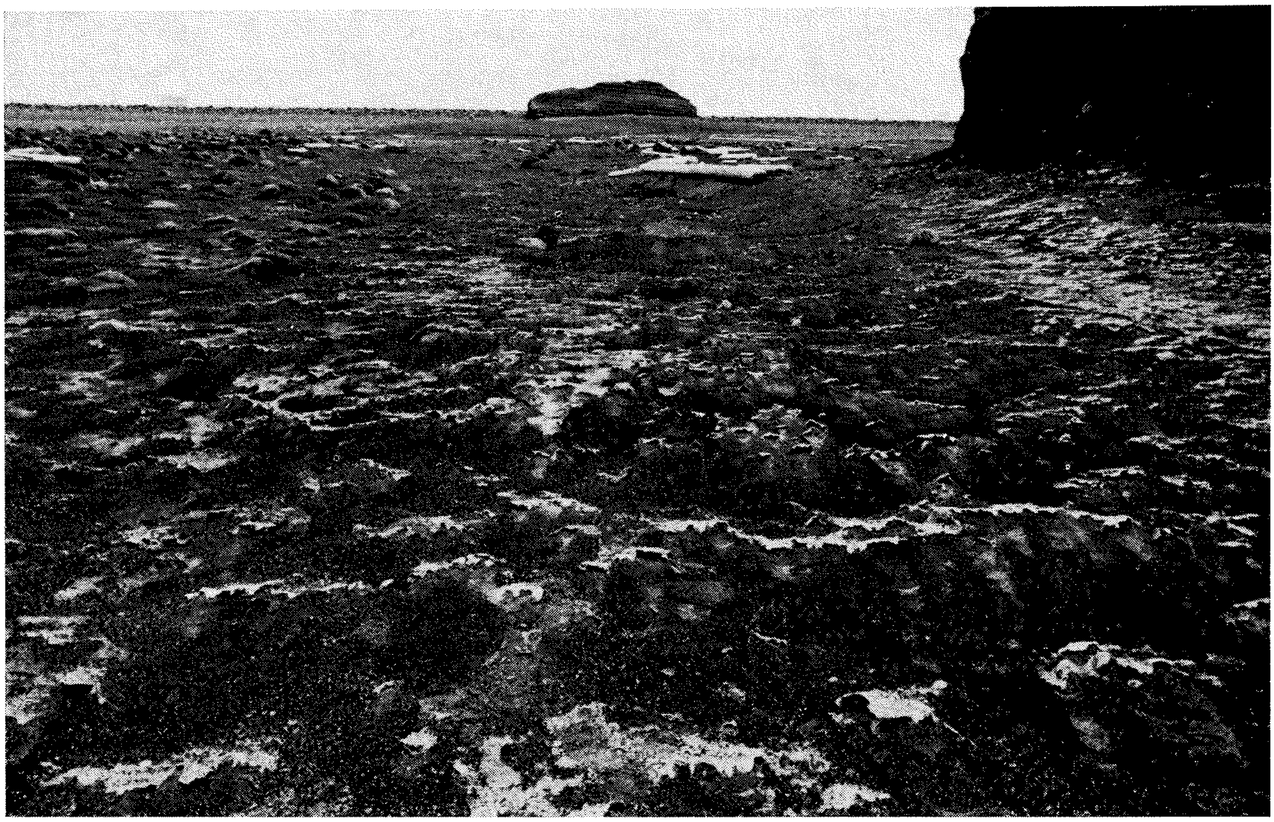

Fig. 11. View along overflow channel draining into the centre of the northern ness from the western shore. Driftwood stranded at 5 m above mean sea level. Flakes of wind-eroded silt left on the gravel bars. Photograph by B. Calles, June 1980.

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

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

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

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

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

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

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

SOME PHYSICAL PROPERTIES OF THE SURTSEY TEPHRA

Introduction

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

Density

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

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

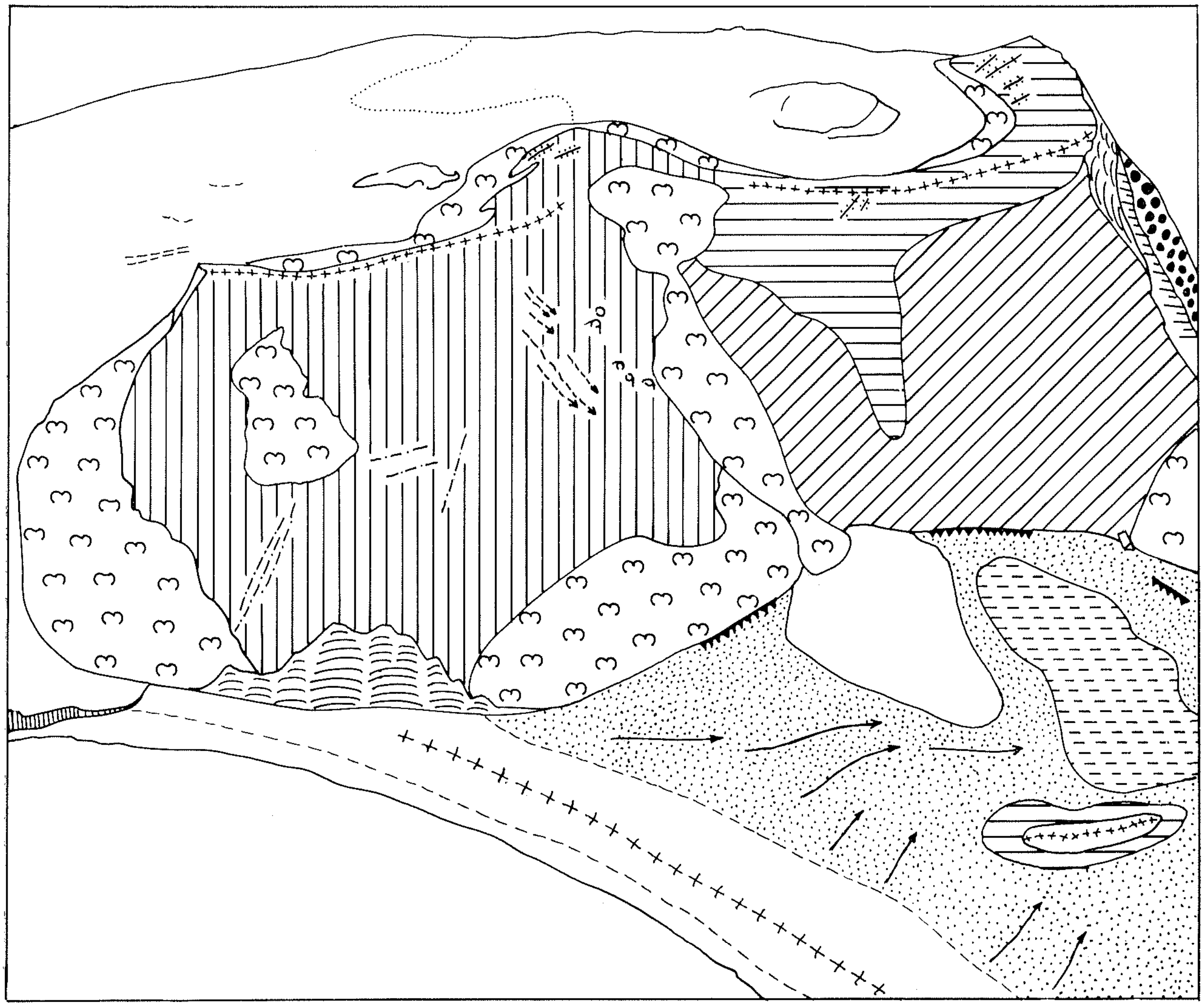

Fig. 13. Geomorphological interpretation of the picture in Fig. 12. For legend cf. Fig. 2. Hatched arrows indicate mudflows. The shore deposits in the foreground are divided into summer shore (foreground) and winter storm deposits with crest line (+++).

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

Settling velocity

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

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

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

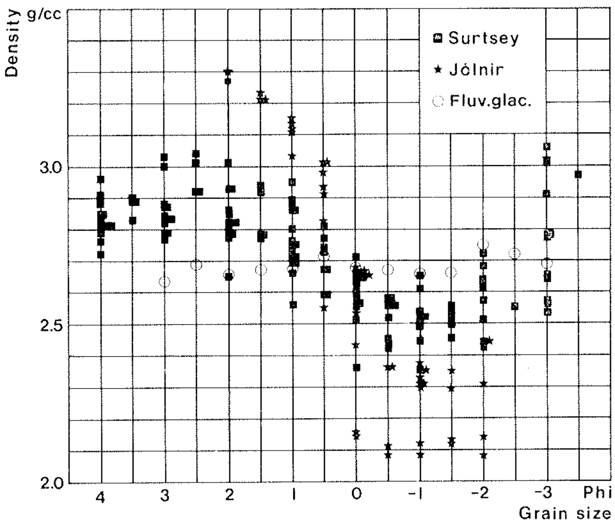

Fig. 14. Observed values of density of individual grain sizes. Samples of tephra from the Surtsey and Jólnir eruptions and Swedish fluvioglacial material of granitic composition.

TABLE I.

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

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

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

Critical erosion velocity

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

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

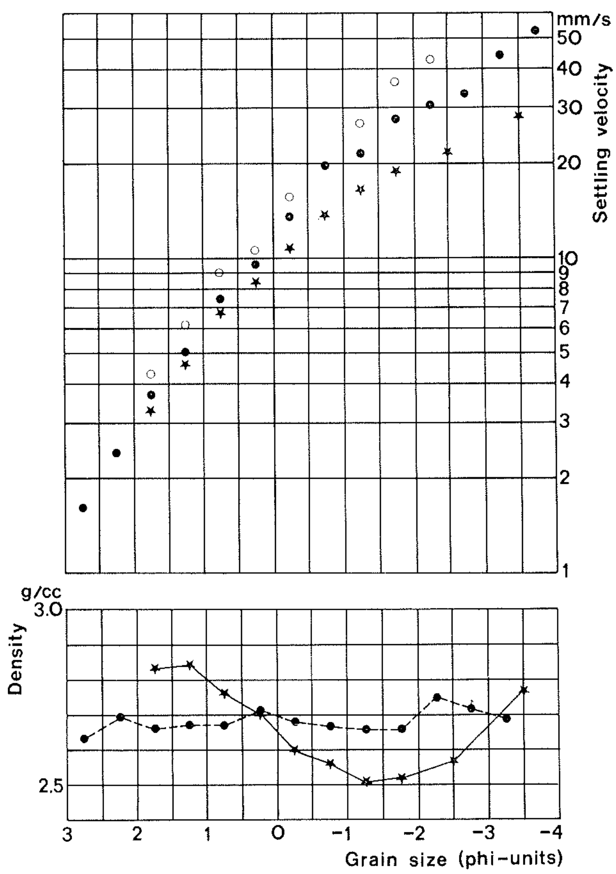

Fig. 15. Settling velocities and density of individual grain sizes. Glass beads: open circles, fluvioglacial material: black dots and Surtsey tephra: black stars.

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

Angle of repose.

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

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

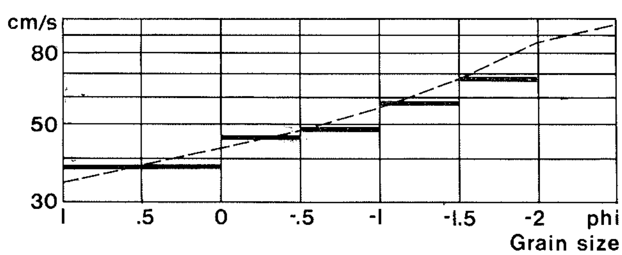

Fig. 16. Observed values on critical erosion velocity of Surtsey tephra compared with values obtained from Sundborg's curve after correction for density (— — —). Reference depth 0.1 metres.

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

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

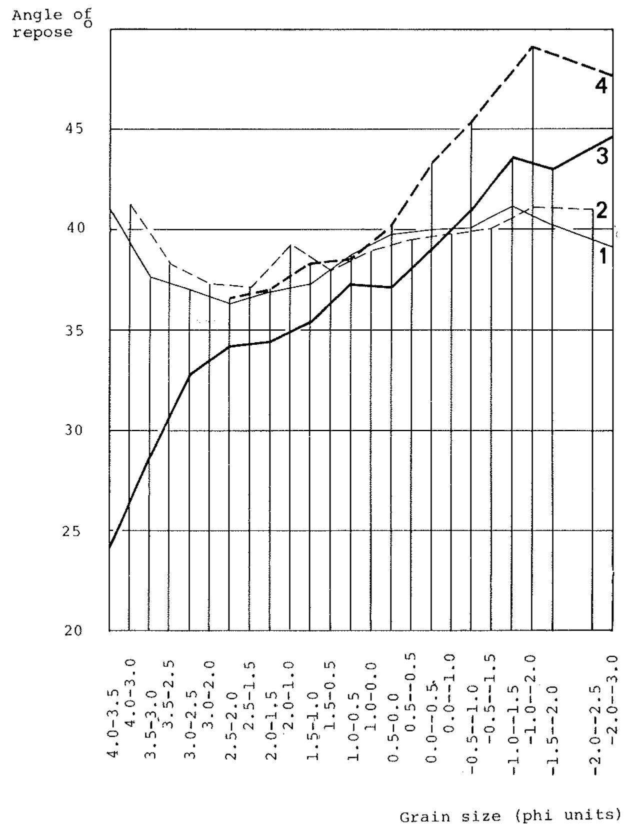

Fig. 17. Angle of repose of Surtsey tephra in different media. 1. ½ phi-units in air; 2. 1 phi-units in air; 3. ½ phi-units in water; 4. Inclination of distal slope produced in running water, ½ phi-units.

