S U R T S E Y   R E S E A R C H
P R O G R E S S   R E P O R T

II.

The Surtsey Research Society
Reykjavik - Iceland

May 1966

INDEX

Page

INTRODUCTION

The submarine eruption that began on the 14th of November, 1963, approximately 20 miles off the south coast of Iceland and the island that it created, Surtsey, have become well known both among scientists and the general public. The eruption on Surtsey ceased in May 1965, but a few days later another eruption started just off the shore of Surtsey. An island was also created there, but did not become permanent and washed away when this eruption stopped in November, 1965. In December the third eruption began on the other side of Surtsey and is still going strong and has formed quite a large island, but, as yet, only of loose material that would not last when the eruption ceases. Thus, although Surtsey itself has been quiet for over a year, it is still surrounded by volcanic activities.

Surtsey immediately caught the interest of scientists, who found there a unique opportunity to study both geology in the making and the settlement of life on a sterile rock out in the ocean. In order to coordinate this activity, the Surtsey Research Committee was formed shortly after the eruption started.

With the scientific interest increasing, the Surtsey Research Committee was changed into the Surtsey Research Society in May 1965. That same month the Society sponsored the Surtsey Biology conference which was held in Reykjavik with participation by scientists from Iceland and abroad, especially from the United States.

Scientists were quite active on and around Surtsey in 1964, and in February 1965 a collection of their progress reports was published by the Surtsey Research Committee.

The following progress reports are the second ones in that series published on Surtsey. They represent work of scientists in 1965, engaged in the Surtsey research projects. They are not, in general, intended to show scientific conclusions. On some subjects scientific papers will soon follow and it is hoped that the program will continue and lead to many more publications of interest.

The Surtsey research program would not have been possible without strong support from several individuals and institutions. In this connection I would like to mention the National Research Council of Iceland, Icelandic research institutions and the Icelandic Coast Guard that have made scientists, equipment, funds and facilities available. The program has also been strongly supported by the United States Atomic Energy Commission, the Office of Naval Research in Washington D.C., and the Duke University in North Carolina. Finally, the program would never have become of the importance it now is without the many great contribution by the Bauer Scientific Trust and the untiring interest of Professor Paul S. Bauer of the American Univerşity, Washington D.C. To all of those and all the scientists working on the program we would like to express our thanks.

For the Surtsey Research Society,

Steingrimur Hermannsson
Chairman

B I O L O G Y

Microbial Life on Surtsey

by
T.D. Brock
Dept. of Bacteriology
Indiana University
Bloomington, Indiana, U.S.A.

1. Introduction.

I visited Iceland during the dates July 25 through August 6, 1965, under sponsorship of the Surtsey-Iceland Research Committee. The purposes of my visit were threefold: 1) to look for early signs of microbial life on Surtsey, especially in marine bacteria of the genus Leucothrix; 2) to study Leucothrix mucor on the coasts of Iceland itself; and 3) to study thermal algae and bacteria in Icelandic hot springs. Although my time was limited, I was able to accomplish most of these goals.

2. Surtsey.

The new eruption altered the possibilities for work on Surtsey, so that my work here was limited. However, I was able to make a number of general observations which may be of some interest in the developing biology of Surtsey.

a) The primary requirement for the development of life is a source of energy. Energy on Surtsey is available in the form of light, but since photosynthetic plants have not developed yet, this source is not being used. Energy is also available on Surtsey in the form of organic substances which are being contributed by the excrement of birds and by materials drifting onto the beach. These materials are obviously secondary sources of energy, and their utilization on Surtsey would not be expected to be different from their utilization elsewhere, thus I did not think it particularly interesting to study microorganisms attacking these things. The contribution of organic matter from these sources should not be underestimated. Literally hundreds of gulls and terns were seen roosting on Surtsey, and on one cliff on the South West side of the island, the rocks were almost white from excrement. The amount of material drifting ashore is also quite high, and I made a large list in about an hour, as seen in Table 1.

Table 1

List of materials drifting onto Surtsey which could serve as energy sources for living organisms

Kelp fronds
Gull feathers
Large tree stumps and logs
Lumber in the form of boards
Board with attached barnacles
Bottles with attached barnacles
Orange peels
Plastic net floaters
Egg carton
Orange crate
Wooden Barrel
Pieces of rope
Dead animals

Other items found on the beach which were nonorganic included: light bulb, metal float, empty bottle, glass fishing float.

The point of making the above list is to emphasize that for a considerable length of time the main influence on the development of life on Surtsey will come from secondary sources which arrive accidentally. For a self-contained ecosystem, the development of photosynthetic plants will be essential. At the moment, several factors will probably inhibit extensive development of terrestrial plants: 1) The continuing accumulation of ash, covering up any plants which take root; 2) the very porous nature of the rock and volcanic ash, restricting water-holding capacity; 3) the very salty nature of the rock and ash, preventing the development of non-halophytic plants. This last point might not be appreciated, but I observed on the South West side of the island that water which had leached through the soil and was dripping down in overhanging caves far above the zone of wave action was very salty, much more so than sea water.

Some organic matter might be created right in the volcano, from termally catalyzed reactions, using inorganic carbon compounds such as CO_2 as primary carbon source. Although probably not important quantitatively, the nature and composition of such materials would be of interest in relation to ideas on the origin of life. However, it would be essential to collect material directly from the eruption, since once the material reached the ground it could be contaminated by birds, etc.

The lagoon in Surtsey has a salinity of sea water, and the water can be inferred to be derived from the sea since I saw a metal fishing float and a bottle in the lagoon which undoubtedly came from the sea during a high water interval. At present this lagoon does not have a high biological development, but if it remains it should become productive, since it is shallow. My pH measurement on lagoon water was 7.25, which is a little low for sea water, so that I assume acidic materials from the volcano are present.

The ultimate biological development of Surtsey will probably be similar to the other islands in the Vestmannaeyjar. Since none of these islands have what would be considered a lush terrestrial vegetation, it is unlikely that Surtsey will be otherwise. Clearly it will be the marine vegetation which will be most highly developed. At present, there are no sea weeds on the rocks of Surtsey. It will be of great interest to follow the development of sea weeds on these rocks throughout the next few years, and this, to my mind, should be the major effect of the biological research.

3. Leucothrix mucor on Icelandic sea coasts.

My earlier work had shown that L. mucor occurred as an epiphyte in temperate waters on sea weeds growing on exposed coasts where there was much wave action. The hydrographic conditions of Iceland suggested that L. mucor would be common here, and this prediction turned out to be true. I isolated several new strains in pure culture from material collected at Cape Reykjanes and along the coast near Reykjavik. In addition, I set up a number of radioautographic experiments which provided quantitative data on the growth rate of L. mucor directly in nature.

The results of this work have been incorporated into a paper: The habitat of Leucothrix mucor, a widespread marine organism, which has been submitted to the journal Limnology and Oceanography.

4. Work on Icelandic hot springs.

I had worked earlier on hot springs of Yellowstone and I found the opportunity to study the Icelandic hot springs very rewarding. In Iceland I visited springs at Hveragerdi, Geysir, Cape Reykjanes, and Reykjadals River by Reykholt. Quantitative studies were done in only one spring, and are found in the report: Temperature Optima for Algal Development in Yellowstone and Iceland Hot Springs.

In general, biological development is less extensive in Iceland than in Yellowstone springs, for reasons that are not completely known. As far as I can tell from the literature, I am the only person who has tried to compare springs from the two sources on a quantitative basis. The higher pH of the Icelandic springs may explain their poorer biological development.

The sea water hot spring at Cape Reykjanes, which is unique in the world, was completely devoid of biological development. The pH of this spring was around 5.0, which is low for sea water, and this may be responsible for its sterility. This spring should be studied further.

I was interested to observe the extent of commercialization of Icelandic hot springs. I expect to prepare in the near future an analysis of the potentialities of hot springs for biological productivity. I would hope, however, that at least some of the Icelandic hot springs could be protected from exploitation, since they are in many ways unique. The use of soap in the Geysir springs, which I observed directly, is undoubtedly responsible for the lack of algal growth in many of the springs in this group. Good conservation ideals on a tourist attraction of the significance of Geysir would require a complete lack of human disturbance.

Report on the Surtsey Investigation in 1965

Terrestrial Invertebrates

by

Carl H. Lindroth, Hugo Anderson and Högni Bödvarsson
Department of Entomology, Zoological Institute
University, Lund

Field work in the "base area", the Westman Islands, notably on Heimaey, including a short visit to Surtsey, was carried out during the period July 20th to 29th by Dr. Lindroth and Mr. Andersson. The resulting collections have not yet been fully worked up but it is already evident that our knowledge of the Invertebrate fauna of Heimaey has been substantially enlarged. Several species new to Iceland have been discovered.

All terrestrial Invertebrate animals observed and collected on Surtsey itself, as far as known, have been available to us. The collection is preserved at the Zoological Institute, Lund, for the time being, but it is agreed that its final place of storage will be at the Museum of Natural History, Reykjavík. Similarly, the first specimen of every species collected on each of the other islands of the Westman group will be deposited there.

The following terrestrial Invertebrates have been observed on Surtsey:

I n s e c t a

Diptera. (Flies and Midges) 6 species.

fam. Chironomidae (det. D.R. Oliver, Ottawa)

Diamesa ursus Kieff. 1 ♀. Leg. Sturla Fridriksson, 14. V. 1964.

Cricotopus sp. 3 ♀. Leg. Jutta Magnússon, 3. VII. 1965.

Gen. sp. (subfam. Orthocladiinae) 1 ♀ (dead). Leg. Sigurdur Helgason, 28. VII. 1965.

fam. Helomyzidae (det. Hugo Andersson, Lund).

Helomyza modesta Meig. 4 dead specimens and 4 empty (hatched) puparia near the lagoon under a piece of wood covered with thin ashes, in a stratum of sand with fragments of Ascophyllum algae and feathers of birds. Leg. Sigurdur Helgason, 24. VII. 1965. This is the first terrestrial animal known to have bred on the island.

fam. Cordyluridae (det. Hugo Andersson).

Scatophaga stercoraria L. ♂. Leg. Sigurdur Helgason, 28. VII. 1965.

fam. Calliphoridae (det. Hugo Andersson).

Calliphora eryhtrocephala Meig. 1 ♀. Leg. Sigurdur Helgason, 28. VII. 1965.

Lepidoptera. (Butterflies and Moths) 2 species.

fam. Noctuidae (det. Per Douwes, Lund).

Agrotis ypsilon Retz. 1 ♂. Leg. Eythór Einarsson, 15. X. 1964.

Plusia gamma L. 1 ♀. Leg. Sturla Fridriksson, 4. X. 1965.

A c a r i d a (Mites)

fam. Gamasidae (det. Max Sellnick, Grosshansdorf pr. Ahrensburg, Germany).

Thinoseius spinosus Willmann. Leg. Sigurdur Helgason, 24. & 28. VII. 1965. This mite was found, together with the dead ♀ of the Orthocladiin midge, on which they seemed to feed, near the lagoon in several specimens. The place is also close to where puparia and dead flies of Helomyza modesta were found. The biology of this mite is known from Germany, where the nymphal stage has been found attached to littoral flies. It seems therefore that the species possesses unusual facilities for passive long-range dispersal.

Plans for 1966.

All three members of the team intend to visit Surtsey and the Westman Islands for a period of about 10 days, in June. Besides general field-work the following points are foreseen:

(1) three glue-traps for catching small air-borne animals should be established on Surtsey;

(2) an artificial freshwater pool - by collecting rainwater in a plast-covered depression in the lava - should be constructed;

(3) nest material from anticipated breeding birds - probably Rissa tridactyla - should be individually collected and investigated on possible occurrence of small animals;

(4) several millions of small, bright yellow plast grains (already available) should be released off shore, at outgoing tide, in the southern part of the main Westman Island, Heimaey. If carried to Surtsey by sea drift, they would be easily discovered.

On Dispersal of Plants to Surtsey

by

Eythor Einarsson
Museum of Natural History
Department of Botany

In a previous report on this same subject (Einarsson 1965) it was reported that one panicle of *Alopecurus pratensis* L. and another panicle of *Anthoxanthum odoratum* L., each of the panicles containing some few seeds, had been collected on the shore east of the lagoon on Surtsey for testing the germination ability of the seeds. There were about 30 seeds in the panicle belonging to the former species, but only 4 in the panicle belonging to the latter one.

The germination ability of these seeds has now been tested and none of them did germinate although they seemed to be fully ripe. Therefore the conclusion must be that the seeds have probably been injured by the salt sea water and lost their germination ability.

The present author made two trips to Surtsey in 1965, the first one on March 19th and the second one on April 4th.

March 19th.

During this visit to Surtsey the author was accompanied by Mr. Sigurdur Hallsson and the main purpose was to search for plants or parts of plants on the lava shores of the west, south and southeast coasts of the island. No macroscopic plants or plant parts were found at all in these parts of the island. Some samples of rock pieces were collected from the surface of the lava and brought to Reykjavik for microscopic studies, but no sign of any plants were found on these rock pieces. Some few samples of sand were also collected from the narrow sand strip in front of the lava on the shore and from holes and fissures in the lava. In one of the samples from a small and shallow hole in the lava a fragment of a pennate diatom frustule was found.

Macroscopic plant parts were also searched for on the east coast between the lava and the lagoon. At the high tide mark the following plant parts were found drifted ashore:

Cakile edentula (Bigel.) Hook. 24 seeds
Angelica archangelica L. 4 seeds

The viability of these seeds was tested and the results were as follows:

Cakile edentula (Bigel.) Hook. 15 seeds turned out to be alive and able to germinate.

Angelica archangelica L. All 6 seeds did not germinate.

Some fragments of macroscopic algae, mostly Ascophyllum nodosum (L.) Le. Jol., were also found on the shore at the same place.

April 4th.

During this visit to Surtsey macroscopic plants and parts of plants were mainly searched for on the east, northeast and north coast of the island. Somewhat above the high tide mark west of the northern end of the lagoon heaps of dead algae, mostly Ascophyllum nodosum (L.) Le. Jol., had been formed by the surf and partly covered by sand. These algae heaps seemed to be excellent habitat for microorganisms as long as it was not quite covered by sand.

East and south of the lagoon parts of the following plants were found drifted ashore.

Vascular plants:

Cochlearia officinalis L. Some few small and fresh green basal leaves.

Matricaria maritima L. 20-30 small fresh green basal leaves.

Poa pratensis L. Some 30 fresh green leaves, some of them with ligules and sheaths.

Algae:

Ascophyllum nodosum (L.) Le. Jol. Some 30 thallus fragments, one of them with an epiphytic growing *Ectocarpus* sp.

Fucus inflatus L. and *Fucus vesiculosus* L. Some few thallus fragments of each species.

Enteromorpha sp. 2 thallus fragments.

Literature

Einarsson, E. 1965: Report on Dispersal of Plants to Surtsey. Surtsey Research Progress Report I, Reykjavik.

Birds observed on Surtsey

by
Finnur Gudmundsson
Museum of Natural History

Introduction.

The following notes on birds observed on Surtsey are based on observations made by various scientists who have visited the island at one time or another. The author of this report made three visits to Surtsey in 1965, viz. on February 20, April 4, and June 3. On the first two trips he was accompanied by Agnar Ingólfsson and on the third trip by Arnthór Gardarsson. Furthermore, Agnar Ingólfsson visited the island again on September 7, 1965. The ornithological observations made during these four visits have been greatly augmented by information supplied by Sigurdur Thorarinsson and Sturla Fridriksson, and some information has also been received from Eythor Einarsson and Sverrir Scheving Thorsteinsson.

As the existing information about bird life on Surtsey has been obtained by scientists in various fields who have only made short visits to the island and at irregular intervals, it is obvious that this information must be fragmentary. If an observer had been stationed on the island for longer periods there is no doubt that many more birds would have been seen, and particularly so if the island had been manned during the migration periods in spring and autumn.

As yet no birds have nested on Surtsey, but in view of the fact that the Vestmann Islands are occupied by huge sea bird colonies, it will probably not be long before the first birds will start nesting there. The successive colonization of Surtsey by birds is *per se* of considerable ecological interest and therefore deserves full attention. A virgin island like Surtsey furthermore provides unique opportunities for studying the role of birds in facilitating the transport of seeds and perhaps also terrestrial invertebrates across ecological barriers, in this case the body of water separating Surtsey from the other islands of the archipelago and from the mainland of Iceland. It would also be of considerable interest to collect certain migratory birds on Surtsey when they return from their winter quarters in spring. Surtsey is now the southernmost point of Iceland and many migratory birds will no doubt make use of the island as their first landing-place when reaching Iceland in spring. The viability of any seeds found in the alimentary canal of such birds should be tested by germination experiments in order to find out if and to what extent birds may in the past have contributed to the colonization of Iceland by plants. The same also applies to another category of birds or the so-called drift migrants, which sometimes reach Iceland in large numbers in autumn and spring and will no doubt also turn up on Surtsey (cf. the turtle dove listed below).

List of Species.

Oystercatcher (Haematopus ostralegus). In 1964 seven oystercatchers were seen on the island on May 14. In 1965 five were seen on April 4, three on May 9, and in the afternoon of June 3 seven came flying from NE toward the island, where they settled. In all these cases the oystercatchers frequented the sandy beach on the north side of the island and on April 4 they were seen feeding on living Euphausids washed upon the shore by the surf.

Ringed Plover (Charadrius hiaticula). On August 19, 1965, two ringed plovers were encountered on the sandy north beach.

Turnstone (Arenaria interpres). In 1965 turnstones were twice observed on the island. On April 4 six turnstones were sitting on the lava front in the southwestern part of the island and on September 7 a flock of fifteen turnstones was seen in the westernmost part of the sandy north beach. The same day 8 turnstones were observed on the lava edge on the south side of the island.

Knot (Calidris canutus). On September 7, 1965, one knot was among the turnstones on the sandy north beach.

Purple Sandpiper (Calidris maritima). On January 31, 1965, a number of purple sandpipers was encountered on the eastern shore of the island.

Dunlin (Calidris alpina). Two dunlins were seen on the island on May 14, 1964.

Sanderling (Crocethia alba). On September 7, 1965, four sanderlings were associating with turnstones on the sandy north beach.

Red-necked Phalarope (Phalaropus lobatus). On June 7, 1964, fourteen red-necked phalaropes were swimming close to the shore on the west side of the island and on August 1 large flocks, amounting to hundreds of birds, were found swimming close to the shores of the island. In early August 1965 red-necked phalaropes were again seen in large numbers close to the island, and on September 7 eight were encountered off the westernmost part of the island.

Great Black-backed Gull (Larus marinus)
Herring Gull (Larus argentatus)
Glaucous Gull (Larus hyperboreus)

Already at an early stage of the Surtsey eruption the new island, which rapidly increased in size, was used by gulls as a resting place. Thus on December 1, 1963, or only two weeks after the eruption had started, unidentified gulls were seen to alight on the island during intervals between explosive eruptions. Later on when the eruption had changed from an explosive to an effusive phase gulls gradually started to rest regularly on the sandy northern beach of the island. There a typical gull roost soon developed where gulls in varying numbers were seen throughout the summer of 1964. On February 20, 1965, at least 50 gulls were seen resting in this part of the island. Most of these birds were great black-backed gulls and among them immature and subadult birds greatly outnumbered adults. Among the greater black-backs there were, however, a few glaucous gulls and a few herring gulls. On April 4 relatively few gulls were present on the island, but this time three adult herring gulls were seen near the lagoon. In late April and in May there were again many gulls roosting on the island, but on June 3 only nine greater black-backs (5 juvenile, 2 subadult, and 2 adult birds) and two adult herring gulls were encountered. Throughout the summer 1965 gulls were roosting on the island in varying numbers and on September 7, 1965, about 80 gulls were present, 30 on the sandy northern beach and 50 on the shore below the lava cliffs on the south side of the island. The majority of these birds appeared to be greater black-backs, while a few glaucous gulls and herring gulls were also present.

Kittiwake (Rissa tridactyla). Along with the true gulls of the genus Larus kittiwakes were probably the first birds to alight on Surtsey and later on they started to roost regularly on the island. During the spring and summer of 1964 small flocks of kittiwakes were repeatedly observed resting on tephra bluffs and ridges away from the Larus gulls which occupied the flat, sandy beach. But in 1965 kittiwakes started to occupy low vertical cliffs which has by now been formed at the lava front by marine abrasion. The first time kittiwakes were found to occupy such sites was on June 3, 1965, when three adult birds and one immature bird were sitting on cliff ledges on the west side of the island. A month later (on July 3) the number of birds occupying this site had increased considerably and the cliffs in this particular place had by now become white-washed by excrements. On July 24 no less than 70-80 kittiwakes were occupying this part of the cliffs, and the same day a flock of about 50 kittiwakes was resting in the lower part of a steep tephra bluff on the north side of the island. On September 7 kittiwakes were occupying cliffs in four different places on the west and south side of the island. Altogether 120 kittiwakes were counted in these four places. Most of these birds were young of the year, a few were second year birds but no adults were present. The same day three young kittiwakes were sitting on the sandy beach on the north side of the island.

Arctic Tern (Sterna paradisaea). On June 7, 1964, a few arctic terns were seen on the island.

Common Guillemot (Uria aalge). Oiled speciments of Uria aalge were repeatedly encountered on the island, the first one being found on October 15, 1964. In 1965 one was found on January 31, five on February 20, one on April 29, three on May 9 and one on August 17. All these birds were still alive when found, but they apparently died soon afterwards and were later eaten by scavengers (ravens and/or gulls).

Turtle Dove (Streptopelia turtur). On October 4, 1964, a turtle dove was seen by Sturla Fridriksson in the lava flow in the southwestern part of the island. The turtle dove is known as an irregular drift migrant to Iceland, particularly in autumn and spring.

Raven (Corvus corax). In the first half of 1965 two ravens were regularly encountered on the island. They were first seen on January 31, but again on February 20, February 28, March 13, March 19 and on May 9. These two birds were at first believed to be a pair and it was thought that they might eventually nest on the island, but they disappeared sometime in May.

Redwing (Turdus iliacus). During migration redwings were occasionally encountered on the island. Thus on April 16, 1964, a few redwings were seen. On October 15 one was seen in the lava west of the crater and on November 25 a few were seen on the sandy north beach and around the lagoon. In 1965 on the other hand no redwings were seen except on October 4, when a few were seen in the lava and near the lagoon.

Wheatear (Oenanthe oenanthe). In 1965 wheatears were observed on the island on three different occasions. On July 3 two were seen at the west side of the lava flow. On September 7 two were seen in the lava south of the crater and on October 4 a few were seen in the lava near the crater and one was found dead west of the crater.

Snow Bunting (Plectrophenax nivalis). Snow Buntings were encountered on the island on three occasions in 1964 but never in 1965. On May 14, 1964, one snow bunting was seen, on August 19 two were seen flying over the lava flow and on October 10 several were seen in the lava.

In addition to the species listed above various species of sea birds have at different times been seen at sea around the island. Among these fulmars (Fulmarus glacialis) and gannets (Sula bassana) have probably been the most regularly occurring species. It may also be mentioned that on June 3, 1965, two geese (probably pink-footed geese (Anser brachyrhynchus)) were seen flying over the island and the same day goose droppings were found on the sandy beach on its north side. This shows clearly that geese must have rested there.

A number of dead birds has also been found washed upon the shore of the island. Thus on June 3, 1965, no less than thirteen fulmars, partly eaten by scavengers, were found along the tide line, and the same day a razorbill (Alca torda) was found dead on the shore. And on April 4, 1965, a mallard (Anas platyrhynchos) was found washed upon the shore. This was an adult male. Other dead birds found on the shore were gulls, kittiwakes and common guillemots.

Report on Research in Mycology, 30 March - 5 April, 1966.

by

T.W. Johnson, Jr.
Duke University,
North Carolina, U.S.A.

The following is a brief report, in compliance with Icelandic regulations, on work done by myself and W.L. Howard (graduate assistant) in Iceland, 30 March - 5 April, 1965.

Four days were spent in collecting samples of driftwood from shoreline locations on the West and South coasts. Fungi were found in 73 of these collections. Specimens were removed from the substratum and preserved in small vials of formalin.

In addition, 40 soil samples were collected. These were air-dried, packaged and stored. Soil samples were taken from diverse ecological habitats, along shorelines, roads, and from open areas under mosses and lichens.

All samples are to be taken to the investigator's laboratory. Fungi occurring on driftwood will be sectioned and identified, and notations made as to species distribution. The soil samples will be treated in the usual manner used to collect aquatic fungi, by adding water to the soil and placing bits of snake skin, hempseed and pollen in the dishes. By this method, we should be able to collect soil-inhabiting species of the primitive fungi.

Collecting areas:

(1) South shore of Hvalfjördur, North of Reykjavik
(2) Shoreline of coastal embayments East of Hafnir
(3) Hot springs area North of Krísuvík
(4) Shoreline of South coast of Reykjanes Peninsula, approximately 20 km East of Grindavík.

When the fungi are identified, a completed list, together with specimens, will be sent for deposit to Dr. Eythor Einarsson, Natural History Museum, Reykjavik

On 4 April 1965, a survey for fungal substrates was made on Surtsey. Driftwood occurring on the East, North and Northeast coasts was generally very dry, and apparently had not been immersed in seawater long enough to become infested by marine fungi. A few bits of driftwood, obviously infested were found along the shore of the small lagoon. Drift algae, primarily *Ascophyllum*, were also found. These were living or dead segments of whole plants. Specimens of the dead material were collected, and will be incubated subsequently for fungi. Common air-borne molds are known to occur on decaying seaweeds, so it is possible that this substratum will be one source of fungal invasion on Surtsey.

A careful survey of lava rocks along the South coast of Surtsey was made for attached algae; none was found. The rocky shore should be examined regularly for the beginnings of intertidal algae. It is possible that the scouring action of water-borne lava particles will prevent the development of algae for some time, but this should be checked frequently.

Preliminary Study of the Development of Population of Marine Algae on Stones Transferred from Surtsey to Heimaey 1965

by

S. V. Hallsson, B.Sc.

During the Surtsey Biology Conference held in May 1965 in Reykjavik it had been suggested that selected substrate from Surtsey be transferred to an adjacent region with a known flora in order to follow the development of possible algal population on such a substrate, and to study the factors on which colonization of marine algae depends.

This report describes preliminary experiments intended to throw light upon some of the factors governing the settlement and population of marine algae on virgin rock.

On the 3rd of June 1965 S. Jónsson and the writer transferred two stones (size approx. 10 x 20 cm) of different shape and physical nature, from the higher littoral zone on the north-east shore of Surtsey to Heimaey, the main island of Vestmannaeyjar. The stones were marked with chrome-yellow marine lacquer and thrown into the higher littoral zone at a relatively sheltered place called Urdir, south-east of the harbour in Heimaey. The rock adjacent to the site of the stones was also painted with arrows to simplify location of the stones for inspection. One of the stones (stone 1), which has an oval and smooth surface, landed in the lower littoral zone beside a large rock covered with Acrosiphonia and Porphyra. The second stone (stone 2), of irregular shape with large holes on the surface, landed in the upper littoral zone amongst prolific algal vegetation, of which the following algae and animals were observed: Porphyra, Barnackles, Ascophyllum nodosum, Gigartina stellata, Ceramium acanthonotum, Rhodymenia palmata, Fucus inflatus, Acrosiphonia albescens, Ulva lactuca and Enteromorpha species.

When examined on the 20th of July, about seven weeks later, no algae or animals were found on stone 1 in the lower littoral zone. Stone 2 in the higher littoral zone, however, was already populated by various species of Diatoms (mucilage of Schyzimenia, Licmophora and Fragellaria) Uruspora mirabilis (fertile), young Ulva, young Acrosiphonia albescens, Rhodymenia palmata and by a fragment of Ceramium acanthonotum and Corallina officinalis. Young barnacles, sea-snails and worms were also found. Three months later, i.e. on the 8th of September, the Diatoms were still present on stone 2, particularly on its base. The Enteromorpha now covered half of the stone along with Ulva, Acrosiphonia albescens, young Fucus and Porphyra, which was affixed in the holes, and few specimen of Ceramium rubrum, Callithamnion and sterile Ectocarpus.

During the summer of 1965 no vegetation was established on the pebble shore of Surtsey from where the rock samples had been taken. The only vegetation encountered was found on firm substrate, on the west coast of the island (see S. Jónsson, this report).

It may be mentioned here that two additional stones (stone 3 with a smooth surface and stone 4 of irregular shape with large holes) were transferred to Reykjavik on the 3rd of June and placed on the beach west of Reykjavik on the 5th of June.

No algae were found during 1965 on stone 4, which had been placed in the lower littoral (Fucus serratus) zone, but green algae was observed on stone 3 in the upper littoral (Ascophyllum) zone, one month after the transference, or on the 6th of July. About a week later Ulva was found growing on this stone and a sea-snail was affixed on its base.

The algae found around stone 3 were Ascophyllum nodosum, Polysiphonia fastigiata, Enteromorpha, Fucus vesiculosus, Dictyosiphon, Acrosiphonia albescens, Ulva lactuca and Porphyra.

Although the stones studied were relatively "old" and newer rock from Surtsey should be studied and examined at shorter intervals, this preliminary study throws light upon two important factors delaying the colonization of marine algae in Surtsey:

(1) The distance of algal population from Surtsey (the nearest island, Geirfuglasker, is 4.4 km from Surtsey).

(2) The extreme mobility of the substrate.

One of the special factors that opposed colonization of marine algae on Surtsey during great part of 1965 was the scouring action of the sea and the sand formed during the lava eruption (see S. Jónsson, this report).

This experiment also confirms what we observed in Surtsey (see S. Jónsson, this report) that diatoms and green filamentous algae are the first settlers on virgin substrate.

This perliminary study seems to indicate that the algal colonization is dependant on the seasonal variation and on certain competition between the species.

Initial Settlement of Marine Benthic Algae on the Rocky Shore of Surtsey, the New Volcanic Island in the North Atlatnic

by

Sigurdur Jónsson
Laboratoire de Botanique de la Sorbonne,
Paris

The occurrence of barren rocky shore of Surtsey covering about the three-quarters of the 7-8 km long coastline makes it possible to study the process of colonization of benthic marine organisms along this coast.

This paper deals with the beginning of the algal settlement, the identification of the algae and their distribution. A survey has also been undertaken of driftweeds washed ashore for the purpose of estimating possible immigration routes of benthic algae to Surtsey.

1. Algal colonization

My first landing on Surtsey was made from a small inlet at the SE coast of the island, on August 29, 1964. The volcanic activity, characterized by intermittent lava streams which had been running into the sea for about 6 months, was then still going on. The SE coast was created by two lava flows of different ages. The more recent flow (fig. 1,1), situated SW of the landing point, offered a rocky shore apparently untouched by marine erosion. But the older flow (fig. 1,2), extending towards NE, was covered by boulders, gravel or sand interrupted by promontories. No macroscopic attached algae were observed on this coast, only fragments of drifted algae, such as Ascophyllum nodosum. Some stone pieces were detached in the upper littoral region from the solid rocky substrate of the two lava flows and preserved for further study in 5% formalin seawater.

Microscopic examination of slides obtained by scraping the surface of the stones revealed no algal vegetation on the recent lava flow. But on the older one, the age of which did not exceed 4-5 months, some very sparse marine benthic Diatoms and rod Bacteria were found. The identification of the Diatoms was made difficult because of the poor silicification of the valves and their inconspicuous striae. But the general feature of the cells and their dimensions, the morphology, the position of the plasts, and in some cases the number of carinal dots indicate that these Diatoms seem to belong to two species: Navicula (Schizonema) mollis (W.Sm.) Cl. and Nitzschia bilobata W. Sm. var. minor Grun., two cosmopolite species, known from the coasts of Iceland (1).

This first investigation seems to indicate that Diatoms, mixed with Bacteria, were the pioneers of the marine benthic vegetation of Surtsey and that their colonization takes place as soon as the rocky shore offers a suitable substrate.

Nine months later, when Surtsey was visited again, the coast had considerably increased due to new lava flows which marked the end of the volcanic activity of the island (fig. 1). The locality of Diatoms previously studied had now disappeared under a new lava flow and could not be followed any more. However, the rocky shore was already bordered by precipitous sea-cliffs, fringed by an abrasion platform. On the NW coast this platform, easily accessible at low tide, was mainly covered with sand and locally by boulders, rocky ridges and caps extending into the sea. These rocky localities (fig. 1, I,II,III,IV) were selected and explored thoroughly during the course of the summer 1965.

A survey, carried out on August 10, under a heavy tephra fall coming from a new sub-marine volcano near Surtsey, revealed, in one of these localities (fig. 1, III), the presence of algae growing directly on the rocks.

The profile of locality III shows a sea-cliff, about 20 m height, overhanging an irregular rocky terrace, which ends in the sea by a very exposed promontory (fig. 2). The surface of the substrate was rough, fissured and alveolate and apparently suitable for algal anchorage. The occurrence of tephra covering the top of the promontory and the foot of the cliff indicated approximately the high tide level of the sea. In the Westmann archipelago this level reaches 2.62 m above the mean low water mark at springtide, with an average tidal amplitude of 2.52 m.

The vegetation seemed to be of two kinds: filamentous green algae and yellow-brownish gelatinous formations.

The green algae grew in isolated tufts or gregarously in scattered patches on the exposed side of the promontory, above and a little below the high water mark line (fig. 2). This level represents the lowest part of the supralittoral region and the uppermost part of the littoral region. These algae (fig. 3, A) are simple multicellular filaments, about 1-3 cm high, and 10μ-50μ broad. Each thread is attached to the substrate by extramatrical rhizoids. The cells, generally as long as broad, are provided with one perforated or fissured parietal chloroplast, containing many pyrenoids of polypyramidal structure. On fixed material, stained according to Feulgen's method, it appears that each cell is multinuclear. Some filaments were fertile, bearing tumid zoidocysts, either empty or full of spores of acuminate structure. These characteristics agree with H. JONSSON's (2) description of Icelandic specimens of Urospora mirabilis Aresch., which is very common along the coasts of Iceland.

Urospora mirabilis grew in pure population in Surtsey. However, three species of Diatoms were found as epiphytes on the filaments of Urospora: Thalassionema nitzschioides Hust., Synedra affinis Kütz. var. parva Kütz. and Licmophora gracilis (Ehr.) Grun. var. anglica (Kütz.) Per., which all occur on the coasts of Iceland (1).

The second type of vegetation encountered in this locality filled the cracks and the anfractuosities of the rock (fig. 3, B), on the sheltered side of the promontory, around high water mark (fig. 2). Further study revealed luxuriant colonies of Diatoms, dominated by Synedra affinis var. parva, associated with a few Thalassionema nitzschioides and broken valves of Licmophora gracilis var. anglica. The rupicole form of Synedra affinis var. parva differs, however, from the epiphytic form by the deformation of the frustules, probably due to desiccation and poor silicification.

From this second investigation it is therefore clear that the first algal colonizers of the barren rocky substrate of Surtsey are Diatoms and filamentous green algae.

One month later, when we came back to Surtsey, the population of Urospora mirabilis had expanded considerably on the rocks and the Diatoms were still in place. New populations of Urospora had also developed in other rocky localities (II, and between III and IV), under similar environmental conditions. But no vegetation was to be found near the excrement of sea-birds, which had occupied the sea-cliffs for one month. This biotope, very common in Iceland, is characterized by nitrophilous algae as Prasiola and Enteromorpha. On the sandy beach, on the northern part of Surtsey and round the salt-water lagoon, situated in this part of the island, the substrate because of its mobility seems insuitable for the fixation of benthic marine algae. No attached algal vegetation was therefore to be found there. Dredgings carried out S and SE of Surtsey, on 15-20 meter's depth, revealed a sea-bottom covered with scoriae, completely devoid of algae.

The marine benthic vegetation found in Surtsey, about 21 month after the emergence of the island and about 15 months after the formation of the first rocky shore seems therefore only to be composed of Diatoms and filamentous green algae. No indigenous benthic animals, such as Barnacles, were met with on this coast.

2. Survey of driftweeds.

Macroscopic marine algae and various floating objects covered with algae are washed upon the shores of Surtsey, especially upon the large sandy beach in the northern part of the island. The following species were met with in the course of the summer 1965.

DIATOMEAE:

Licmophora paradoxa (Lyngb.) Ag., pure colony on Fucus vesiculosus, and mixed colonies on driftwood.

Fragilaria islandica Grun., many ribbon-liked colonies on driftwood with Licmophora paradoxa.

Thalassionema nitzschioides Hust., on driftwood, in company with Licmophora paradoxa.

Synedra affinis Kütz. var parva Kütz., on driftwood.

Nitzschia lanceolata W.Sm., on driftwood.

Amphora angusta (Greg.) Cl., on driftwood.

Navicula complanata Grun. var. hyperborea (Grun.) Cl. (?), on driftwood.

Navicula sp. (unidentifiable fragments), on driftwood.

Nitzschia sp. (unidentifiable fragments), on driftwood.

RHODOPHYCEAE:

Polysiphonia fastigiata (Roth) Grev., on Ascophyllum nodosum.

Rhodymenia palmata (L.) Grev., on driftwood.

PHEOPHYCEAE:

Ascophyllum nodosum (L.) Le Jollis, cast ashore.

Chordaria flagelliformis (Müll.) AG., on driftwood.

Chorda filum (L.) Stackh., on driftwood.

Fucus vesiculosus L., cast ashore.

Laminaria digitata (L.) Lam., on driftwood.

CHLOROPHYCEAE:

Ulothrix flacca (Dillw.) Thuret, on fishing net-float.

Urospora mirabilis Aresch., on fishing net-float.

Ulva lactuca L., on driftwood.

Acrosiphonia albescens Kjellm., on driftwood.

Among the species quoted above, which all occur along the coasts of Iceland, one finds those which have already colonized the rocky shore of the island, viz. *Synedra affinis* var. *parva* and *Urospora mirabilis*. This fact may explain how these species have immigrated into Surtsey. It should also be noticed that *Ascophyllum nodosum* is the most common algae cast ashore very probably because of its great abundance on adjacent coasts and also on account of its great floatability. The nearest locality known of this species is to be found at Heimaey, at 16.5 km from Surtsey.

Discussion

Until now *Urospora mirabilis* has been found only in pure population at Surtsey. However, it is known from H. JONSSON's work (3) that this species belongs to an algal community, generally composed, along the coasts of Iceland, by several associations where *Ulothrix flacca*, *Bangia fuscopurpurea* and *Porphyra umbilicalis* are predominating. None of these species have yet colonized Surtsey, but it can be assumed that they will do so in the near future. It therefore appears that *Urospora mirabilis* is the *pioneer species* of this community. It is also known (4) that the first vegetation of the supralittoral region, to which this community is confined, does not develop, as do the pioneers of the sublittoral region, into different climax communities. It can therefore be added that *Urospora mirabilis* is definetively established on the shore of Surtsey. If so, it is probable that *Codiolum gregarium*, the corresponding unicellular sporophyt of *Urospora*, soon will appear on Surtsey. From unpublished personal data it is known that this type of heteromorphic life cycle occurs in Iceland.

A striking fact is the small number of algal species established until now at Surtsey. This is even more striking as the algal vegetation on the adjacent coasts, the nearest of which is just 4,4 km away, appears luxuriant, containing about 100 species (the marine Diatoms not included). This situation may, however, be due to two factors exercising their influence on the colonization patterns of algae in Surtsey: the relative isolation of the island and the severe environmental conditions encountered there. An attempt to demonstrate the first of these has been made by following the sequence of colonization on clean substrate transferred from Surtsey to Heimaey, in a well established floral area (see S.V. Hallsson, this report). Within a month and a half the surface of the rock had already been colonized by 8 species of algae. Young Barnacles and Sea-snails occurred also. The distance of Surtsey from adjacent algal vegetation seems therefore to act as an obstacle which delays the dispersal of the algae to the island. The second factor involved, even more important, is the mechanical action of the sea along the very exposed coasts of Surtsey, viz. by scouring the surface of the substrate by means of suspended particles and thus preventing the fixation of spores. This corrosive action is more intensive in the intertidal region than in the supralittoral region. This fact may explain why the first colonization is taking place in the supralittoral region and not in the lower region of the coast.

The marine algae represent the only vegetation actually established in Surtsey. One coastal species of higher plants, *Cakile* probably *edentula*, was found last summer on the sandy beach by FRIDRIKSSON (5), but this first terrestrial growth succumbed soon later under a heavy shower of hot falling tephra from an adjacent submarine volcano. It is perhaps worth mentioning that these plants grew near some thalli of *Ascophyllum nodosum* cast ashore. It seems therefore likely that the driftweeds met on the shore, may, by means of their decomposition, give rise to organic matter, which enables the implantation of coastal growth. This may also be true for filamentous Fungi, insect pupae and living Acarida found last summer by S. HELGASON (personal communication) in rotted thalli of *Ascophyllum*, buried under the ash.

Our observations can hardly be compared with those carried out after the terrible eruption of Krakatau in 1883. Indeed, when visited for the first time by botanist, 3 years later, the island was already reoccupied by 11 species of Ferns, 15 species of higher plants and 6 species of blue-green algae, mixed with Bacteria and Diatoms. Nothing is therefore known about the beginning of the colonization (6, 7). Marine benthic algae are not mentioned, probably because of their absence on the coast, which seems to have been of sandy nature only. No comparison is either available with other recent submarine volcanic areas, for example the Isle of Faial, in the Azores, as no studies seem to have been devoted to this problem. On the other hand it is of interest to note that the initial phase of algal settlement of Surtsey shows a succession similar to that observed experimentally on artificial surfaces submerged by HUVÉ (8) in the Mediterranean Sea, although the species differ in the two areas.

Acknowledgements.

Thanks are due to Madame Marie-France MAGNE, Assistant at the Laboratoire de Biologie Végétale Marine de la Sorbonne (Paris), for the identifications of the marine Diatoms.

References.

1. Östrup E. - 1918. Marine Diatoms from the coasts of Iceland, Bot. Iceland, II, p. 347-394.

2. Jonsson H. - 1903. The marine algae of Iceland. III. Chlorophyceae, Bot. Tidskr., 25, p. 337-377.

3. Jonsson H. - 1912. The marine algal vegetation of Iceland. Bot. Iceland, I, p. 1-186.

4. Hartog, den C. - 1959. The epilithic algal communities occurring along the coast of the Netherlands. Thesis.. Amsterdam. 241 p.

5. Fridriksson S. - 1965. The first species of higher plants in Surtsey the new volcanic island. Náttúrufr., Vol. 35, p. 97-102.

6. Treub M. - 1888. Notice sur la nouvelle flore de Krakatau, Ann. Jardin Buitenzorg, 7, p. 213-223.

7. Ernst A. - 1907. Die neue Flora der Vulkaninsel Krakatau, Vierteljahrschr. Naturw. Gesellsch. Zürich. 52, p. 289-363.

8. Huvé P. - 1953. Etude expérimentale du peuplement de surfaces rocheuses immergées, en Méditerranée. C.R.Ac.Sc. (France), 236, p. 419-422.

Explanations to figures.

Fig. 1. Two superimposed sketch maps of Surtsey showing the outlines of the island, the nature of the coast and the rocky localities surveyed in 1964 (1,2) and in 1965 (I, II, III, IV). Note the extension of the rocky shore and the alteration of the sandy beach during this time.

(After aerial photos from the Icelandic Geodetic Institute).

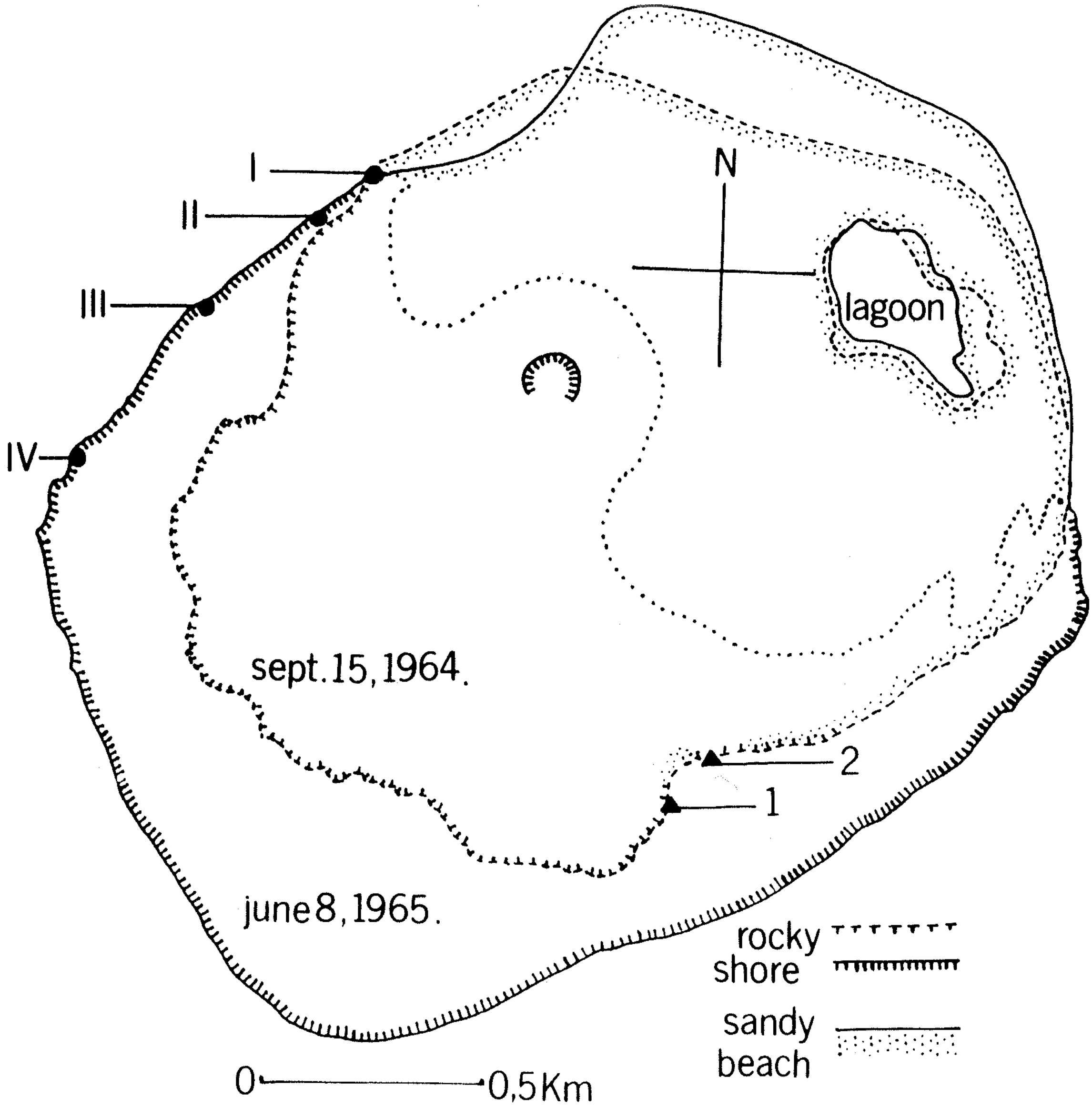
Fig. 2. Cross-section of locality III, showing the position of the vegetation around the high water mark line. MHHW: mean higher high water. MLLW: mean lower low water.

Fig. 3. The first macroscopic benthic vegetation found in Surtsey.

A. Green carpet of Urospora mirabilis (arrow)
B. Gelatinous formation of Diatoms (arrow).

Scale: match-stick: 4,5 cm.
(Photographer: H. Kristinsson)

Fig. 1



N
lagoon
I
II
III
IV
sept.15,1964.
june 8,1965.
2
1
rocky
shore
sandy
beach
0
0,5Km

Fig. 2

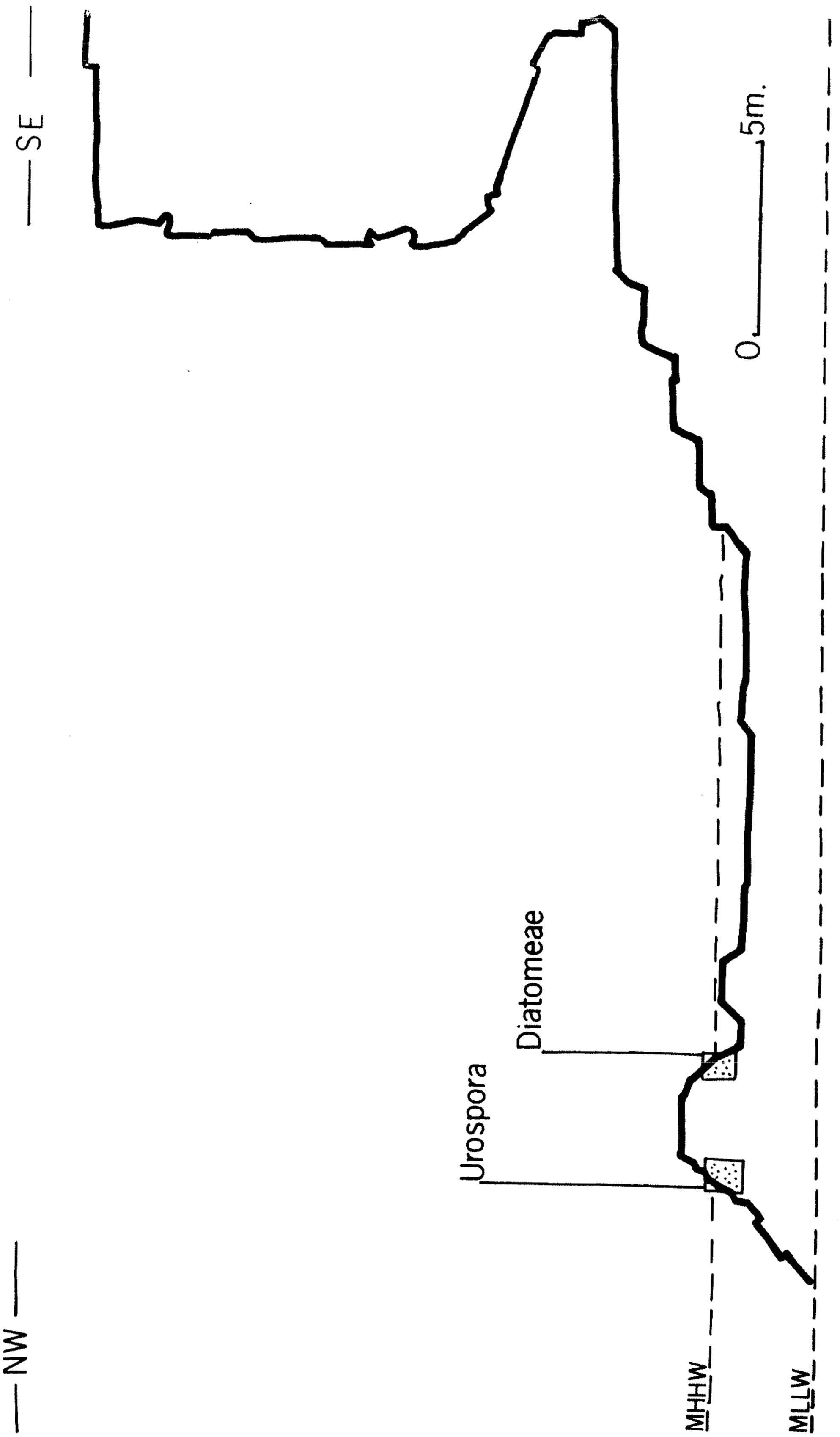


Fig. 3

Preliminary Report on the Vascular Flora of the Lesser Westman Islands

by

Sturla Fridriksson and Björn Johnsen
University Research Institute, Reykjavik

Introduction

The prospect of future colonization of terrestrial plants on the volcanic island Surtsey, is affected by the available source of species on the adjacent land masses as well as means of dispersal and environmental conditions on Surtsey.

As a background for the evolution of colonization of plants on the new island a good knowledge of the flora of these land masses is necessary. In the manual of vascular plants of Iceland, such as Flóra Íslands by Stefán Stefánsson (1924) and Íslenzkar Jurtir by Áskell Löve (1945), records are made of the occurrence of vascular plants in the Westman Islands as well as the various locations on the adjacent mainland. A thorough study of higher plant life on Heimaey, the only inhabited island of the Westman Islands group, was carried out by Baldur Johnsen (1939) who also made some studies on Bjarnarey. A few observations have been made on the vegetation of the lesser islands, although no floral lists were available. It was thus considered of primary value to carry out a thorough investigation of the vegetation of these islands. The work was sponsored by the Surtsey Society with a grant from the United States Atomic Energy Commission.

Some Topographical Features

According to present knowledge, geologists believe the Westman Islands to have been created by volcanic activity towards the end and after the last Glaciation. The formation of Surtsey has clarified facts concerning the origin of other islands in the group which lie along a NE-SW tectonic fissure, which is a part of the Atlantic ridge. Remnants of volcanic craters are noticable throughout the islands, which are mostly made of palagonite tuff (consolidated volcanic ash) with streaks and veins of intruded basalt. The palagonite tuff accounts for most of the bedrock, but large areas of Heimaey and Surtsey are also covered with lava. These two are the largest islands, and they show greater variation in topography than the smaller members of the group, some of which are mere stacks, 50 m high with a mantle of vegetation on the slanting summit. The soil in the older islands is rather deep, loessy in character, fertile and rich in organic matter due to birds droppings. Sea birds inhabit the islands in great numbers; among these is the puffin (Fratercula arctica) which digs deep nesting holes in the soil on the top of the islands whereas the other bird species inhabit the cliffs.

Climate

No meteorological records have been carried out on Surtsey or the smaller islands. On Heimaey, however, there is a meteorological station with available records from 1872.

The climate is highly oceanic. It is relatively warm and moist in comparison to the average climate on the mainland or, for example, the island of Grímsey. The precipitation is the seventh highest, and the mean temperature the third highest in Iceland. (See Table I).

Excursions

Various excursions were made to the smaller islands from Heimaey, which was used as a base of operation. The study commenced in early July 1965 when the students, Björn Johnsen and Sigurdur Helgason went to the Westman Islands, later to be joined by other groups of investigators. The last trip was made on Sept. 9th. On all these excursions ecological survey was carried out and herbarium material collected as well as live specimen for laboratory study. Following is brief account of the excursions.

Excursion No. 1. July 9th to Brandur.

The party left Heimaey at midday with the boat t/b Adolf piloted by H. Johnsen.

Brandur island is an old volcano with the crater bowl facing the sea on its southwest side. Landing conditions there proved tolerable compared to other islands yet to be explored. The island is extremely steep and rugged; nevertheless the ecological survey was carried out and plant specimens collected. The party stayed overnight in a small hut and had to leave at noon the following day because of the unexpectedly early arrival of the coastguard vessel, which was to take the expedition to the other islets.

Excursion No. 2. to Geirfuglasker and Thrídrangar.

The coastguard boat Árvakur, on its annual visits to the lighthouses on Geirfuglasker and Thrídrangar, carried the party to the precipitous rocky islet of Geirfuglasker. When arriving, a rubber boat was manned and padded to the rock. The party succeeded in landing there safely in spite of rough sea and climbed about 50 m up the steep cliff to the summit. The climb was facilitated by chains bolted to the cliff which is very rough due to differential erosion. The summit of the rock is almost level and only a few hundred square yards in area. A thick layer of volcanic ash carried from Surtsey had accumulated there and partly killed and buried the extremely sparse vegetation.

The next destination was Thrídrangar (Three Pillars), two hours trip by boat WNW from Geirfuglasker. Conditions there are quite similar to those of Geirfuglasker as regards landing and ascending, but the islet is still smaller in size.

Excursion No. 3. July 13th to Álsey.

The party arrived on Álsey by evening with the boat t/b Soffia piloted by J. Bryngeirsson. Landing conditions there are quite difficult except in calm sea. The expedition was assisted by bird collectors, who were on the island during the bird hunting season. The following day the island was explored and an ecological study performed. Samples of living plants were taken. The party had to leave for Heimaey the same evening although the work was not quite completed.

Excursion No. 4. July 21st to Ellidaey.

The trip was made on the boat t/b Soffia piloted by H. Jonsson. Participants were C.H. Lindroth and H. Anderson, Swedish entomologists, S. Jónsson algologist, and S. Helgason. The landing and ascending conditions were favourable. Later that day strong wind delayed the return of the boat, and the rough sea made the landing extremely difficult but at last the party succeeded in getting on board and returned to Heimaey.

Excursion No. 5. July 23rd to Sudurey.

The party left Heimaey by the boat t/b Soffia piloted by H. Jonsson. Participants were S. Jónsson and B. Johnsen. The first landing was on Brandur island to collect additional samples of living plants for cytological studies. Then the course was taken to Sudurey and a successful landing made although conditions are extremely difficult there compared to other islands. As the party had disembarked and supplies had been unloaded the boat returned to Heimaey. The island is surrounded by precipitous cliffs on three sides. On the fourth side there is a high (160 m) and steep slope which had to be climbed in order to reach the top. The following day the plant life and algae were studied and samples collected. The expedition left the island by nightfall.

Excursion No. 6. July 25th to Ellidaey.

The party left Heimaey at midday with the boat t/b Hlýri piloted by B. Gudmundsson. Participants were S. Jónsson, B. Johnsen and S. Helgason. The course was taken to the shallows east of Heimaey and samples of algae collected by a bottomscraper. Currents were favourable and the results excellent. Samples of algae were also taken from shoals between Ellida-island and Bjarnar-island. A short excursion was made to Ellidaey and samples collected.

Excursion No. 7. August 4th to Hellisey.

The party left for Hellisey on the boat t/b Hlýri piloted by B. Gudmundsson. The island is crescent-shaped and precipitous with the concavity facing the main wind direction, and during winter the surf reaches high. Without the help of a guide, who knew the routes, the steep ascent was made with difficulty. The vegetation is sparse at lower levels but increases gradually until it forms a continuous mantle on the top. The plant-life and algae were studied and samples taken.

Excursion No. 8. August 8th. A second trip to Geirfuglasker.

The party left Heimaey with the boat t/b Adolf piloted by H. Johnsen. Participants S. Jónsson algologist. The main purpose of the trip was to collect algae from Geirfuglasker. The trip was quite successful.

Excursion No. 9.

An excursion to Súlnasker was made on September 10th by a helicopter supplied by the Icelandic Coast Guard, piloted by B. Jónsson. Participants were S. Fridriksson and S. Helgason. The island is 80 m high with vertical cliffs on all sides and quite unaccessable. A study was carried out on the vegetation of the island during a three hours' stay.

Excursion No. 10.

An excursion was made to the south coast of Iceland on August 17th to 25th for a botanical study of the mountain isolates of Pétursey, Hjörleifshöfdi and Hafursey.

Vegetation

The flora of the Westman Islands consists of 150 species of vascular plants according to Johnsen (1939). All the species recorded on the smaller islands are similarily found growing on Heimaey. On these islands the vegetation is prolific but scanty in species, with a total of only 27 species of vascular plants. On Ellidaey, the largest of the smaller islands, the number of species is 22, but on the pinnacles of Geirfuglasker and Thrídrangar the species recorded were four and two respectively.

The species found on each individual island are listed in Table II.

An attempt was made to classify the species of the Westman Islands according to geographical distribution and life forms. The species are compared with those of four other Icelandic isolates. Three of those are tuff mountains isolated by alluvial gravel and sand, and situated on the mainland in the neighbourhood of Mýrdalur: Pétursey was found to have 73 species, Hjörleifshöfdi 75, and Hafursey 89 species. The fouth isolate is the island of Grímsey, situated off the north coast of Iceland with a total of 116 species.

The comparison shows that the number of Arctic species increases with increased latitude, changing from no Arctic element in the flora of Súlnasker and Geirfuglasker to 42% Arctic species in the flora of Grímsey. The majority of the species of the Westman Islands, or 74 to 100%, are of European type, which reflects the thermal condition of these respective locations rather than a difference in floral communities in possible glacial refugia in the northern and southern part of the country. (See Mölholm Hansen, 1930, for classification).

The ratios of various life forms (Raunkier, 1907) on the islets are comparable to that of Heimaey, but the Westman Islands group differs in this respect from the three inland isolates as well as from Grímsey. Chameophytes are more frequent on the mainland, but the percentage of Annuals is higher on the Westman Islands. The percentages of Geophytes and Hemicryptophytes on the islands are similar to that of the mainland. (Table III).

The vegetation of the smaller islands can be classified into four plant communities: The puffin-colony vegetation, the dry meadow land, the coastal cliff vegetation, and the angelica cluster.

I. The puffin-colony type forms the bulk of the vegetation on the southern islands, and is usually situated on slopes facing the sea where the puffin (Fratercula arctica) nests in deep holes. The nesting holes are rather closely packed, two to three holes per square meter. The three main species of vascular plants growing there are: Festuca rubra, Matricaria maritima and Stellaria media. The Festuca is predominating with the approximate cover of 70%, while Matricaria and Stellaria are the associated species.

The soil is deep and damp with high content of organic matter. The fertility-level of the soil is extremely high as a result of bird droppings. These high fertility conditions are quite selective, presumably favouring the red fescue rather than other grass-species. At this level the fescue remains highly vegetative and has a high leave to culms ratio. The puffin-colony vegetation has intense bluish-green tint, contrasting the bleaker tint of the dry meadow land. This difference becomes more conspicuous towards autumn, as the grass in the dry meadow-land reaches maturity and becomes higher in fiber-content and wilts earlier than in the puffin colony. The soil is broken up by the puffin into small columns with tufts of red fescue covering the network of tunnels and trenches. Thus this honeycomb-structure of soil appears to be a continuous mat of vegetation. However, where there is a break in the fescue cover, the associated species have a chance to establish themselves.

Whenever the breeding grounds of puffin are densely populated the growth of the red fescue is hampered by the excavation of the birds. On these occasions the associated species are favoured, sometimes even allowing the Matricaria to predominate, but, in rare instances, Cochlearia and Atriplex occupy the space.

Apparently this high fertility level, the special water retention of the turf soil, as well as the intense aeration caused by the digging, play an important role in this selective habitat. The soils differ as to the extent of aeration from other highly fertile soils in Iceland such as those of hayfields in the neighbourhood of stables and farmhouses. In that case Poa annua dominates, but is hardly present in the vegetation of the puffin colony except in one instance, i.e. on the island of Súlnasker, where it was found growing on the edge of a small basin containing rain water.

II. The dry meadow land vegetation has a wide distribution, being the second largest plant association on the southern islands and predominating on the northern islands. It is situated on the level or sloping summits and where the soil is dry and too shallow for the puffin to dig their nesting holes. (The puffin colony association can be regarded as a derivative of the grassfield as the puffin hardly establishes nesting colonies except in grass covered soil. On some of the islands any pure grassfield is hardly to be found as it is occupied and deformed by the presence of the puffin). The soil of the dry meadow land is rich in organic matter due to the high annual productivity of this community and its low decomposition. A layer of turf is thus formed at the top. On the southernmost island this top layer includes some fresh volcanic ash derived from the Surtsey eruption. The thickness of the ash varies in proportion to the distance from its source of origin. On the island Álsey 14 km distant from Surtsey the ash layer was 2-3 cm thick. Below the turf layer the soil is rich in minerals, which derive from the basic tuff below. The grassfield is to some extent fertilized by various seabirds constantly swarming over the islands during the nesting period. This accounts for a rather high fertility level of the soil and vigorous growth. The dry meadow land has a predominance of grasses, with Festuca rubra covering 61% of the total area, Poa pratensis covering 32%, Agrostis tenuis 3%, and the associated species covering the remaining 4% as an average of measurements from Álsey, Brandur and Sudurey. The associated species are Ranunculus acris, Poa trivialis, Rumex acetosa, Cerastium caespitosum and Taraxacum acromauris. All these species are of common occurrence in cultivated grassfields in Iceland (S. Steindorsson 1964, p. 124).

As a rule the grassfield vegetation resembles some cultivated grasslands as regards to species and growing conditions. The bryophyta are completely absent from this plant community as is the case of well cultivated hayfields.

The growth of the grass species is vigorous. The height of mature culms reaches 20 inches, and the yield is five to six tons of dry hay per hectar (5 - 6000 lbs/acre) judged from samples collected in Sudurey and Álsey. The productivity is thus quite high, almost comparable to that of an average cultivated hayfield in Iceland. When this observation was made no sheep had been grazing on the southern islands since the volcanic activity started in the Surtsey area. A number of sheep had previous to that been grazed on the islands all the year around as far back as records go. The grazing of the sheep may be selective to some extent; in dry season the sheep have a tendency to feed on the more succulent broad leaved herbs as drinking water is limited. It is the farmers' opinion that the vegetation on the islands has been more productive after the volcanic activity commenced and that Matricaria and Ranunculus are now more abundant. The volcanic activity may have affected the growth directly by the fertilizing effect of the ash or indirectly by terminating the grazing of sheep.

III. The coastal cliff vegetation is situated in the splashing zone, forming a fringe around the islands, which is, however, not necessarily continuous. It is the vegetation of the slanting slope but is interrupted wherever the cliffs are too steep to hold this type of vegetation. Its lower margin is at high tidemark and the upper border is contiguous with the puffin colony. This zone varies in width, reaching higher level on the southern side, which is exposed to the Atlantic where the surf is more intense than on the side facing the mainland. This vegetation does not form a continuous mat. The various plants are only found growing in small patches in depressions and cravasses, where some soil or anchorage is to be found on the otherwise bare rock. Estimated ground-coverage is one to five percent of the total area. The predominating species are Puccinella maritima and Cochlearia officinalis with Armeria vulgaris, Atriplex patula and Plantago maritima as associated species.

IV. The Angelica cluster is situated on slopes or rocky shelves on the northern sides of some of the islands. It is described by Johnsen (1939) but was not investigated by our group.

Concluding remarks.

In general the vegetation on the larger islets is predominated by the grasses, especially Festuca rubra, which seems to be favoured by the environmental conditions present.

The surface of the islands is generally sloping towards the sea, preventing water from accumulating. During periods of drought, which can last for several weeks, the soil may become so dry that only the highly drought resistant species survive.

In addition the fertility level of the soil, the effect of the velocity and frequency of winds, the splashing of sea water, as well as the grazing of sheep, are important environmental factors and presumably account for the fact, that no woody plants grow wild on the islands, with the exception of three woody species found on the lava of Heimaey. The high precipitous cliffs, reaching considerable depths below sea level and thus devoid of gravel beaches, exclude some coastal species and hinder dispersal by sea.

The sizes of the individual islands evidently cause further limitations, as the number of species was found to be roughly proportional to the area of the islands.

It is evident that all these highly special environmental factors cause great limitations as to the number of plant species and their association on the islands.

Although the migration of plants is restricted to some extent by the isolation of the islands, the flora of each individual island has to be regarded as a climax community primarily governed by the present environmental conditions.

BIBLIOGRAPHY

Hansen H., Mölholm 1930: Studies on the vegetation of Iceland. Copenhagen.

Johnsen, Baldur 1939: Observations on the vegetation of the Westman Islands. Societas Scientarum Islandica. Vol. XXII.

Löve, Áskell 1945: Íslenzkar jurtir. Einar Munksgård. Köbenhavn.

Raunkier, C. 1907: Planterigets Lifsformer og deres Betydning for Geografien. Copenhagen.

Stefánsson, Stefán 1924: Flóra Íslands. 2nd edition. Reykjavík.

Steindórsson, Steindór 1964: Gróður á Íslandi. Almenna Bókafélagið. Reykjavík.