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

Summary

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

COASTAL CHANGES

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

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

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

Areal Changes

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

TABLE II.
Areal changes 1975—1980 (hectares)

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

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

ACKNOWLEDGEMENTS

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

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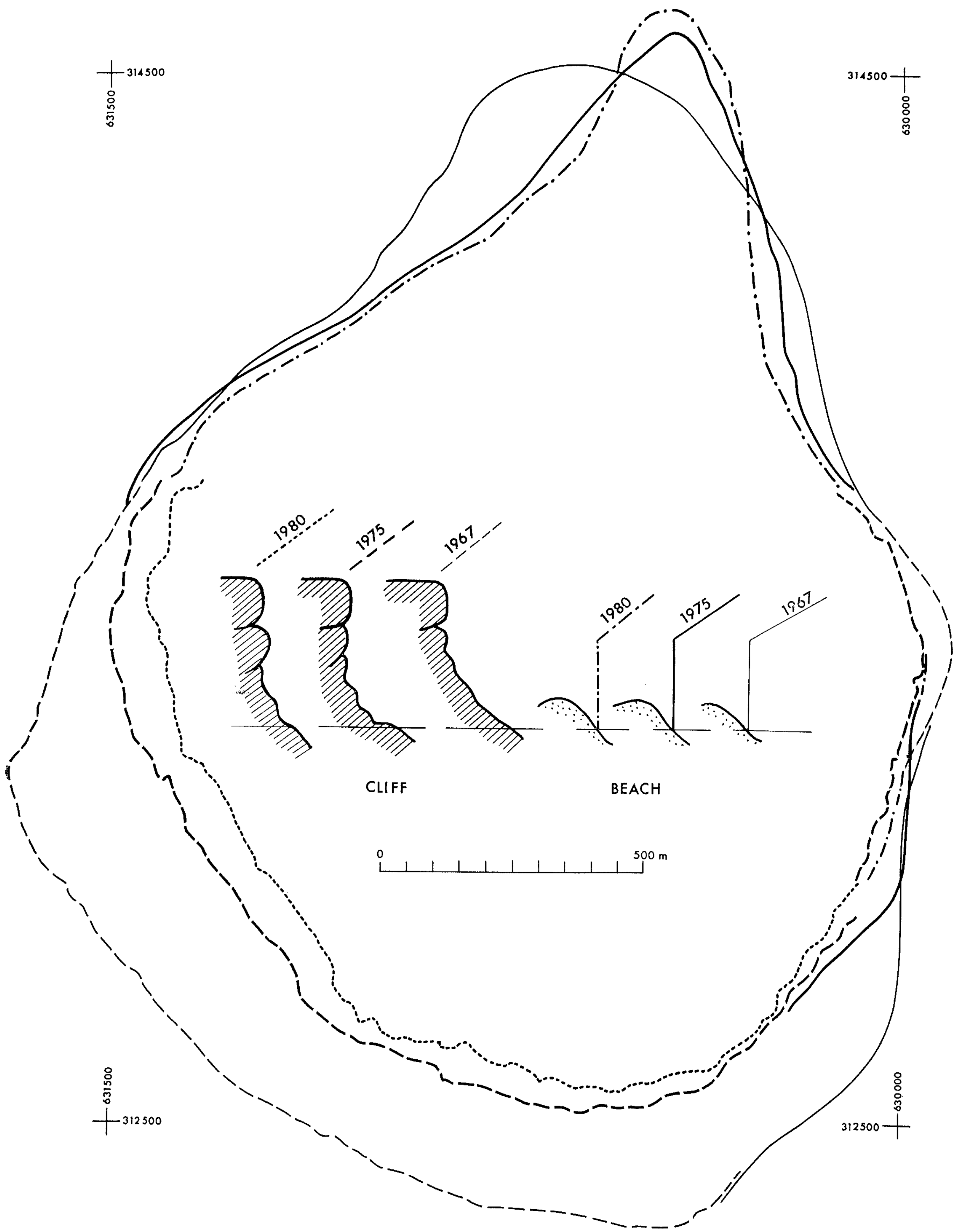

Fig. 18. Cliffline and shoreline of August 21, 1980, July 11, 1975 and July 17, 1967. Based on photographs by Landmaelingar Íslands and ground control by the authors.

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Some observations on the sediments of Surtsey

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INTRODUCTION

Surtsey is geomorphically very active. The island marks the southernmost point of Iceland (Fig. 1), and due to the relatively steep submarine slope, the ocean waves first break on the island itself (Norrman 1970). The tephra of Surtsey is still largely unconsolidated (Jakobsson 1972, 1978), and this, along with the lack of vegetational cover, allows wind and running water freely to erode the island. The purpose of the present investigation is to observe erosion and sedimentation on the island, and to map the distribution of the various sediments.

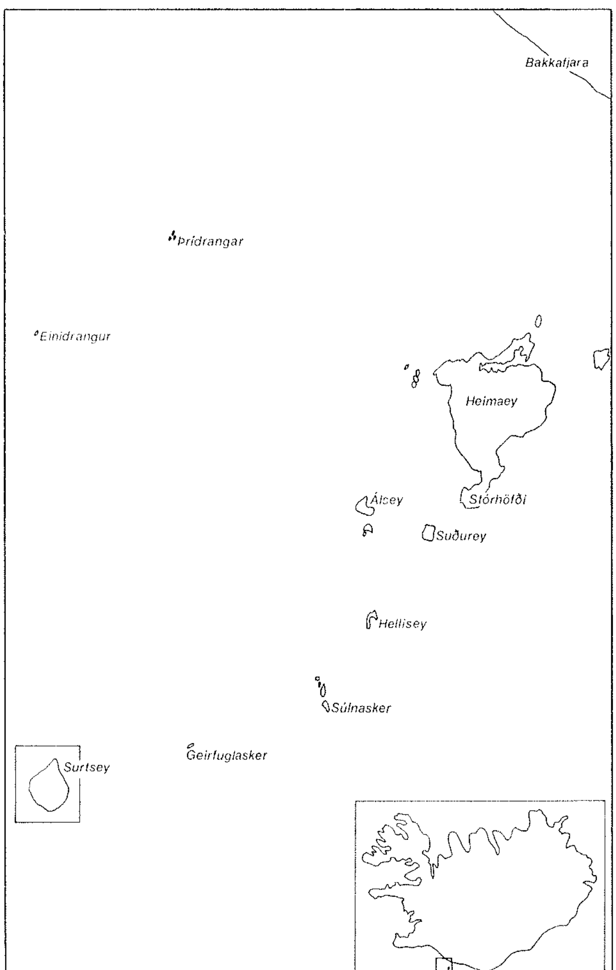

Fig. 1. A map showing the location of Surtsey.

Volcanic activity in Surtsey

Thorarinsson (1965a, 1965b, 1966, 1967, 1968) followed the course of events of volcanic activity in Surtsey. He also made valuable comments on the morphological development of the island. In a very brief summary, his observations were the following:

On the 14th of November 1963 it was first noticed that a submarine eruption was in process about 20 km SW of Heimaey. During the following days an island was built up, hooflike in shape, usually open towards SW. By the end of the year, the island had grown to the height of 145 m a.s.l., with a diameter of 1100 m. By that time only one crater, later to be called Surtur I (SI), was active.

On the 2nd of February 1964 volcanic activity started in another vent, Surtur II (SII), west of SI, and by 7th of February only SII was active. In April 1964 the phreatic activity had built a tephra wall thick enough to seal the vent off from the sea, and the eruption changed from phreatic to an effusive phase. For the next 13½ months lava flowed at intervals, considerably enlarging the island. On the 17th of May 1965 the activity of SII stopped.

During the next 14 months, phreatic eruptions built successively up two islands: Syrtlingur, ENE of Surtsey, and Jólnir, SW of Surtsey. Both islands reached a stage where they were more than 60 m in height and 650 m in length. The sea rapidly broke down the small islands after the volcanic activity stopped.

On the 19th of August 1966 effusive activity started in SI. Lava was seen flowing at intervals for the next 10 months, last on the 5th of June 1967. During this phase, few small parasitic cones around SI were active, but for a short time only, and without any considerable lava production.

Thorarinsson (1968) estimated the total production of eruptives during the Surtsey eruption to be $1.1-1.2 \times 10^9$ m^3, and he suggested that 70% of the total volume was tephra.

Review of research concerning the sediments of Surtsey

The contribution of Thorarinsson has already been mentioned. Norrman (1968, 1970, 1972a, 1972b, 1978, 1980) has monitored morphological changes in Surtsey, with special reference to the development of the northern ness and beach developments on the island. He points out, that costal erosion is rapid and that the coastline changes markedly from year to year. According to Norrman (1978, 1980) the coastal erosion amounts to 60 hectares between the years 1967 and 1975. Norrman et al. (1974) map the distribution of beach material on the island, and publish grain size distribution curves for 15 samples of sand from the lava area of Surtsey. Fridriksson et al. (1972) publish a substrate map of Surtsey, intended for comparison with a vegetation map compiled in 1970. Jakobsson (1971, 1972, 1978) discusses the consolidation and palagonitization of the Surtsey tephra, and publishes grain size distribution curves for some tephra samples (Jakobsson 1971). Sheridan (1972) deals with grain sizes of tephra and beach sand on the island. Lorenz (1974) discusses various aspects of the tephra, and deals with the structural properties of the tephra cones. Einarsson (1966) discusses various physical properties of the Surtsey tephra. Walker & Croasdale (1972) compare surtseyan tephra with strombolian-hawaiian tephra.

The origin of the Surtsey sediments

The primary source of unconsolidated sediments in Surtsey is tephra, formed during the phreatic phase of activity in SI and SII. The tephra is found bedded in the tephra cones, in the form of palagonite tuff and in the form of reworked sediments. Another source of sediments is the lava (Norrman et al. 1974).

Primary tephra is characterized by poor sorting and grain sizes ranging from silt to boulders, while eolian deposits are characterized by better sorting, and dominant grain sizes of silt and sand (Sheridan 1972, Norrman et al. 1974). Material transported by the force of gravity and running water is characterized by poor sorting (Norrman et al. 1974). The beach sand and the boulder ridge bordering the northern ness originate from two sources: a) glassy sand formed by fragmentation of the lava by rapid cooling when it entered the sea, and b) sand and boulders formed by the crushing effects of the breakers and grinding by the surf (Thorarinsson 1965b). Tephra eroded from the island constitutes but a small fraction of the beach sand (Thorarinsson 1967, Norrman 1968). A small fraction of the tephra found on Surtsey originates from phreatic activity in the small islands of Syrtlingur and Jólnir (Thorarinsson 1967).

METHODS AND TREATMENT OF DATA

The field work was carried out as a part time study in July and August 1979, with a check up in June 1980. Observations were made all over the island, with particular reference to structural and textural properties of the sediments. Many samples were collected for future analyses. When samples of tephra were collected, precautions were made to collect representative samples, usually from single beds, around 10 cm thick. Samples of eolian sands were collected as horizontal cores through dunes and ripples. One sample was collected from a deep pit formed by

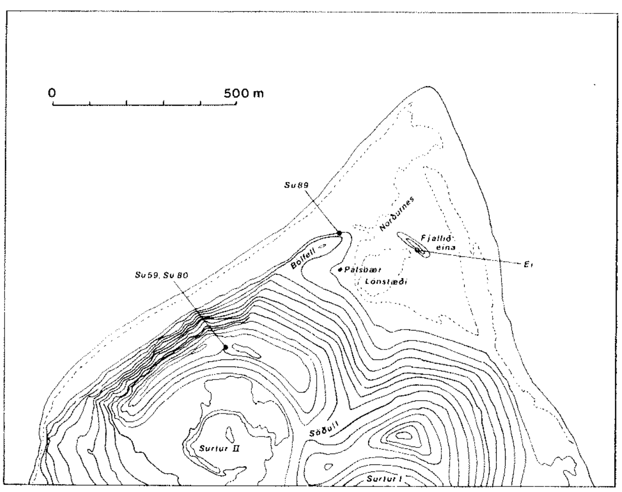

Fig. 2. Location of tephra samples. Major localities on the island: Pálsbaer: Scientist hut; Lónsstaedi: Old lagoon site; Nordurnes: Northern ness; Södull: Saddle. Base from Norrman (1978).