Steindórsson, Steindór 1964: Flóra Grímseyjar. Journal of Icelandic Botany, p. 89-94.

Veðráttan 1944 og 1962 (A Meteorological Bulletin). Veðurstofan. Reykjavík.

TABLE I

Mean precipitations and temperatures at Stórhöfdi, Westman Islands, Vík, Mýrdal, and Grímsey, 1901-1930, 1931-1960.

Meteorological stations	Jan.	Feb.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.	The whole year
					Mean Temperatures in °C								
Westman Islands (Stór-höfdi) 1901-1930	1.1	1.3	1.6	3.0	5.7	8.5	10.2	9.6	7.5	4.8	2.4	1.4	4.8
Westman Islands (Stór-höfdi) 1931-1960	1.4	1.6	2.7	3.7	6.2	8.5	10.3	10.2	8.4	5.6	3.8	2.5	5.4
Vík, Mýrdal 1901-1930	0.9	1.2	1.5	3.1	6.2	9.3	11.0	10.5	8.0	4.9	2.3	1.3	5.0
Vík, Mýrdal 1931-1960	1.2	1.2	2.6	3.9	6.9	9.5	11.3	11.0	9.0	5.6	3.7	2.3	5.7
Grímsey 1901-1930	- 1.8	- 1.9	- 2.0	- 0.8	2.2	5.7	7.7	6.8	5.5	2.6	0.2	- 0.9	2.0
Grímsey 1931-1960	- 0.5	- 1.1	- 0.4	0.2	3.4	6.3	8.1	8.3	6.7	3.9	1.9	0.3	3.1
					Precipitation in mm								
Westman Islands (Stór-höfdi) 1921-1930	160	147	197	99	84	72	90	89	125	93	129	160	1373
Westman Islands (Stór-höfdi) 1931-1960	138	104	109	97	81	81	84	108	132	166	141	156	1397
Vík, Mýrdal 1931-1960	182	159	164	171	143	167	169	188	237	238	212	226	2256
Grímsey 1951-1962													662

THE METEOROLOGICAL BULLETIN, Veðráttan, 1944-1962, Reykjavík.

TABLE II

Floral list from ten islets of the Westman Islands group.

Species	Life forms[1)]	Ellidaey 0.46 km^2	Bjarnarey 0.32 km^2	Álsey 0.25 km^2	Sudurey 0.20 km^2	Brandur 0.10 km^2	Hellisey 0.13 km^2	Súlnasker 0.04 km^2	Geirfuglasker 0.02 km^2	Thrídrangar 0.01 km^2	Surtsey 2.5 km^2
Agrostis stolonifera	$H-E_3$				x						
Agrostis tenuis	$H-E_3$	x	x	x	x						
Archangelica officinalis	$H-A_2$	x	x	x	x						
Armeria vulgaris	$CH-A_3$	x	x			x	x				
Atriplex petula	$TH-E_2$			x	x	x	x	x	x		
Cakile edentula	TH										(x)
Cerastium caespitosum	$CH-E_3$	x	x	x	x	x					
Cochlearia officinalis	$H-E_4$	x	x	x	x	x	x	x	x	x	
Euphrasia frigida	$TH-A_2$	x	x		x						
Festuca rubra	$H-E_4$	x	x	x	x	x	x	x			
Leodonton autumnalis	$H-E_3$	x	x	x	x						
Matricaria maritima	$H-E_3$	x	x	x	x	x	x	x	x		
Montia lamprosperma	$TH-E_4$		x		x						
Plantago maritima	$H-E_4$	x	x	x		x	x				
Poa annua	$TH-E_3$		x	x	x			x			
Poa pratensis	$G-E_3$	x	x	x	x	x					
Poa trivialis	$H-E_2$	x	x	x	x						
Puccinella maritima	$H-E_3$	x	x	x	x	x	x	x	x	x	
Ranunculus acris	$H-E_4$	x	x	x	x						
Ranunculus repens	$H-E_4$	x			x						
Rumex acetosa	$H-E_3$	x	x	x							
Sagina procumbens	$CH-E_3$	x	x	x	x						
Saxifraga caespitosa	$CH-A_3$	x	x	x							
Saxifraga rivularis	$H-A_3$			x							
Sedum roseum	$H-A_2$	x	x	x							
Silene maritima	$CH-A_1$	x	x	x	x	x					
Stellaria media	$TH-E_4$	x	x	x	x	x	x	x			
Taraxacum acromauris	$H-E_2$	x	x	x	x						

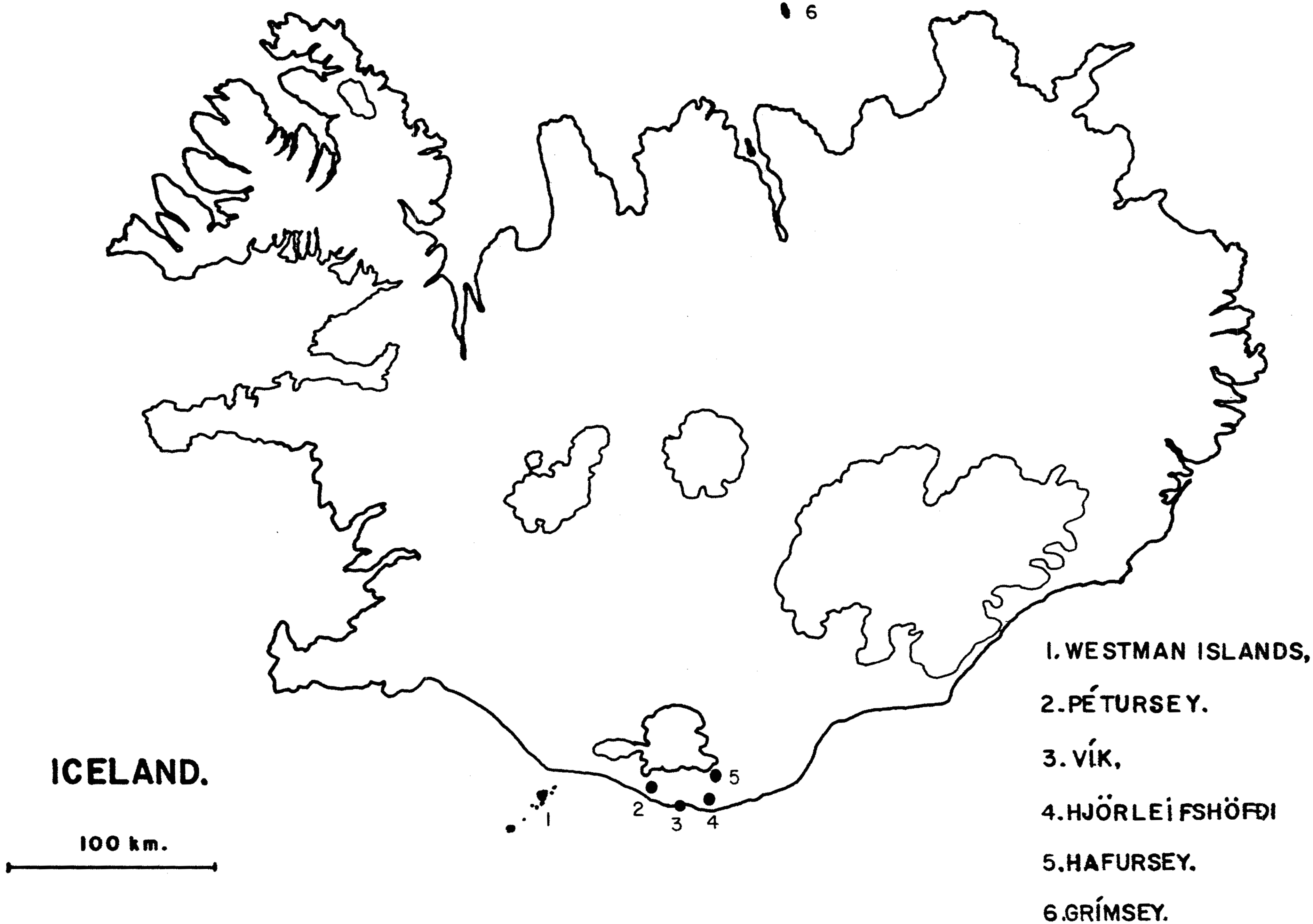
1) For explanations of terms see Table III and Raunkier, C., 1907.

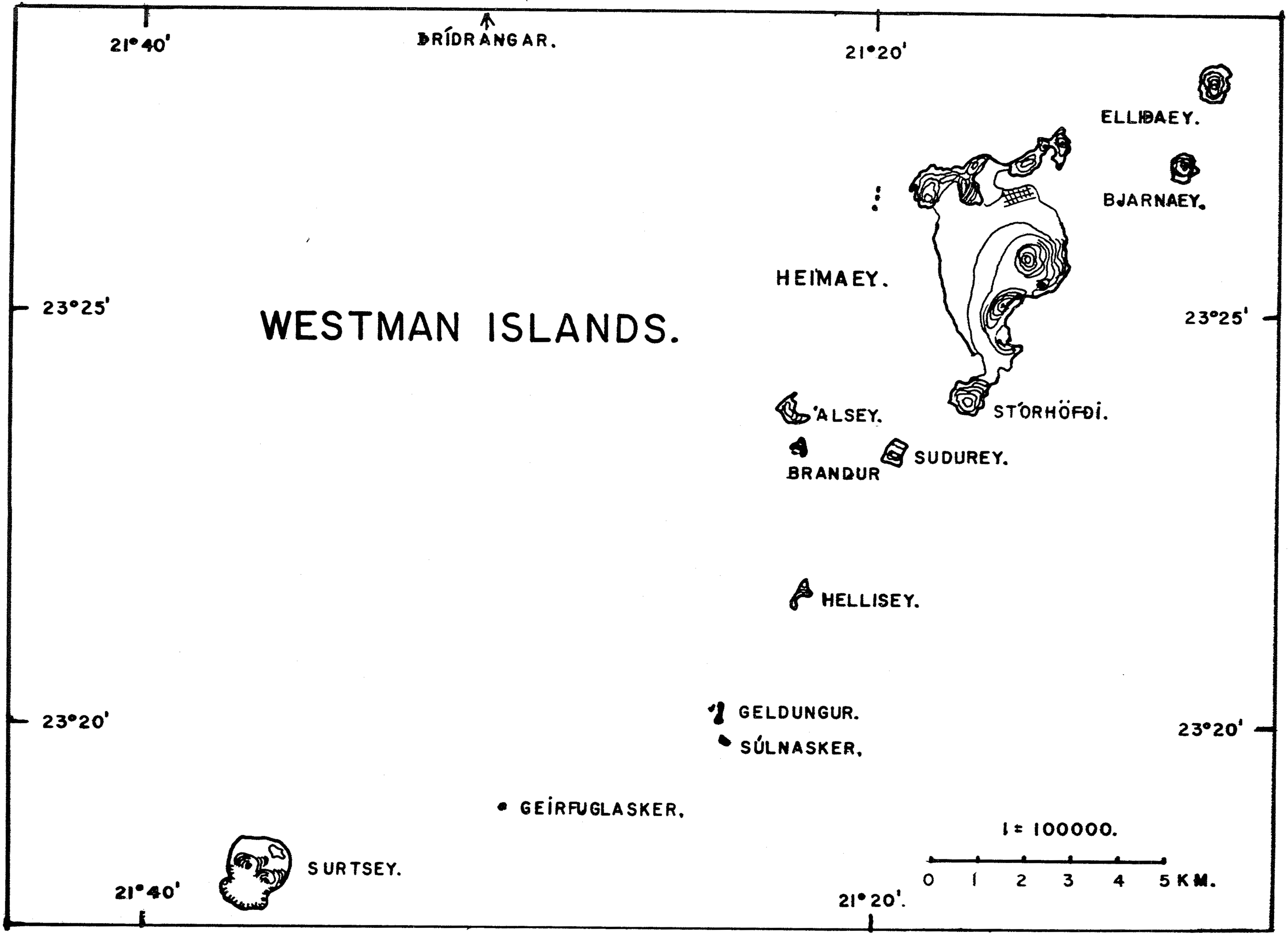
TABLE III

Life forms and number of species from nine Westman Islands, three inland mountain isolates and Grímsey

Locations	No. sp.	A %	E %	PH %	CH %	H %	G %	TH %	HH %
Grímsey	116	42	58		15.5	61.2	12.0	7.7	5.2
Hafursey	89	39	61	1	26	58.4	6.7	8.0	
Hjörleifshöfdi	75	36	64		26.6	54.6	9.3	9.3	
Pétursey	73	29	71		24.6	60.0	7	8	
Heimaey	150	26	74	0	13.4	61.7	8	13.4	3.4
Ellidaey	22	27	73		18	63.6	9	9	
Bjarnarey	22	18	82		12.5	62.5	8.3	16.6	
Álsey	22	18	82		18	63.6	4.5	13.6	
Sudurey	21	14	86		14.2	57.0	4.7	24.0	
Brandur	11	18	82		27	45.4	10	18	
Hellisey	8	12	88		12.5	62.5	0	25	
Súlnasker	7	0	100			71		28	
Geirfuglasker	4	0	100			75		25	
Thrídrangar	2	0	100			100.0			
The smaller islands, total	30	23.3	76.7		16.7	60.0	6.7	16.7	0

A Arctic species
E European species
PH Pheophytes
CH Chamaephytes
H Hemikryptophytes
G Geophytes
TH Therophytes
HH Hydrophytes, Helophytes


ICELAND.
100 km.
6
1
2
3
4
5
1. WESTMAN ISLANDS,
2. PÉTURSEY.
3. VÍK,
4. HJÖRLEIFSHÖFÐI
5. HAFURSEY.
6. GRÍMSEY.



WESTMAN ISLANDS.
ÞRÍDRANGAR.
21°40'
21°20'
23°25'
23°20'
ELLIÐAEY.
BJARNAEY.
HEIMAEY.
STÓRHÖFÐI.
ÁLSEY.
BRANDUR
SUDUREY.
HELLISEY.
GELDUNGUR.
SÚLNASKER.
GEIRFUGLASKER.
SURTSEY.
1 = 100000.
0 1 2 3 4 5 KM.

The Possible Oceanic Dispersal of Seed and Other Plant Parts to Surtsey

by

Sturla Fridriksson
University Research Institute
Reykjavík

Seed and other parts of vascular plants have been observed among the debris constantly being washed ashore on Surtsey. These plant parts are mostly of coastal species, nine of which have been found growing on the smaller neighbouring islands. All parts that could be identified are of species found growing on Heimaey as well as the mainland of Iceland. The various plant parts are listed in Table I. The records are based on the author's findings as well as those of Einarsson (1965).

Some of these plant fragments have been collected to test their viability after their apparent immersion in salt water, (see also Einarsson, this report).

A laboratory experiment with freshly collected seed immersed in sea water for different length of time allows the suggestion that seeds of some of these species could keep their germinating ability after oceanic dispersal.

This experiment was performed in order to determine for how long seeds of some Icelandic plants could survive in sea water.

Seeds from three coastal plants and three Arctic plants were collected. The seeds were stored in covered glass flasks containing sea water at 2°C. At regular time intervals 25 seeds were removed from each flast, washed in fresh water and their germination ability tested. (See Table II).

It should be noted that the seed of all the coastal species had not fully entered dormancy when this experiment was started. Their germination ability was therefore low during the first weeks but increased gradually as time advanced.

At the end of a four months' period the effect of the salt water exerted but minor changes on the viability of the seed. At the end of an eight months' period the viability of the seed began to decrease and Cardaminopsis petrea had apparently completely lost its germination ability.

In Table II the salinity of the sea water is recorded in the last column. Salinity has increased slightly from the original 3.09% due to evaporation. The deviation, however, does not exceed that of the ocean surrounding Iceland.

The experiments indicates that seeds of these species can keep their viability immersed in sea water up to 224 days. This time would allow them to be carried by currents great distances even from one continent to another where they could germinate if conditions allowed.

BIBLIOGRAPHY

Fridriksson, Sturla (1964): The Colonization of the Dryland Biota on the Island of Surtsey off the Coast of Iceland. Náttúrufræðingurinn 34, p. 83-89.

Einarsson, Eythór (1965): Report on dispersal of plants to Surtsey. The Surtsey Biology Conference, Proceedings, p. 19-21.

TABLE I

Species and parts of vascular plants recorded drifted ashore in Surtsey

Species	May 21st-64	Aug. 1st-64	Aug. 19th-64	Oct. 15th-64	Nov. 25th-64	Jan.21s -65
Alopecurus pratensis				Panicle with seeds		
Angelica archangelica				Old stem		
Anthorantum odoratum				Panicle with seeds		
Atriplex patula			Plant with seeds			
Cakile edentula					4 seeds	
Cochleria officinalis	Plant parts with flowers		One green leaf			
Elymus arenarius	1 seed				1 seed	
Euphrasia sp.				1 inflores- cence		
Festuca rubra			Leaves and culms	2 stems and leaves. Panicle		Leaves
Galium boreale				1 stem and leaves		
Ligusticum scotium	3 leaves					
Matricaria maritima	25 leaves Young plant		2 umbels with seed			Leaves
Mertensia maritima				1 plant part		
Poa pratensis	Leaves, stolons	Plant part				
Polygonum viviparum					1 seed	
Sedum rosae	Leaves and stem		Flower stalk	Plant part		
Silene maritima				1 calyx		

TABLE II

Percentage of germinating seed following storage in seawater at 2°C

Species	Number of weeks in sea water						NaCl %
	1 %	2 %	4 %	8 %	16 %	32 %	
Silene acaulis	70.3	100.0	92.1	84.0	57.0	42.3	3.18
Cardaminopsis petrea	83.2	38.4	15.6	52.0	52.0	0.0	3.12
Cerastium alpinum	100.0	91.3	46.7	90.0	90.0	74.0	3.12
Matricaria maritima	6.6	10.0	30.0	24.1	40.0	54.5	3.26
Plantago maritima	5.1	20.0	66.7	72.0	72.0	50.5	2.61
Cakile edentula	0.0	30.0	20.0	60.0	85.4	37.5	3.27

The Pioneer Species of Vascular Plants in Surtsey, Cakile Edentula

by

Sturla Fridriksson
University Research Institute, Reykjavik

The first species of higher plants to colonize the new volcanic island of Surtsey was discovered on June 3rd 1965.

Small seedlings of Cakile edentula were found growing upon the sandy beach north of the small lagoon on the island. On June 8th an expedition discovered some 20 additional seedlings of the same species growing approximately 50 m east of the previous location.

The plants were all growing in a mixture of tephra and decaying seaweed (Ascophyllum nodosum), which evidently formed a suitable medium for the germination and growth of the young plants.

The plants had grown from seed that apparently had been washed ashore, possibly along with the seaweed, which might act as a float, aiding dispersal of seed by ocean.

The seedlings of the pioneer colonists, however, did not mature, but succumbed a few weeks later under a shower of ashes carried from the volcanic crater of Syrtlingur located NE of Surtsey. The fall of fresh tephra from this satellite volcano thus delayed the colonization of higher plants on Surtsey. (Fridriksson 1965 a, 1965 b).

It was not surprising to find Cakile as the first species of vascular plants to grow in Surtsey, and thus becoming a pioneer plant in the possible future succession of the coastal region of the island. Seed of Cakile had previously been found drifted ashore in Surtsey but when tested it did not show any sign of germination (Fridriksson 1964). It was however, assumed that the seed would not be greatly affected by the salinity of the sea, as Cakile is a coastal species having seed with a thick cork capsule, which protects it and keeps it floating for a considerable length of time.

It had even been suggested by Löve and Löve (1947, 1956) that *Cakile* was one of those species found in Iceland which could have been carried by ocean currents to the country from the coast of America. This assumption was based on the authors' cytological studies, which indicated that the European *Cakile* (sp. *maritima*) is diploid compared to the tetraploid (sp. *edentula*) of America, the Azor Islands and Iceland.

The discovery of the pioneer plant in Surtsey shows that living *Cakile* seed is being dispersed over such distances as between Surtsey and some *Cakile* colony, the nearest being on an island 20 km away. A test of the viability of *Cakile* seed after immersion in sea water furthermore supports the possibility of dispersal of such living seed over still greater distances. (See Fridriksson,this report).

BIBLIOGRAPHY

Fridriksson, Sturla (1964): The colonization of the dryland biota on the Island of Surtsey off the coast of Iceland. Náttúrufræðingurinn Vol. 34, p. 83-89.

Fridriksson, Sturla (1965 a): Biological records on Surtsey. The Surtsey Biology Conference, Proceedings, p. 22-24.

Fridriksson, Sturla (1965 b): The first species of higher plants in Surtsey the new volcanic island. Náttúrufræðingurinn, Vol. 35, p. 67-102.

Löve, Áskell and Doris (1947): Studies on the origin of the Icelandic flora. Rit Landbúnaðardeildar B-flokkur nr. 2, p. 29.

Löve, Áskell and Doris (1956): Cytotaxonomical conspectur of the Icelandic flora. Acta Horti Gotoburgensis 20, p. 176-178.

REPORT

on the Marine Biological Survey Around and on Surtsey

by

Unnur Skúladóttir
Marine Research Institute

Materials and Methods.

For bottom samples the following instruments were used:

Petersen grab
Rectangular dredge
Bobertson bucket dredge
Ring dredge

For collecting zooplankton the following instruments were used:

Hensen net
Icelandic high speed plankton sampler

For collecting the larvae of bottom animals: a small hand-towed plankton net was used.

Investigations, which were started in 1963, have been continued in much the same manner with three surveys of the sea around Surtsey. Observations were again made along the four sections directed east-west and north-south from Surtsey, at $\leq$ 1, 3, 7 and 12 nautical miles respectively off the island. Besides this zooplankton was collected on one or more sections farther west in the Selvogsbanki region.

Surveys of the shore of Surtsey have been made in seven visits to the island.

Observations and Results.

The three surveys of the sea around Surtsey were carried out in March, May and August. The zooplankton was collected at all the stations of the "Surtsey cross" and also along other sections farther west. In the May survey no zooplankton was collected. The phytoplankton was collected at every second station along "Surtsey cross" and also along the section west of the "Surtsey cross" and next to it. In the May survey, however, the phytoplankton was only collected along the north east and south sections of the "Surtsey cross". The larvae of bottom animals were collected at the stations next to Surtsey at 1 - 6 stations in each survey. The bottom samples were collected according to the tables I-III.

No samples have been worked up yet apart from one sample containing one animal. This has, however, only been identified as far as the genus. The specimen was caught by a rectangular dredge on May 5th-6th, 200 m (0.1 nautical mile) north of Surtsey, at a depth of 70 m. The depth there was 120-130 m before the eruption. The animal is a nudibranch, a Coryphella species.

On May 18th one extra station was worked 0.2 nautical miles south-west of Surtsey, at the depth of 85 m. Here again the depth was 120-130 m before the eruption. The lava brought up by the rectangular dredge carried a colony of some hydrozoa.

On August 9th-10th a remarkable sample was obtained, 0.1 nautical miles west of Surtsey at a depth of 82 m. The sample was obtained by the rectangular and contained mud and quite a few animals in it. The mud sample was analysed by Dr. Sigvaldason, a geochemist. He maintains the mud consists of volcanic material from the eruption which started east of the island on the 23rd of May 1965. It is of interest to note that on November 16th-17th 1964, a bottom sample was obtained by the rectangular dredge 0.2 nautical miles west of Surtsey at a depth of 70 m. This contained new lava and 4 species of animals, Sigurdsson (1965).

The island was visited on the following dates: January 18th, January 31st, March 18th, April 29th, June 6th, July 3rd and August. Animals found were:

1. Pelagic animals which had drifted ashore. Of these, euphausids and amphipods were the most prominent. There were also barnacles on debris and arrowworms. On separate occasions one benthonic fish egg was found, probably from a Cottus species, eggcapsules of a gastropod, a few cephalopods, both decapods and an octopod, and some calanus on driftwood. None of these are of interest as immigrants.
2. Two unidentified microscopical animals, one of which is a nematode. These specimens were found on washing a small piece of rock which was loosened from a creek of a large rock. These animals may very well have drifted ashore like the other macroscopical animals not being confined to the intertidal zone.

No macroscopical living animals which could be living in the sand or on the rocks of the intertidal zone of Surtsey were ever to be found.

On June the 3rd, rocks from Surtsey were transferred to Westman islands and to the mainland. Of the two stones which were planted in a rocky shore at the Westman islands, one had already ulva and newly settled barnacles on it when reviewed one month later. The other rock did not have any inhabitants, but it was situated further down the shore. The chemical constitution of the rock does not seem to account for the absence of barnacles and other animals on the rocky shores of Surtsey.

Participating scientists:

Ingvar Hallgrímsson
Jutta Magnússon
Adalsteinn Sigurdsson
Gunnar Jónsson
Unnur Skúladóttir
Thorunn Thordardóttir

Reference:

Adalsteinn Sigurdsson (1965): Report on the Marine Biological Survey around and on Surtsey. Surtsey Research Progress Report I.

TABLE I.

The distribution of bottom samples taken on the "Surtsey cross" March 29th-30th.

Direction from Surtsey	Distance from Surtsey. Nautical miles	Depth meters	Bottom samples containing animals	Bottom samples containing nothing or no animals
North	1	105	S	
East	1	125	S	
South	1	126	P	
	1	130	P	
	3	153	H S	
	7	195	H S	
West	1	100	S	
	3	137	S	P

denotation

Petersen grab	P
Rectangular dredge	S
Robertson bucket dredge	F S
Ring dredge	H S

TABLE II.

The distribution of bottom samples taken on the "Surtsey cross" May 5th-18th.

Direction from Surtsey	Distance from Surtsey. Nautical miles	Depth meters	Bottom samples containing animals	Bottom samples containing nothing or no animals
North	0.1	75	S	P
	3	103		P
	7	87		P
	12	80		P
East	0.2	120		S
	1	127	S	
	3	95		S
	7	135		S
South	1	115	S	
	3	135-132	2 P and HS	
	7	158-185	2 HS	
South-West	0.2	85	S	
West	1	100	S	
	3	130	S	2 P
	7	135	P and K	
	12	158-160	HS and K	

Denotation the same as in table I.

TABLE III.

The distribution of bottom samples taken on the "Surtsey cross" August 9th-10th.

Direction from Surtsey	Distance from Surtsey. Nautical miles	Depth meters	Bottom samples containing animals	Bottom samples containing nothing or no animals
North	1	82		S
	0.2-0.3	82	S	
South	1	?	S	
	7	186	FS	
	0.1	82	S	
West	1	115	FS	
	3	128	FS	

Denotation the same as in table I.

G E O C H E M I S T R Y

Petrography and Chemistry

by

Sigurdur Steinthorsson
University Research Institute

Summary

Samples of volcanic ash and lava have been collected in Surtsey at various times during the eruption, which started Nov. 14, 1963, and is still in progress (May '66). The rock is alkali olivine basalt containing about 13% olivine. The composition of the feldspar has varied with time from An66 at the beginning, to An53. The composition of other minerals has, as far as can be discerned, remained uniform. 3 chemical analyses and trace-element evaluations of 4 samples are given, and the inference is drawn that differentiation has taken place mainly as a result of settling of olivine.

Introduction

As outlined elsewhere in this book various facies of the Surtsey eruption may be distinguished, and in this account a short review of the petrography and chemistry of samples representing perhaps 4 of these will be presented. The final report of this aspect of the eruption is being prepared, and this note may, therefore, be looked upon as a summary of procedure and results.

The facies to be distinguished here are:

a. Surtur explosive phase, Nov. 14, '63 - Apr. 4, '64
b. First lava of Surtsey, contains large xenocrysts, Apr. 4, '64 - end of April.
c. Lava-flows in Surtsey July 9, '64 - late May 1965. It is possible that during May and June 1964 the eruption continued as submarine lava-flows (pillow lava?).

d. Syrtlingur explosive activity NE of Surtsey, June - October, 1965.

e. Jólnir explosive activity SW of Surtsey, Dec. 26, '65 and still active (May '65).

A multitude of thin sections have been made of material collected at various times during the eruption, and chemical analyses have been made, and are being made, of all the five facies listed above. In this report, however, complete analyses of only a, b and d, and trace element evaluations representing a, b, c and d, are given.

PETROGRAPHY

The Surtsey material may be labelled as alkali olivine basalt. Usually the solidified rock contains much glass, and as a result only two of the modal analyses represent the end point of crystallization. When fully crystallized, however, the rock shows doleritic texture, and poikilitic intergrowth of feldspar, pyroxene and magnetite (ore).

Fig. 1 shows the course of crystallization as deduced from the modal analyses. The plots are distributed on the basis of glass-content in the rock, with 100% glass as a hypothetical completely molten rock, 0% glass in the fully crystallized rock. The plot is based on the assumption that the chemical composition in the Surtsey material (Syrtlingur excluded) changed so little that all the samples would have given rise to approximately the same modal composition if fully crystallized.

As seen from Fig. 1 no analysis falls between about 60 and 100% crystallization. It seems that the liquid had become so saturated with crystallizing nuclei when only 40% remained uncrystallized, that the whole mass crystallized upon quenching. Consequently the curves for pyroxene and magnetite are calculated from the given end-points, and the remaining liquid at any given

Table 1. Modal analyses of rocks from Surtsey

	1	2	3	4	5*	6	7
glass	84.3	60.4	60.1	60	57.0	54.9	53.6
olivine	7.7	14.3	12.1	13	14.5	11.6	12.3
feldspar	7.3	24.9	27.8	27	28.0	33.5	31.7
pyroxene	-	-	-	-	-	-	-
opaque	0.7	0.4	-	-	0.5	-	2.4

	8*	9	10	11	12	13
glass	42.7	-	-	83.3	74.5	63.8
olivine	15.6	16.4	9.0	12.4	23.1	20.1
feldspar	40.0	48.0	45.7	4.3	1.6	15.6
pyroxene	-	25.8	34.8	-	-	-
opaque	1.7	9.8	10.5	-	0.8	0.5

1. Thin section 944. Tuff from Surtur, coll. 1.12.63.
2. " " 1158. Last lava to flow in Surtsey, coll. 29.4.65.
3. " " 1197. Glowing Surtsey-lava, coll. 15.10.64.
4. " " 1196. Volcanic bomb, Surtsey, 15.10.64.
5. " " 1195. Volcanic bomb, Surtsey, Apr. '64.
6. " " 1089. Lava, Surtsey, Aug. '64.
7. " " 1090. Glowing lava rescued from the sea, Surtsey, 24.1.65.
8. " " 1097. Surtsey-lava, coll. 27.2.65.
9. " " 1088. Dolerite from Surtsey, probably flowed Nov.- Dec. '64.
10. " " 1159. First lava in Surtsey, coll. Apr. '64.
11. " " 1170. Syrtlingur, coll. in Surtsey 4.10.65.
12. " " 1156. Syrtlingur, coll. on a coast-guard vessel 10.8.65.
13. " " 1202. Syrtlingur, coll. on the island itself 4.7.65.

* The so-called glass in this section is in actual fact groundmass, i.e. minute crystals impossible to distinguish.

point between 60 and 100% crystallized. Inspection of thin sections reveals that during the last stage of crystallization magnetite and pyroxene have crystallized simultaneously, but with the latter rather leading.

The course of crystallization as deduced from Fig. 1 is as follows: Olivine comes out first, and is fully crystallized when 70–80% of the rock is still molten. Next comes feldspar and is the sole crystallizing mineral in the melt until about 40% of the liquid remains, whereupon pyroxene, and later magnetite, come in, and all three minerals crystallize together until all liquid is used up (eutectic). The small amount of magnetite present prior to its full entry occurs as small cubic inclusions in the olivine.

As stated on an earlier page the texture in the fully crystallized rock is poikilitic, but the olivine, which was fully crystallized early on, tends to be rounded, which possibly indicates some resorption.

Fig. 1 also gives evidence of settling of olivine in Syrtlingur; the broken curves show higher concentration of olivine, and lower of feldspar, than the corresponding curves for Surtsey. No bombs were recovered from Syrtlingur - hence the great amount of glass in all the three samples.

MINERALOGY.

The composition of olivine has remained uniform throughout the eruption as far as can be detected. Olivine from the Surtur ash-cloud, collected 30.11.63, has refractive index n = 1.679 (Fo 87), and olivine from Syrtlingur ash-cloud, collected 4.10.65, gives n = 1.673 (Fo 89)(1).

Feldspar. Usually two generations may be distinguished: phenocrysts with composition An 66, and members of the groundmass changing in composition from An 60 to An 53. The large labradorite crystals present from the beginning of the eruption in Nov. 1963 till the end of April 1964 have been dealt with by Wenk (2), and a mention was made by the present author of their possible fate in a previous progress report (3).

Table 2. Feldspar-composition

		A	B	C	D	E	F
An %	Phenocrysts	66	66	66-53	-	56	56
	Groundmass crystals	60	57	53	53	52	

A	1.12.63	(944)	D	Nov.- Dec. 64	(1088)
B	Apr. 64	(1159)	E	29.4.65	(1158)
C	Aug. 64	(1089)	F	Syrtlingur 4.10.65	(1170)

As seen in Table 2 the labradorite phenocrysts are present in specimens A, B and C. In the latter, however, the crystals are but ghosts of their former splendour, showing reverse zoning from An 66 at the margin to An 53 (same as the groundmass) in the centre with a belt of clouding (exsolution) inbetween. It is assumed that one or both of two possibilities was the cause of their disappearance: a) The crystals had accumulated in the topmost part of the magma column before the eruption, and by the end of April the magma containing the crystals had been extruded. b) The crystals became unstable in the changing environment (as reflected by the composition of the groundmass), and were resorbed - an instance of which is seen in section 1089 (C) where, apparently, the crystal is changing composition to match circumstances, beginning in the middle and working towards the margin (reverse zoning with the intermediate belt of clouding).

The microphenocrysts in sample E must be of later origin, perhaps formed from the same magma at a greater depth (different P and T).

CHEMISTRY

Table 3 represents 3 analyses of Surtsey material, which indicate considerable variation in composition with time. It seems likely that settling of olivine has been the main factor in bringing out the differentiation of the magma, as shown by both the modal analyses and the marked increase of MgO in Syrtlingur (S-4). Fig. 2 illustrates the position of the Surtsey rocks on an extended Ol-Di-Hy-diagram, with analyses from Hekla (4,5) and the shield-volcano Skjaldbreiður (6) for comparison. On Figs. 3 and 4 are plotted the variations in AFM and Na-K-Ca respectively, both indicating quite considerable differentiation; graphs from Hekla, Skjaldbreiður, Hawaii (7) and the Skaergaard (7) are inserted for comparison. In Fig. 3 the two triangles in the middle of the Hekla-line delimit the end-points of the 1947-eruption.

The ratio CaO/MgO is the main distributive factor for the Surtsey-plots on the Ol-Di-Hy-diagram (Fig. 2); the marked increase in olivine (MgO) in Syrtlingur, plus the decrease in Na_2O, has effected the shifting of S-4 towards the Ol-corner of the Ol-Di-Hy-triangle. A possible differentiation line is drawn on the diagram.

Trace-element analyses are presented in Table 4 together with the values for G-1 and W-1 (8) and plotted in chronological order in Fig. 5. Systematic variation is, once more, evident - Cr, Ni and Co increase, Sr, Zr and Zn decrease, and Y and Rb rather decrease, whereas Cu and V change trend from S-3 to S-4.

This eruption has lasted longer than most in historic time in Iceland. The volume of the material is, however, not at all tremendous, and, perhaps, a suitable moral to this research is, that one straw does not represent the whole stack, and one or two samples of a rock (even as mundane as basaltic lava) may give deceiving information about the whole.

Table 3. Rock Analyses and Norms from Surtsey

Chem. Analyses				Norms				
	S-1	S-2	S-4			S-1	S-2	S-4
SiO_2	46.50	46.71	44.89		Or	3.34	3.34	2.22
Al_2O_3	16.80	16.68	14.70		Ab	24.10	22.01	15.20
Fe_2O_3	1.65	1.61	1.16		An	29.47	30.30	30.86
FeO	10.80	10.00	10.80		Ne	1.99	1.70	
MnO	0.20	0.20	0.22		Wo	6.61	6.61	4.99
MgO	7.62	9.46	15.02	Di	En	3.60	3.90	3.20
CaO	9.45	9.62	8.77		Fs	2.77	2.38	1.46
Na_2O	3.32	2.97	1.80	Hy	En	-	-	1.60
K_2O	0.57	0.55	0.38		Fs	-	-	0.53
H_2O^+	0.22	0.03	0.20	Ol	Fo	10.78	14.00	23.38
H_2O^-	0.03	0.07	0.22		Fa	9.59	9.18	11.22
TiO_2	2.28	1.72	1.46		Mt	2.32	2.32	1.62
P_2O_5	0.33	0.27	0.21		Il	4.26	3.19	2.74
					Ap	0.67	0.67	0.34
					H_2O	0.05	0.10	0.42
	99.57	99.89	99.83			99.55	99.80	99.78

S-1 Ash from Surtur, collected 1.12.63.

S-2 First lava in Surtsey, coll. April 1964.

S-4 Ash from Syrtlingur, coll. 11.8.65.

Table 4. Trace-element Evaluations in Surtsey-rocks.

	S-1	S-2	S-3	S-4	G-1	W-1
Co	86	98	90	126	2.4	50
Cr	150	155	215	300	15	125
Cu	54	77	89	87	14	120
Ni	95	125	198	310	no	75
Rb	14	15	13.5	11	220	22
Sr	330	300	260	220	250	160
V	140	170	165	145	15	240
Y	26	24	21	19	13	24
Zn*	-	75	72	66	40	83
Zr	135	100	86	80	210	110

S-1 Ash from Surtur, coll. 1.12.63.
S-2 First lava in Surtsey, coll. Apr. 1964.
S-3 Last lava to flow in Surtsey, coll. 29.4.65.
S-4 Ash from Syrtlingur, coll. 11.8.65.
G-1, W-1. Standard samples (8).

* Standard values for Zn from Spectrochemical Analysis (9).

References cited

(1) Tröger W.E. (1959. Optische Bestimmung der gesteinsbildenden Minerale. Stuttgart.

(2) Wenk E., Schwander H. und Wenk H-R. (1965). Labradorit von Surtsey. Act. Nat. Isl. vol. II - No. 5.

(3) Steinthórsson S. (1965). Surtsey: Petrography and Chemistry. Surtsey Research Progress Report I.

(4) Einarsson T. (1950). Chemical Analyses and Differentiation of Hekla's Magma. Soc. Sci. Isl. Hekla series IV, 4.

(5) Tryggvason T. (1965). Petrographic Studies on the Eruption Products of Hekla 1947-1948. Soc. Sci. Isl. Hekla series IV, 6.

(6) Tryggvason T. (1943). Das Skjaldbreid-Gebiet auf Island. Bull. of the Geol. Inst. of Uppsala, Vol. XXX.

(7) Turner F.J. and Verhoogen J. (1960). Igneous and Metamorphic Petrology. New York.

(8) Taylor S.R. and Kolbe P. (1964). Geochemical Standards. Geochim. et Cosmochim. Acta, vol. 28 no. 4.

(9) Ahrens L.H. and Taylor S.R. (1961). Spectrochemical Analysis. Reading, Mass.

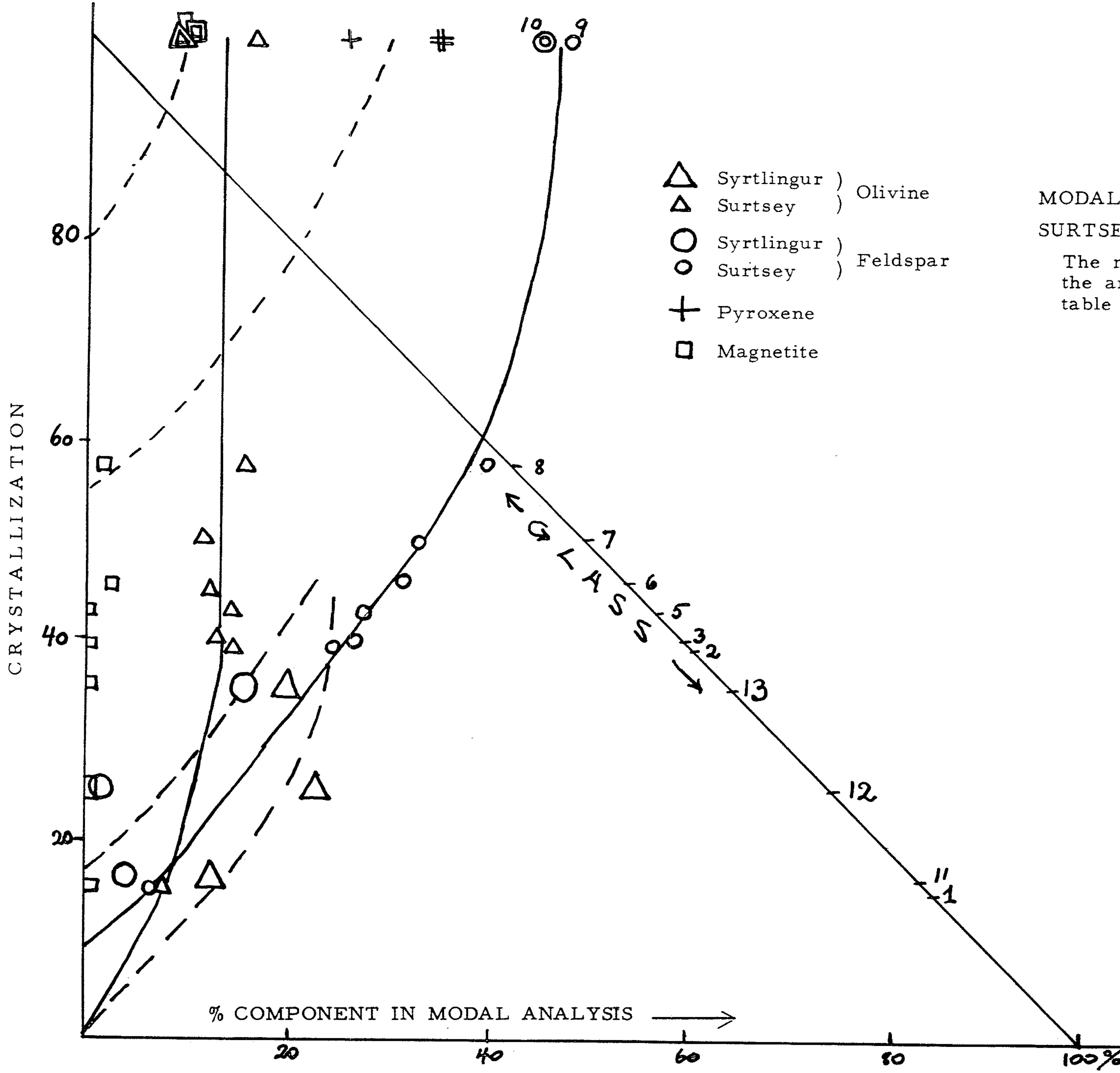


Fig. 1

MODAL ANALYSES FROM SURTSEY AND SYRTLINGUR

The numbers represent the analyses listed in table 1 in text.

Fig. 2

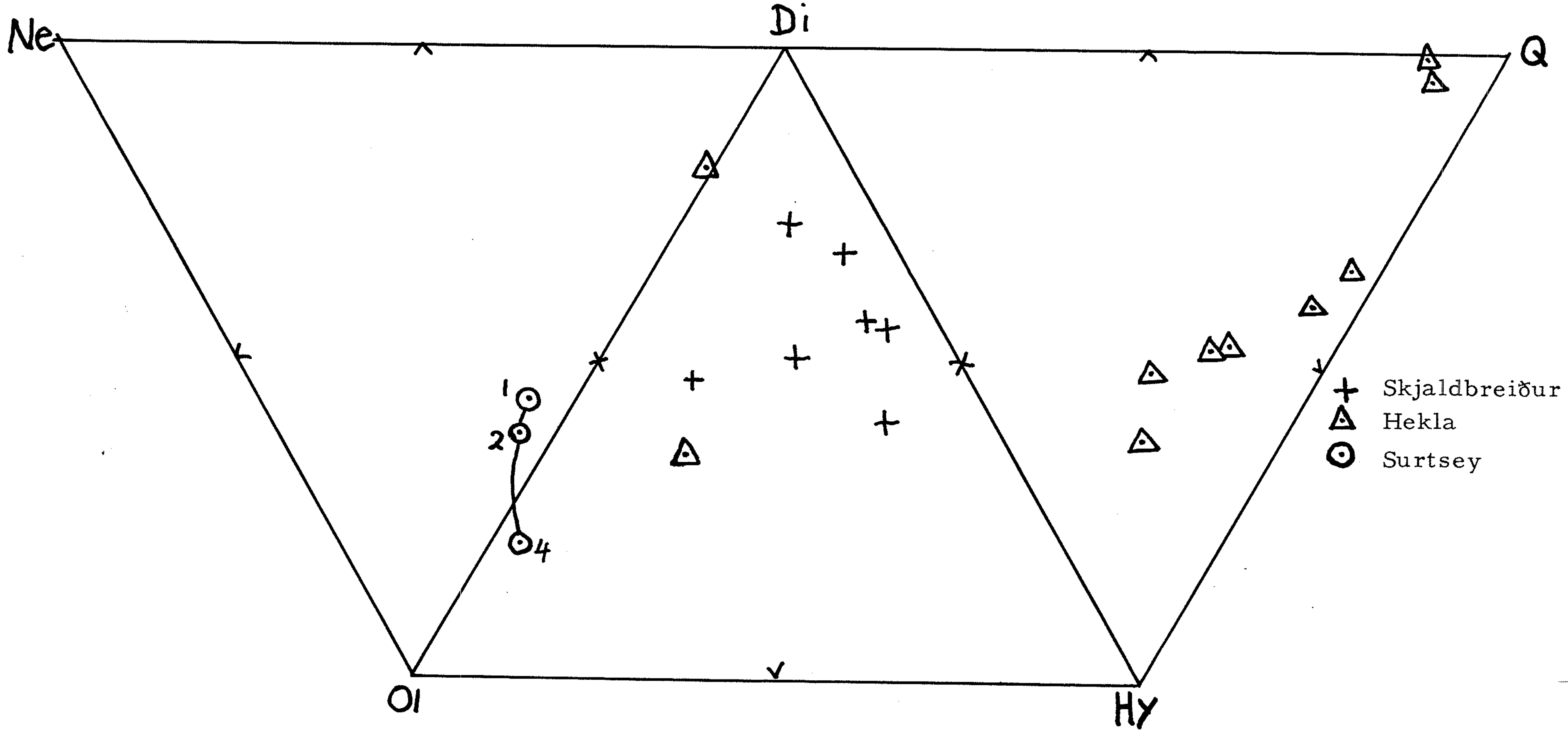
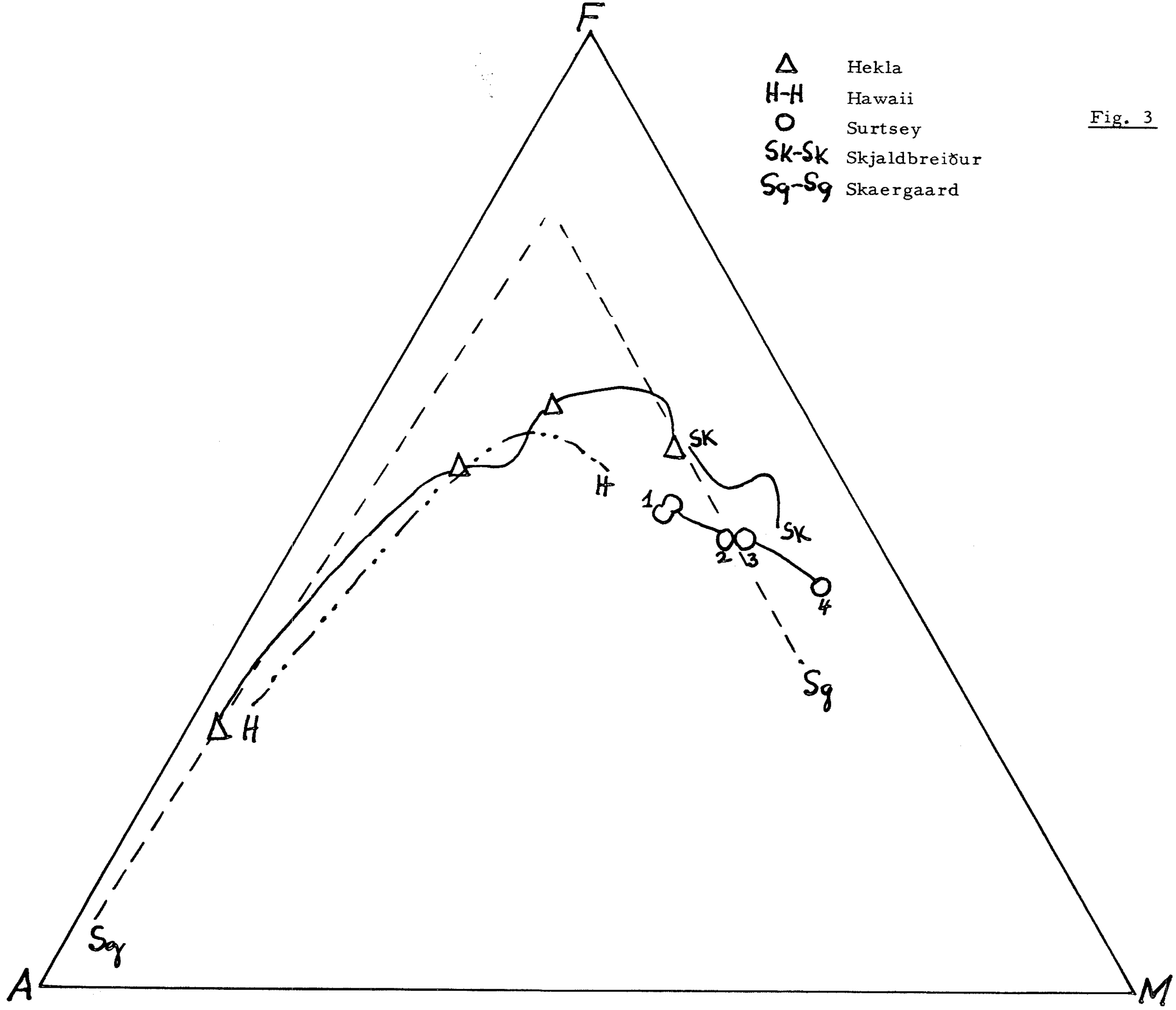
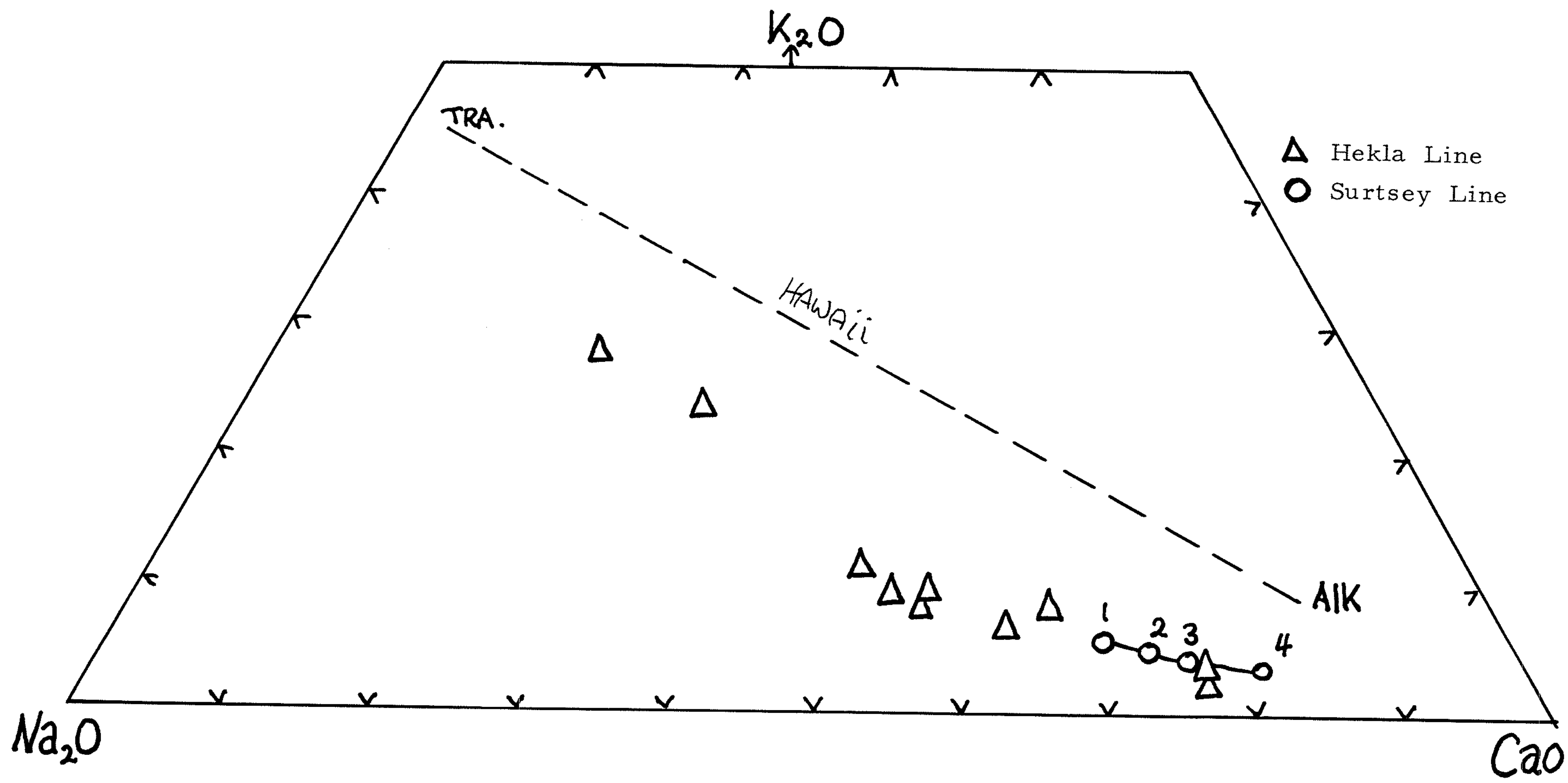


Fig. 3



F
A
M
Δ Hekla
H-H Hawaii
O Surtsey
Sk-Sk Skjaldbreiður
Sg-Sg Skaergaard
SK
SK
H
H
Sg
Sg
1
2
3
4

Fig. 4



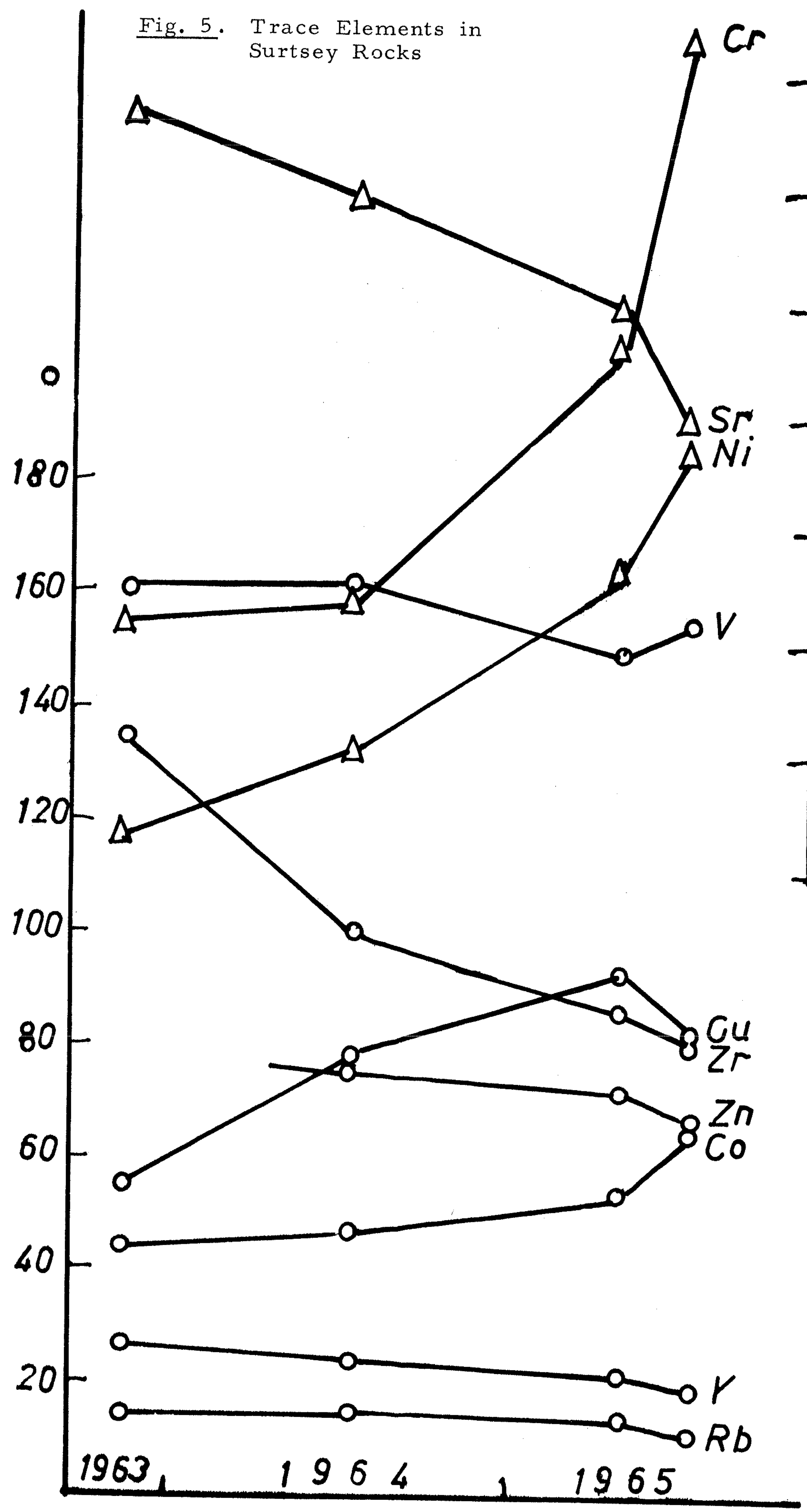


Fig. 5. Trace Elements in Surtsey Rocks
Cr
340
300
260
Sr
220
Ni
180
V
140
100
Cu
Zr
Zn
Co
Y
Rb
180
160
140
120
100
80
60
40
20
1963
1964
1965

Advance Report on "Acid" Xenoliths from Surtsey

by

Haraldur Sigurdsson
The University Research Institute

In the course of the Surtsey eruption a number of xenoliths have been ejected. This report deals solely with the "acid" xenoliths collected by numerous scientists that have visited Surtsey, and it is a pleasure to acknowledge our debt to all those who have contributed to the collection, especially Jens Tómasson, Jón Jónsson and Dr. Finnur Gudmundsson, who supplied very valuable material. Work is still in progress on this study, and the author would be most grateful for any additions to the present acid xenolith collection.

The great majority of the acid xenoliths were collected from volcanic ash just after the explosive phase ceased, but in addition the late Tómas Tryggvason collected an excellent specimen of an acid xenolith enclosed in lava on Surtsey. The latest acid xenoliths were gathered by Dr. Finnur Gudmundsson on the beach of Surtsey from amongst drifting pumice from Syrtlingur on June 3rd, 1965, and these xenoliths were almost certainly brought up by the Syrtlingur eruption.

The acid xenoliths collected are sub-rounded to spherical, and range in size from 2 cm to 10 cm in diameter. They are invariably coated with a veneer of dark-brown to black basaltic glass, and are therefore easily overlooked in the tephra. Microscopically the acid xenoliths are divisible in two:

(a) dense, chalky-white or light-grey and fine grained xenoliths;

(b) coarse grained, yellowish xenoliths of granitic or granophyric texture.

The first mentioned group is by far the more abundant, whereas only 2 samples of granitic xenoliths are available to the author. But, as will be shown later, the xenoliths from Syrtlingur are closely allied to and derived from the granitic xenoliths.

Dense fine grained xenoliths.

These xenoliths are very similar as a group, consisting of an entirely crystalline mass, generally partly "sphaerulitic" and with a felty mass of fine crystals or microlites 0.05 - 0.1 mm in length. Most of the minerals present are too small to permit identification by the optical microscope, but an x-ray diffraction study of these is in progress. Tridymite is an ubiquitous constituent in the dense, fine grained xenoliths, in small "nests" of twinned, wedge-shaped crystals of very low birefringence and low refractive index.

Cordierite is certainly present in one xenolith and possibly in some others. Cordierite has been identified by x-ray diffraction methods in specimen No. 1162 where it occurs as small rectangular crystals of good habit, optically positive, $2V_{\gamma}$ 80-88^{o}. Very fine plagioclase needles and laths are the chief constituents in the sphaerulitic patches.

Other minerals are not identified so far.

TABLE I

Dense, fine grained acid xenolith from Surtsey:

SiO_2	60.80	Norm:	
Al_2O_3	21.97	Qz	18.70
Fe_2O_3	0.26	Or	2.05
FeO	0.76	Ab	26.65
MnO	0.01	An	46.60
MgO	0.29	Wo	3.78
CaO	11.16	En	0.82
Na_2O	2.92	Fs	1.00
K_2O	0.34	Mt	0.30
H_2O^+, H_2O^-	1.20	Ap	0.11
TiO_2	-		
P_2O_5	0.04		
	99.75%	Analyst:	H. Sigurdsson

Granitic and granophyric xenoliths.

Only two good samples of this type are available. Specimen No. 1165 is a grey rock fragment, 1-2 mm in grain size, showing granitic texture with rare granophyric intergrowth around some of the plagioclase laths. Plagioclase, quartz and alkali feldspar are the chief minerals. The twinned plagioclase has $2V_\gamma$ 68-75^o, and a universal stage determination indicates the composition Ab_{88} (low temp. series). Both microcline and orthoclase are present, the latter in graphic intergrowths with quartz. Zircon is a common accessory.

The xenolith is coated by a thin veneer of colourless glass, n = 1.495, formed by the fusion of feldspar and quartz. Glass is also present within the xenolith, as a thin vesicular film between all the mineral grains in the rock. At the time of eruption the granite xenolith had already been partially fused by the enclosing basic magma, but the resulting liquid became quenched to glass on ejection from the crater.

Xenolith No. 1166 is of granitic texture, grey coloured and medium grained, consisting of plagioclase and orthoclase with subordinate quartz. Plagioclase, determined on the U-stage, has $2V_\gamma$ 63-68°, and an optic orientation indicating Ab_{75}. Refractive index on β is 1.546 (Ab_{72}). The alkali feldspar is orthoclase, and the combined values of refractive index (β = 1.531) and extinction angle indicate Or_{50} Ab_{40} An_{10}.

In the core of the xenolith little melting has occurred, except of an unknown ferromagnesian mineral, leaving dark-brown patches of glass. In the outer part vesicular glass separates the individual minerals, which grades into an entirely glassy envelope in the outermost zone.

Some of the feldspars in this xenolith have not undergone simple melting at once, but instead individual feldspar grains have reverted to an aggregate of minute high-temperature minerals, which mimick the optical orientation of the parent feldspar so that twinning may be preserved and the entire aggregate remain in optical continuity.

The mineral composition of these aggregates is as yet unknown. The outermost glass of the xenolith is colourless, n = 1.498 and the boundary between the acid glass and the enclosing basaltic glass is quite sharp.

Specimen No. 511 was amongst those collected from Syrtlingur ash, and consists of a very frothy, vesicular light-grey glass. No crystals are present except for accessory zircon. Refractive index of this glass is n = 1.495. It is believed that this specimen represents the complete fusion of a granitic xenolith, such as those described above.

Discussion.

The material here represented indicates the presence of granitic rocks at depth below Surtsey, as well as acid rocks of unknown texture, represented by the dense, fine grained xenoliths. The granitic xenoliths have undergone varying degrees of fusion, brought about by the fluxing action of volatiles from the basic magma as well as the mutual fluxing of quartz and feldspar within the xenolith at the high temperature available in the magma (1170°C).

Attention is drawn to the absence of hybridisation between the granitic liquid and the basalt magma; even basaltic olivine crystals enclosed within acid glass are devoid of corrosion or reaction features.

The dense, fine grained xenoliths are consistently crystalline and never contain glass. They are believed to be the pyrometamorphic product of a rock, possibly of an original sedimentary nature or an igneous rock of a very unusual composition (e.g. an igneous cumulate), now completely recrystallized. The oxides SiO_2, Al_2O_3 and CaO constitute 94% of the dense, fine grained xenolith. Their composition is therefore amenable to a study in the system $CaO-Al_2O_3-SiO_2$ (Rankin and Wright, Am. J. Sci., 39, 1915, p. 25). The xenolith falls on the binary eutectic anorthite - mullite, very close to the ternary eutectic point tridymite - mullite - anorthite, whose liquidus temperature is 1345°C. The absence of glass in the dense, fine grained xenoliths is therefore readily accounted for, as the magma certainly never reached the extreme temperatures required to melt material of this composition.

The work in progress on acid xenoliths from Surtsey is part of a wide-embracing study on acid xenoliths collected from a range of volcanic rocks from all parts of Iceland. Among these are specimens collected from Tertiary basalts, Pleistocene palagonite tuffs as well as recent lavas and cinder cones. It is possible that this material may have a bearing on the enigmatic - and fashionable - question of the nature and composition of the Icelandic crust.

Report on Collection and Analysis of Volcanic Gases from Surtsey

by

Gudmundur E. Sigvaldason and Gunnlaugur Elísson
University Research Institute, Reykjavik

The present progress report summarizes the results of gas analyses on samples from Surtsey in 1965. The lava production stopped during May 1965 and after that gas sampling has not been attempted since no vigorous fumarolic activity is found on the island.

Of several attempts which were made to collect gases during 1965 only two were successful. The collections were made using the same apparatus as described in the previous report, but the water trap was cooled in a water bath (ca. 10°C) instead of air.

The analysis are presented in table 1 and 2. The samples from Jan. 18 are heavily contaminated with air, whereas the samples from February 21 contain only 0.07% of inactive gases indicating complete absence of contamination.

On two occasions,Oct. 15 1964 and Febr. 21 1965, it has been possible to collect gases without any obvious contamination. A number of unsuccessful attempts were made and it might be worth while to compare conditions at sampling sites where good and poor samples were obtained.

The sampling sites can be divided into three groups:

1. Cracks in cooling lava, where sampling tube could be lowered into the still glowing interior of the lava stream. Temperature already below the solidus or around 800-850°C.
2. Narrow cracks in the consolidated roof of a lavatube, with large discharge of lava. The lavatube is essentially closed except for the small cracks in the roof where the gases escape under pressure.

3. Active chimneys (hornitos) on consolidated lava surface. Openings are wide with respect to the cracks mentioned under group 2 and the gases are released under atmospheric pressure.

Quality of samples from group 1 sites is poor. The only active gas found is CO_2 in small quantities (less than 1.0%) and the rest is air.

Conditions representing the group 2 sites were observed on Oct. 15 1964. This is a somewhat idealized condition, which is probably not often found under volcanic eruptions. The group 3 sites are likely to be found in most lava eruptions and special attention should be given to sites of this kind. Increasing contamination from air is found with increasing diameter of the chimney opening. Comparison of our samples from Jan. 18 and Febr. 21 1965 shows this clearly. The first samples collected from a chimney with a one meter opening are heavily contaminated, but the latter samples where the opening was ten times smaller is apparently free from any air contamination. Spattering from the chimneys may cause some difficulty by clogging the sampling tubes.