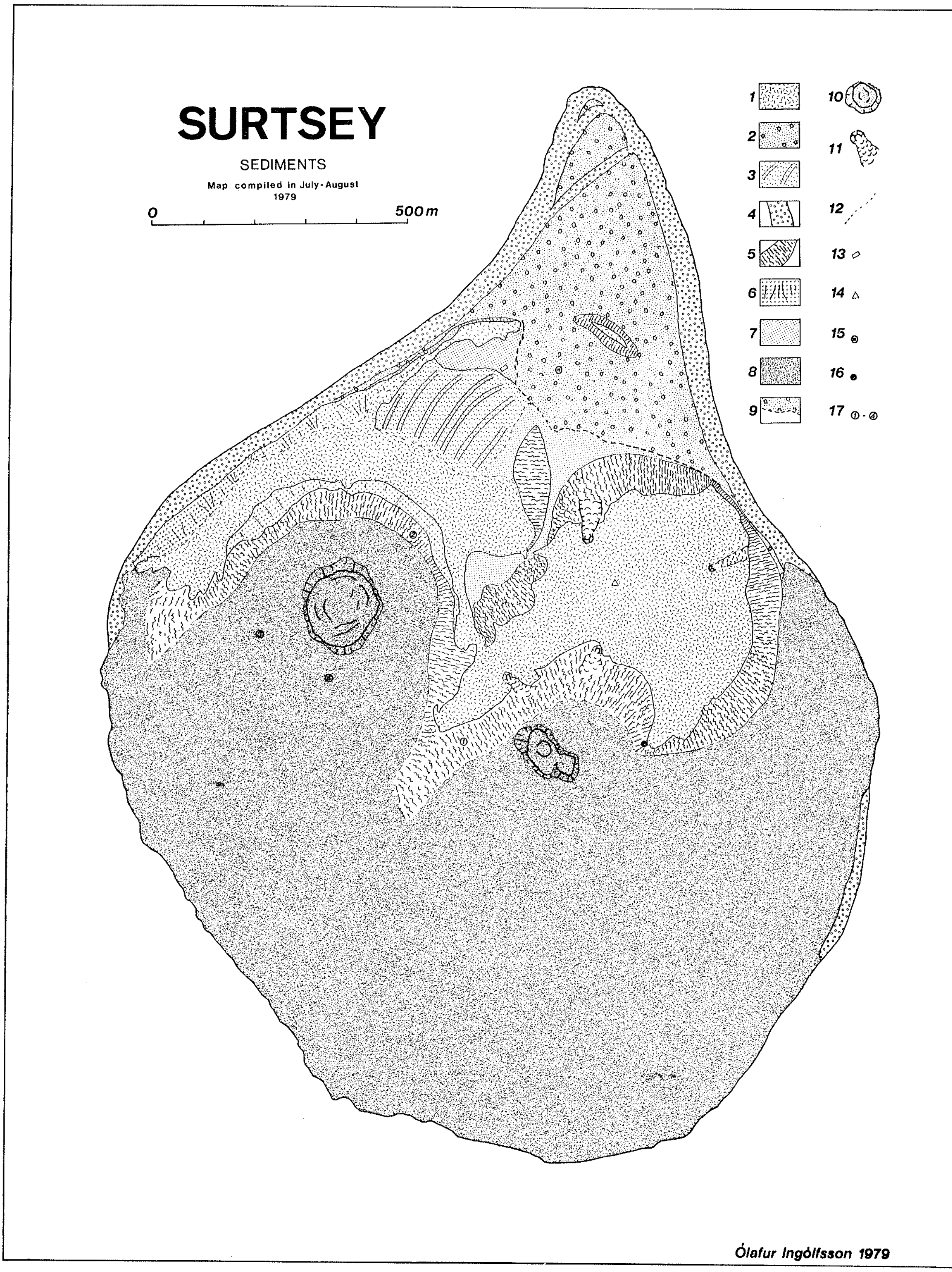

Fig. 3. Map showing the distribution of various sediments on Surtsey, as in the summer of 1979. Legend: 1) Tephra and palagonite tuff, 2) Beach sediments, 3) Mudflows and solifluction, 4) Boulder ridge, 5) Eolian sand in ripples and dunes, 6) Talus, 7) Assorted sediments, 8) Windblown sandcover on lava, 9) Evidence of swash as marked by driftwood, 10) Lava craters, 11) Parasitic cones, 12) Boundary not clear, 13) Pálsbaer (Scientist hut), 14) Lighthouse, 15) Pit in the old lagoon site, 16) Drill site, 17) Location of samples of eolian sand. Base of map: Air photograph of Surtsey, no. 4410, taken in July 1979 by the Icelandic Geodetic Survey.

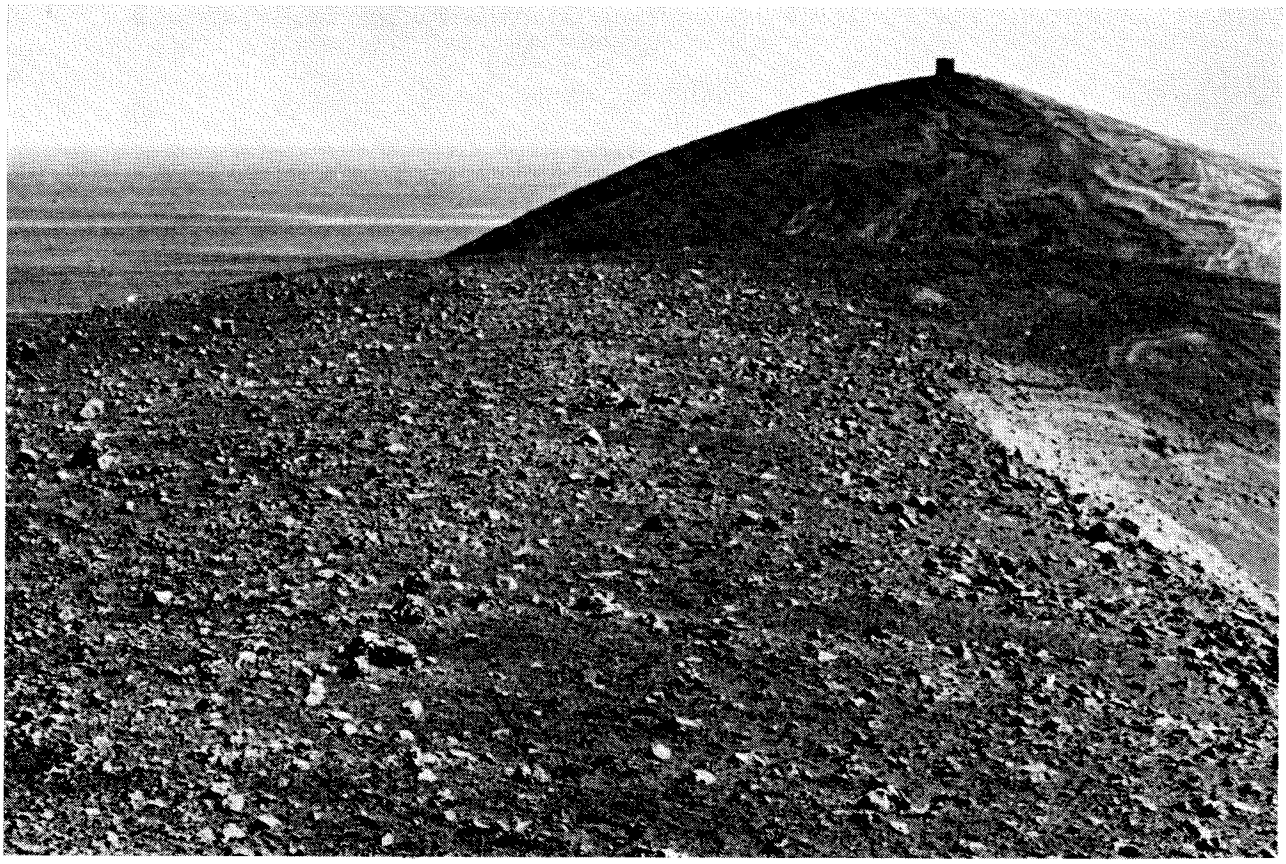

Fig. 4. Top of the SII tephra cone, viewing towards ESE. SI cone in background, with lighthouse on highest point.

a cave-in in the lava south of SII. The structure of the northern ness was observed in a pit dug in an old lagoon site on the inner part of the ness (Fig. 2). The size of the samples collected ranged from 250 to 600 grms.

After randomly halving the samples down to a size of 90—200 grms, they were washed in about 200 ml of distilled water. Jakobsson (1971) warns that seasalt may cause cohesion among the silt particles, which could cause the silt fraction to be underestimated if the samples were not washed before sieving. In order to check this statement, washed and unwashed parts of the samples were sieved for comparison. Only washed samples are represented in the grain size distribution curves in this paper. After washing, the samples were dryed for 24 hrs at 90°C, and then sieved with one phi interval. The grain size scale used is the phi scale, as proposed by Krumbein (1934). For calculating the mean, the equation presented by Folk & Ward (1957) was used, but equations presented by Inman (1952) for calculating sorting and skewness.

Figure 3 shows the distribution of the various sediments on Surtsey as mapped in the summer of 1979. The sediments of Surtsey have only been transported over short distances, so the classification of sediments in a given locality usually is matter of qualitative estimation. When preparing the map, units were chosen for each locality on the basis of which group of sediments was the most abundant one.

CLASSIFICATION AND RESULTS

Mapping unit 1: Tephra and palagonite tuff

Primary tephra is found in the tephra cones of SI and SII, in Bólfell and Fjallid eina (Figs. 2 and 3). Jakobsson (1978) points out, that consolidation and palagonitization of the tephra is almost entirely confined to the eastern tephra cone (SI). On the top of SII, pebbles to cobbles are the most abundant grain sizes (Fig. 4), as the wind blows away finer particles. Thorarinsson (personal communication, 1980) has monitored the lowering of the tephra cones due to wind erosion, taking readings from stakes, vertically inserted in the cone rims. According to his observations, the maximum denudation measured during the period July 1967 to August 1970 occured on the northern rim of SII, 92 cm. During the same period of time, the central part of the highest rim of SI was lowered by 52 cm. The maximum denudation during the period 1970

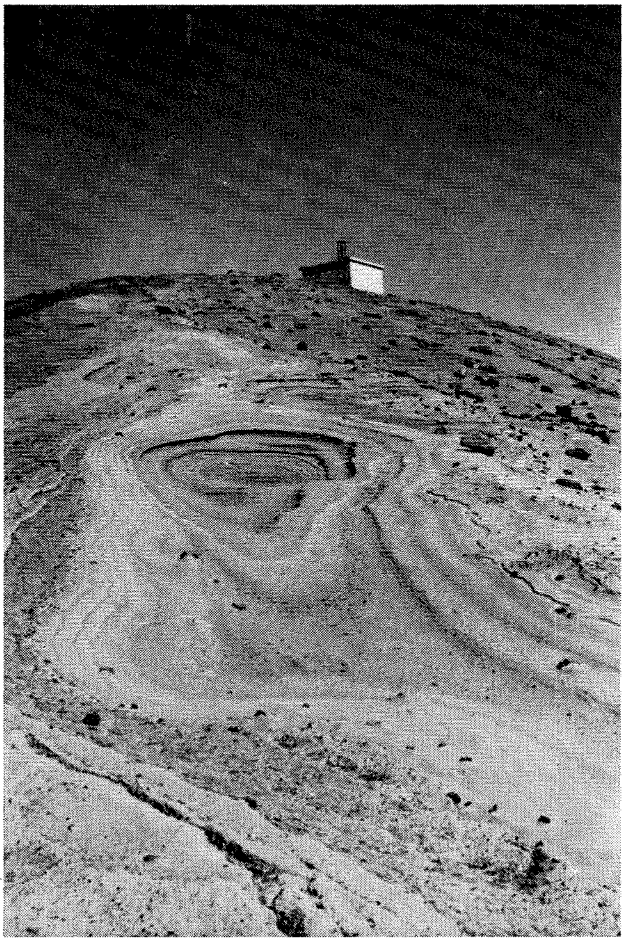

Fig. 5. Wind -eroded pothole in palagonite tuff on the interior of SI. The pothole is 0.4 m deep, with a diameter of 1.5 m.

to 1976 occured on the central rim of SI, 40 cm, but only 10 cm on the rim of SII. Between 1976 and 1979 the rim of SII was lowered by 5 cm. Thus the maximum denudation measured between the years 1967 and 1979 equals about 110 cm, and the rate of wind erosion on the tephra cones is slowing down. Thorarinsson (personal communication, 1980) estimates that since phreatic activity stopped in Surtsey, the maximum lowering of the tephra cones due to wind erosion equals 1.5—2.0 m.

The palagonite tuff on the interior slope of SI is being wind eroded, often resulting in erosional features such as potholes (Fig. 5). The erosion has left the small lavas from the parasitic cones on the interior of SI standing on pillars of palagonite tuff. By measuring the vertical pillar span, the average denudation on the interior of SI can be estimated to be 30—45 cm since the time of the lava flows (January 1967).

Four samples of tephra, collected by S. P. Jakobsson (Table I) were sieved (for location see Fig. 2). The results correspond fairly with those obtained by Sheridan (1972). The cumulative frequency curves (Fig. 6a) show the very poor sorting of the material, the curves bein concave in form as a result of high percentage of silt.

TABLE I
Size distribution parameters of tephra.

Sample no	Mz	Sorting	Skewness	Date coll.
Ei	1.28	2.77	0.21	1970
Su 59	0.06	3.25	0.40	7/7 1971
Su 80	—0.05	2.50	0.36	10/8 1974
Su 89	0.87	2.92	0.32	5/9 1975

After washing, two samples, Ei and Su 59, showed a bigger proportion of silt than before washing. Samples Su 80 and Su 89 showed no significant changes in the silt proportion after washing. Samples Ei and Su 59 were collected at an earlier date than samples Su 80 and Su 89 (Table I). The result that the older samples show changes in silt proportion after being washed, could lead to the conclusion that seasalt

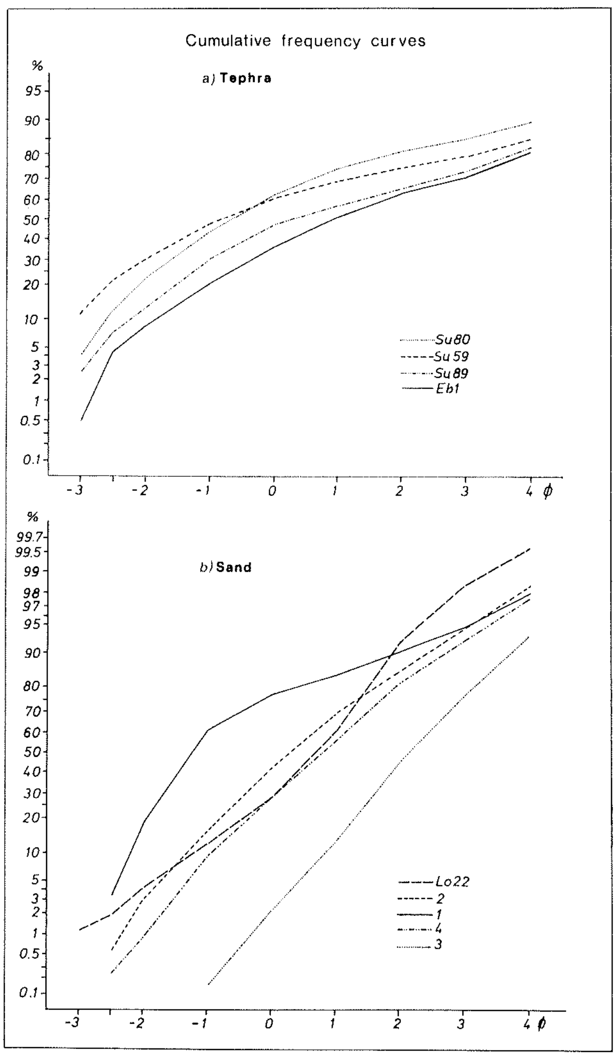

Fig. 6. Cumulative frequency curves.

indeed causes cohesion among the finer particles of the tephra, but is being washed away by rainwater as time passes. More data are needed to test this hypothesis further.