Common to sampling sites of group 2 and 3 is development of flames, and these form a positive indicator of the presence of gas discharge. Attempts to collect gases where no flames were present either failed or gave poor results.

On the basis of our field observation combined with the chemical analysis of the gases we are led to believe, that the process of degassing from a lavastream at $1400^{o}k$ is essentially restricted to a relatively short time after the lava has appeared at the surface. During this short period of time the lava looses up to 80-90% of its volatile constituent (see also Björnsson, this report) in essentially the same proportions as initially present in the magma. The liberation of the 10-20% volatiles, which are left after vigorous gas release in the fresh lava has subsided, goes very slowly and the chemistry of the gases is likely to alter because of reactions with air and the crystallizing rock.

Ellis (1959) computed a theoretical composition of magmatic gases using existing thermodynamical data. A composition with molecular ratios H_2O : CO_2 : H_2 : S_2, 100 : 10 : 2 : 1 was used as a basis for the calculation since this composition is similar to many geothermal and volcanic gases. In atomic ratios this composition is H : O : C : S, 100 : 60 : 5 : 1 and our sample from Febr. 21 1965 has the atomic ratios 100 : 60 : 4 : 2. In spite of the higher sulphur content and somewhat lower carbon in our sample, it is of interest to compare the theoretical values at $1400^{o}K$ with the actual composition of the Surtsey gases. The last column of table 1 gives the theoretical values from Ellis, which are strikingly similar to some of our samples. This fact gives us a certain degree of confidence to state, that the gas samples from Surtsey may be close to chemical equilibrium at PT conditions of the sampling site.

References:

Björnsson, S.: (This report)

Ellis, A.J. (1957): Chemical equilibrium in magmatic gases. Am. J. Sci. 255, p. 416.

Sigvaldason, G.E. and G. Elísson: Preliminary report on collection and analysis of volcanic gases from Surtsey. Surtsey Research Progress Report, 1965.

TABLE I

	15.10.1964		21.2.1965			theoretical composition Ellis (1959)
H_2O	79.20	79.20	86.16	86.16	86.13	86.0
HCl	0.80	0.80	0.40	0.40	0.43	
SO_2	5.40	4.02	3.28	1.84	2.86	1.49
CO_2	9.18	9.64	4.97	6.47	5.54	8.05
H_2	4.56	4.88	4.74	4.70	4.58	3.58
CO	0.68	0.70	0.38	0.36	0.39	0.82
N_2	0.18	0.76	0.07	0.07	0.07	
CH_4	0.00	0.00	0.00	0.00	0.00	
T^oK	1400			1400		1400

TABLE II

	25.11.1964	18.1.1965		21.2.1965			
SO_2	3.9	3.4	5.6	24.4	13.7	21.3	
CO_2	4.3	3.9		37.0	48.1	41.2	
O_2	16.0	12.1	17.3	0.0	0.0	0.0	
H_2	0.0	0.0	0.0	35.3	35.0	34.1	34.0
CO	0.0	0.0	0.0	2.8	2.7	2.9	2.8
N_2	75.8	80.6	77.1	0.5	0.5	0.5	0.75
A							0.008
T^oK	1400	1400			1400		

Radon in magmatic gas at Surtsey and its possible use for determining the content of water in the magma

by

Sveinbjörn Björnsson
State Electricity Authority
Department of Natural Heat

Abstract.

The average radon activity of magmatic gas sampled on 21 February 1965 at the lava crater of Surtsey was found to be 125 ± 5% pC/l of gas. The radium content of the lava was found to be less than $0.4 \cdot 10^{-12}$ g/g. The radioactivity of a 5 g sample prepared was less than the background activity in the ionization chambers used for the measurements. An attempt for determining the radium content by more sensitive methods is in preparation.

A method is suggested for estimating the water content of the magma by calculating the radon content of the magma before eruption from its radium content and measuring the radon/water ratio in the liberated magmatic gas.

The radium content of the Surtsey lava is not known at present, but calculations based on an average radium content in similar basalts and the observed radon/water ratio in the magmatic gas gave a water content of 0.9 wt. % in the erupted magma.

Introduction.

During the lava phase of the Surtsey eruption several attempts were made to sample magmatic gas from the active crater. Gas samples were taken for chemical analysis, the measurement of the D/H - ratio in H_2 - gas and water vapor and the measurement of radon.

The radon content of magmatic gas is of considerable interest, because the determination of radon in the gas and its parent nuclide, radium, in the lava may supply information for estimating the content of water in the magma.

Sampling of gas.

The gas samples for radon measurement were taken simultaneously with samples for chemical analysis and deuterium measurements using a common sampling apparatus. The sampling procedure is described by Árnason (1,2) and Sigvaldason and Elísson (3,4).

Measurement of radon.

The activity of radon in the gas sample was measured by conventional methods (e.g. Evans (5)) using a 4-liter-ionization chamber and a Victoreen 475 A vibrating reed electrometer for reading the ionization current of radon in equilibrium with its decay products. The equipment was calibrated with the aid of a standard 0,099 μC radium-solution.

The background current in the ionization chambers was equivalent to a radon activity of 2 pC. The radon activity of samples containing less than 2 pC could therefore only be determined with a limited accuracy.

Measurement of radium in lava.

In order to estimate the initial concentration of radon in the magma an attempt was made to determine the radium content of the issued lava. The sample used for the radium analysis was a lava-bomb, which was ejected from the crater, while the gas samples were taken on 21 February 1965.

The chemical preparation of the sample was performed by B. Árnason at the Physical Laboratory of the University of Iceland.

The preparation was similar to that described by Hudgens et al. (6). 5 g of lava were repeatedly dissolved in HF and fused with Na_2CO_3, until the lava was completely dissolved. The solution was then sealed off in a glass gas-washing-bottle identical to the bottle containing the standard-radium-solution. Great care was taken that no materials, which absorb radon (e.g. grease, rubber) were in contact with the radon generated in the bottle. After 30 days the radon had attained equilibrium with its parent nuclide. The radon was then transferred into an evacuated ionization chamber by blowing bubbles of N_2 through the solution until the radon was completely washed out of the solution. The method is described in detail by Lucas, (7).

The same method was used for transferring radon from the standard radium solution into the chamber for calibration.

Results.

Radon. The results of the radon measurement are shown in Table I. The samples taken on 25 November 1964 and 18 January 1965 were heavily contaminated with atmospheric air. Chemical analysis (see Sigvaldason and Elísson (3,4)) indicated a 90 - 95% contamination. If sample 1 and 2 are corrected for contamination, they indicate a radon concentration of the order of 100 pC/l.

On 21 February far better samples were obtained. They contained less than 0.75 % N_2, which indicates less than 1% atmospheric contamination, if any at all. Samples 5, 7 and 8 gave consistent values for the radon concentration with an average of 125 $\pm$ 5% pC/l.

Radium. The radium content of the solution containing 5 g of dissolved lava was found to be less than 2 pC. An accurate determination of the radium content was not possible, because the radon activity generated by the prepared sample was less than the background activity in the ionization chamber.

Discussion of the results.

Radon and radium. In uncontaminated samples of magmatic gas the average radon content was 125 ± 5% pC/l.

The radium content of lava issued at the same time was found to be less than 0,4 · 10^{-12} g/g. This indicates a radon content in the magma less than 0,4 pC/g. Further attempts to determine the radium content of the lava are necessary. If the measurements are made with present apparatus, about 50 g of lava must be dissolved for a radium analysis.

The basalt of Surtsey is of the alkali - olivine type (Steinthorsson (8)). In alkali - olivine basalts in Japan Heier and Rogers (9) found an uranium content of 0,48 ± 20% ppm and 0,57 ± 13% ppm respectively. If a radioactive equilibrium between uranium and radium is assumed this would correspond to a radium content of 0,16 · 10^{-12} ± 20% g/g and 0,19 · 10^{-12} ± 13% g/g respectively.

In a review article on the radioactivity of basic rocks Heier and Carter (10) found an average value for the uranium content of 14 analyses of island basalts from Hawai, Japan and the Mid Atlantic ridge to be 0,46 ppm, which corresponds to an equilibrium value of radium of 0,16 · 10^{-12} g/g.

The upward limit for the radium content of the Surtsey lava given above, is consistent with this average value.

Liberation of gas from magma.

Before the results above are used for estimating the water content of the magma a short discussion of the mechanism of the liberation of gas from magma is necessary. As the magma ascends the solubility of gases decreases with falling pressure, and the magma may become oversaturated for some of its gas components. Bubbles of gas will then be created in the magma. In rapidly ascending magma great oversaturation may occur before any bubbles are formed. After the formation of bubbles each component of the gas will strive to establish an equilibrium between the liquid and gas, determined by its solubility in the magma. Because of the high viscosity of the magma (Einarsson (11)) travel of bubbles relative to the magma is negligible and gas will therefore not escape before the bubbles reach the surface of the lava lake in the crater.

The composition of the gas accumulating under the roof of a lava lake will be the same as in the bubbles and will depend on the amount of each component initially dissolved in the magma and the solubility of these components at about 1100^{o}C and 1 atm pressure.

<u>Water</u>.

The solubility of water in magma has been thoroughly investigated. See e.g. Göranson, (12), Khitarov et al. (13) and Hamilton et al. (14).

Russel, (15) and Kurkijan et al. (16) have observed that a plot of the solubility (mol %) of water in molten alkali silicates versus the square root of pressure resulted in a straight line relationship in the pressure region below one atmosphere. Similar plots of the data obtained by Hamilton et al. (14) for basalts at 1100^{o}C in the region of 1000 - 6000 bars pressure (1 kp/cm^2 = 0.98 bars) show that the solubility (mol %) is linerarly related to the square root of pressure. The straight line passes through the origin and has a slope of 0.33 (mole %/(bars) $\frac{1}{2}$). The solubility in moles % versus pressure in bars in basalt at 1100^{o}C will be expressed by the formula

$$S = 0.33 \sqrt{P}$$

According to Hamilton et al. (14) this straight line relationship between solubility and the square root of pressure might be interpreted to indicate that water entering the solution is fixed in the liquid structure as hydroxyl ions. Accordingly, each mole of water is visualized as entering the melt in the following manner:

$$H_2O \text{ gas} + O^{=} \text{melt} = 2\ OH^{-} \text{ melt}$$

It then follows, at constant temperature, that

$$\frac{\left[f_{OH^{-}melt}\right]^2}{\left[f_{H_2O\ gas}\right]\left[f_{O^{=}melt}\right]} = K$$

Therefore, as a first approximation, the concentration (the solubility) of OH^{-} in the melt at a given temperature varies as the square root of the water pressure.

The experimental data of Hamilton et al. (14) do not reach below 1000 bars pressure, but the facts that their empirical straight line goes through origo and that this relationship has also been observed for pressures below one atmosphere, indicate, that extrapolation of this line to lower pressures will give us a good estimate for the solubility of water in basaltic magma at 1100°C down to pressures of about one atmosphere.

In this way we obtain a solubility of 3.3 mole % (1.1 wt %) at 100 bars pressure, 1.05 mole % (0.35 wt %) at 10 bars and 0.33 mole % (0.1 wt %) at 1 bars pressure. 100 bars pressure corresponds approximately to 380 m depth in magma.

From these results we may deduce that magma, containing less than 0.1 wt % of water, would never saturate and no bubbles would be formed by the water vapor. If it contains 0.35 wt %, saturation will occur at about 40 m depth and about 70% of the water will be expelled at the surface. If the water content is 1 wt % the magma will saturate at 350 m depth and 90% of the water vapor will be liberated. Since the magma is rapidly ascending, bubble formation may first occur after a some degree of oversaturation but once the bubbles are formed, liberation of the water will rapidly proceed.

Argon and radon.

It is well established by the workers of the K - Ar - method that fresh lava contains no detectable amount of argon. We may therefore conclude that argon has a negligible solubility in magma at 1 atm pressure and 1100°C. Radon is an inert gas like argon and the only difference in their solubility will be due to their different atomic mass. The solubility of radon under these circumstances is therefore likely to be of the same order as that of argon and we may expect practically all radon in the magma to be given off into bubbles and liberated.

Other volatile components.

The solubility of other volatile components in magma is less known. Their liberation will greatly depend on their degree of saturation in the magma. The solubility of those components, which approximately obey the Henry's law, will decrease approximately linearly with decreasing pressure. If some of these components are in saturated solution in the magma at pressures higher than 10 bars, they will be liberated into bubbles to more than 90% and thus their proportions in the sampled gas will be approximately the same as initially in the magma.

If the solubility of the components is proportional to the square root of the pressure as for water, saturation at 100 bars pressure is necessary for attaining 90% liberation.

Other components, which are so rare in the magma that they never reach saturated solution, in spite of the greatly reduced solubility at lower pressure, will not be liberated in the same proportions as other components.

Basaltic magma is believed to come from magma chambers below 30 km depth or pressures above 8000 bars. Gas components, which obey the square root law as water and do not reach saturated solution on their ascent with the magma, will have had a concentration in the magma chamber which was less than 1/90 of the saturation value at these depths. Components obeying the Henry's law will have had a concentration less than 1/8000 of the saturation value.

Evidence is lacking for estimating,, if these low concentrations are realistic.

Water content of the magma.

After these considerations of the liberation of gas from magma, we may now proceed in our attempt to estimate the water content of the magma with the aid of radon. In the magmatic gas at Surtsey each liter of volatile gases was accompanied by about 5 g of water (Sigvaldason and Elísson (4)) and carried a radon activity of 125 pC. This radon activity is equal to that contained in 625 g of magma, if we take a radium content of $0.2 \cdot 10^{-12}$ g/g as a probable value for the radium content of the lava in Surtsey.

As already discussed above practically all radon will be liberated from the magma. Regarding the rapid ascent of magma and the great force of the escaping gases, we may assume that the gas is sampled a relatively short time after its liberation from the magma and therefore the decay of radon after liberation is negligible. (Radon decays with an half life of 3.8 days). Thus we come to the conclusion that 625 g of magma have liberated 125 pC of radon. As radon and water vapor are equally distributed in the gas, the 5 g of water which accompanied 125 pC of radon must also have been liberated from 625 g of magma. The magma has then given off 0.8 wt % of water. The solubility of water in the basaltic magma at $1100^{\circ}C$ and 1 bar pressure was above estimated to be 0.1 wt %. If this amount is added to that liberated, we obtain a water content of about 0.9 wt % in the magma.

It must be emphasized that this result is still uncertain. The radium content used in the calculations above was an average value for alkali-olivine basalts and not the actual radium content of the Surtsey-lava, which is not known at present. The method is also based on estimates of the solubility of radon and water in magma at 1100^{o}C and 1 bars pressure. A direct measurement of the solubilities would give a sounder basis.

Nevertheless, the radon method seems to be of value for estimating the water content of magma in future eruptions.

Comparison with earlier observations.

It would be interesting to compare this result to the findings of other workers, but actual estimates of the water content in erupted magma seem to be scarce.

MacDonald, (17) has estimated the content of gas in the magma erupted in the Mauna Loa summit eruption of 1940. The total volatile content was found to be approximately 1 wt % of the lava extruded during the first few hours of the eruption and 0.5 wt % of the lava being extruded a week later. The result was based on estimates of the amount of erupted magma and the amount of gas being liberated. According to MacDonald (17) it is probable that the average volatile content of the magma erupted in this eruption was less than 1 wt %.

Einarsson (18) investigated the physical and chemical properties of the lava erupted by the volcano Hekla in 1947-48. According to his observations the lava appeared tranquilly flowing in the crater in a spongy state having a specific weight of 0.6 - 0.8 and still retaining practically all its gas content. The water contained in the vesicles was less than 0.03 wt % of the lava and analyses of the lava which gave 0.35 wt % water on the average therefore showed practically the whole primary water content of the magma at great depths. Bombs and pumice thrown out at the beginning of the eruption had practically the same specific weight and the same water content as the tranquilly flowing lava.

Einarsson (18) has investigated scoriae at many volcanic centers in Iceland and found them to be of the spongy type and similar in density to the Hekla material. In his opinion this indicates that as a rule the lava became oversaturated with gases (water) only just before it reached the surface, and that therefore the water content of magma is as a rule quite insignificant, 0.5 wt % or less.

Friedman (19) has measured the water content of a series of basaltic pumice and lava samples collected during the 1959-1960 summit and flank eruptions of Kilauea volcano, Hawaii. Samples of finely vesicular pumices of density $\sim$ 0.3 g/cc from the summit eruption of Kilauea Iki were found to contain 0.064 to 0.099% H_2O by weight, but similar samples from the Kapoho flank eruption had water contents of 0.086 to 0.104 wt % H_2O.

Friedman (19) believes that the water extracted from the finely vesicular glassy pumices represents the water present in the magma just prior to eruption. Errors due to uptake of additional water from the surroundings were minimized by (1) a skin of non-vesicular lava on the surface of the pumice lumps, (2) rapid collection of the material shortly after eruption, and (3) the selection of large pieces of pumice for analysis.

Samples of coarsely vesicular pumice and lavas and also crystallized lavas were also analyzed; however, the results obtained (on these samples) varied widely from replicate to replicate.

According to Friedman (19) it is evident that during the eruption of these materials, water was lost from the large open vesicles. In addition varying amounts of water were lost during the partial or total crystallization of the lava during cooling.

It is interesting to note that the water content of the Hawaiian pumices found by Friedman (19) is very similar to the saturation value of 0.1 wt %, which we found by extrapolating the data of Hamilton et al. (14) down to 1 bar pressure. On the other hand Einarsson (18) found a water content of 0.35 wt % in the Hekla lava. Similar results have been obtained by Tolstikhin (20) for the water content of the Quarternary effusives of Kamchatka and the Kurile Islands, estimated from 265 rock analyses. The average water content in basic and intermediate rocks was found to be 0.40 wt %, ranging from 0.1 wt % to 3 wt %.

TABLE I

Radon activity in magmatic gas at Surtsey

Sample of gas	Volume of sample ml	Activity of radon in liter of sample pC/l	Atmospheric contamination of sample	Activity of radon in liter of magmatic gas (corrected for atm. cont.) pC/l
25. Nov. 1964				
Sample 1	250	12 ± 25%	90%	120
18. Jan. 1965				
Sample 2	250	6 ± 40%	90-95%	40-160
Sample 3	250	nil.		
21. Feb. 1965				
Sample 5	189	136 ± 5%	nil.	136 ± 5%
Sample 7	208	119 ± 5%	nil.	119 ± 5%
Sample 8	206	120 ± 5%	nil.	120 ± 5%

Literature:

(1) B. Árnason: Measurements on the D/H - Ratio in H_2 - Gas and Water Vapour collected at the Volcanic Island Surtsey during the Year 1964. Surtsey Research Progress Report I, p. 27-33. Feb. 1965.

(2) G.E. Sigvaldason and G. Elísson: Preliminary report on collection and analysis of volcanic gases from Surtsey. Surtsey Research Progress Report I, p. 34-39. Feb. 1965.

(3) B. Árnason: (This report)

(4) G.E. Sigvaldason and G. Elísson: (This report)

(5) R.D. Evans: Apparatus for the determination of minute quantities of radium, radon and thoron in solids, liquids and gases. Review of Scientific Instruments 6, 99-112, (1935).

(6) J.E. Hudgens et al.: Nucleonics, 9, no. 2, p. 15 (1951).

(7) H.F. Lucas, jr.: A fast and accurate survey technique for both radon - 222 and radium 226. In the Natural Radiation Environment p. 315-331. The University of Chicago Press 1964.

(8) S. Steinthorsson: (This report)

(9) K.S. Heier and J.J.W. Rogers: Radiometric determination of thorium, uranium, and potassium in basalts and in two magmatic differentiation series. Geochim. & Cosmochim. Acta, 27, 849-60, (1963).

(10) K.S. Heier and J.L. Carter: Uranium, thorium and potassium contents in basic rocks and their bearing on the nature of the upper mantle. In the Natural Radiation Environment p. 63-86. The University of Chicago Press, 1964.

(11) Th. Einarsson: (This report)

(12) Goranson, R.W., 1931: The solubility of water in granitic magmas. Amer. J. Sci. 22, 482-502.

(13) Khitarov, N.I., E.B. Lebedev and A.A. Kadik: Solubility of water in granitic melt at pressures up to 7000 atmospheres. Geochemistry, (English translation) no. 10, p. 992-994, 1963.

(14) Hamilton, D.L., C.W. Burnham and E.F. Osborn: The solubility of water and effects of oxygen fugacity and water content on crystallization in mafic magmas. Journal of Petrology, 5, pt. 1, pp. 21-39, 1964.

(15) Russell, L.E.: Solubility of water in molten glass. J. Soc. Glass. Tech. 41, 304-17, 1957.

(16) Kurkjian, C.R. and Russell, L.E.: Solubility of water in molten alkali silicates. J. Soc. Glass. Tech. 42, 130-44, 1958.

(17) G.A. MacDonald: Activity of Hawaiian volcanoes during the years 1940-1950. Bull. volcanologique, T. 15, p. 120-179, 1954.

(18) Th. Einarsson: The Eruption of Hekla 1947-1948 IV, 3. The flowing lava. Studies of its main physical and chemical properties. Vísindafélag Íslendinga, 70 pp., Reykjavík, 1949.

(19) I. Friedman: Water and Deuterium in Hawaiian Pumices. (Manuscript)

(20) O.N. Tolstikhin: Amount of juvenile water liberated during formation of effusive rocks. Geochemistry (English translation), No. 11, pp. 1119-1124, 1961.

Measurements of the D/H-ratio in hydrogen and water vapour collected on the volcanic island Surtsey during the year 1965 (continued)

by

Bragi Árnason
University of Iceland, Physical Laboratory
Reykjavik, Iceland

During the year 1965 collection of gas in Surtsey was continued. More trips were made to the island, but in only one of them did the circumstances allow the collection of pure magmatic gases. This was at February 21st. On that day it was possible to enter the main crater and to get quite close to the eruption vent. Some small gas chimneys were found. The chimneys were similar to that found on October 15th 1964 and described in an earlier report[1].

We started to collect gas samples from a chimney approx. 100 cm in diameter. After collecting the first sample, the behaviour of the gas flux began to change and after the third sample had been obtained it was obvious that the gas was now mixed with atmospheric air.

Then a new chimney was sought and found. This chimney was only 5-10 cm in diameter. Another five water samples and two gas samples were collected from the second chimney.

The method of collection and analysis is the same as described in the previous report.

The results are expressed as deuterium depletion (negative δ value) relative to SMOW (Standard Mean Ocean Water, having D/H-ratio of about 158 10^{-6})[2].

The accuracy is within $\pm$ 0.1 percent for the water analysis and $\pm$ 0.2 percent for the gas analysis.

The results are listed in Tab. 1.

Two of the analyses on hydrogen gas, sample no. 6 and 8, show almost the same result as the previous one from October 15th 1964. Gas sample no. 2 is approx. 4 percent higher. This sample is thought to be contaminated with a small quantity of atmospheric air. The analyses of the water samples are in good agreement with the data obtained on October 15th and November 25th 1964.

According to Sigvaldason and Elisson[3] the gas contained 86.16 percent water vapour and 4.72 percent hydrogen. Using this data for sample no. 6 and 8 the δ-value for the total hydrogen excaping from the magma is calculated and listed in column 4.

Table. 1. Measurements on the D/H-ratio in hydrogen and water vapour collected in Surtsey on February 21st 1965.

Sample no.	Water % δ	H_2-gas % δ	Total hydrogen % δ
1	- 5,08		
2	- 4,82	- 11,0	
3	- 4,73		
4	- 4,72		
5	- 4,95		
6	- 5,02	- 14,85	- 5,55
7	- 4,85		
8	- 4,88	- 15,65	- 5,45

References:

1) Bragi Árnason (1965): Measurements on the D/H-ratio in H_2-gas and water vapour collected at the volcanic island Surtsey during the year 1964. Surtsey research progress report I, p. 27-33.

2) H. Craig (1961): Standard for reporting concentrations of deuterium and oxygen-18 in natural waters. Science, Vol. 133, No. 3467, p. 1833-1834.

3) G. Sigvaldason and G. Elísson, this report.

G E O L O G Y

The Surtsey Eruption
Course of events and the development of Surtsey and other new islands

by
Sigurdur Thorarinsson
Museum of Natural History
Reykjavik, Iceland

Introduction.

As stated in my former report (SRPR I, pp. 51-55) my main contribution to the research work connected with the Surtsey eruption has been to follow the different phases and changing habits of the eruption and also to study the changes of the island(s) due to the destructive forces, mainly marine abrasion.

As before I have enjoyed the helpfulness of the Director of the Coast Guard Service, Pétur Sigurdsson, and the Director General of Aviation, Agnar Kofoed Hansen, when I needed a trip to the eruption area.

Since my first report was written I have made nearly 40 reconnoitring flights over the Surtsey area and been on Surtsey eleven times. As to the course of events I have received much valuable information from the pilot Sigurjón Einarsson, who has been over Surtsey 200 times since the eruption started. Another pilot who has given me a lot of information is Björn Pálsson. The two men working in the control tower of the Vestmannaeyjar airfield, Bjarni Herjólfsson and Skarphéðinn Vilmundarson, have on my request kept a diary about the behavior of the eruption.

Aerial mapping.

Using the Coast Guard Service's aircraft SIF, the Icelandic Survey Department has aerialphotographed Surtsey and adjacent areas nine times, viz.: Febr. 17, 1964; April 11, 1964; June 16, 1964; Aug. 25, 1964; Dec. 15, 1964; Febr. 23, 1965;

April 21, 1965; Aug. 24, 1965; Febr. 6, 1966. The maps here reproduced are based on these aerial photos and on a trigonometric survey carried out in Surtsey by the Survey Department during the summer of 1965.

Course of events.

When I wrote my previous report in late February 1965, the effusion activity was still going on in Surtsey. It continued until the middle of May 1965. Lava was for the last time seen flowing in Surtsey May 17. The total area of the lava flow above sea level was then 1.53 km^2 and the area of Surtsey 2.45 km^2. The height of the lava dome was then practically the same as it had been Oct. 23, 1964, the dome proper 100 m high and the highest point of the crater rim 118 m. The total volume of lava, including its submarine part, consisting to a great extent of hyaloclastites (pseudotephra), pillow lava and pillow lava breccia, can only be roughly estimated as we still lack bathymetric maps. A likely estimate is 250 a 300 million m^3, corresponding to an average volume increase of 7 a 8 m^3/sec. during the 13 1/2 months of effusive activity. Although varying considerably from day to day the lava flow on the whole gradually diminished throughout the winter of 1964/65. During the last months of effusive activity the average flow hardly exceeded 3 m^3/sec.

The Syrtlingur phase.

No sooner had the activity in Surtsey come to an end than there were signs of submarine activity 0.6 km ENE of the island. May 22 (possibly already May 11) vapour was seen rising from this place. May 28 the submarine cone, which was in progress protruded the sea level for the first time. The tiny spot visible seemed to consist of lava lumps and not of scoria and lapill. June 6 the island was 16 m high, its diam. 170 m. This island was washed away the following days, but became visible again

June 14. June 16 its height was 37 m and its max. diam. 190 m. Aug. 24 its height was 45 m, max. diam. 420 m and its area 0.08 km^2. Sept. 15 its height was 67 m, max. diam. about 650 m, and its area about 0.15 km^2. Two days later its height probably exceeded 70 m, but from then on the destructive forces, mainly the marine abrasion began to get the better of the constructive ones. The eruption kept on, although on a gradually diminishing scale and the volcano was last seen in action Oct. 17, but after a very stormy week it had completely disappeared Oct. 24, and no activity has later been observed in this place.

The island never got an official name, but it was popularly called Syrtlingur, that is little Surtur. Its activity was strikingly similar to that of Surtsey during its explosive phase, although on a much smaller scale, periods of intermittent explosions alternating irregularly with continuous uprush. Fig. 1 shows a typical activity in Syrtlingur. During the most powerful uprush paroxysms the tephra columns reached about 700 m height. Tephra was spread all around. When the activity of Syrtlingur ended the thickness of the tephralayer on the northeasternmost part of Surtsey was 3.5 m, but on the southwesternmost part of the lava flow it was only 2 cm. The total volume of tephra produced by the Syrtlingur activity, the socle of the island included, is of the order of 50 mill. m^3, corresponding to an average production of 4 m^3/sec. during the 5 months its activity lasted. This is roughly one tenth of the productivity of Surtsey during its first months.

Activity SW of Surtsey.

On Dec. 26, 1965, submarine volcanic activity was for the first time observed about half a naut. mile SW of Surtsey. The ridge that was piled up there protruded the sea surface for the first time Dec. 28, and since then a small island has repeatedly disappeared and reappeared. It has reached a max. height of about 40 m and a max. length of 250 m. Its activity was of the same type as Syrtlingur, but was on a still smaller scale. The max. height of tephra-columns observed was about 250 m. Febr. 24, when this is written, the eruption is still going on.

The total volume of tephra and lava produced by the two Surtur vents and other vents that have been active in the adjacent area has now exceeded 0.8 km^3. The eruption is now the second largest recorded in Iceland since the settlement 1100 years ago, only the "Mývatn Fires" 1725-1729 did last longer.

The Surtsey activity has shifted at least four times to a new vent (fissure). The distance between the NE-most and SW-most of these vents is 5 km, direction N65°E —— S65°W, whereas the individual fissures seem to run about N25°E —— S25°W and the system of eruption fissure thus seems to be arranged en échelon.

Area changes of Surtsey.

The map, Fig. 3, worked out by the Icelandic Survey Department, shows the outlines of Surtsey at various times. Table I is based on this map and on measurements of the diameter and height of the island carried out by officers on the coast guard vessels and supplemented by my photos. The figures before Febr. 17, 1964, cannot be regarded as accurate. The figures within brackets are based on the knowledge that there was practically no change of the area of Surtsey and its lava flow between the end of April and July 9, 1964, and between May 17 and Aug. 24, 1965.

The diagram, Fig. 4, is based on Table I and on measurements of the height of Surtsey carried out many times.

Studies on Surtsey.

Continued studies of the lava flow when it entered the sea strengthened the writer's impression of the rapid formation of pseudotephra or hyaloclastites, which must constitute a considerable part of the submarine part of the advancing lava flow. The similarity between Surtsey and the glacial table-mountains of Iceland and the tuyas of British Columbia is obvious. The main difference seems to be that Surtsey was built up in an open and often stormy sea which for months was constantly breaking through the crater ring and flooding the vent and thereby prolonging the phreatic explosive activity of the volcano, whereas the tablemountains were piled up in calm water. Consequently airborne pyroclastics (tephra) are likely to constitute a proportionately much greater part of oceanic table-mountains than the glacial ones.

My geomorphological studies in Surtsey during the summer of 1965 were similar to those carried out before, viz. studies of the increasing roundness of blocks and gravels, studies of the changing profiles of the lava shore etc. The thickness of the tephra layer from Syrtlingur was measured several times all over the island. The material has not yet been worked out in any detail.

Text of figures

Fig. 1. Typical explosive (phreatic) activity in Syrtlingur. 1. Small. 2. Medium size. 3. Big explosions. 4. Nearly continuous uprush. 5. Continuous uprush. 6. No observations.

Fig. 2. Surtsey and Syrtlingur Aug. 24, 1965. Shaded: Lava covered area. The Icelandic Survey Department.

Fig. 3. The changing outlines of Surtsey according to aerial photographic mapping by the Icelandic Survey Department.

Fig. 4. Diagram showing the area increase of Surtsey and its lava flow and the increasing height of the island.

Fig. 1

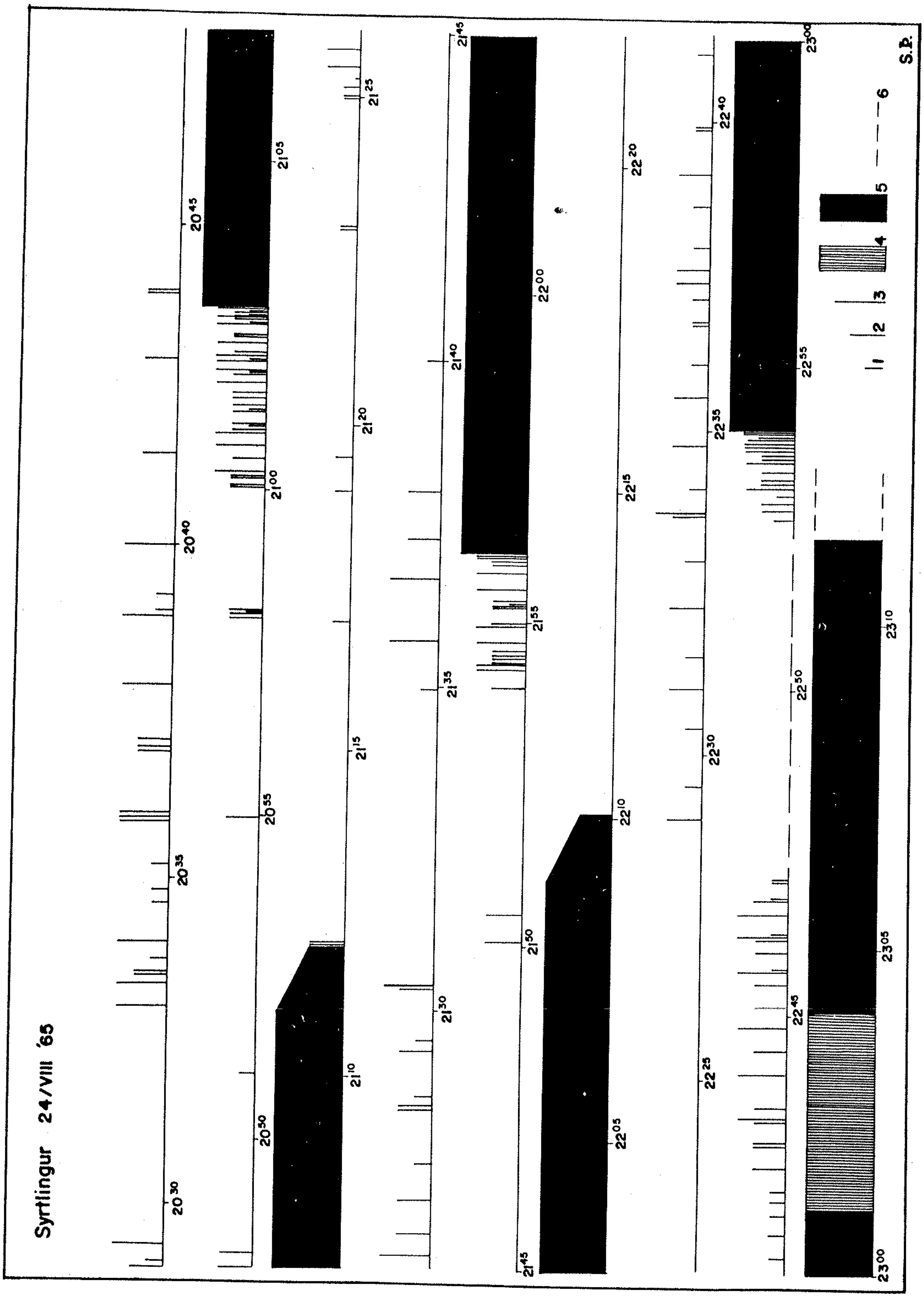


Fig. 2

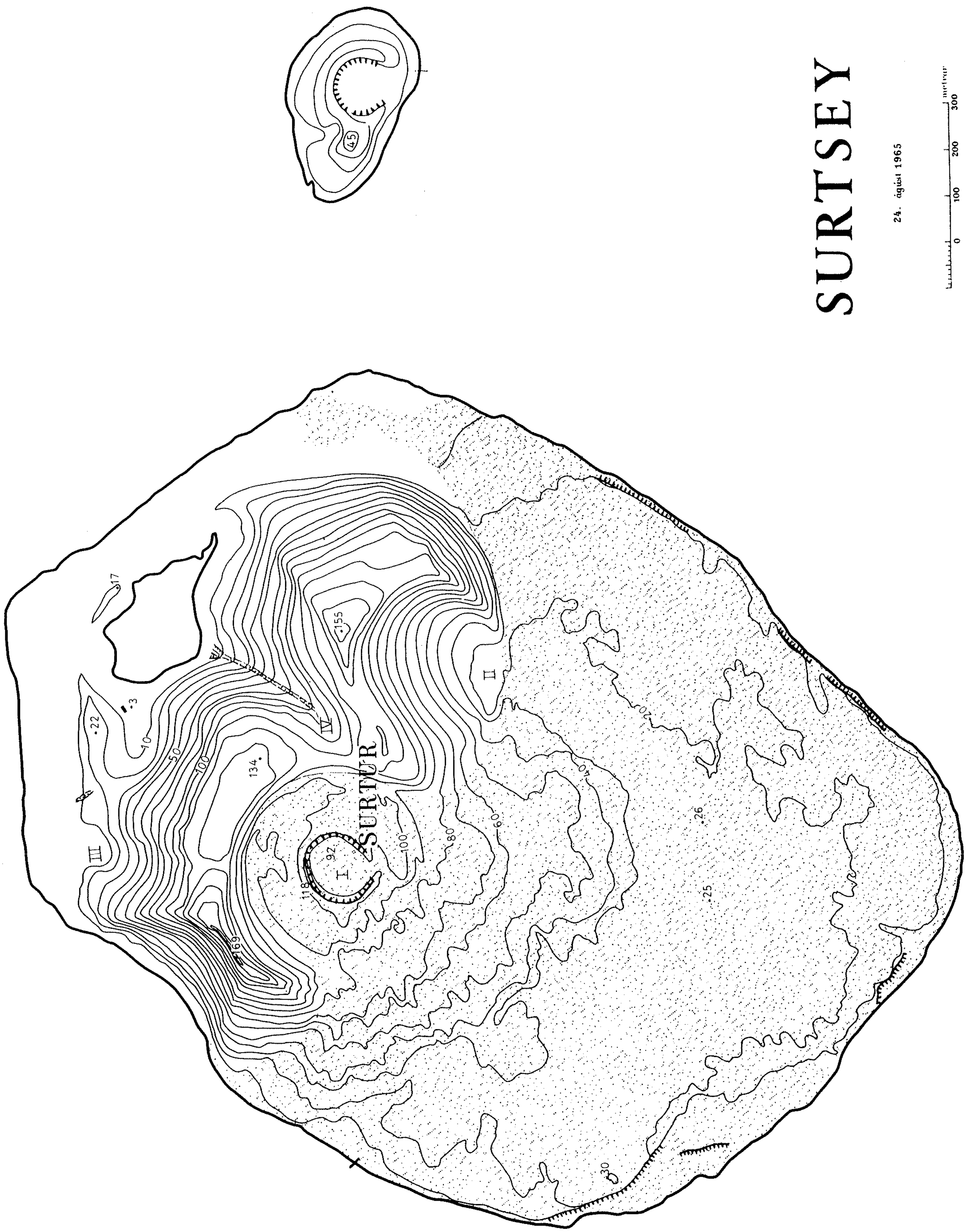


Fig. 3

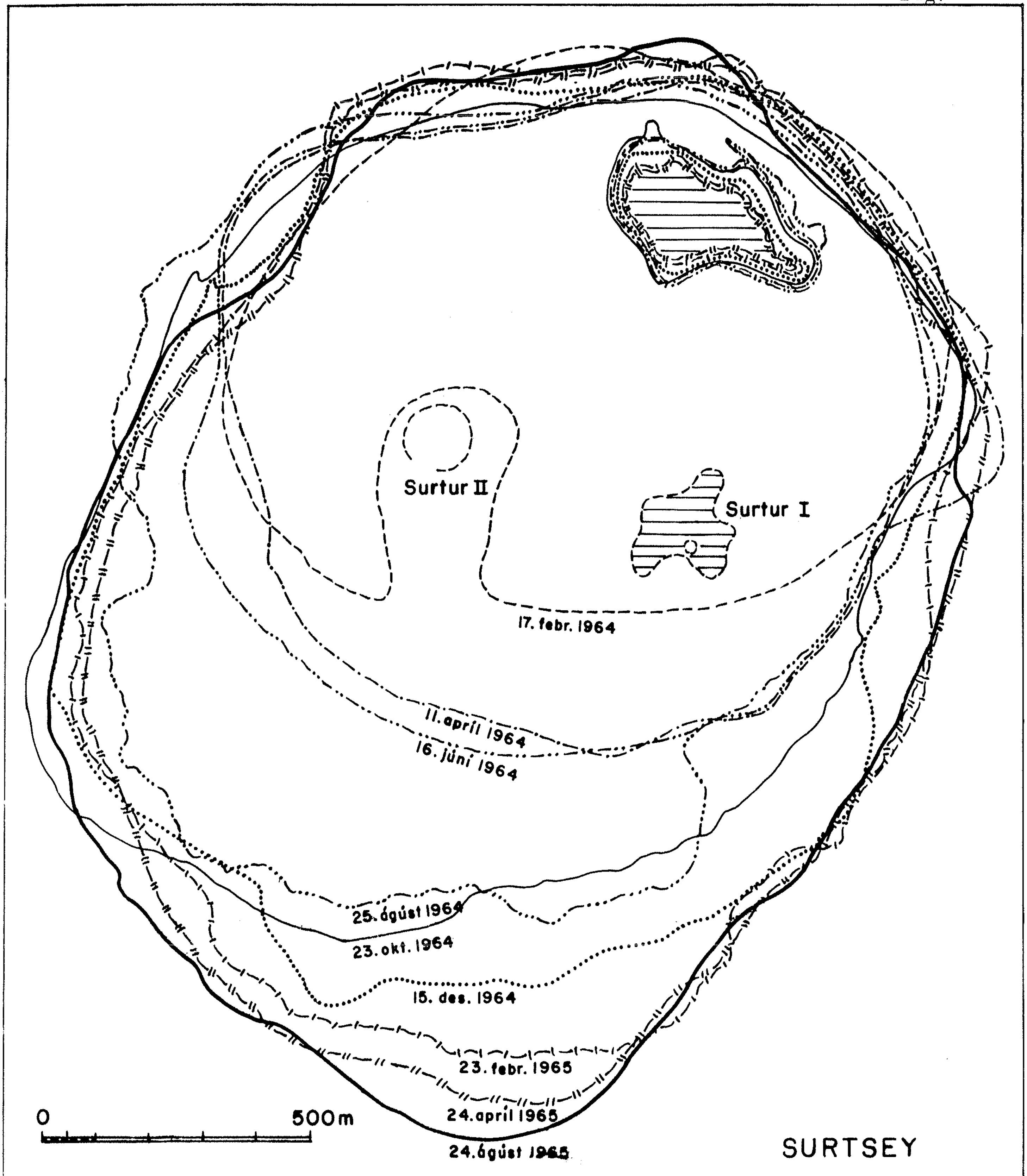
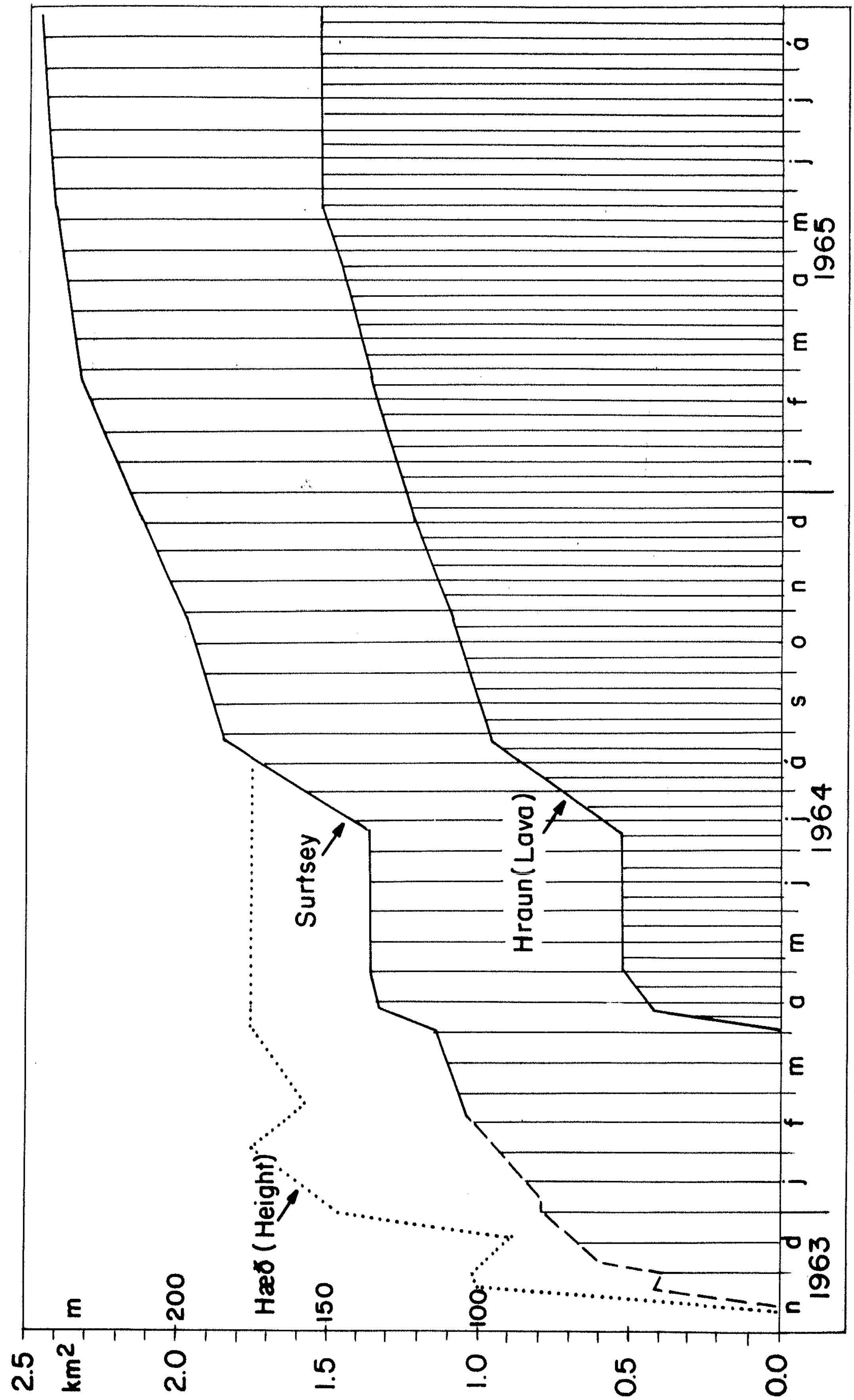
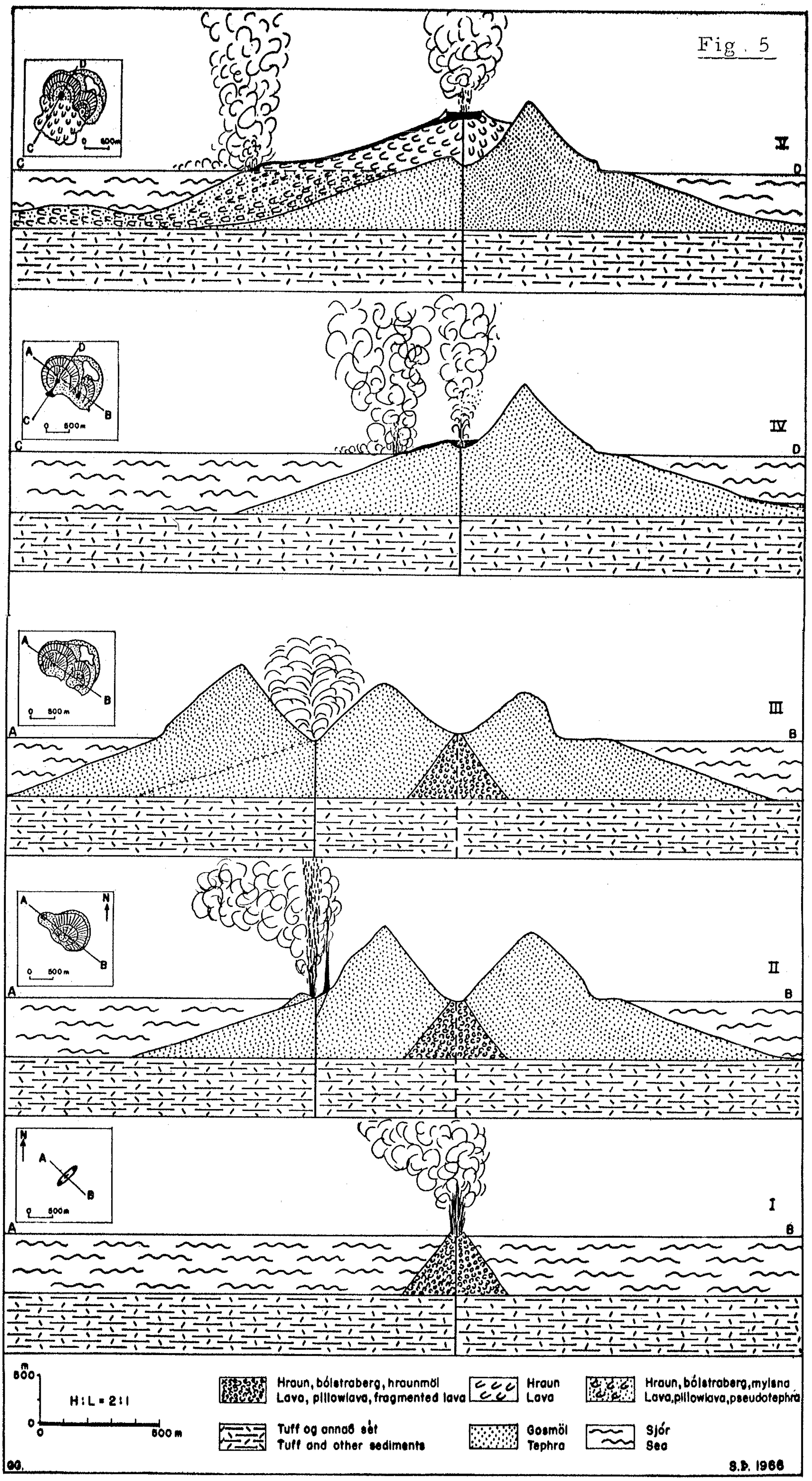

Surtur II
Surtur I
17. febr. 1964
11. apríl 1964
16. júní 1964
25. ágúst 1964
23. okt. 1964
15. des. 1964
23. febr. 1965
24. apríl 1965
24. ágúst 1965
0
500m
SURTSEY

Fig. 4


2.5
km²
2.0
1.5
1.0
0.5
0.0
m
200
150
100
Hæð (Height)
Surtsey
Hraun (Lava)
n d j f m a m j j á s o n d j f m a m j j á
1963
1964
1965



Sections, somewhat schematized, illustrating the development of Surtsey. I. Nov. 15, 1963; II. Febr. 5, 1964; III. End of March, 1964; IV. April 4, 1964; V. Aug. 25, 1964.

TABLE I

Area changes of Surtsey and its lava flow in hectares.

	Total area ha	Increase ha	Increase ha/day	Lava ha	Increase ha	Increase ha/day
1963:15. nóv.	0					
		8	8.00			
16. "	8					
		32	8.00			
20. "	40					
		- 3	- 0.30			
1. des.	37					
		23	3.30			
7. "	60					
		30	0.55			
1964:31. jan.	90					
		12	0.70			
17. feb.	102					
		13	0.30			
4. apr.	115			0		
		18	2.50		42	6.05
11. "	133			42		
		4	0.20		8	0.40
30. "	(137)			(50)		
		0	0.00		0	0.00
16. júní	137			50		
		0	0.00		0	0.00
9. júlí	(137)			(50)		
		45	0.95		46	0.95
25. ág.	182			96		
		14	0.25		14	0.25
23. okt.	196			110		
		17	0.30		13	0.25
15. des.	213			123		
		21	0.30		14	0.20
1965:23. feb.	234			137		
		2	0.05		9	0.15
24. apr.	236			146		
		9	0.40		7	0.30
17. maí	(245)			(153)		
		0	0.00		0	0.00
24. ág.	245					

A Contribution to the Morphology of Surtsey

by
Gudmundur Kjartansson
Museum of Natural History
Reykjavik, Iceland

The conclusions outlined in the following are for the most part based on field-studies made during many years before the beginning of the Surtsey eruption, and also in my regrettably few visits to Surtsey in the time interval November 1963 to December 1964. These visits count only three landings for several hours on the island, eight voyages along its coasts, and five flights over it. The most part of these visits were made possible by the courtesy of the Icelandic Coast Guard primarily, and also the Civil Aviation Administration and the Icelandic Survey Department. For other visits I have paid the expenses myself. All last year, 1965, I was impeded from fieldwork in Surtsey by bad health.

My view, outlined below, that morphological features of Surtsey are analogous with those of a certain type of Pleistocene volcanoes in Iceland (the "stapis" or tablemountains) was advanced in a lecture, "Stapakenningin og Surtsey", at an ordinary meeting in the Societas Scientiarum Islandica, on November 25th, 1965. With a little addition this lecture was prepared to appear as an article in Náttúrufrædingurinn, 4th issue, 1965, but it has to wait till the next issue, the 1st of 1966. As this article (24 typewritten pages) is written in Icelandic it does not fit into the present "Reports". What follows is only the Summary in English and most of the pictures of the still unpublished article: A Comparison of Tablemountains in Iceland and the Volcanic Island of Surtsey off the South Coast of Iceland.

Terms like Inselberge, tablemountains and several others have been suggested by foreign explorers for a special type of volcanic mountains in Iceland. In Icelandic they are called stapar (sing. stapi). These are isolated mountains with steep sides and flat or gently convex tops. Near the base, and usually up to a level above the middle of their sides, the stapis consist of móberg (i.e. basaltic hyaloclastic and more or less palagonitized rocks) and pillow-lava, but the top with its sharp edges is made up of lava flows. All these rocks are of Late Pleistocene age.

In the first decades of this century it was debated by geomorphologists, mostly Germans, whether these volcanoes owed their peculiar shape to erosion or to tectonic forces, i.e. whether they were Zeugenberge or Horste. The latter view gained ground as time went on, without being proved, however, in the case of any single stapi. In 1943, after studying some stapis in South-western Iceland, the present writer pointed out a third possibility; the the stapis were piled up by subglacial eruptions. According to this hypothesis the móberg and the pillow-lava structures at the base are the result of rapid chilling in the melt water, whereas the normal flows of lava on the top were extruded subaerially when the mountain had emerged above the ice surface. The steep walls of the surrounding ice prevented the spreading of the erupted material and moulded the mountain almost into its present shape.

More recently similar views have been advanced on the origin of mountains of the stapi type, first by W.H. Mathews (1947) on the Tuyas in British Columbia, and later by R.V. van Bemmelen and M.G. Rutten (1955) on the tablemountains of

Northern Iceland, whereupon this theory of "interglacial accumulation" was accepted by most students of the móberg formation (including the present writer) as the most probable interpretation of the origin of stapis. However, the validity of the theory had not been fully proved in the case of any Icelandic mountain. It was opposed by Trausti Einarsson (1958 and 1963), and facts mentioned in the present article are not indicative of such an origin for all mountains of the stapi type. Further, the theory lacked actualistic support, as repeated subglacial eruptions in Iceland in historic time do not seem to have created any stapis.

It was not until the present writer's investigation of the volcano Leggjabrjótur in Central Iceland that evidence was brought forth of at least that mountain having been formed in accordance with his hypothesis of 1943 (Kjartansson 1964).

Finally, the eruption of Surtur, beginning in November, 1963, and still slightly active in January, 1966, has now piled up a kind of stapi before our eyes. But this new stapi, Surtsey, was not like its Pleistocene counterparts formed in an ice-sheet, but in the sea. Consequently it is somewhat anomalous, especially with regard to its shape. The lack of surrounding ice-walls may be responsible for less steepness of its submarine slopes and the heavy erosion of oceanic waves has already severely deformed its flanks at sea level.

In the formation of Surtsey as well as in that of the older stapis, mutatis mutandis, four different stages and four corresponding rock facies are distinguishable (Fig. 4):(1). Basaltic magma extruding on the bottom of deep water (or thick ice) forms a subaqueous pile of pillow-lava. High pressure prohibits explosive activity - (2). As the top of the pile reaches a level of sufficiently decreased water pressure explosions set in, probably at a depth not exceeding 20-30 metres. Explosive activity, conditioned by the easy access of water into the vent, continues with production of pyroclastic material. Crater walls of this material rise above the water-level. - (3) When these walls become continuous around the crater and sufficiently watertight, the activity turns effusive. Lava of the shield volcano type covers the emerging top of the pile. - (4) Lava streams flowing into the water (or onto the ice) are solidified rapidly by its chilling effect and pile up to form high and steep subaqueous fronts consisting of a mixture of brecciated and pillowy lava.

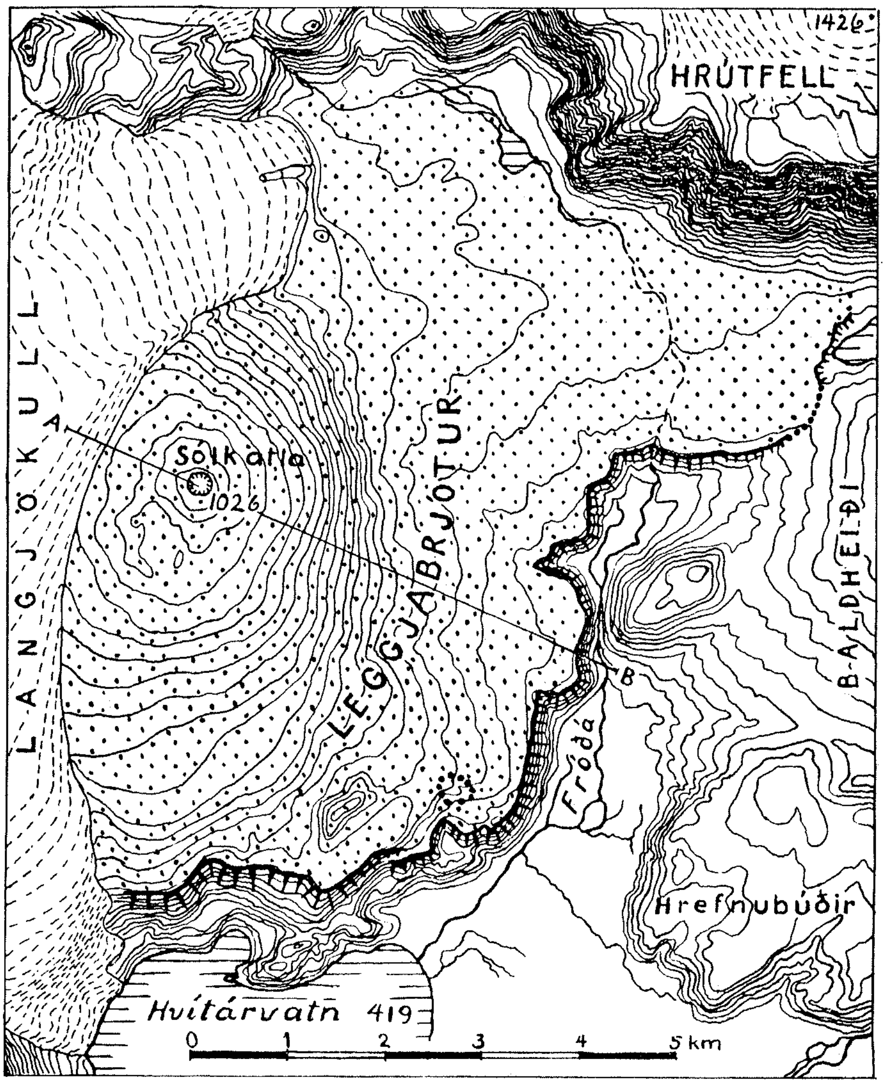


Fig. 5. The tablemountain Leggjabrjótur with its summit crater Sólkatla.

Dotted area: lava from Sólkatla, never glaciated. Thick toothed line : high edge of lava, come to rest in deep water or against the steep margin of the Pleistocene ice-sheet. Dotted line: low (normal) edge of lava solidified on land (visible only on a short section north-west of Baldheiði and around a small outcrop of bedrock near the south-eastern edge of the lava). Elsewhere, the edge of lava is buried under debris (in the north) and under glacier ice (in the west).
A - B: section shown in Fig. 4.
Contours according to the U.S.A. Army Map of Iceland.

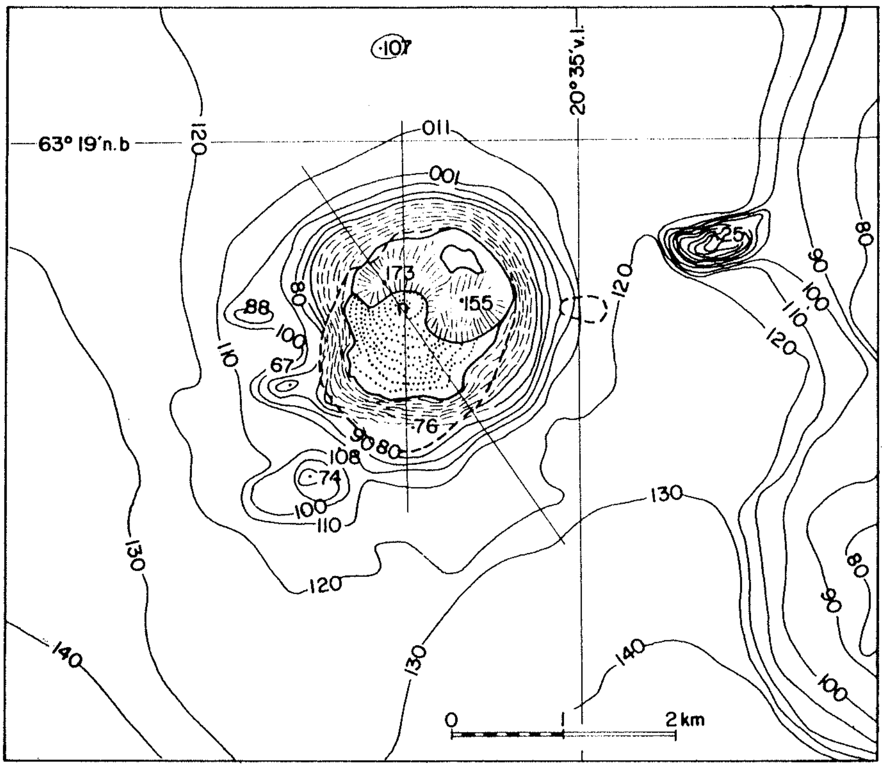
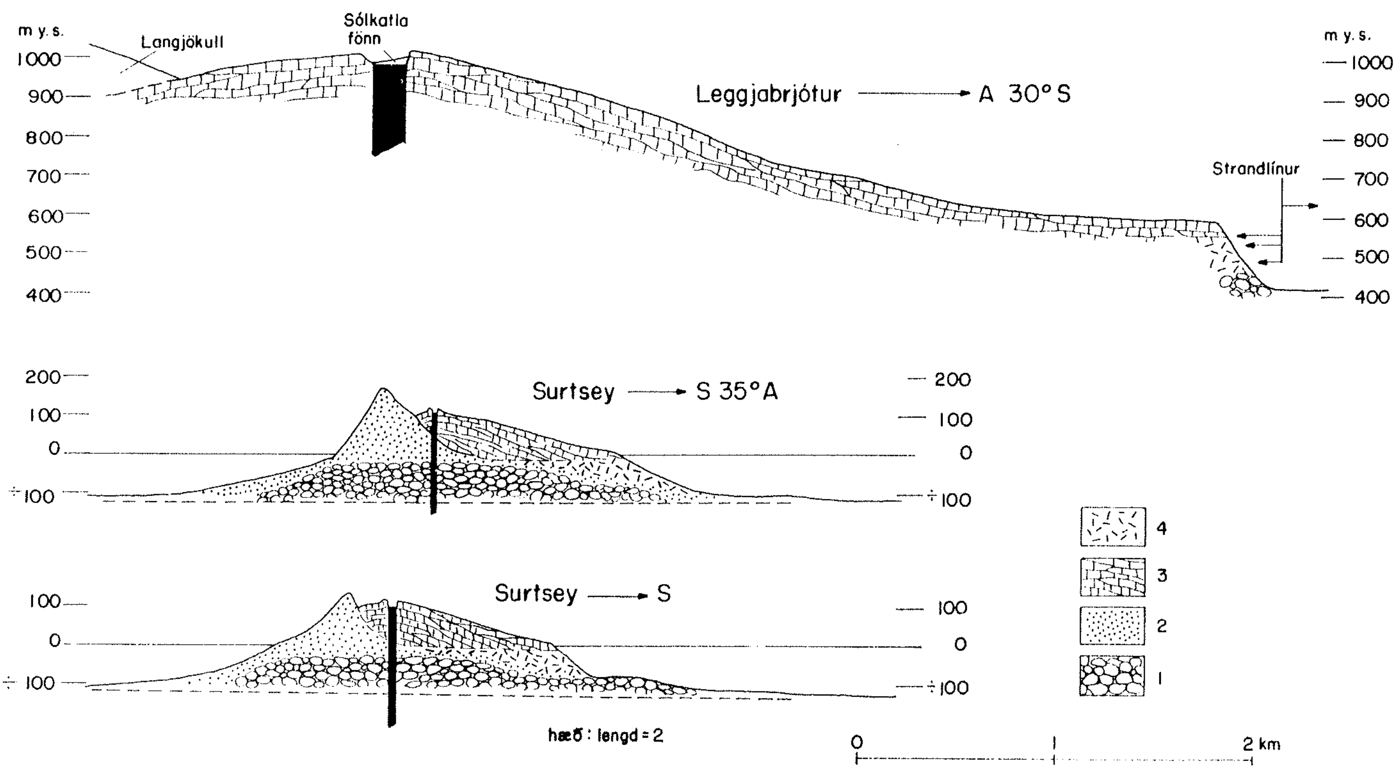


Fig. 3.

A chart of the surroundings of Surtsey according to echo soundings by the Icelandic Hydrographic Service in July - August, 1964. Coastline of Surtsey and Syrtlingur in August, 1965, inserted with thick dash-line.



E.B. Fig. 4. G.K. 1965

Sections of Surtsey and Leggjabrjótur (cf. Figs. 3 and 5) in equal scale, vertical exaggeration 2:1. Rock structures below sea level, suggested. - 1: pillowlava with increasing content of volcanic breccia and tuff near the top. 2: tephra, mostly tuff. 3: lava-flows of the shield volcano type, possibly with pillow structure near the base. 4: Coarse breccia, probably containing pillows, scattered and in clusters. "Strandlínur"= shore-lines; "fönn" = névé.