Mapping units 2 & 4 : Beach deposits

Beach deposits are mainly found north of the tephra cones. The most frequent wind directions in Surtsey are southerly- and easterly winds (Norrman 1970, Einarsson 1976) with corresponding wave directions. Norrman (1980) suggests that winds from WSW and SW are the most importand ones for the morphological development of the island. The SW-coast of Surtsey is constantly being eroded, and material is transported by ocean streams and wave action north along the east- and west coasts of the island. The northern ness is thus being built out, forming a cuspate foreland (Norrman 1970). The position of the ness is up to a point dependant on the most frequent wind directions, and has changed somewhat over the years (Norrman 1968, 1970, 1972a, 1972b, 1978, Norrman et al. 1974), though the average trend in recent years has been a move towards the east (Norrman 1980). The northern ness is bordered by a boulder ridge, reaching in some places 6 m a.s.l. At times, especially during heavy winter storms, the swash overrides the boulder ridge, carrying driftwood up to 5—6 m a.s.l. on the inner part of the ness.

The inner part of the ness was originally occupied by a lagoon, formed by large scale slumping and subsidence of the tephra pile (Norrman 1970). The lagoon was reduced in size by a small lava flow in January 1967 (Thorarinsson 1968), and has since then been gradually filled up by sediments. The surface of the former lagoon site is now roughly 2 m a.s.l. (Moore 1982), and the lava is almost entirely buried in sand.

In the summer of 1979 a pit was dug in the old lagoon site (for location see Fig. 3). In the walls of the pit, the structure of the lagoon filling could be observed (Fig. 7). The filling is built up of thin beds and laminae of silt, sand and gravel. The sand and silt appears to be deposited in water, with characteristic ripples and load casts. The silt-sand contact is frequently deformed, which could be due to the force of gravity in a saturated environment. A plausible explanation is, that swash, overriding the boulder ridge, carries material from the beach to the inner parts of the ness and deposites it there. The swash also erodes the foot of the tephra cones above the ness, and deposites the material in the area between the cones and the boulder ridge. The silt beds and laminae suggest that the area is flooded for some time, long enough to allow silt to be independently deposited from the water.

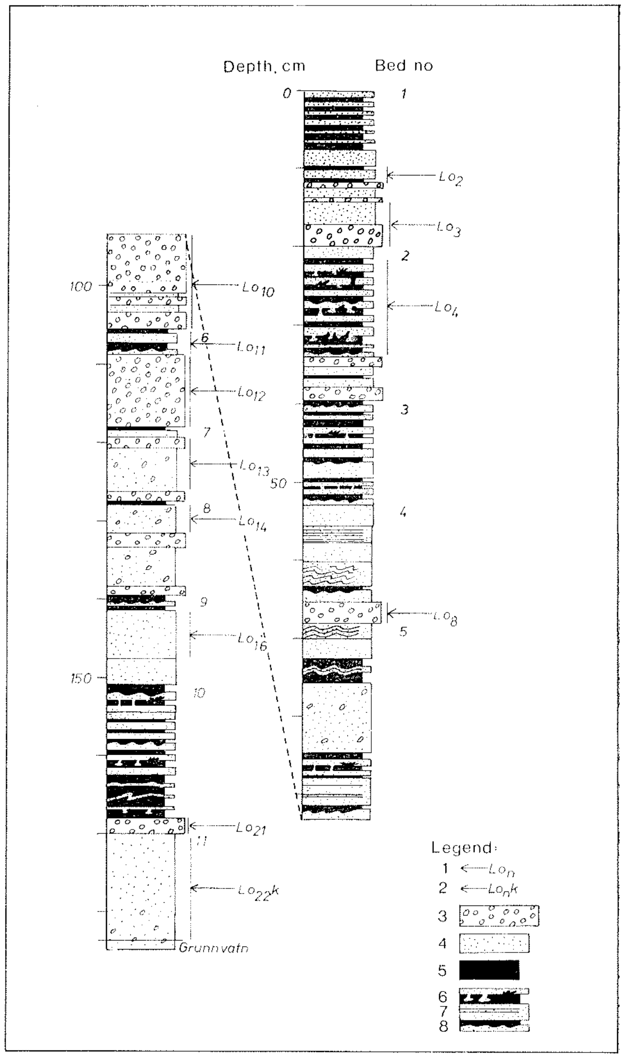

Fig. 7. Columnar section through the lagoon sediments. Legend: 1) Sample no, 2) Grain size analysis no, 3) Pebble gravel, 4) Sand, 5) Silt, 6) Load casts, 7) Laminae, 8) Ripples. — Grunnvatn: Ground water.

According to this reasoning, wind, mudflows and solifluction contribute to the northern ness by transporting material to the foot of the cones, making it available for the swash to transport and deposit on the ness.

Fieldwork in the spring of 1980 confirmed previous observations. Following heavy April storms, the swash had obviously overridden the boulder ridge. On top of the surface bed of 1979 in the old lagoon site, about 15 cm thick bed of rippled sand, coated by a laminae of silt, had been deposited.

In dry weather, the ness is subject to deflation. The dominant grain sizes at the surface of the

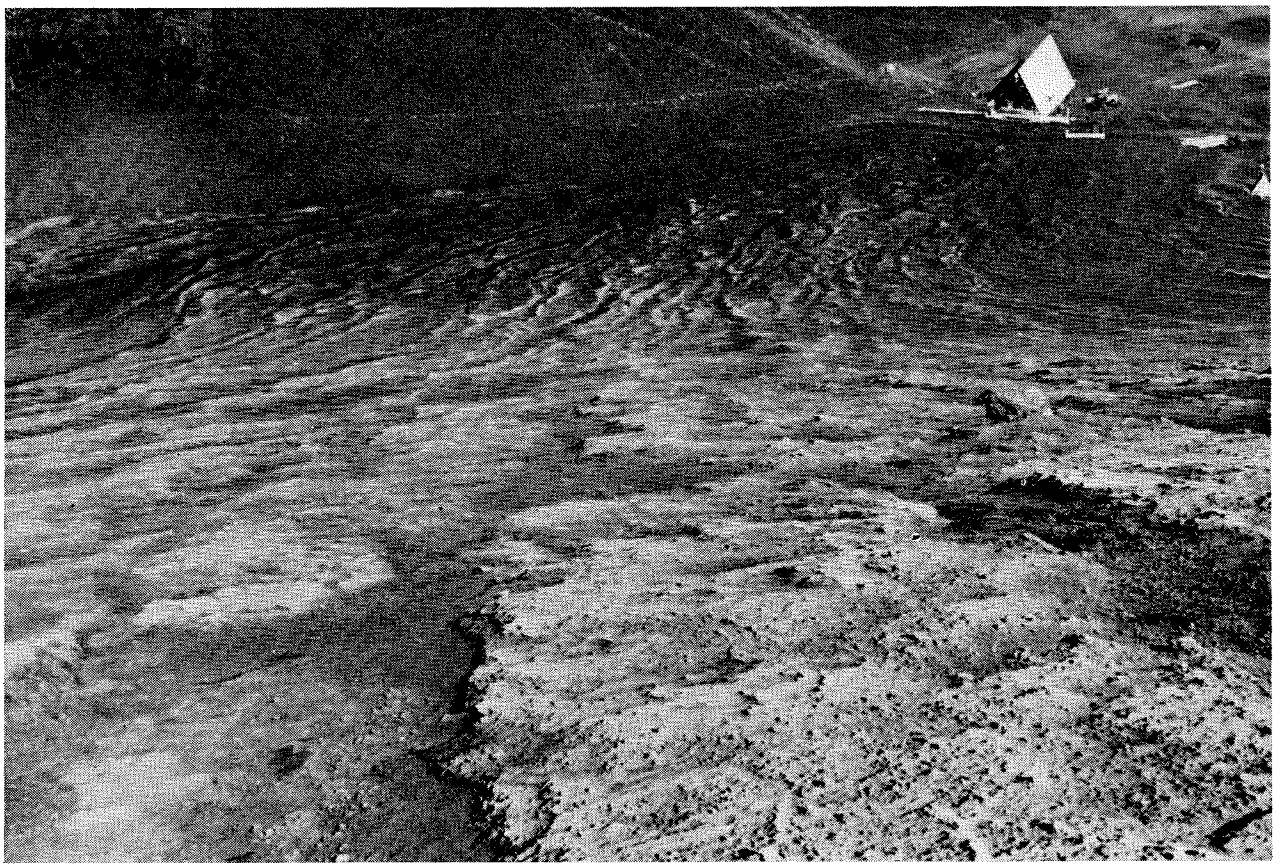

Fig. 8. Mudflow channels on the north facing slope of SII.

ness range from coarse sand to boulders (see foreground of Fig. 9). This corresponds with the observations of Norrman (1980).

In the pit, brackish groundwater was reached at the depth of approx. 1.85 m (bed no. 11 on Fig. 7). Grain size analysis shows that the material of bed no. 11 is poorly sorted (So: 1.15) with mean grain size of coarse sand (Mz: 0.52), and markedly low proportion of silt (see sample Lo_{22} on Fig. 6b). Measurements of the water-level in the pit clearly showed the tidal cycle, ranging in height from 1.5 to 5 cm between adjacent high and low tides. The time of high tide in the pit was out of phase with that of the open ocean, with an average of 5.82 hours after the last peceding high tide in Vestmannaeyjar, as determined from tidal tables (Moore 1982). The pit is 260 m distant from the ocean, and the damping of the tidal flux and the retardation of the tidal cycle clearly demonstrate the limited permeability of the material constituting the northern ness (Moore 1982).

Mapping unit 3: Mudflows and solifluction

The north facing slope of SII is characterized by numerous mudflow channels. Usually the channels are 1-3 m wide, reaching down the entire length of the slope, turning eastward at its foot, away from Bólfell. The mudflow material is very poorly sorted, with grain sizes ranging from silt to boulders. The north facing slope of SII is shiftingly affected by mudflow and wind drift activity, depending on weather conditions. Westerly and northerly winds, usually without precipitation, cause deflation in the area (Fig. 9).

Field observations in 1979 and 1980, as well as the evidence of air photographs, suggest that most of the mudflow channels are old and relatively stable phenomena, changing but minimum from year to year. During heavy rains, water flows down the slope, eroding the channels, and building fans at the foot of the slope.

Solifluction on the slope above Pálsbaer (scientist hut) is considerable. A stake set up for measuring purposes in August 1979, had been transported 2.5 m down the slope in June 1980. The load of sediments pressing against Pálsbaer also bears witness to the solifluction (Fig. 8). In July 1979, an estimated 70 tns of material had to be dug away from the hut in order to prevent the load from pushing the hut off its foundations or further tilting it. In June 1980 an estimated

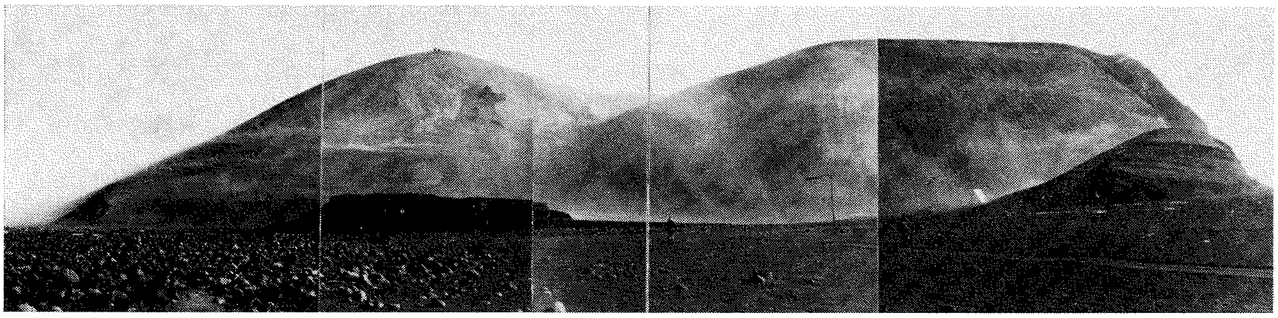

Fig 9. Deflation east along the north facing slopes of the tephra cones. Also notice the coarse material on surface of the northern ness in foreground. Photographed on August 7, 1979. Estimated wind force is 30–35 knots from WNW.

8 tns of material which had accumulated since July 1979 had to be dug away from the hut.

Mapping units 5 & 8: Eolian sand

Eolian sand in Surtsey can be assigned to two groups: Sand dunes and ripples around the tephra cones (mapping unit 5), and windblown sand cover on the lava area (mapping unit 8). The difference between the two groups is demonstrated in Table II and Fig. 6b.

Table II
Size distribution parameters of eolian sand

Sample no	Mz	Sorting	Skewness
1	–0.77	2.02	0.47
2	0.38	1.45	0.34
3	2.23	1.12	0.11
4	0.82	1.37	0.02

Samples no. 1 and 2 were collected from ripples and dunes, but samples no. 3 and 4 from the lava area (for location see Fig. 3). The former group is characterized by poor to very poor sorting, with dominant grain sizes of coarse and very coarse sand. Samples representing the second group, show better sorting and dominant grain sizes of medium and fine sand. Both groups have an upper size limit of grains at –2.5 phi (6 mm), and considerable better sorting than the tephra (Table I and Fig. 6a).

The differences between the two groups reflect different modes of transport. The dune-ripple material is transported by saltation and creeping along the surface, while the sand on the lava has been transported in suspension and by saltation.

Sample no. 3 was collected from a 10 m deep pit, formed by a cave-in in the lava south of SII during the winter of 1965-66. At the bottom of the pit, on top of the Jólnir tephra, windblown sand accumulated over the years. Sample no. 3 shows dominant grain size of fine sand, with a high silt percentage, and markedly best sorting of the samples analysed.

The ripple and dune sediments show a tendency to bimodality, with a higher percentage of finer material on the lee sides. It is difficult to recognize any characteristic dune pattern in Surtsey, probably due to the short transport of the sediments and the ever shifting wind directions.

The main source of dune-ripple material is probably the unconsolidated NW-facing cliff of SII. Another source is the northern ness. Huge mass-transport of windblown material takes place east along the tephra cones (Fig. 9), and the largest dunes are found on the NE and E-side of SI. The most important wind directions for dune- and ripple formations are proably the relatively dry westerly and northerly winds.

Quantitative measurements of how much of the windblown material actually is blown off the island are lacking. Such data, however, could give valuable information on the probable future development of soils and vegetation on the island. An efforts was made to estimate this, by using planimeter, maps, air photographs and the data of Norrman (1978, 1980) on aerial changes of the island due to coastal erosion. This effort did not give any convincing results, as the unknown factors and variables are too many for the results to pass statistical tests.

Mapping unit 6: Talus material

Talus material, extremely poorly sorted, with small tops in coarse sand and cobbles, is found almost everywhere on and beneath the slopes of the tephra cones. However, it only forms independant sediments on the interior slopes of SII and beneath the NW-facing cliff, elsewhere not readily distinguishable from other sediments. The material is transported by force of gravity from the top of SII, transforming the western rim into sharp edges. Material falling down the NW-cliff tends to be directed by erosion scars in the cliff, resulting in typical interwoven colluvial fans at the foot of the cliff.

Mapping unit 7: Assorted sediments

Sediments belonging to this unit are too mixed to be successfully assigned to any of the other units described in this paper. This material is a conglomerate of eolian sand, mudflow- and talus sediments. As a whole, the material is very poorly sorted, though lenses of better sorted material occur, and structurally diffuse. These sediments are mainly found in the saddle between the tephra cones, and they reach from the saddle onto the northern ness.

DISCUSSION, FUTURE RESEARCH ACTIVITY

Due to the short transport of the sediments of Surtsey, identification and mapping of the sediments is a difficult task, were qualitative estimates are unavoidable. Still, one can within reasonable limits of confidence distinguish between sediments transported and deposited by sea, wind, running water and gravity. The use of grain size parameters is justifiable, as it leads to convincing results. The island is an excellent spot to observe the interaction between erosion and deposition, and further research could give important clues as to the formation of soils in Iceland. Future research could also give answers to questions concerning the role of pyroclastics and reworked sediments in the Icelandic móberg-formation.

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Dredge hauls from Vestmannaeyjagrunn, Iceland

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INTRODUCTION

The Vestmannaeyjar volcanic system forms the southernmost part of the Eastern Volcanic Zone of Iceland (Jakobsson 1979). Vestmannaeyjar (Westman Islands) are made up of 17 islands (>100 m long) and numerous skerries and shoals. The volcanic activity of this system has apparently always been of low intensity. The oldest exposed rocks belong to the so-called Nordurklettar formation on Heimaey, and are probably of late Glacial age (Jakobsson 1979). A 1565 m deep drill hole on Heimaey indicates that this formation rests on marine tuffaceous sediments at about 180 m below sea level (Tómasson 1967); the sediments are of Quaternary age and the uppermost part being probably of Pleistocene age (Símonarson 1982). There have been identified 17 Holocene (Postglacial) eruption sites (single eruption units) with remnants above sea level, including the recent Surtsey and Heimaey eruption sites. In addition, a submarine eruption may have occurred south or southeast of Hellisey in 1896 (Thorarinsson 1965a).

Petrological studies of the Vestmannaeyjar volcanic system have hitherto been limited to the islands and the skerries. Bathymetric maps reveal numerous steep hills on the surrounding shelf (Vestmannaeyjagrunn), and it has been suggested that these hills and peaks have been built up in Recent submarine eruptions (Jakobsson 1968). According to local fishermen fresh volcanic rocks („brunagrjót") have been carried up with fishing-nets from several of these hills, including the unnamed hill southeast of Surtsey, and Trintur northnortheast of Thrídrangar (Eyjólfur Gíslason, pers. inform. 1966).

In August 1974 rock samples were dredged from eight prominent submarine hills by Dr. Kjartan Thors, on board the r/v Hafthór, of the Marine Research Institute, Reykjavík, — the submarine hill Surtla, which formed in the Surtsey eruptions, was included for comparison. In November 1982, rock samples were in addition dredged from the submarine hills of Syrtlingur and Jólnir by Kjartan Thors and the author, on board the r/v Árni Fridriksson. Previously, a few sediment grab samples had been collected from the sea bottom around Surtsey, and they will also be briefly discussed.

THE ROCK DREDGE HAULS

The dredge hauls were obtained with the common rock dredge, which has a mesh measure of 7 cm (cf. Kristjánsson et al. 1976, Fig. 3). In some cases, however, smaller rock pieces than 7 cm across were obtained if embedded in mud.

A summary of data for the eleven locations is given in Table I, altogether there are 16 dredge hauls. The location of the dredge hauls is shown in Fig. 1. All the collected material is considered to be *in situ* material with the exception of dredge haul H74—D7, 2 (Bensaklakkur) and dredge haul H74—D9 (hill E of Bensaklakkur). In the following brief description, the dredge hauls are arranged according to estimated age, judging from the degree of roundness, alteration (palagonitization), weathering and erosion, -e.g. with reference to experience from Surtsey, cf. Jakobsson & Moore (1982).

1. Dredge hauls from the recent Surtsey eruption sites

Four dredge hauls were collected from the submarine hills Surtla, Syrtlingur and Jólnir which formed in the Surtsey eruptions of 1963-

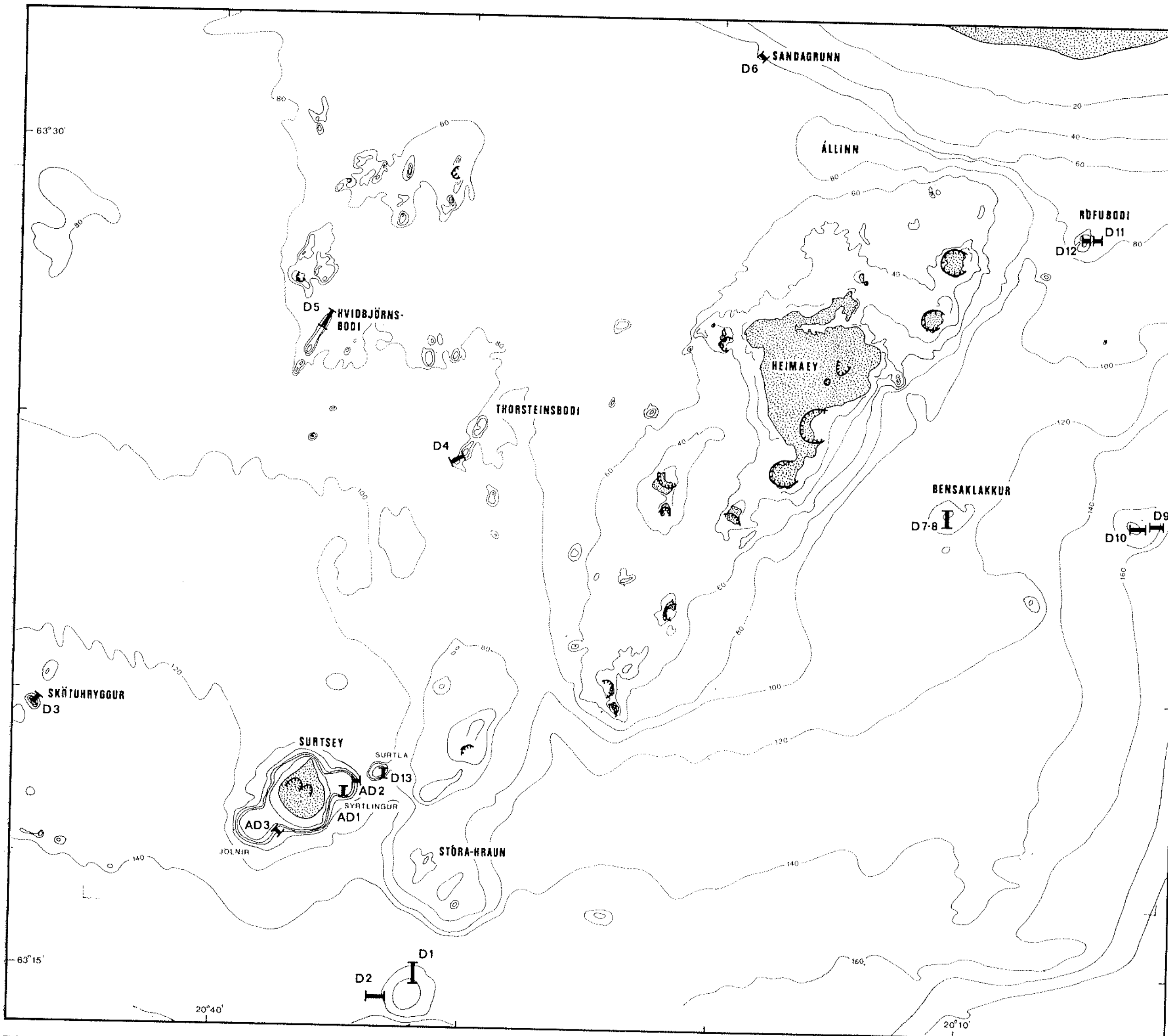

Fig. 1. Bathymetric map of Vestmannaeyjagrunn, after Map. no. 321 (Vestmannaeyjar), Icelandic Hydrographic Service, 1982. The Hafthór rock dredge hauls of 1974 are indicated with D-numbers, and the Árni Fridriksson of 1982 with AD-numbers, cf. Table I. Also shown are Holocene phreatic eruption sites above sea level.

1967: H74—D13 (Surtla), A82—D1 and D2 (Syrtlingur) and A82—D3 (base of Jólnir). Islands were built up but subsequently washed away at the sites of Syrtlingur and Jólnir, but at Surtla a submarine ridge remains. The samples from Surtla and Syrtlingur consist of coarse, angular, dense and fresh scoria, and pieces of fresh vesicular basalt, but no pillow lava was observed. Many of the pieces are covered with a considerable amount of biological growth.

The dredge haul A82—D3 was collected from the southeast base of the Jólnir hill, i.e. from the rugged part of the reflection profile in Thors & Jakobsson (1982, Fig. 3), and consists solely of fragments of pillow lava with fresh glassy surfaces. This is probably part of the flat submarine ridge, which is believed to have formed during May—June 1964, when there was a lull in the subaerial lava flow from the lava crater of Surtsey (Einarsson 1965, Thorarinsson 1965b).

2. Dredge hauls of supposed Holocene (Postglacial) age

Four dredge hauls each of which contains only one rocktype, are considered to have formed after the last glaciation: H74—D1—D2 (hill SE of Surtsey), H74—D3 (Skötuhryggur), H74—D10 (hill E of Bensaklakkur) and H74—D12 (Rófubodi), cf. Table I and Fig. 1. Some of the pieces in these dredge hauls are obviously broken off solid mass of rock, but many have been lying loose. Surfaces are fresh and angular, although glass occasionally shows incipient palagonitization; only traces of secondary minerals are found. No traces of mud or glacial erratics were found in these samples, except in the case

TABLE I

Data on the rock dredge hauls from Vestmannaeyjagrunn. Compare Fig. 1 and Table II. Samples collected from r/v Hafthór in August 1974 are marked H74; those collected from r/v Árni Fridriksson in November 1982 are marked A82.

Location, and dredge haul no.	Latitude and longitude	Depth. Sample weight	Rock-type populations; references to chemical analyses
Hill SE of Surtsey H74-D1(4637)	63°14.8'N 20°31.7'W	125-150 m 2 kg	1. Subrounded basalt scoria (lapilli) embedded in mud, with traces of palagonite. Possibly Holocene (Postglacial).
Hill SE of Surtsey H74-D2(4639)	63°14.4'N 20°33.3'W	140-155 m 18.5 kg	1. Angular pieces of fresh, vesicular basalt. Probably Holocene. Probably same rock-type population as H74-D1. Chemical analysis in Table II, no. 3.
Skötuhryggur H74-D3(4640)	63°19.8'N 20°47,0'W	60-100 m 20.5 kg	1. Tuff-breccia, incoherent, traces of palagonite. Probably Holocene. Chemical analysis in Table II, no. 2.
Thorsteinsbodi H74-D4(4641, 4643)	63°24.2'N 20°30.5'W	40-80 m 5.5 kg	1. Tuff and tuff-breccia, with eroded and weathered surface; slightly palagonitized and with calcite fillings. Probably pre-Holocene.
Hvidbjörnsbodi H74-D5(4642, 4644)	63°26.8'N 20°35.8'W	20-70 m 2.5 kg	1. Tuff with eroded and weathered surface; palagonitized, with a few calcite fillings. Probably pre-Holocene.
Sandagrunn H74-D6(4645)	63°31.6'N 20°18.5'W	20-40 m 2.0 kg	1. Tuff, with eroded and weathered surface; considerably palagonitized. Probably pre-Holocene.
Bensaklakkur H74-D7(4646)	63°23.4'N 20°10.7'W	70-100 m 24.5 kg	1. Tuff and tuff-breccia, with weathered surface; palagonitized; covered with mud. Probably pre-Holocene.
			2. Rounded boulder of transitional basaltic andesite. Glacial erratic.
Bensaklakkur H74-D8(4647)	63°23.4'N 20°10.7'W	70-100 m 6.0 kg	1. Coarse tuff, considerably palagonitized, partly covered with mud. Probably pre-Holocene. Not same rock type population as H74-D7.
Hill E of Bensaklakkur H74-D9(4648)	63°23.3'N 20°02.1'W	125-150 m 0.8 kg	1. Fine sand and silt, semiconsolidated, no layering visible. Possibly mainly Holocene.
Hill E of Bensaklakkur H74-D10(4649)	63°23.2'N 20°03.0'W	110-125 m 1.0 kg	1. Angular pieces of scoria and tuff, traces of palagonite, partly embedded in mud. Probably Holocene. Chemical analysis in Table II, no. 1.
Rófubodi H74-D11(4651)	63°28.4'N 20°04.9'W	50-70 m 45.0 kg	1. Tuff-breccia, palagonitized, with eroded and weathered surface. Probably pre-Holocene.
Rófubodi H74-D12(4650)	63°28.4'N 20°05.3'W	50-55 m 10.0 kg	1. Angular pieces of fresh scoria (mostly lapilli) and coarse tuff, traces of palagonite. Probably Holocene. Chemical analysis in Table II, no. 5.
Surtla H74-D13(4638)	63°18.5'N 20°33.1'W	50-100 m 19 kg	1. Dense, fresh scoria. Submarine eruption Dec. 28, 1963-Jan. 6, 1964. Chemical analysis in Table II, no. 4.
Syrtlingur A82-D1(8066)	63°18.2'N 20°34.7'W	30-40 m 7 kg	1. Angular pieces of fresh vesicular basalt. Submarine and subaerial eruptions from May to October, 1965.
Syrtlingur A82-D2(8067)	63°18.4'N 20°34.2'W	60-80 m 0.6 kg	1. Angular pieces of fresh scoria. Submarine and subaerial eruptions from May to October 1965. Same rock-type population as A82-D1.
Jólnir (base of hill) A82-D3(8068)	63°17.4'N 20°37.3'W	85-95 m 70 kg	1. Fragments of pillow lava with fresh glass surface. Submarine lava flow from Surtsey in May-June 1964?

of H74–D10, were scoria of lapilli size was partly embedded in fine sand and silt.