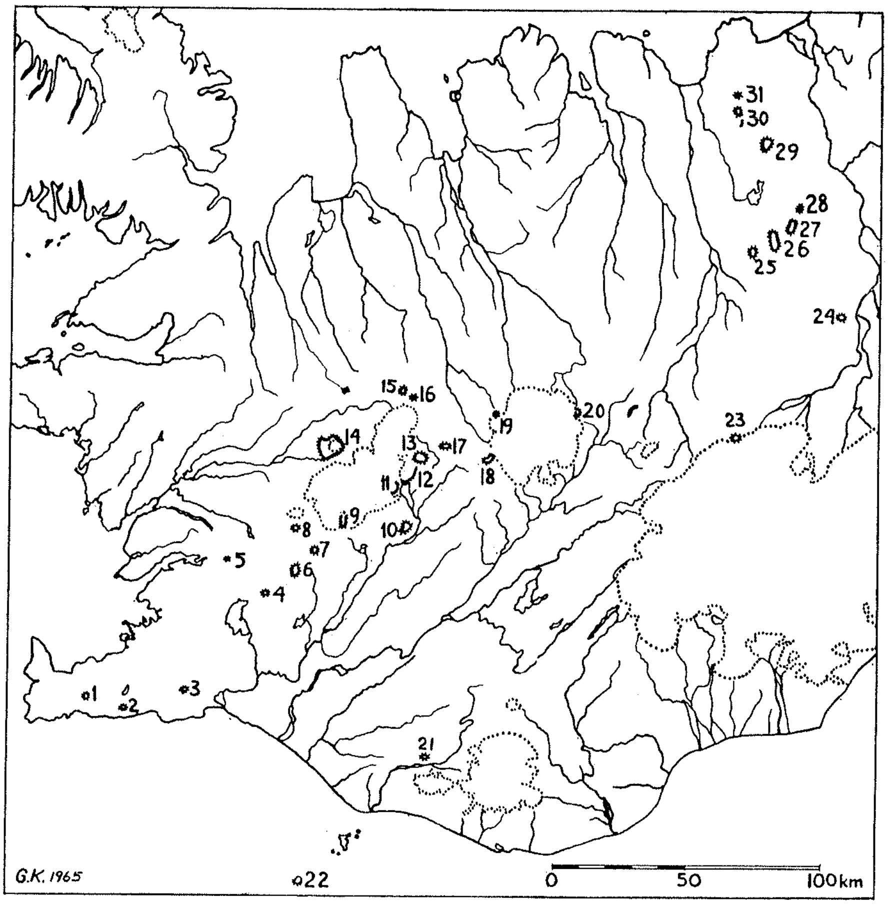


Fig. 1. Tablemountains in Iceland.

1 Fagradalsfjall, 2 Geitahlíð, 3 Geitafell, 4 Hrafnabjörg, 5. Hvalfell, 6 Skriðan, 7 Hlöðufell, 8 Stóra-Björnsfell, 9 Hagafell, 10 Bláfell, 11 Skriðufell, 12 Leggjabrjótur, 13 Hrútfell, 14 Eiríksjökull, 15 Krákur, 16 Lyklafell, 17 Kjalfell, 18 Blágnípa, 19 nafnlaust fjall upp af Álftabrekkum, 20 Miklafell, 21 Þórólfsfell, 22 Surtsey, 23 Kistufell, 24 Herðubreið, 25 Sellandafjall, 26 Bláfjall, 27 Bláfjallsfjallgarður, 28 Búrfell, 29 Gæsafjöll, 30 Lambafjöll, 31 Höfuðreiðarmúli.

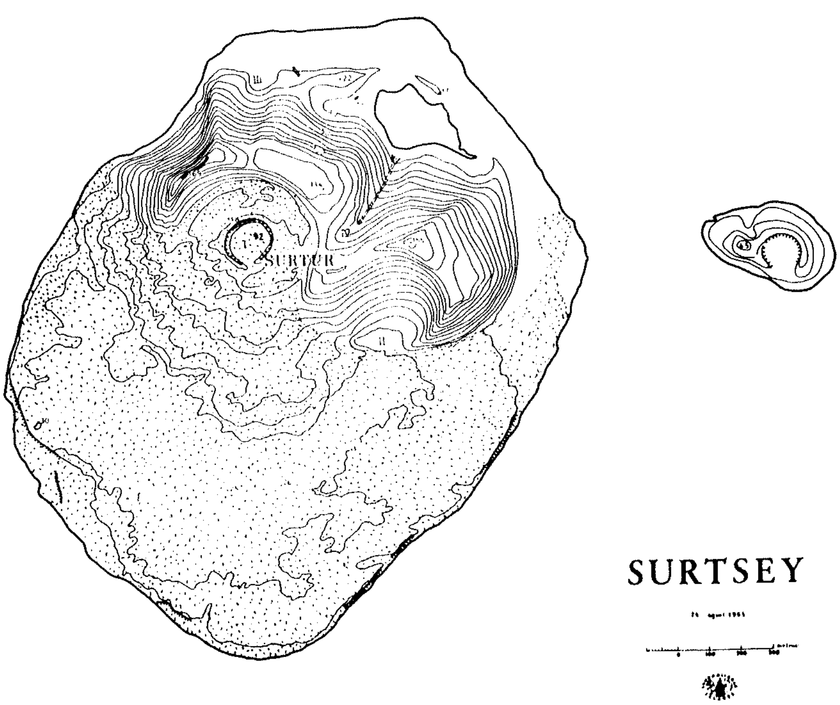


Fig. 2. Surtsey and "Syrtlingur" on August 24th, 1965. The lava is indicated by stippling: the hills consist of tuff, and the flat strip along the shore is made up of beach deposits.

G E O P H Y S I C S

Earth Tremors from the Surtsey Eruption 1963-1965

A Preliminary Survey

by

Hlynur Sigtryggsson and Eiríkur Sigurdsson
The Icelandic Meteorological Service

Four seismological stations were in operation in Iceland when the Surtsey eruption began. They are listed below, together with their coordinates and distance from Surtsey.

Station	Lat. N	Long W	Distance from Surtsey
Akureyri	65°40'	18°06'	291 km
Kirkjubæjarklaustur	63 47	18 03	137 "
Reykjavík	64 08	21 54	117 "
Vík í Mýrdal	63 25	19 01	80 "

The seismograph at Akureyri was a Mainka instrument, with a magnification of about 100, measuring N-S ground motion. No tremors were observed there from Surtsey due to distance and low magnification of the instrument.

The seismograph at Kirkjubæjarklaustur is a vertical Willmore instrument. The maximum magnification used was about 10000, for a ground period of 0.1 to 0.7 seconds.

At Reykjavik three seismographs were operated, one Sprengnether E-W, and two vertical component seismographs. One of them was a Sprengnether short period seismograph. The third seismograph was a Willmore, which was connected to a galvanometer of 1.4 sec. period. Since this galvanometer is not designed for use with the seismograph, the magnification was unknown, but was estimated to be about 1300 for a ground period of 0.3 to 1.5 sec. Some rearrangements were made during the eruption, the most important one on December 12, 1963, when a N-S component Sprengnether was connected. After that only one vertical component was used at any one time, either Sprengnether or Willmore depending on circumstances. All the Sprengnether seismographs were operated with a magnification of 400 or 1000.

At Vík a Mainka N-S seismograph was in operation, magnification 40 was used.

The present survey is based mainly on seismograms from Reykjavik, since they were most readily available for evaluation, but seismograms from Vík and Kirkjubæjarklaustur were used in several cases.

Microseisms are quite strong in Iceland, and their intensity shows a strong correlation with wind and swell. In relatively quiet weather their period is 1-5 seconds and the ground amplitude is 1 to 5 μ. In strong weather with heavy seas the period is 6 to 7 sec. and the amplitude is 20-30 μ or more. Changes in average amplitude take place rather slowly, over several hours. The ground waves which originated at Surtsey and will be described later, had to be distinguished from the usual microseisms. In stormy weather this proved to be very difficult.

From November 1st to 20th hardly any unusual activity could be observed on the seismograms at Reykjavik. The only exception occurred on November 12th, from 1400 to 2400*, when very weak waves with a period of 0.8 to 1.2 sec. were intermittently observed, which is much shorter than normal for microseism at that time. Otherwise the seismograms were quite usual. All earthquakes could be traced to other sources, and the microseisms were normal for the season.

At Kirkjubæjarklaustur several very weak earthquakes were registered on the 6th to 8th November, some of which were from an origin at a distance of 140 kilometers, approximately the same as to the eruption later on. From 1100 on the 12th to 0130 on the 13th weak tremors with a period of 0.2 to 0.4 period was observed, and again between 1100 and 1600, with a maximum between 1300 and

---

* All times are given in GMT.

1400. Similar tremors were also observed on the 14th from about 0500, but their amplitude was much smaller than before, and diminished gradually and disappeared in the afternoon. Small and very rapid tremors with a period of 0.1 sec. were observed on the 13th between 0600 and 1300, but they may have been caused by ice drift on a river near the seismograph or other local sources.

Shortly after midnight on November 21st other kind of tremors made their appearance, and were much in evidence for months to come. These waves were quite regular, their period was usually 2.0 sec., but sometimes it dropped to 1.5 sec. especially when the waves were weak. These waves often lasted for hours, but their increase and decrease took place in only a few minutes, and was much more rapid than for regular microseisms. This characteristic and the regular period distinguished these waves from the usual microseisms. Changes in their intensity sometimes coincided with marked changes in the eruption (on December 1st for example), and when a seismograph was operated in the Westman Islands they were observed there also, but with a larger amplitude. It is therefore considered almost certain that these waves originated in the vicinity of Surtsey. At Kirkjubæjarklaustur these waves were also observed, but wave components with a period of 0.7 - 1.5 sec. were also in evidence. The seismograph had its maximum sensitivity near this range.

The waves just described were first observed on November 21st, as stated before, but their amplitude increased considerably on December 1st at 1407-1411. They were very much in evidence on Dec. 2nd and 3rd, and again on 7th to 8th, but diminished after that. Still they were observed every day from time to time until the end of the year, but were very weak after Dec. 22nd, with a period of close to 1 sec. They increased again on Dec. 30th, but disappeared on January 4th 1964 for the time being.

The first earthquake, which definitely had an origin near Surtsey, occurred at 1219 Dec. 17th 1963 (magnitude 3.8) and another much weaker just before 2300. On the 23rd at 2306 there was again a small quake, followed by several still smaller quakes on 24th. Still another small quake was at 2010 on January 3rd, followed by a stronger one at 1052 on the 4th. From January 7th to 10th fifteen earthquakes were observed at Reykjavik and several more at Kirkjubæjarklaustur. Four of these earthquakes were felt at Westman Islands, on the 7th at 2210 and 2231, 8th at 0133 and 9th at 1633. The three first felt earthquakes had a magnitude of 4.2, the last one 4.6.

On January 11th the long waves were observed again and had a maximum intensity on the 13th and 15th, but were obscured by microseisms on the 19th. Two rather small earthquakes were observed at Reykjavik on January 23rd at 1106 and 1421. These two and three more were observed at Kirkjubæjarklaustur.

The long waves appeared again at Reykjavik on the 24th in the afternoon, and were very strong the following day between 1109 and 1157 (amplitude 10μ). They were very pronounced the next six days, but disappeared on the 31st about 0230 and were not observed again with certainty until February 12th. The maxima of these waves in the period from January 20th to March 31st 1964 is given in Table I. The amplitude is given on those days when microseisms were not pronounced. The long waves almost disappeared from the Reykjavik observations on 28th to 29th of March, but very weak tremors were observed on 17th to 24th of April and in the evening of July 9th. The long waves were not observed again until next summer.

An earthquake from Surtsey was observed at Reykjavik at 1752 on January 31st 1964, and the following day eleven quakes were observed, at 0004, 0203, 0257, 0729, 0743, 0857, 1140, 1452, 1554, 1555 and 1658, but twice as many were observed at Kirkjubæjarklaustur. The earthquakes at 0257, 0729, 0857 and 1452 were the strongest ones, with a magnitude of 3.2 to 4.5. Some of these quakes were felt at Westman Islands.

Two small earthquakes were registered at Kirkjubæjarklaustur at 1047 and 1156 on March 9th, and also at 1015 on July 14th, 1964.

After that no tremors or earthquakes originating at Surtsey until May 1965 were observed.

On May 8th 1965 at 1041 a small earthquake or tremor with a probable origin at Surtsey was observed in Reykjavik. This tremor was followed by many others the next twelve days. They are listed below, and magnitude is assigned to the largest ones. The times of the earthquakes and tremors are as follows: On the 9th at 1601 (small), 10th at 0251 (magnitude 4.2) and 0315, 11th at 0033 and 0759 (both small), 13th at 0102 (very small, followed by very weak tremors the same day and the next), 14th at 1718 (magnitude 4.2) and 2140 (weak tremor), 15th at 0703 and 1718 (magnitude of both 3.7), 16th at 0711 and 0810 (both small), same day at 1320 (magnitude 4.0), 17th at 2357 (small), 18th at 0115 (very weak tremor). On the 19th six earthquakes were registered, the largest at 1415 (magnitude 4.2). The others, which were much smaller were registered at 1513, 1536, 1611, 1655 and 2038. Weak indefinite tremors were also registered at 1433 and 1453. An earthquake at 1501 on the 20th (magnitude 3.8) concluded this series. No tremors or earthquakes originating near Surtsey were observed during the next month.

Regular waves, similar to those observed first on Nov. 21st 1963, again made their appearance on July 3rd in the forenoon, after an absence of over a year. Their period was now 1.2 to 2.3 sec., 1.2 being most frequent. They were observed daily (except July 5th) until August 11th, but with varying intensity and frequency. On August 12th to 14th the waves seem to diminish and almost disappear. But strong microseisms on these days may partly obscure them.

Late on the 14th the waves increased again and were visible until 11th of September, although they were disturbed by microseisms on August 23rd and 24th. The period in August was 1.3 to 2.0 sec. The waves had maximum amplitudes on August 31st and September 9th, and had then a period of 1.2 sec. September 12th to 15th microseisms were intense, and no waves from the eruption could be distinguished. They were however observed again September 16th to 18th (period 1.2 sec.). September 19th to October 1st they were very weak or entirely absent, but microseisms were strong during the first days of this interval. October 2nd to 7th the eruption waves were observed again, this time with a period of 1.0-1.2 sec., but after that they were hardly visible at all to the end of the month, but microseisms were strong, especially on 12th to 20th and 26th to 27th.

Earthquakes began again in the Surtsey area on October 28th. The seismographs at Reykjavik registered the first quake at 1155 (magnitude 3.5). Earthquakes from Surtsey had not been registered since May 20th. The next earthquake was observed at 1055 on Nov. 4th, it was somewhat weaker than the previous one. The third one was at 1934 on the same day (magnitude 3.9), and a quake on Nov. 5th at 0152 may also have originated in the Surtsey area. Further earthquakes from Surtsey were the following (magnitude is given in parenthesis when determined): November 9th at 0227 (3.4), 13th at 0107 (4.2), 17th at 1048 (4.4), 1143 (4.4) and 1546 (4.2), 21st at 1027 (4.2), 22nd at 0003 (4.6), 23rd at 1125 (3.5), 24th at 1119 (3.6) 1139 and 1623 (both small). On November 27th at 0007 a small earthquake was observed which may have originated near Surtsey.

Tremors and regular waves were observed every now and then in November, especially on the 1st, 2nd, 5th, 6th, 8th, 9th, 12th, 21st, 23rd and 24th.

No earthquakes are known to have originated at Surtsey in December 1965, but tremors were observed on the 4th, 6th, 12th, 22nd and 27th.

On February 24th to 27th the ground wave activity often seemed to be at maximum near the high tide. Spring tide was at maximum on these days. The examples are so few, however, that it is difficult to decide if the coincidence is significant or dependent on chance alone.

Table I. Times and Amplitude of Ground Waves from the Surtsey Eruption, January 20th to March 21st, 1964. Observed at Reykjavik.

The amplitude given is the N-S ground motion in μ. The magnification of the seismograph used was 750 at T_g = 2.0 seconds.

Date	GMT	Amplitude
20/1	2111-2123	
24/1	1630-1640	
"	1839-1930	5
25/1	1109-1157	10
27/1	2203-2244	
28/1	0152-0333	
"	0701-0727	13
"	1511-1541	
"	2011-2018	12
29/1	0005-0050	
"	0513-1200	
30/1	1403-1407	
"	1844-2015	
16/2	2232-2241	
17/2	0532-0545	
21/2	2111-2123	
24/2	1630-1640	
"	1839-1930	4.5
26/2	1709-1716 *	
"	1722-1744	5
27/2	0429-0433	
1/3	0926-1004	
2/3	2032-2050	5
4/3	1857-1900	
"	2000-2234	
8/3	1123-1130	
9/3	0621-0641	
"	0849-0912	8
11/3	0049-0055	
"	0540-0607	3
12/3	0147-0149	3
"	0347-0407	
18/3	1855-1902	
"	2105-2131	5
21/3	0637-0736	

* Short regular waves, T_g = 1.0 sec.

Recording of earthquakes and tremors in the Vestman Islands Jan. 23, - April 11, 1964

by

Gudmundur Pálmason
State Electricity Authority
Department of Natural Heat

In the first Surtsey Research Progress Report from February 1965 it was mentioned that a provisional seismograph was operated in the Vestman Islands from Jan. 23, to April 11, 1964. The seismograms have now been read and the results are given in this report together with a few remarks on the relation between seismic events and the course of the eruption during this period.

Instrumentation.

The seismograph consisted of three seismometers and a Visicorder recorder, whose galvanometers were connected without amplification to the seismometers. The seismometers were a Willmore vertical component, nat. freq. about 1 c/sec, an ABEM vertical component, nat. freq. 6 c/sec, and a three component Hall-Sears seismometer, nat. freq. 4.5 c/sec. One channel of the recorder was connected to a chronometer, whose time signals were corrected by comparison with WWV radio signals. The galvanometers had a natural frequency of 40 c/sec and a sensitivity of 0.18 mm/microvolt.

The damping of the seismometers was not critically adjusted as the main objective was to collect information on the frequency of seismic events in relation to the course of the eruption. The Willmore seismometer was only slightly damped, but the others were fairly well damped.

The equipment was installed in a house in the Vestman Islands town at a distance of 22.3 km from the main crater of Surtsey.

Seismic Events and their Relation to the course of the Eruption.

The seismic events on the records are mainly of two types, sudden shocks, and a more or less continuous tremor. The frequency of shocks during the recording period was by far the largest on February 1, when over 20 shocks were recorded. On that day eruption started with a fountain activity in the crater, which was later to become the main crater.

The tremor occurred every now and then during most of the recording period. The main indication of its relation to the eruption is from the first days of April. No tremors were recorded from the beginning of April until at 21:15 on the evening of the 3rd. Then tremor started and continued for about six days. The lava flow from the main crater was observed for the first time on the 4th of April. It is therefore probable that the tremor in this case is associated with the beginning of the flow of the lava from the main crater.

The seismic events as read from the seismograms are given in the following table. E denotes a sudden shock and T a more or less continuous tremor. Amplitudes are read from the trace of the Willmore seismometer. Events with trace amplitudes less than about 2 mm are not included. Due to insufficient damping of the seismometer, these amplitudes do not represent actual earth motion.

Acknowledgements.

The Icelandic Meteorological Office supplied a Willmore seismometer and the Physical Laboratory of the University of Iceland supplied a chronometer for these measurements. The rest of the equipment was from the State Electricity Authority. Mr. Sveinbjörn Björnsson assisted in setting up the equipment in the Vestman Islands.

TABLE

Date 1964	Hour GMT	Max. trace amplit. mm	Remarks
23/1	11 06 21	32	E
"	11 06 33	ca 50	"
"	11 06 45	10	"
"	11 06 53	9	"
"	11 07 01	10	"
"	11 07 - 11 09	6	T
"	14 00 00	6	E
"	14 20 27	3	"
"	14 20 31	6	"
"	14 20 42	46	"
"	16 35 - 16 58	3	T
"	23 45 51	3.5	E
24/1	00 36 - 00 41	3.5	T
"	00 43 15	4.5	E
"	01 53 - 01 55	3	T
"		ca 2	Minor tremor most of the day
"		" 2	
25/1	04 30 - 05 00	5	T
"	08 30 - 08 40	3	T
"	11 08 - 11 48	6	Strong tremor
26/1	06 37 - 06 40	3.5	T
"	15 15 - 15 20	2.5	T
27/1	01 55 - 02 05	3.0	T
"	08 20 - 08 50	4	T
28/1	02 47 - 03 33	4.5	T
"	06 57 - 07 25	6.5	T
"	13 28 - 14 04	7	T

Date 1964	Hour GMT		Max. trace amplitude mm	Remarks
29/1	00 04	- 00 42	5	T
"	11 40	- 11 55	3	"
"	12 35	- 13 20	3	"
"	14 25	- 15 22	2.5	"
"	20 00	- 20 35	2.5	"
"	21 00	- 01 00 30/1		T most of the time
30/1	01 00	- 21 00		T most of the time
"	14 00	- 15 00	2-3	T
"	18 15	- 20 30	2-3	T
"	20 27 33		3	E
"	21 43	- 21 55	2.5	T
"	22 37	- 22 41	2.5	T
"	22 48	- 22 55	2.5	T
31/1	01 15	- 01 22	3.5	T
"	02	- 03	2.5	T most of the time
"			2.5	E
"	13 42 16		14	"
"	17 51 35		3	"
"	17 51 44		14	"
"	21 46 40		10	"
1/2	00 03 17		10	"
"	00 03 26		62	"
"	01 21 43		ca 10	"
"	02 02 40		20-30	"
"	02 02 49		ca 50	"
"	02 56 45		14	E
"	02 56 51		97	"
"	02 58 23		9	"
"	03 42 38		11	"

Date 1964	Hour GMT		Max. trace amplitude mm	Remarks
1/2	03 43 29		5	E
"	03 43 38		35	"
"	06 42 55		12	"
"	06 43 03		64	"
"	07 14 08		5	"
"	07 28 24		33	"
"	07 28 33		95	"
"	07 39 07		9	"
"	08 57 03		ca 50	"
"	08 57 12		100	"
"	11 36 31		6.5	"
"	11 40 01		9	"
"	11 40 11		50-60	"
"	14 51 29		12	"
"	14 51 38		89	"
"	15 54 21		11	"
"	15 55 00		11	"
"	15 55 10		35	"
"	15 54 09		4.5	"
"	16 17 38		5	"
"	16 57 39		5	"
"	16 57 43		28	"
"	16 57 48		69	"
"	17 38 52		6	"
2/2	00 30	- 01 00	3	T
"	01 00	- 06 00	3	"
"	21 00	- 24 00	2	"
3/2	13 05		2.5	T
"	14 00		2.5	"
"	00 00	- 24 00	2.5	Continuous tremor most of the day

Date 1964	Hour GMT		Max. trace amplitude mm	Remarks
4/2	21 45	- 22 45	2.5	T
5/2	05 48	- 06 25	2.5	T
"	09 25	- 09 26	2.5	T
"	16 04	- 16 05	4	T
6/2	00 00	- 21 00	2	Almost no tremor most of the day
7/2	13 24	- 14 10	3-6	Seven minor shocks
8/2	00 00	- 21 00	2	Minor tremor
"	09 15	- 09 20	2.5	T
"	12 50		3.5	E, small
"	14 33	- 14 34	2.5	T
"	17 11		3.0	E, small
9/2	01 00		4.0	E, small
"	02 07	- 02 13	2.5	T
"	05 05	- 05 24	2.5	"
"	07 50	- 07 51	2.5	"
"	12 33		2.5	E, small
"	12 22	- 14 21	3.5	Five minor shocks
"	16 03		4.0	E, small
"	17 41	- 18 06	2.5	T
10/2	01 55		3.0	E, small
"	16 34		3.0	" "
"	21 05	- 21 47	2-4.5	Four minor shocks
"	23 54	- 23 55	3.0	T
11/2	09 38		4.0	E, small
"	10 59	- 11 03	4.0	Two minor shocks
"	15 09	- 15 20	3.0	T
"	17 19	- 17 30	2.5	T
12/2	00 30	- 00 43	4.5	T
"	02 48	- 02 49	2.5	"

Date 1964	Hour GMT		Max. trace amplitude mm	Remarks
12/2	04 15	- 04 47	2.5	T
"	05 05	- 05 10	3.0	"
"	06 27	- 06 37	2.5	"
"	07 42	- 07 47	3.5	"
"	10 12	- 10 14	3.0	"
"	12 36	- 12 45	3.5	"
"	13 10	- 13 15	3.5	"
"	14 16	- 14 35	2.5	"
"	15 22	- 15 30	3.0	"
"	19 21	- 19 22	2.5	"
"	20 35	- 20 40	2.5	"
"	21 47	- 22 09	4.0	"
13/2	03 07	- 03 08	4.0	T
"	05 08	- 05 22	2.5	"
"	07 10	- 07 16	3.5	"
"	09 30	- 09 40	3.5	"
"	12 30	- 13 05	3.0	"
"	13 57	- 14 05	2.5	"
"	15 27	- 15 33	5.0	"
"	15 56	- 16 10	2.5	"
"	17 30	- 17 33	2.5	"
"	19 06	- 19 12	3.0	"
"	20 01		2.5	E, small
"	20 30	- 20 45	2.5	T
"	00 00	- 20 45	2.0	Continuous tremor most of the day
"	21 26	- 21 27	3.0	T
"	23 14	- 23 20	5.5	"
"	23 52	- 00 02 (14/2)	3.0	"
14/2	00 33	- 01 10	2.5	"
"	02 49	- 02 58	4.5	"
"	04 57	- 05 00	2.5	"

Date 1964	Hour GMT		Max. trace amplitude mm	Remarks
14/2	07 36	- 07 50	3.0	T
"	08 23	- 08 45	2.5	"
"	10 06	- 10 15	2.5	"
"	10 43	- 10 48	3.5	"
"	15 44	- 16 14	2.5	"
"	17 43	- 17 47	3.0	"
"	17 59	- 18 02	3.0	"
"	18 52	- 20 25	3.0-4.5	"
"	22 38	- 22 50	4.5	"
15/2	00 11	- 00 22	4.0	T
"	01 50	- 01 53	3.5	"
"	03 08	- 03 21	5.0	"
"	04 36	- 04 40	3.5	"
"	06 23	- 06 31	3.0	"
"	08 32	- 08 45	8.5	"
"	10 57	- 11 14	3.5	"
"	13 10	- 13 29	3.0	"
"	15 02	- 15 13	3.0	"
"	17 13	- 17 26	4.5	"
"	19 15	- 19 30	2.5	"
"	21 00	- 21 08	3.0	"
"	22 00	- 23 00	2.5	"
"	23 50	- 00 15 (16/2)	2.5	"
16/2	03 14	- 03 23	5.0	"
"	05 30	- 05 37	4.0	"
"	07 14	- 08 07	3.0	"
"	09 52	- 09 59	3.0	"
" ca	11 01		5.5	E
"	12 13	- 12 34	4.5	T
"	14 33	- 14 41	3.0	"
"	17 26	- 17 38	3.0	"
"	00 00	- 24 00	2.5	Tremor groups most of the day

Date 1964	Hour GMT		Max. trace amplitude mm	Remarks
16/2	20 07	- 20 08	4.5	T
"	21 55	- 21 57	3.0	"
"	22 27	- 22 41	5.0	"
17/2	05 30	- 05 44	5.0	T
"	09 15	- 10 52	3-3.5	"
"	13 39	- 13 57	3.0	"
"	19 11	- 19 12	4.5	"
18/2	00 00	- 24 00	2.5	Many tremor groups
"	01 06	- 01 08	3.0	T
"	01 57	- 01 58	3.0	"
"	03 55	- 04 05	4.0	"
"	06 27	- 06 39	5.5	"
"	09 00	- 09 11	4.5	"
"	12 28	- 12 39	3.5	"
"	15 13	- 15 14	3.0	"
"	20 58	- 21 10	3.0	"
"	21 37	- 21 45	3.0	"
"	23 52	- 23 59	3.5	"
19/2	02 16	- 02 21	3.0	T
"	00 00	- 24 00		Almost no tremor
20/2	00 00	- 24 00		- " -
21/2	09 46	- 10 00	2.5	T
"	15 24	- 15 44	3.0	"
"	16 00	- 18 00	2.5	"
"	21 03	- 21 19	7.5	"
"	23 38	- 23 46	3.5	"
22/2	03 10	- 03 19	6.5	T
"	04 05	- 04 07	3.0	"
"	06 35	- 06 50	4.0	"
"	08 00	- 08 05	4.5	"
"	09 30	- 10 30	5.0	"

Date 1964	Hour GMT		Max. trace amplitude mm	Remarks
22/2	12 01	- 12 13	4.0	T
"	12 32	- 12 34	3.5	"
"	14 00	- 15 00	4.0	"
"	17 32	- 18 22	3.5	"
"	00 00	- 20 00	2.5	Continuous tremor most of the day
"	20 14	- 20 28	5.0	T
"	22 09	- 22 33	3.0	"
"	23 16	- 23 18	3.5	"
"	23 48		5.0	E, small
23/2	02 18	- 02 23	7.5	T
"	05 13	- 05 40	3.0	"
"	01 00	- 07 45	2.5	Almost continuous tremor
"	18 45	- 19 18	2.5	T
24/2	00 42	- 01 12	3.0	"
"	03 04	- 03 09	3.5	"
"	03 40	- 03 51	3.5	"
"	05 00	- 06 15	3.5	"
"	07 30	- 08 15	2.5-3.0	"
"	11 02	- 11 18	3.0	"
"	13 00	- 14 15	3.5	"
"	15 58	- 16 36	4.5	"
"	18 34	- 19 25	7.5	"
"	20 34	- 20 50	3.5	"
"	23 05	- 23 33	4.0	"
25/2	00 45	- 01 30	5.0	T
"	02 45	- 03 27	3.0	"
"	05 50	- 05 56	5.5	"
"	08 50	- 08 56	5.5	"
"	13 08	- 13 12	3.0	"
"	17 14	- 17 41	7.0	"

Date 1964	Hour GMT		Max. trace amplitude mm	Remarks
25/2	18 58	- 19 20	3.0	T
"	20 25	- 20 51	4.0	"
"	22 11	- 22 16	3.0	"
"	23 45	- 00 00	2.5	"
26/2	02 50	- 03 15	2.5	"
"	04 27	- 04 33	4.0	"
"	06 30	- 07 33	2.5-5.0	Almost continuous tremor
"	14 30	- 14 41	3.0	T
"	16 40	- 17 56	3.5	"
"	19 06	- 19 09	3.5	"
"	21 19	- 21 30	4.5	"
27/2	02 47	- 03 10	4.5	"
"	05 00	- 05 40	4.0	"
"	07 12	- 07 15	2.5	"
"	08 00	- 08 09	5.0	"
"	09 03	- 10 30	4.0	"
"	13 13	- 13 25	3.0	"
"	16 32	- 16 55	3.0	"
"	19 27	- 19 30	5.0	"
"	20 18	- 20 20	10.0	T (E ?)
"	21 08	- 21 09	9.0	- " -
28/2	02 45	- 03 17	11.0	T (E ?)
"	03 45	- 09 00	4-6.0	Almost continuous tremor
"	09 06	- 10 20	7.5	- " -
"	11 00	- 15 35	6.5	- " -
"	19 53	- 19 55	2.5	Disturbance
"	20 21	- 20 30	5.0	T
29/2	03 26	- 03 29	4.0	T
"	11 36	- 12 15	7.5	"
"	18 02	- 18 10	5.0	"
"	20 44	- 20 45	3.0	"

Date 1964	Hour GMT		Max. trace amplitude mm	Remarks
1/3	04 08	- 04 11	3.0	T
"	09 14	- 09 49	5.0	"
"	17 33	- 17 34	4.0	"
"	18 05		4.5	E, small
"	22 15	- 22 21	2.5	T
2/2	05 24	- 05 26	5.0	T
"	06 05	- 06 07	5.0	"
"	07 06	- 07 54	3.5	"
"	16 44	- 16 47	4.0	"
"	22 30	- 22 49	5.0	"
3/3	09 24	- 09 45	2.5	"
"	10 32	- 10 36	3.0	"
"	13 49		3.0	"
"	23 07		3.0	"
4/3	00 39	- 00 50	3.0	T
"	01 27	- 01 38	4.5	"
"	04 33	- 04 40	5.0	"
"	11 49	- 12 20	3.0	"
"	16 09	- 16 51	2.5	"
"	17 49	- 18 11	3.0	"
"	19 00	- 19 30	2.5	"
"	20 15	- 21 00	5.5	"
"	22 20	- 22 40	3.5	"
5/3	11 53	- 12 30	3.0	T
"	13 18	- 13 26	5.0	"
"	16 24	- 16 30	3.0	"
"	21 57	- 22 02	3.0	"
6/3	07 31		3.0	"
"	10 00	- 13 40	5.0	"
7/3	02 28		3.0	"
"	12 15	- 13 00	4.0	"

Date 1964	Hour GMT		Max. trace amplitude mm	Remarks
8/3	05 35	- 05 50	3.0	T
"	07 39	- 08 03	3.5	"
"	11 05	- 11 31	4.5	"
"	13 11	- 13 20	3.0	"
"	14 45	- 15 47	3.5	"
"	17 05	- 17 38	4,5	"
"	18 54	- 19 02	3.0	"
9/3	06 15	- 06 45	4.0	T
"	08 48	- 09 10	6.0	"
"	10 54	- 11 15	3.5	"
"	16 55	- 17 45	4.0	"
10/3	01 15	- 01 58	5.0	T (E, small)
"	09 10	- 09 45	3.5	"
"	15 15	- 15 35	4.0	"
"	16 30	- 17 15	5.5	"
"	17 59	- 18 30	3.5	"
"	21 10	- 21 20	3.5	"
11/3	02 46	- 02 57	5.0	T
"	05 35	- 06 08	5.0	"
"	15 25	- 16 30	4.5	T (E, small)
12/3	00 05	- 00 45	3.0	T (E, small)
"	02 05	- 02 19	3.0	T
"	14 31	- 14 51	6.0	"
"	15 34	- 16 03	6.0	"
13/3	03 18	- 04 43	4.5	T
"	08 39	- 09 10	3.0	"
"	13 25	- 13 30	3.5	"
14/3	06 52	- 07 10	3.0	T
"	09 54	- 10 01	3.5	"

Date 1964	Hour GMT		Max. trace amplitude mm	Remarks
15/3	05 42	- 06 15	7.5	T
"	15 38	- 15 50	5.5	"
16/3	00 15	- 00 50	3.5	T
"	00 00	- 24 00	2.5	Almost no tremor
17/3	01 30	- 11 30	2.5-8.0	Many small tremor groups or shocks
18 /3	03 30	- 04 23	3.5	T
"	06 30	- 19 00	2.0-3.0	Many small tremor groups
"	21 03	- 21 30	6.0	T
19/3	01 59	- 02 02	3.0	T
"	10 12	- 10 19	3.5	"
"	18 20	- 18 28	3.0	"
"	01 00	- 20 00	2-3.0	Many small tremor groups
20/3	10 58	- 11 10	4.0	T
"	20 25	- 22 00	3.5	"
21/3	06 30	- 08 00	2.5	T
22/3	00 00	- 24 00	2.5	Minor tremor groups
23/3	00 00	- 24 00		Minor tremor groups
24/3	21 00	- 01 00 (25/3)	3.0	Minor tremors
25/3	00 00	- 24 00		Quiet
26/3	08 15	- 08 35	5.0	T
"	17 00	- 19 00	2.5	Minor tremors
27/3	00 00	- 24 00		Quiet
28/3	00 00	- 24 00		Quiet

Date 1964	Hour GMT		Max. trace amplitude mm	Remarks
29/3	23 11	- 23 17	3.0	T
30/3	01 05	- 01 42	3.0	Minor shocks, otherwise quiet
31/3	ca 18 00	- 22 00	2.0-2.5	T
1/4	00 00	- 24 00		Quiet
2/4	00 00	- 24 00		"
3/4	00 00	- 20 15		"
"	20 15	- 24 00	2-2.5	Continuous tremor
4/4	00 00	- 24 00	2.5	" "
5/4	00 00	- 24 00	2.5	" "
6/4	00 00	- 24 00	2.5	" "
7/4	00 00	- 24 00	2.0	" "
8/4	00 00	- 24 00	2.0	
9/4	00 00	- 24 00	2.0	Minor tremor
10/4	00 00	- 24 00		Almost quiet
11/4	06 30	- 09 00	2.5	Minor tremor
"	14 50	- 17 00	2.5	" "

Electric Disturbances and Charge Generation at the Volcano Surtsey

by

Sveinbjörn Björnsson
State Electricity Authority
Department of Natural Heat

Observations during the first tephra phase of the Surtsey eruption.