Dredge haul H74–D9 (hill E of Bensaklakkur) consists of semiconsolidated fine sand and silt (mud). This material has not been investigated in detail, but judging from the apparently rapid process of consolidation of the bottom sediments in the area (Alexandersson 1972), it may be suggested that it is mainly of Holocene age.

3. Dredge hauls supposedly pre-Holocene

Six dredge hauls (each of which contains one rock-type population) from four submarine hills are considered to be of pre-Holocene age. With reference to the results from the drilling in Heimaey (Tómasson 1967), it seems likely that these rocks are of Upper Pleistocene age, and then most probably of Late Glacial age: H74—D4 (Thorsteinsbodi), H74—D5 (Hvidbjörnsbodi), H74—D6 (Sandagrunn), H74—D7,1 (Bensaklakkur), H74—D8 (Bensaklakkur) and H74—D11 (Rófubodi), cf. Table I and Fig. 1. All the rock samples of these six dredge hauls are broken off a solid mass. The pieces are, with one exception, tuff or tuff-breccias, usually showing eroded (glacial?) and weathered surface; alteration is distinct to considerable. Many of these samples have been covered by unconsolidated to semiconsolidated thin layers of mud (fine sand and silt). An investigation of the petrography of these dredge samples strongly indicates that they belong to the Vestmannaeyjar volcanic system.

4. Dredge haul containing erratic material

One dredge haul, H47—D7 (Bensaklakkur), contained one piece of rounded erratic rock. Judging from thin-section analysis, this is a transitional basaltic andesite, very similar to some of the lavas of the Eyjafjöll volcanic system, as e.g. the 308—Hamragardar lava (Jakobsson 1979). In this connection it is of interest to note, that in the tephra deposits of Surtsey, and Saefell of Heimaey, a wide assortment of erratic rocks are found, including rocks of foreign origin, as gneiss, granite, schist and carbonate sediments. These erratics must have been transported to the area by drift ice.

SEDIMENT GRAB SAMPLES

During a biological investigation in August 1966, Nicolaisen (1967) collected seven samples of the uppermost unconsolidated sediment on the seafloor around Surtsey. The samples were collected by means of a Smith-MacIntyre bottom sampler. By estimate the sampler may have reached some 10—20 cm into the soft sediment.

One sample was collected 0.1 nautical mile due north of Surtsey, and consists of fresh and angular basaltic glass and basalt fragments, all of sand size (Jakobsson 1971). The material is a mixture of watersorted Surtsey tephra and detritus from the Surtsey lava.

The other samples were collected at a distance of 1, 3, 7 and 12 nautical miles due west of Surtsey, and 7 and 12 miles due east of Surtsey, cf. Fig. 1. The samples collected 1 and 3 miles west of Surtsey consist solely of fresh and angular basaltic glass in the silt and sand fractions. The material is watersorted tephra, and there is no doubt that it stems from the Surtsey eruptions. Although the samples contained many living bottom animals (Nicolaisen, pers. inform. 1967), no erratic material could be detected by microscopical investigation.

The sample collected 7 miles west of Surtsey contains, besides basaltic tephra from Surtsey, a considerable amount of erratic material, and a few shell fragments. The samples collected 12 miles west of Surtsey, and 7 and 12 miles east of Surtsey, contain, besides tephra from Surtsey, a large amount (some 40-60 percent) of erratic glass and rock fragments, and shells.

Although it is not possible to state it explicitly, the investigation suggests that the deposition of Surtsey pyroclastics on the seabottom around Surtsey was mainly within a radius of 3 to 7 miles ($5\frac{1}{2}$—13 km) from the island.

PETROLOGY

The dredged rocks of Vestmannaeyjagrunn bear a close resemblance to the investigated rocks of the islands (Jakobsson 1979). Phenocrysts of euhedral olivine are ubiquitous, often enclosing picotite (chromium spinel) which, however, occasionally is found free; plagioclase is common as microphenocrysts and is found more disperse as macrophenocrysts, whereas augite and magnetite are not found as phenocrysts.

Chemical analyses and CIPW-norms of five of the rock-type populations which are supposedly of Holocene (Postglacial) age, are presented in Table II. The major element analyses indicate mild alkali olivine basalts with normative content of nepheline varying between 2.4 and 5.4 percent. The Vestmannaeyjar basalts have been divided into two groups, called VE—I and VE—II, the latter group being more common (Jakobsson 1979). The MgO— content of VE—I has been found to vary between 9.1—10.0 percent and that of VE—II between 5.6—8.2 percent. Thus H74—D10 (hill E of Bensaklakkur) is of the primitive VE—I type, whereas the others belong to the VE—II type.

Available chemical analyses of the Surtsey lavas have hitherto indicated that they belong to the VE—I group (Jakobsson 1979). It is thus a surprise to learn that the chemical analysis of

TABLE II.

Chemical analyses and CIPW-norms of dredged rocks of Vestmannaeyjagrunn, compare Table I. Analyses 1-3 and 5 have been previously published in Jakobsson (1979, Table 1.). Analyst: Greenl.Geol. Survey, Chem. Lab., I. Sørensen.

	1.	2.	3.	4.	5.
Loc.	E of Bensaklakkur	Skötuhryggur	SE of Surtsey	Surtla	Rófubodi
Dredge no.	H74-D10	H74-D3	H74-D2	H74-D13	H74-D12
Sample no.	4649	4640	4639	4638	4650
SiO_2	46.40	46.24	46.50	46.99	46.66
TiO_2	2.14	2.27	2.49	2.38	2.82
Al_2O_3	14.77	15.87	15.88	16.22	16.19
Fe_2O_3	1.56	1.76	2.88	2.34	2.26
FeO	9.71	10.68	9.93	9.90	10.77
MnO	0.23	0.26	0.27	0.19	0.27
MgO	9.49	8.21	7.36	7.01	5.75
CaO	10.53	9.30	9.64	9.68	9.76
Na_2O	2.83	3.78	3.37	3.80	3.60
K_2O	0.64	0.59	0.67	0.68	0.82
P_2O_5	0.17	0.25	0.25	0.36	0.31
H_2O	0.97	1.14	0.56	0.25	0.32
Sum	99.44	100.35	99.80	99.80	99.53
C I P W weight-norm					
OR	3.78	3.49	3.96	4.02	4.85
AB	19.62	21.97	24.72	23.93	24.72
AN	25.71	24.59	26.23	25.19	25.60
NE	2.35	5.43	2.05	4.46	3.11
DI	20.66	16.31	16.31	16.84	17.19
OL	19.64	19.99	16.49	17.38	14.40
MT	2.26	2.55	4.18	2.30	3.28
IL	4.06	4.31	4.73	4.52	5.36
AP	0.39	0.58	0.58	0.83	0.72
FeO*/MgO	1.17	1.49	1.70	1.71	2.23

Surtla (H74—D13, Table II) shows it to be of the VE—II type. A number of new, unpublished analyses of the Surtsey extrusives have in fact shown, that there is a distinct, gradual chemical gradient with time during the Surtsey eruption (Jakobsson, in prep.), where the Surtla rocks are among the most evolved in composition. This indicates that the above-mentioned grouping of the Vestmannaeyjar basalts has to be revised.

THE SUBMARINE REMNANTS OF SURTLA, SYRTLINGUR AND JÓLNIR

During the Surtsey volcanic activity of November 1963—June 1967, there were eruptions at three sites outside Surtsey itself. At the first site no island was formed, at the other sites islands were formed but subsequently washed away by wave action. It will be of interest here to examine the fate of these three submarine hills in connection with the study of the other submarine hills and peaks of Vestmannaeyjagrunn.

Surtla was built up by submarine activity 2.5 km eastnortheast of Surtsey from about December 28, 1963 to January 6, 1964. An eastnortheast trending ridge more than 100 m above the seabottom was built up, but no island was formed. The depth to the top of the ridge was 23 m on February 23, 1964 (Thorarinsson 1965b).

In early May, 1965, volcanic activity started 0.6 km eastnortheast of Surtsey, and on May 28 an island, Syrtlingur, was formed by phreatic activity. In September 1965 the island reached a height of more than 70 m and a length of 650 m. In early October the eruptions ceased, and on October 24, 1965 the island had disappeared.

On December 26, 1965, explosive volcanic activity was observed 1 km southwest of Surtsey, and on December 28 the island Jólnir was born. Jólnir reached a height of about 70 m, and a length of 560 m. Eruptions were last observed on August 10, 1966, and in late October, 1966, the island had completely disappeared (Thorarinsson 1968). In the above-mentioned eruptions only tephra (pyroclastics) was formed, as far as the record goes.

A detailed bathymetric map of the Surtsey area was made in July—August 1964 by the Icelandic Hydrographic Survey (Kjartansson 1966, Fig. 5); another map was made by B.E.T. Humphrey in July 1967 (Norrman 1970, Fig. 1). In July 1973 the Icelandic Hydrographic Service made another map of the area (Sea Chart No. 321 (Vestmannaeyjar), Reykjavík 1982). Finally, echosoundings were made from the r/v Árni Fridriksson in November 1982. An examination of these data, and other unpublished data reveals that the morphology of these submarine hills has changed considerably since the volcanic activity ceased. The top of each hill has been eroded continuously down as shown in Fig. 2, and at the same time each hill has become wider to form platform with steep slopes (Fig. 1). According to Norrman (1970) who investigated the three hills in June 1968, their erosion is due both to currents and wave action. The fact that both the Jólnir and Surtla hills seem mainly to have been enlarged towards southwest and south also indicates that (westerly) bottom currents are at least partly responsible for the erosion, — possibly mainly below a depth of 17—22 m where the curves in Fig. 2 become flattened. The fact that the Syrtlingur hill does not show this feature may be because this hill is on the lee side of Surtsey with respect to the heavy southwest waves, which appear to have the greatest erosional force on Surtsey. According to local fishermen (Eyjólfur Gíslason pers. inform. 1966)

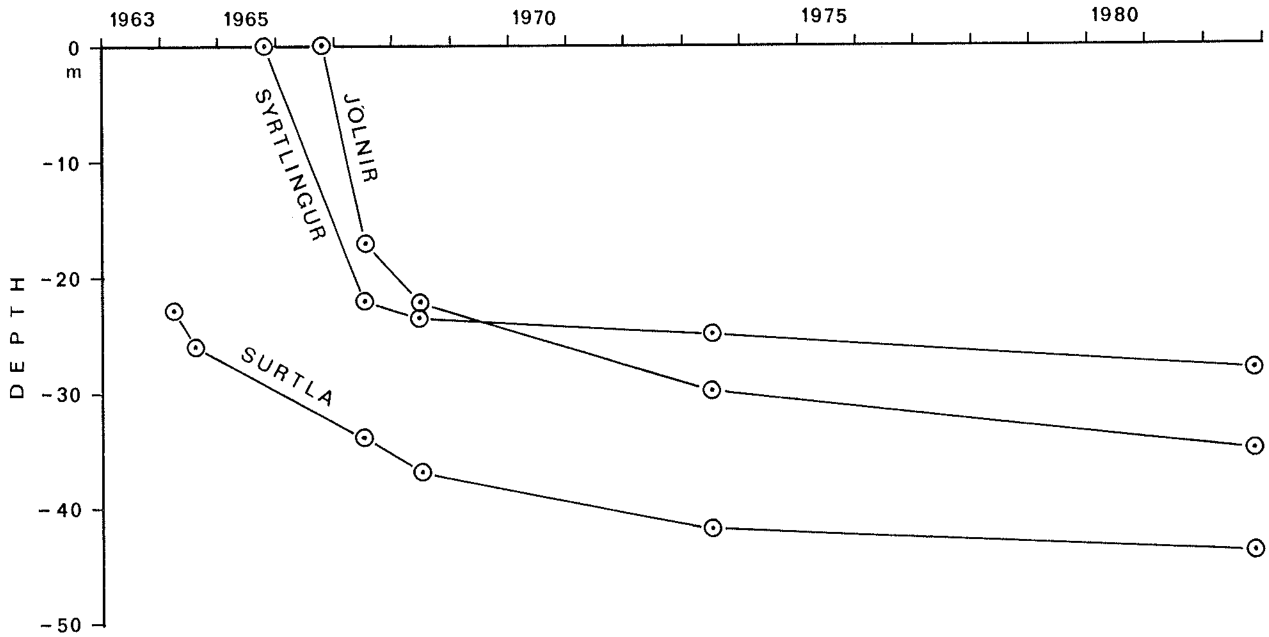

Fig. 2. The lowering of the submarine hills of Surtla, Syrtlingur and Jólnir with reference to mean depth of the top platform, according to various sources.

there is always less amount of sediments and coarser sediments on the east side of the submarine hills of the Vestmannaeyjagrunn. This is in accordance with unpublished results of the Marine Research Institute (Svend Aage Malmberg, pers. inform. 1982), that the resultant near-bottom currents in this region are towards the west.

DISCUSSION

This investigation on Vestmannaeyjagrunn shows that the submarine hills and peaks of this area are both of Holocene (Postglacial) age, and pre-Holocene age. With the exception of the Surtsey eruption sites, four out of eight hills investigated are likely to have erupted during Holocene time (four eruption units), and five hills at earlier times, most probably during Upper Pleistocene time (six eruption units); two hills, Rófubodi and Bensaklakkur, contain two distinguishable eruption units (Table I). The petrologic investigation shows that all these rocks belong to the Vestmannaeyjar volcanic system.

The collection of sediment grab samples on the sea floor around Surtsey indicates that during the Surtsey eruptions, appreciable amounts of pyroclastics were deposited on the bottom but mainly within a radius of a few nautical miles from Surtsey.

The most recent submarine hills Surtla, Syrtlingur and Jólnir, formed in 1963—1966, have suffered rapid continuous erosion (Fig. 2), probably both by wave action and currents, and are now shaped into flat-topped hills (Fig. 1), with a minimum depth of 28—44 m below sea level. The rapid erosion shows the hills to be built up of loose pyroclastics down to this depth interval, if not further down.

It is noticeable that the four submarine hills, where Holocene eruptions have taken place outside the Surtsey area (Fig. 1), have all been eroded down to a level below the abovementioned depth interval, with the exception of a small peak on Rófubodi which reaches 12 m depth. Moreover, these Holocene hills mostly exhibit broad features, whereas the identified older hills are steep and may reach shallow levels. This suggests that the pre-Holocene hills have suffered glacial erosion, where the loose material of their sides has been scraped away. According to Egloff & Johnson (1979) the insular (continental) shelf and the insular margin off SW and S-Iceland has been extensively modified by glacial action, and morainal debris has been deposited on the erosional surface. To the southwest of Vestmannaeyjar, moraine-like deposits have been discovered at the insular margin.

On the other hand, if a Holocene eruption is large enough to build up an island, where there are conditions for the loose tephra to be consolidated through the process of palagonitization as in Surtsey (Jakobsson 1971), the consolidated core may withstand erosion, as is the case for the present islands and skerries of Vestmannaeyjar, with the sole exception of Nordurklettar, Heimaey, which probably is subglacial.

With these results in mind, it is not probable that there are many additional submarine hills of Holocene age in this area, the most likely cases will be Hólar, Stóra-Hraun, Bankahryggir, Nýja-Hraun og Sandahraun.

The submarine and subaerial volcanism of the Vestmannaeyjagrunn is most probably the main source of the material which has built up the shelf in this area, as Alexandersson (1972) has noted. The following calculation supports this assumption. As mentioned above, the Vestmannaeyjar formation probably extends down to about 180 m below sea level, judging from the information from the drill hole (Tómasson 1967). The Vestmannaeyjar volcanic system probably covers an area of 800—1000 km^2, and the average water depth in the area is thus about 60—80 m, depending on how large an area is credited to the system. The volume of the formation is then 80—120 km^3, and the bulk of it will be pyroclastic sediments. The volume of material produced by the volcanic system during the last 12 thousand years has been estimated $\geqslant 3.5$ km^3 (Jakobsson 1979). Assuming that the sediments will make up 3 times the volume of solid volcanic rock, and that 90 percent of the material is deposited within the area of the system, it will, with the present rate of production, take 80—125 thousand years to build up a formation of the size of the Vestmannaeyjar formation, and this is about the age previously suggested for this formation.

The reason for the present shape of Vestmannaeyjagrunn (Fig. 1) is probably as follows. The main zone of volcanism (Jakobsson 1979) runs from Surtsey/Stóra-Hraun towards northeast through Heimaey and to Állinn. The most vigorous volcanic activity has been in the Heimaey area. Outside this zone there are only a few scattered eruption sites. As westerly currents are dominating near bottom, there is a rather steep slope southeast of a line between eastern Heimaey and Stóra-Hraun, whereas the shelf dips gently towards southwest on the other side of the active volcanic zone.

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Two seismic reflection profiles from the vicinity of Surtsey, Iceland

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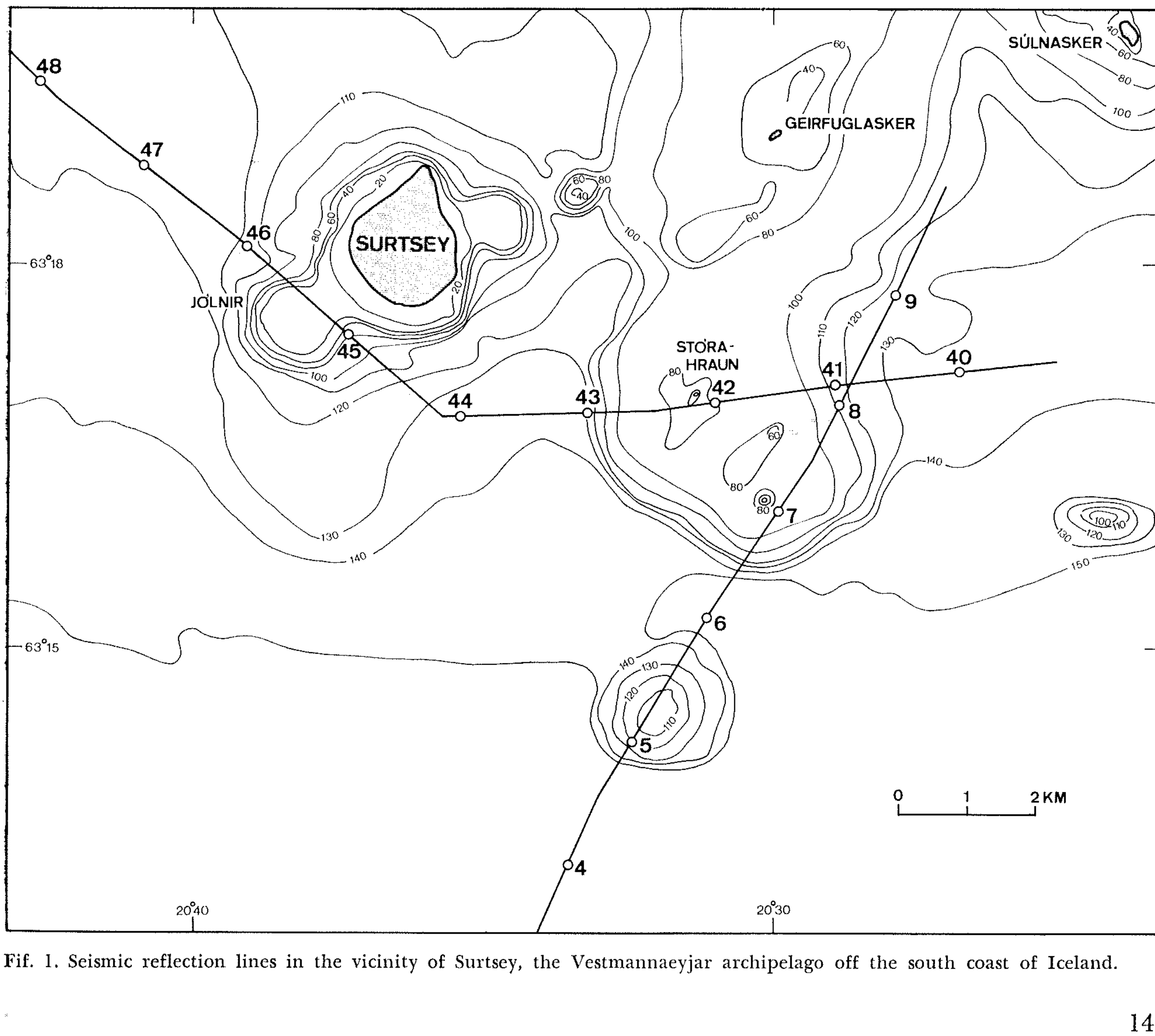
A seismic reflection survey carried out on the r/v Árni Fridriksson in October 1980 included two lines in the vicinity of Surtsey, off the south coast of Iceland. Although not perfect, the profiles contain information on the stratigraphy of the area around the island. The survey lines are



Fif. 1. Seismic reflection lines in the vicinity of Surtsey, the Vestmannaeyjar archipelago off the south coast of Iceland.

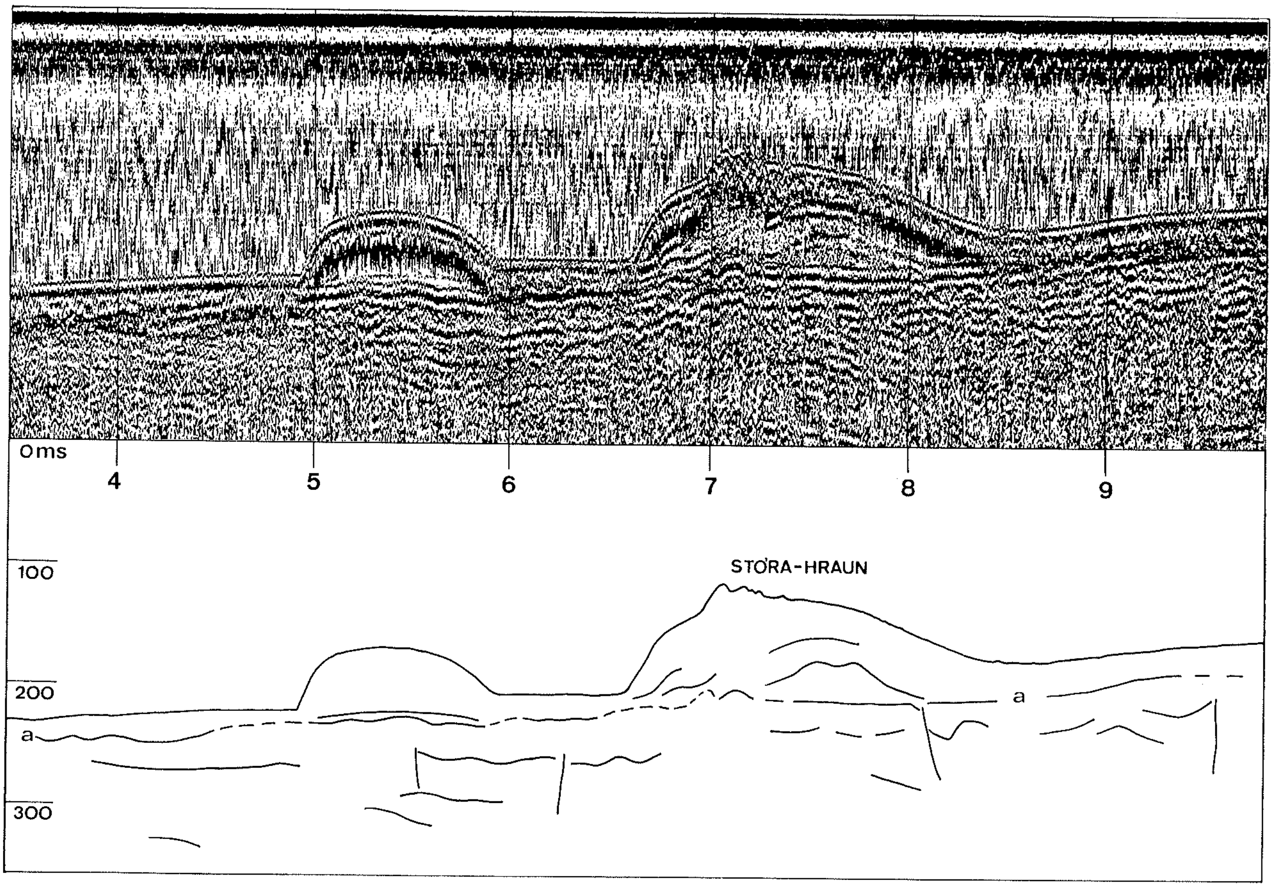


Fig. 2. Original, and interpreted profile from SW to NE. The reflector "a" is assumed to mark the top of Pleistocene sediments. Vertical scale in milliseconds of two-way travel time. Horizontal divisions of one nautical mile.

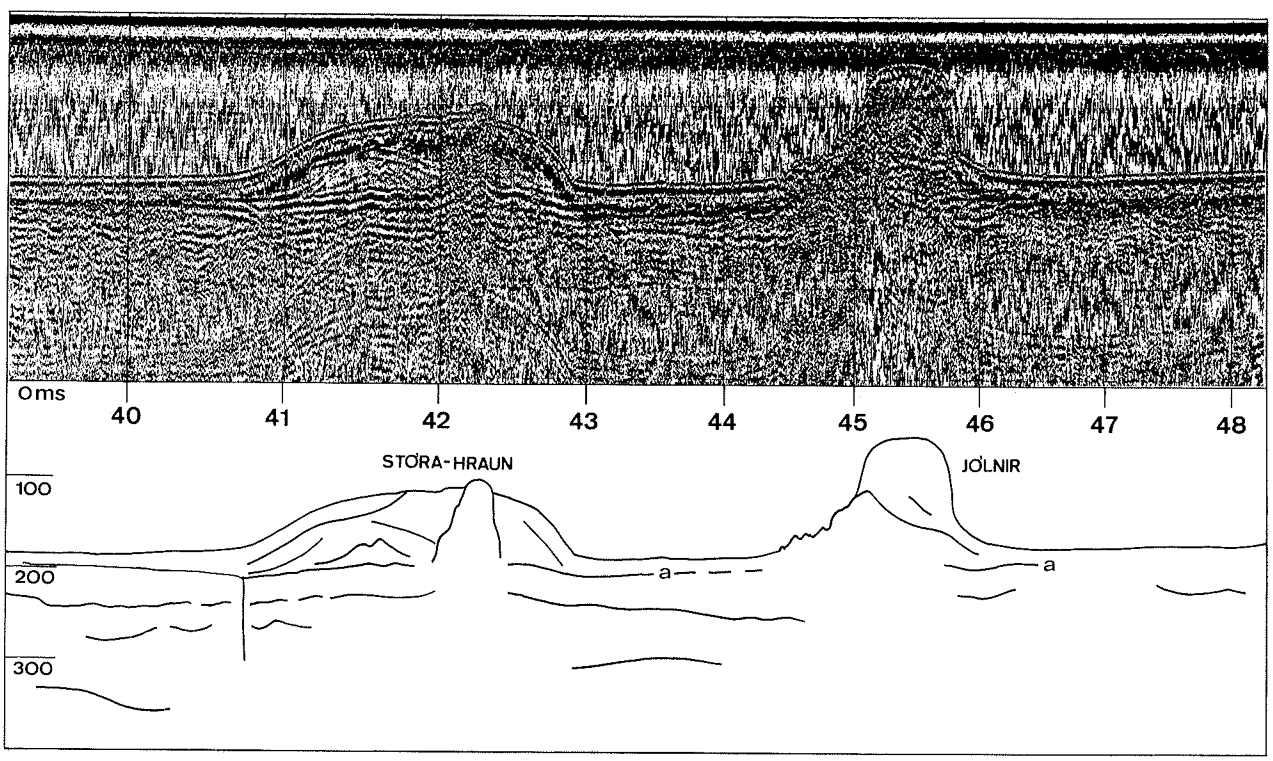


Fig. 3. Original, and interpreted profile from E to W. Legend and scale as in Fig. 2.

displayed in Fig. 1, and the two profiles in Figs. 2 and 3.

In essence, the profiles show three volcanic mounds on an otherwise relatively flat sea-floor. The southernmost of these is as yet unnamed, but the other two are Stóra-Hraun and Jólnir.

The volcanic features rest on a stratified sequence with a layering that is visible some 100 meters below the sea-floor. Sediments in this area are therefore at least 100 meters thick, and probably considerably thicker. It is not surprising to find an accumulation of sediments in this area: a borehole drilled in 1964 on nearby Heimaey island, penetrated a massive pile of pyroclastic sediments, mostly marine, before reaching crystalline rocks at 850 meters below sea-level (Pálmason et al. 1965, also discussed by Tómasson 1967 and Alexandersson 1972). Fossiliferous sedimentary xenoliths are common in the pyroclastics of Surtsey and Heimaey. The xenoliths are assumed to stem from the above-mentioned sedimentary sequence, and an examination of the fossils indicates different Quaternary ages (Símonarson 1982). Some of the xenoliths have even been lithified during Holocene time (Alexandersson 1972).

It is likely that the sediments in our profiles correspond to the uppermost part of the sedimentary accumulation discovered under Heimaey. From the uneven, faulted nature of the sediments in our profiles we assume that they are of late Pleistocene age, and that the reflector labelled "a" in the profiles marks the top of Pleistocene.

The volcanic mounds seem to rest on reflector "a" as far as can be judged, and should therefore be of Holocene (Postglacial) age. This is certainly true of Jólnir, formed during May—October 1965. Dredge samples from the nameless hill in the south also indicate a Postglacial age (Jakobsson 1982). As seen on the left-hand side of Fig. 2, this hill is made up of a rather homogeneous mass of material which is quite transparent to the seismic signal. This section of the hill probably represent an accumulation of pyroclastic deposits without a great deal of crystalline material. In contrast the two sections of Stóra-Hraun shown in Figs. 2 and 3 exhibit internal reflections indicative of a more complex structure. Fig. 3 shows the summit of Stóra-Hraun to be part of a seismically opaque (crystalline) plug which penetrates a pile of transparent (pyroclastic) material. Layering within the pile indicates a least one episode of eruption older than the one represented by the plug. Furthermore, the bathymetry of Stóra-Hraun (Fig. 1) shows at least three peaks, indicating more than one eruptive vent.

The section of Jólnir shown on Fig. 3 reveals two main stratigraphic divisions. The base of Jólnir is made up of a mound of mainly opaque material rising to a minimum depth of some 115 milliseconds (equivalent to about 85 meters). The opaque nature of this feature suggest that it is of crystalline material. A proof of this point came in November 1982 when a dredge sample taken from the deep southeastern flank of Jólnir yielded fragments of pillowlava (cf. Jakobsson 1982). The origin of this unit is probably to be found in the Surtsey submarine activity of approx. May-July 1964 (Thorarinsson 1965). A bathymetric survey carried out in 1964 (cf. Kjartansson 1966, Fig. 5) revealed a positive feature in this spot which later surveys showed to have been buried by the 1965 Jólnir eruption.

The upper portion of Jólnir is a rather homogeneous mass of transparent (pyroclastic) material showing faint traces of stratification. This is undoubtedly the product of the phreatic activity of the Jólnir eruption of December 1965 — August 1966.

Ash from volcanic activity in the Vestmannaeyjar archipelago has undoubtedly been spread over the adjacent shelf area. The smoothness of the sea-floor between the volcanic hills in our profiles is without doubt due to a blanket of volcanic ash spread from modern eruption sites. The finer structure of this blanket (lying on top of reflector "a") is beyond the resolution of our instruments, and it is therefore not possible to assign it to particular eruptions.

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Fossils from Heimaey, Iceland

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Fossiliferous sedimentary xenoliths are known from Mýrdalur and the islands Heimaey and Surtsey, South Iceland (Fig. 1). Data from a 1565 m deep drillhole on Heimaey show a 700-800 m thick series of sedimentary layers in the stratigraphic column below the island (Pálmason et al., 1965). These beds have probably supplied the fossiliferous xenoliths which were carried upward with hot magma and are now found in hyaloclastites on the surface. On Heimaey the marine part of the sedimentary sequence is about 640 m thick and marine strata occur inland at least as far as Mýrdalur. According to Alexandersson (1972), sedimentological evidence supports the idea that a sedimentary basin once existed in this part of the Neovolcanic zone and the sedimentary sequence might represent a wedge of sediments, derived from sources to the west.

In 1974 the present author published a preliminary report on fossils from xenoliths found on Surtsey. Since then xenoliths from Heimaey have been investigated and the fossils found in them are listed below:

A. Foraminifera:

Quinqueloculina seminulum (Linné, 1758) (3 specimens)
Oolina sp. (1 specimen)
Cibicides lobatulus (Walker & Jacob, 1798) (68 specimens)

B. Mollusca:

Buccinum undatum Linné, 1758 (1 fragmentary spire)
Cylichna sp. (1 fragmentary specimen)
Nucula (Leionucula) tenuis (Montagu, 1808) (1 umbonal fragment)
Nuculana (Nuculana) pernula (Müller, 1779) (3 fragments without umbo)
Portlandia (Yoldiella) cf. *lenticula* (Møller, 1842) (1 specimen with articulated valves)
Portlandia sp. (1 fragmentary specimen with articulated valves)
Musculus (Musculus) cf. *niger* (Gray, 1824) (1 fragment without umbo)
Pododesmus cf. *(Monia) patelliformis* (Linné, 1761) (1 umbonal fragment)
Astarte (Astarte) cf. *sulcata* (da Costa, 1778) (1 fragment without umbo)
Tridonta (Tridonta) borealis (Chemnitz, 1784) (1 fragment without umbo and 1 internal cast)
Cerastoderma edule (Linné, 1767) (1 fragment without umbo)
Serripes groenlandicus (Chemnitz, 1782) (1 fragmentary left valve)
Spisula (Spisula) elliptica (Brown, 1827) (1 umbonal fragment)
Macoma (Macoma) calcarea (Chemnitz, 1782) (1 fragment without umbo and 1 internal cast)
Arctica islandica (Linné, 1767) (2 umbonal fragments and several fragments without umbo)
Hiatella (Hiatella) arctica (Linné, 1767) (1 fragment without umbo)
cf. *Mya (Mya) truncata* Linné, 1758 (1 internal cast)

C. Cirripedia:

Balanus (Balanus) balanus (Linné, 1758) (3 complete wall rings and several parietal plates)

D. Echinoidea:

Several indet. spines

The foraminifera are rather poorly preserved and most of the macrofossils are fragmentary. Only a few bivalves were found with articulated valves (paired). The shells are generally out of growth position and apparently somewhat transported.

All the species are marine and no extinct species was found. However, the occurrence of *Portlandia (Yoldiella)* cf. *lenticula* is interesting as this species does not belong to the present Icelandic fauna. According to Ockelmann (1958), the species is known from West and East Greenland, Jan Mayen, Svalbard, the Murman Coast, the Barents Sea, Novaya Zemlya, the Kara Sea, the Siberian Arctic Sea, Parry Islands and along the Norwegian coast southwestward to Bodø. It has been found at great depths north of the Faeroe Islands and the Shetlands, but only empty shells have been met with in southernmore local-

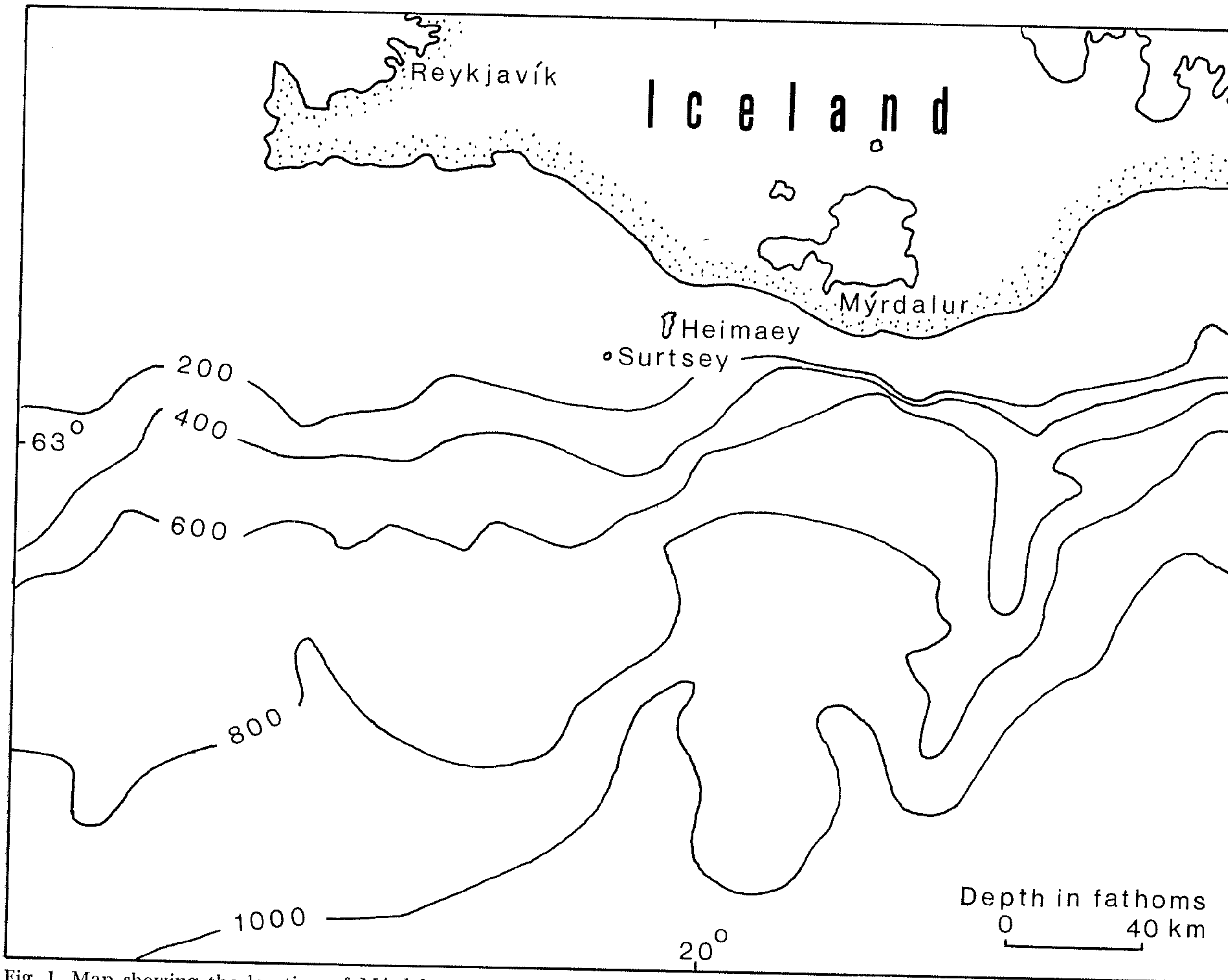

Fig. 1. Map showing the location of Mýrdalur, Heimaey and Surtsey.

ities. The species seems panarctic, ?circumpolar, with a depth range from 0-13 m (East Greenland) to 1400 m (west of the Shetlands). In East Greenland the species seems to prefer a bottom of clay or mud, occasionally mixed with sand and gravel. In Iceland *P. (Y.) lenticula* is known in the Lower Pleistocene Breidavík deposits on Tjörnes peninsula, North Iceland (Gladenkov, 1974; Gladenkov et al., 1980) and the Upper Pleistocene Saurbaer deposits in Gilsfjördur, West Iceland (Bárdarson, 1921).

The Heimaey xenoliths may originate from any level within the sediments below the island and the species found apparently belong to faunas of different Quaternary ages. Alexandersson (1972 p. 106) had some fragments of *Arctica islandica* from xenoliths, collected on Surtsey, dated radiometrically. The dated fragments were taken from two blocks: "one block (mainly "outer fraction") was approximately 11.000 years old while the other (mainly "inner fraction") was 6200 years". These dates indicate Late Quaternary (Holocene) age. However, the occurrence of *Portlandia (Yoldiella)* cf. *lenticula* indicates that some of the xenoliths from Heimaey are of Pleistocene age. This is supported by the occurrence of *Cerastoderma edule,* known in the Lower Pleistocene Mýrdalur (Skammidalur) xenoliths (Áskelsson, 1960), but unknown in autochthonous Icelandic sediments of younger Pleistocene or Holocene ages (cf. Símonarson, 1981). Apparently, the latter species did not reapper in Iceland until after 1940.

As it is impossible to separate different faunas, ecological conclusions seem inappropriate. However, it should be pointed out that species with their present northern limit of distribution within the high-boreal and low-arctic subregions are prominent. The depth of formation was apparently variable, but lack of sedimentary structures showing wave- and current-influence indicate depths were the hydrodynamic forces were relatively small (cf. Alexandersson, 1972).

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APPENDIX

Addition to the list of fossils from Surtsey (cf. Símonarson, 1974): *Serripes groenlandicus* (Chemnitz, 1782) (1 left and right valve almost articulated and certainly belonging to the same specimen).

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