Spectacular lightning activity accompanied the first tephra phase of the Surtsey eruption. Investigations of the electric disturbances were reported in the Surtsey Research Progress Report I, (1965). An account of this work has now been published by Anderson et.al. (1965). The main result of these observations was that a net positive charge was carried upward from the volcano by the volcanic cloud. The net concentration of charge in the eruption plume near the crater was estimated to be of the order of 10^5 or 10^6 elementary charges per cubic centimeter.

Over the crater the cloud had no detectable dipole structure but about 2 km downwind from the crater the electrified cloud was found to be bipolar. There was a stream of net positive charge above one of net negative charge.

The maximum negative potential gradients observed under the plume were associated with a light fall of tephra. The observations were not sufficient to determine, whether this association was merely the result of our being directly under the cloud dipole from which the tephra was falling or whether the falling tephra was negatively charged.

Observations during the lava phase of the Surtsey eruption.

As the active vent was closed off from the sea, the explosive eruptions and lightning ceased. Lava streams flowed down to and into the sea and produced dense white clouds which were found to contain strong positive charge. The charge density in these clouds varied from + 10^6 to about + 10^8 elementary charges per cubic centimeter.

Similar charge densities were obtained by Blanchard (1964) at the WHOI, USA in his laboratory experiments. In recent investigations he has found that roughly + 10^{-8} C are released to the air per cubic centimeter of sea water splashed on the hot lava. The charge carriers are presumed to be tiny sea-salt particles or brine droplets that are produced in prodigious numbers whenever sea water comes into contact with hot lava. The mechanism of charge generation probably is a surface effect. If the charge carriers leave the hot lava as dry sea salt particles, it is possible that the charge generation results from a solid-solid contact mechanism.

A detailed account of the field observations and the laboratory investigations is given by Björnsson, Blanchard and Spencer (1966).

Observations during the later tephra eruptions at Surtsey.

Potential gradient.

The electrical field around the eruption plume of the volcanic island "Syrtlingur" was found to be similar to that of Surtsey. The volcanic cloud carried a net positive charge. Under the plume there was a diminished positive potential gradient but no reversal of the field, as was the case under the eruption plume of Surtsey. Lightning were often seen in the eruption column but the electric activity was much less than in the first tephra phase of the eruption of Surtsey.

On July 24, 1965, Mr. Valgardur Stefánsson, State Electricity Authority, sailed on a rubber boat under the eruption cloud of "Syrtlingur" equipped with an electrometer and a radioactive probe for potential gradient measurements. About 800 m distant from the crater he found a positive field under the plume but each time a shower of wet tephra approached the boat from above the field decreased and remained low until the fall of tephra ceased. On one occasion the fall of dry tephra at about 1600 m distance from the crater was associated with an increase in the positive potential gradient.

The charge on the tephra.

First attempts to measure the charge on the tephra falling from the eruption cloud were undertaken by the author on 8 March 1966 at the crater "Litli Surtur" in the sea about 800 m south-west of the island Surtsey. The active vent was continuously ejecting steam and tephra up to about 300 m height and had built a small island reaching only several meters above the ocean surface. Strong wind from north blew the volcanic cloud out to the sea.

The electric observations were made on a ship, which sailed several times under the eruption cloud about 150 to 200 m down-wind from the crater. The ship was equipped with an electrometer and a radioactive probe for potential gradient measurements, a shielded catcher (similar to that by Scrase (1938)) for measuring the charge carried by falling tephra and a Faraday-cage for space charge measurements.

The potential gradient upwind and on both sides of the plume at a distance of about 200 m from the crater was positive and greater than 1000 v/m or more than eight times the normal fair weather gradient. Accurate measurements of the gradient were not possible because of inadequate probe exposure. This time no readings of the gradient were taken under the plume.

The ship sailed under the plume only 150-200 m downwind from the crater. Tephra was being erupted up to an height of about 300 m and fell on the ship about one minute after its ejection from the crater. The tephra falling into the shielded catcher carried a strong negative charge.

Approximately $- 3 \cdot 10^{-9}$ C were carried by a sample of 15,5 g of dry tephra. The sample consisted mainly of porous grains. About 45 weight % of the grains were greater than 1 mm in diameter. Maximum diameter was 5 mm. The Faraday cage had a sensitivity equivalent to a space charge of 10^4 elementary charges per cubic centimeter, but no charge was indicated during the voyage. During tephra fall most of the tephra did not enter the cage but was held by the grounded 1 mm mesh walls of the cage.

Discussion.

It is highly probable that the positive charge arising from the zone, where lava flowed into the sea, is generated by the same mechanism as that found by Blanchard (1964), when sea water is splashed on hot lava.

In the tephra eruptions the situation is more complicated. Positive charge was found to dominate in the volcanic cloud over the crater and in the upper part of the downwind plume. This charge was either ejected from the crater or rapidly generated in the eruption column just above the crater during vigorous eruptions of tephra and steam (Anderson et al. (1965)).

Negative charge was found on the tephra falling in the vicinity of the crater. One might suggest that the tephra particles have selectively acquired negative charge by collision with negative ions flowing into the atmosphere by point discharge from the sea or the ship. But the facts that the Faraday cage did not detect any space charge on the voyage and that the tephra was sampled within a minute after its ejection from the crater make this suggestion rather improbable.

A more likely suggestion would be that negative charge is generated by the same process as the positive charge by a charge separation mechanism working in the crater or the eruption column close to the crater.

As it appears probable that the contact of sea water with magma was the cause of the explosive eruptions at Surtsey, we might suggest that this has also been the cause of the charge generation. We know from Blanchard's laboratory investigations and the field observations during the lava phase of the Surtsey eruption that positive charge is generated when sea water is splashed on molten lava.

Similar charge separation will occur, if drops of sea water or condensing vapor contact the glowing tephra particles in the eruption column. The drops will be splashed into tiny droplets or salt particles, which are positively charged, but the tephra particles will be left negative in the air. Most of the tephra falls from the cloud in the vicinity of the crater and brings the negative charge to the earth but the positive droplets or salt particles are carried upwards into the volcanic cloud.

The same applies if the crater is flooded by sea water which contacts molten lava. Positive charge will be ejected on droplets or salt particles. The lava may stay in contact with the ground or be ejected as negatively charged tephra particles, which for the most part fall back on the walls of the crater.

After these considerations we may conclude that all electric phenomena observed at Surtsey can be explained as the result of the charge separation, which occurs when sea water is splashed on molten lava. This conclusion does however not exclude that other mechanisms of charge generation may also have played a role.

Subglacial eruptions.

Blanchard has recently tested the charge generation with water from two rivers which drain the glaciers that cover the

Icelandic volcanoes Katla and Grímsvötn. A positive charge was released to the air, when this water was splashed on hot lava. If this water is similar to that which takes part in the sub-glacial, phreatic eruptions at Katla and Grímsvötn then it is possible that glacial melt water plays a major role in the generation of the intense electrical activity that has been observed in these eruptions. Further, a net positive charge should be carried by the eruption clouds.

Literature

Anderson et al. (1965): Electricity in Volcanic Clouds. Science, 148, pp. 1179-1189.

Björnsson, S., D.C. Blanchard and A.T. Spencer (1966): Charge Generation in Oceanic Volcanoes. (In press)

Björnsson, S.: Some Geophysical Observations at Surtsey in 1964. In Surtsey Research Progress Report I, Feb. 1965.

Blanchard, D.C. (1964): Charge Separation from Saline Drops on Hot Surfaces. Nature, 201, pp. 1164-1166.

Scrase, F.J. (1938): Electricity on Rain. Geophys. Mem., Lond. 75, pp. 1-20.

Studies of Temperature, Viscosity, Density and Some Types of Materials Produced in the Surtsey Eruption

by

Professor Trausti Einarsson
The University of Iceland

I. Temperature.

Temperature was studied with the same optical pyrometer, which I used in the Hekla eruption of 1947-48 (1, p. 22). Two runs of laboratory comparisons with a thermocouple were done during the earlier studies and a third was added now in collaboration with Professor Thorbjörn Sigurgeirsson. The results are shown in Fig. 1. The accuracy of a single pyrometer measurement appears to be 20-25^{o}C. In the third run comparison was also made with Sigurgeirsson's thermocouple, which he used in Surtsey on 15th Oct. 1964.

On the second day of the eruption, Nov. 15th, 1963, I observed at close quarters from the Coast Guard vessel Albert. In daylight no glowing material could be perceived in the eruption columns. In darkness sporadic glowing stones were seen, the temperature not surpassing 650-700^{o}C. At this time the eruption was submarine, and the material thrown out had no doubt been cooled by the water. The low maximum temperature is, nevertheless, remarkable. When one considers that a bomb of 20 cm diameter, surrounded by cold water, should retain its central temperature unaffected for about 10 minutes, one might expect to find occasionally the original temperature of the magma when such and larger bombs split in the air. It seems possible, therefore, that the magma temperature was very low.

The character of the eruption remained the same for several months, i.e. the material was non-luminous, only sporadic bombs of a deep red glow were observed. In the beginning of April 1964 lava began to flow. On April 9th I observed the lava fountains in the crater from an airplane, in broad daylight. The conditions were not favourable for a temperature measurement, but my estimate was close to 900°C. On August 19th I studied the lava fountains at close quarters, obtaining the temperature 1000°C. On October 15th I got 1070-1100°C. On the same day I found 1070°C in a lava tongue at the lava front 900 m from the crater along the flow path. By thrusting a thermocouple deep into this tongue, Sigurgeirsson obtained 1110-1130°C. The difference may be due to some surface cooling. In later studies Sigurgeirsson found temperatures around 1140°C with a thermocouple (this report).

It would appear from these data (Fig. 2) that the lava temperature increased very markedly from beginning to the end of the eruption. Unfortunately, comparisons with thermocouple studies are not possible for the period where the main rise took place. But the pyrometer observations are supported indirectly by a study of the erupted material, cf. III.

II. Viscosity.

For the estimate of viscosity in the flowing lava three methods were used: 1) Lava-penetrometer, i.e. an iron stick thrust into the lava (cf. 1, p. 15); 2) Velocity of flow; 3) Waves in the crater lake. The first method was difficult to use because of the great fluidity of the lava. After several attempts I finally (Oct. 15th 1964) obtained as a fair measure of the viscosity in a lava tongue at the front that the stick sinks 10 cm in 0.5 seconds under its own weight. With the assistance of Mr. Bragi Árnason of the University Physical Laboratory this was found to correspond to a viscosity of $5 \cdot 10^3$ poises.

For the same lava tongue the formula for the velocity $v = g\,h^2 \varrho\, \sin\alpha / 2\eta$, gives $\eta = 2 \times 10^4$ poises, with the values $v = 40$ cm/17 sec; $\alpha = 5^o$; and estimated depth $h = 25$ cm. The breadth was 35 cm. The viscosity found in this way is probably a little too great, as forming of crust will impede the flow of such a small tongue.

During my visit of August 19th 1964 I observed waves in the lava pond. The pond was 10-12 m in diameter and surrounded by perpendicular walls. At a certain spot arose 10-15 m high fountains in a rapid succession, this being the main exit of gas, or the top of the funnel. Each time a big fountain arose, a broad wave started from the spot and moved towards the walls. Here the lava surface then rose for a short time by 2-3 m, after which the surface became plain again. There was no reflection of the wave, the energy being lost through the great viscosity. Beside the main exit of gas, big bubbles exploded here and therein the entire pond like vapour bubbles in a porridge; they produced 1/2 - 1 m high gushes, but no waves were formed. These observations suggested a method for obtaining the viscosity in the lava pond.

H. Lamb (2, pp. 625-28) has considered the influence of viscosity on surface waves. With $r = {}^{n}/_{\varrho}$ = kinematic viscosity, c = velocity of the waves, λ = wave length, he defines a number $\theta = \frac{2\pi r}{c\lambda}$. Then the type of motion can be judged by the roots of the equation $(x^2 + 1)^2 = 16\,\theta^3(x - \theta)$. Two complex roots cancel out as they violate certain conditions. The remaining roots are admissible and may be real or complex according to the magnitude of θ. For a low value of the viscosity and not too small wavelengths θ is small. The roots are complex and give ordinary waves of slowly decreasing amplitude with time and distance of travel. In the case of a very viscous fluid, such as treacle or pitch, θ may be large even when the wave-length is considerable. The admissible roots are then both real. One root represents a slow creeping of the fluid towards a state of equilibrium and the other root represents a wave dying out rapidly. Obviously the margin between periodic and aperiodic motion is found where the two real roots merge together. This I found to occur for $\theta = 1.31$. Hence wave motion is found for $\frac{2\pi r}{c\lambda} = 1.31$; with $c = (g\lambda/2\pi)^{1/2}$ we get $r \leq 2.61\lambda^{3/2}$ (cf. Fig. 3) or $\eta = 2.61\rho\lambda^{3/2}$. The meaning of the formula is: in a fluid of given viscosity, long progressive waves are possible, but below a certain wave-length, given by the above condition, no such waves are possible. Observing the shortest occurring waves then gives the viscosity.

During my first observation it was clear that the occurring waves were of the order of a very few metres. A second time, October 15th, 1964, I was better prepared for what to observe and conditions were very favourable, cf. Fig. 4. The lava rushed up in fountains at A, then flowed with great speed and in great quantity down a low fall F into a broad stream S and then disappeared into the tunnel G. Waves, 1 m high and 1-2 m broad, continually rushed down the main stream S. At the side of the main stream was a quiet pond V, partly sheltered from the fall by the promontory B. But every now and then waves were formed at the promontory and moved into the pond. I observed the waves from C, in shelter of the narrow wall around the crater. The waves were close to 1 m broad and died out after a travel of 1-2 m from B. Smaller waves were not seen; large gas bubbles exploded here and there in the pond, and especially in the main stream, but they never caused wave motion. Taking the breadth of the observed wave to correspond to a half wave-length, we get with $\rho = 1.5$ (cf. III), $\eta = 1\text{x}10^4$ poises. As to the state of this lava cf. III. This is probably the best value for the viscosity. The low value obtained with the penetrometer is probably caused by the advanced porosity of the lava in the tongue - the lava was foamlike. But all methods agree as to the order of magnitude.

III. Study of some types of material produced in the eruption.

Description of samples from different times of the eruption:

1) Fallen on deck of the Coast Guard vessel Albert at 9 o'clock, 15th Nov. 1963 (second day of the eruption) when the ship sailed under the ash cloud. The material consists of small glass fragments less than 5 mm in diameter; in thin section this is translucent brown sideromelane with very small gas bubbles indicating the very beginning of gas release; practically unexpanded glass. All grains sink in water. Bulk density of watersoaked material 1.4. The glass is all of a single type in contrast to 2). There is a fair amount of loose crystals which is not the case in 2).

2) Fallen on deck of the Coast Guard vessel Albert Nov. 16th. The material consists mainly of expanded irregular small lumps, 1-2 cm in diameter. About 1/13th by weight floats in water. In each lump one recognizes generally two or three types of glass: a) a dark-grey skin, 1 mm thick; it is much cracked and distorted as a result of expansion of the interior of the lump. But the glass in the skin is devoid of bubbles. Clearly the skin was formed by quenching of each lump before expansion began.** b) under the skin is brown glass with fine pores. Sometimes it occupies all the interior, but mostly the central part consists of c) much expanded glass of bluish lustre, due to oxydation of the iron; there is no sharp limit between b) and c).

These small lumps of pumice are in principle similar to the much larger bread-crust bombs, which one could observe in the Hekla eruption of 1947-48 (1, p. 54). Summarizing the genesis of the Surtsey pumice of sample 2) we conclude: Before gas was released, i.e. under considerable pressure, the magma was split into small fragment, mostly below 1 cm across. The fragments were then quenched on the surface and it seems the most likely theory, considering later observations of the flow of lava into the sea, that splitting and quenching took place at the sea-bottom (depth 130 m, pressure 14 atm.). As the smooth surface of the original skin suggests a fracture surface, we should visualize the process of splitting as shattering due to rapid uneven cooling. Immediately after formation, the grains come under low pressure, i.e. they were formed in an explosion and immediately thrown into the air. Cooling of such small grains must be a matter of a very few minutes at most, but still there was time for expansion of the interior and for oxydation of the iron. The latter fact is of special interest.

In my study of the Hekla bombs quoted above, it was pointed out that the internal oxydation was related to the decrease of pressure, but because of the slow cooling of the very much larger pieces than we are dealing with here the process was not fully clear. Here we have a magma which must have approached the surface relatively slowly and it had been released of most of the original pressure (many thousand atmospheres) when it was shattered. Yet, it was in a very short time after shattering and after the final, but relatively small relief of pressure, that oxydation took place together with release of gas. It is therefore clear that it is the release of gas which is the direct cause of the oxydation. It is probably the loss of hydrogen and the consequent availability of oxygen in the melt that oxydized the iron.

Besides the primary fragments of pumice, which we have discussed, there is in the sample some amount of such unexpanded grains as we found in 1). These are always much worn. Most of the later material was worn, and we may remark at once that the origin of the wearing was obvious: the greater part of the material which was thrown up in an explosion dropped back into the crater. It was therefore thrown out many times and much worn in the turbulent sea in the crater before it finally settled as lapilli outside the crater.

3) Sample taken by Dr. Thorleifur Einarsson close to Surtsey on Nov. 21st, 1963. Very fine-porous translucent glass containing a considerable amount (10%) of crystals. The biggest grains are 3-4 mm, but the most common size is only 0.05 mm. Worn material.

4) Sample taken from a crater wall on Dec. 16th, 1963, by Professor Thorbjörn Sigurgeirsson. Bulk density of dry material 1.20; water-soaked 1.62 (container filled with dry material gives the first figure; addition of water until all is soaked and the water stands at the edge of the container, gives the second figure). Average density of individual grains is then 2.06. Washing cleans away 18% of the mass as fine silt. In the remainder are grains mostly in the interval 1-8 mm; grains of 3-8 mm generally worn.

On August 19th 1964 I took the three following samples from a crater wall on the east side of Surtsey. The sea had eroded the southern half of the crater so that a good section was available.

5) Base of wall. Density of dry material 1.36; water-soaked 1.72. Average density of grains 2.11. Washing cleans away 48% of finest material. In remainder, diameters of 1-3 mm most common, but a few grains of 5-10 mm occur. Grains all equidimensional and considerably worn.

6) Layer at 6-8 m depth on inner side of crater; one of the coarser layers in the section. Grains of 5-20 mm common. Density, dry 1.30; water-soaked 1.65. Average density of

grains 2.02. Washing cleans away 31% of the material; the remainder mostly in interval 1-10 mm; equidimensional worn grains. Higher layers mostly finer than 6); alternation of lapilli and layers with small bombs, irregular pieces of pumice and fragments of sandstone from the sea bottom. Sample 7) is taken from a lapilli layer.

7) Density, dry 1.24; water-soaked 1.68; average density of grains 2.20. Washing leaves 86% of material, in the interval 1-10 mm; equidimensional and worn. Crystallation of same degree as in 3). The samples 4), 5), 6) and 7) give very similar values for the density. The average of the dry material is 1.28 and the average for grain density is 2.10. This grain density corresponds to 23.5% bubble volume in the average grain, if the density of the dense glass is taken as 2.75.

In the Surtsey mound of glassy material as a whole, the material is considerably compressed and the bulk density must be higher than 1.28. But it must be lower than 2.10 and the average of these figures, 1.69, may be taken as a reasonably correct value. To convert the volume of the mound into volume of compact glass of density 2.75 we must then multiply by the factor 1.69/2.75.

As a crude measure of the mound I take here a cone with 30^o side inclination; height 130 m below and 30 m above sea-level; area of section at sea-level 2 km^2. The volume is then 0.395 km^3, corresponding to dense glass of 0.243 km^3. This is about 60% of Hekla's production in the eruption of 1947-48. It must be emphasized that the assumed geometry of the mound is an idealization.

8) On Oct. 15th 1964 I took some samples of spatters which had recently been thrown over the rim of the crater in fountain activity. The density of two pieces with a weight of

413 g is 1.42 and of two other pieces of weight 372 g is 1.43. In the 2-4 cm thick spatters the porosity is considerably greater in the middle than towards the surface and the expanded interior has the characteristic blue lustre due to higher oxydation of iron. In a thin slide across a 2-3 cm thick spatter the pores are 0.15-1.05 mm in the crust, i.e. in the original spatter, but increase to 3-4 mm in the centre. A probable figure for the density of the original spatter is 1.5 which corresponds to a pore volume of 45%, or about twice the value found for the material of the early explosive phase of the eruption. This suggests an easier expansion of the gas bubbles, due to higher temperature and lower viscosity than earlier in the eruption.

The spatter is, furthermore, crowded with crystals; a measurement by S. Steinthorsson gave 60% glass, 27% feldspar, and 13% olivine. The olivine crystals are usually much thicker than the glass walls between the bubbles and it is also clear for the feldspar that it must have existed in the melt in the crater. There are no such crystallites or needles that might suggest crystallization in the spatter itself. Thus we may safely conclude that the magma is already 40% crystallized when it appears in the crater. This is 3-4 times the amount of crystals found in the glass of the explosive phase, which may be an indication of difference in viscosity. From the point of view of viscosity we see that the fluid we are dealing with is very special: gas bubbles make out one half of the volume, while the other half is nearly evenly divided between a fluid melt and loose floating crystals.

The high degree of crystallization has also a clear relationship to the temperature. The heat of crystallization is about 90 cal/g and the specific heat is about 0.25. Complete crystallization, therefore, releases heat which would suffice for raising the temperature by 360°C. By the 40% crystallization of the rising magma the temperature might rise 143° if no heat was lost. S. Steinthorsson (this report) found that the olivine was about the same in the spatter as in the early material. The difference lies in the 27% of feldspar found in the spatter. This difference in crystallization corresponds to a difference in temperature of about 100°C. It is most likely that there was no time for loss of the heat released by crystallization and that of the 1140°C measured in the lava, about 100° were acquired through crystallization of feldspar during the rise of the magma. The temperature "proper" of the magma would then have been near 1040°C. We then arrive at this picture: In the beginning of the eruption the magma reaching the surface of the earths crust was probably rather cool due to loss of heat to the cold walls of the fracture. The temperature may have been considerably below 900°C, possibly even as low as 700°; the temperature actually found in exploding bombs. At this time the melt was too viscous for any crystallization to take place in the rising magma. Slowly the erupted magma became hotter as the loss of heat to the walls decreased but during the early, explosive phase the change was small.

The eruption changed over to effusion as a result of blocking of sea-water and the temperature appears to have been still as low as 900°C at that junction. But now gradually a certain chain reaction begins to work: increase of temperature lowers the viscosity, which increases crystallization; this in turn raises the temperature and so on.

There are interesting aspects of general interest in this process in a rising undercooled magma. Suppose the original magma temperature is 1200°. Small amount of crystallization raises the temperature to 1250° and this temperature will block further crystallization, so the process cannot go further. In another example the original temperature be 900°. Then it appears that the process can run to such a length that the magma crystallizes completely during rise, and the process stops the eruption. In a melt of intermediate temperature the process seems to be of importance.

IV. Flow of lava into the sea.

Several cases exist in Iceland where it is either known or can be safely inferred that a postglacial lava has flowed into water and no very marked effect of the water is discernable. One finds, it is true, one peculiarity: distortions and great cracks that suggest some havoc played by steam. In my first study of the lava in Surtsey I found just such peculiarities where sea erosion had opened access to the interior of a lava flow. On March 20th, 1965, I observed lava flowing into the sea and saw how it was completely split up into small fragments on contact with the water. A 1 m broad tongue flowed pretty rapidly down to the beach during retreat of the sea. The next wave overran the frontal part of the tongue and changed it completely into small fragments that ran down the beach with the backwash. In this way the lava was constantly cut off at the beach, being changed into glass fragments which the waves carried along the shore. Part of this material formed an 8-12° steep "sand" beach along cliffs of the island, and much of it was transported farther to gather as a broad flat on the western part of the island.

In front of the "sand" beach, onto which the lava was flowing, there was a 40-45° submarine slope, probably mainly "sand". It is then clear that at least in some cases the theory presented first by Fuller (3,4)* is verified: the lava entering water first builds a "delta" of foreset layers of fragmental material on which it then gradually proceeds as if on dry land. Foreset beds of breccia covered directly by a cap of lavas are quite common in the volcanic breccias of Iceland (5,6). Although the Surtsey material is not very typical for these breccias, some similarity of origin may be assumed.

V. Some general remarks on the release of magmatic gas and resulting changes in its composition.

The multi-component gas given off by a magma, and sampled for analysis, must generally be expected to have a composition rather different from that of the gas originally contained in the magma, due to the complications of the process of gas release. To analyze this process one must consider, on one hand, how the gas in general is given off, on the other hand, study the differential release due to different solubilities of the gas components. Of some of the relevant factors in this process we have a fair idea, others are quite unknown.

---

* "A fluid lava on encountering a local body of water would tend to granulate like molten slag and would thus form a fine breccia, which would accumulate to a depth approximately equal to that of the water. The fine breccia would settle until its surface attained an angle of repose which, owing to the roughness of the fragments, would be relatively steep. If the molten cascade continued to pour out into the water, the accumulation of granulated glass would gradually advance like the foreset bedding of a delta. The inclined bedding would be preserved by the thin sheets and the ropy or ellipsoidal masses, which failed to granulate. Except for the possible effects of rising steam, the flow would gradually advance on top of these foreset beds as if on dry land".

We consider first the release of gas in general. The observation mentioned in III, 3, concerning the unexpanded crust of pumice, indicates that when the magma met the sea-water, probably at a depth of 130 m, i.e. under a pressure of 14 atmospheres, gas release by bubble-formation had not begun. This pressure corresponds to the weight of a 50-65 m high column of magma that is more or less porous. We may then expect that later, when the lava had a free subaerial surface in the crater, gas release by bubble formation took place only in the uppermost 50 m or so of the lava column. The extreme fineness of the bubbles (less than 1 mm) in the spatter studied (III, 8) might even suggest that the bubbles began to form at a much shallower depth; otherwise the bubbles would have expanded due to decrease of pressure.

Such small bubbles are incapable of rising individually in a melt of viscosity 10^4 poises: they move passively with the rising magma (a bubble of 1 mm diameter needs about 2 hours to rise 1 cm through the melt; Stokes law). It is only or mainly where differential or shearing movement takes place in the magma that bubbles may coalesce and form larger bubbles that are capable of marked relative rise; such bubbles may be seen to burst at the surface of the lava (cf. discussion of gas release in Einarsson 1949, pp. 9-15). Fountain activity must be considered as due to the bursting of such bubbles. These large bubbles may be said to be of a second generation, while the study of volcanic materials seems clearly to show that the first and primary generation consists of a dense network of very small bubbles, changing the magma into a sponge. This after all is the normal process of gas release from an oversaturated fluid. If the gas release could be impeded until the magma was very much supersaturated, i.e. until the pressure had fallen, say to atmospheric pressure, the process of release would be rather explosive and the release would take place into the free atmosphere and not into the closed spaces of the small bubbles.

Analogy to geyser activity, where the water boils explosively after superheating, would then be very close. But such a process seems not to take place, considering the generally fine spongy state of the material thrown out in fountains; explosive release of gas throughout a mass would produce a different type of material.

The main release of gases from the rising magma then takes place into closed spaces of bubbles, first at the highest pressure, later at a gradually lower pressure, and it is this gas that becomes available for analysis.

If the solubilities of the gas components were all equal then the free phase in the bubbles and the dissolved phase would have the same composition. This is at any rate true if the gas volume is a small part of the melt. But for a large gas volume it is not true; very sparse components will then have a less percentage in the free phase than they had originally in the dissolved phase.

If on the other hand the solubilities are different for the various components, and this must be assumed to be the case, then the free phase will be significantly different from the original dissolved phase, whether the gas volume is small or large. We do not know the solubilities and an exact calculation of this difference cannot, therefore, be made. But for sake of demonstration of the effect we shall choose some arbitrary figures.

We shall first consider a stage where the volume of the bubbles is 5% of the magma and the pressure is assumed to be 10 atmospheres which seems realistic. The stage is assumed to last long enough for equilibrium between the two phases of gas to be reached. In the free phase the gas is assumed to have the following composition in mole percentages: H_2O 80%; SO_2 5%; CO_2 8.8%; H_2 6%; A 0.2%. Argon is arbitrarily included because of its interest in connection with the K/A dating method.

We next assume that the water content of the magma is 0.4% by weight, in equilibrium with the partial pressure 8 atm. of the vapour in the bubbles. 1 cm^3 of the melt then contains 54 cm^3 of vapour, reduced to 1 atm. and a temperature of 1150^{o}C, and the corresponding solubility for 1 atm. partial pressure is 6.75 cm^3.

For the other gases we have no data and we must select arbitrary figures. The solubility in water at 20^{o}C and 1 atm. is SO_2 39.4 cm^3/cm^3; CO_2 0.878 cm^3; H_2 0.0184; A 0.037 cm^3. We shall tentatively assume that for the magma, and reduced to 1 atm. and 1150^{o}C, the solubilities are in all cases 1/5 of the above values. As the partial pressures in the gas phase are given, we can find the gas dissolved in the melt: H_2O 54 cm^3/cm^3; SO_2 3.94 cm^3; CO_2 0.155; H_2 0.0022; A 0.00015.

To these amounts we now have to add the free phase. The quantity per cm^3 is multiplied by 10 to reduce to 1 atm. pressure, and by the factor 5/95 as the gases are 5% of the magma. We then get the additions: H_2O 0.42 cm^3 giving a total of 54.42 cm^3; SO_2 0.0263, total 3.97; CO_2 0.0463, total 0.201; H_2 0.0316, total 0.0338; A 0.0011, total 0.00125. The original percentages are thus in the same order: 92.7; 6.76; 0.34; 0.058; 0.0021.

The difference between this and the released gas is very marked. In the process very little of the water and SO_2 has been freed, but 23% of the CO_2, 93.5% of H_2 and 88% of A.

We now assume that the magma part considered rises close to the surface. The bubble volume will increase by a factor of 10, due to change of pressure, and become 34.5% of the magma volume. At the same time further gas will be released and we assume a stage with 50% gas volume under a pressure of 1 atm. and equilibrium between the dissolved and free phases. The free gas is considered to have the same composition as in the first case. The gas per cm^3 of melt is now in each case 1/10th of what it was in the first case, assuming validity of Henry's law. We then find the following percentages for the original gas in the melt: 91; 6.52; 1.52; 0.88; and 0.03. The following amount of the original gas was retained in the melt: H_2O 87%; SO_2 89%; CO_2 15%; H_2 0.37%; and **A** 0.75%.

The gases that finally leave the melt, and eventually are sampled for analysis, will be a mixture of gases released at various depths, and would then correspond to intermediate conditions between the two calculated cases.

As a general rule it is clear that small components of low solubility will very largely disappear from the melt.

If we consider a free lava surface then gases will diffuse out of it, no partial pressure will be built up as the gases are carried away in the atmosphere, and the gas content of the magma should decrease exponentially with time. But this process is certainly much slower than the expulsion by means of bubble formation and cannot contribute markedly to sampled gases. But insofar it does, the diffusivity of the various gas components must influence the percentages.

In summary, the gases begin to be released as densely set very small bubbles at a depth of 50 m or less in the rising magma. The surface of the bubbles being relatively large, equilibrium may be established between the free and dissolved phases. As the hydrostatic pressure decreases, the bubbles expand, partly without and partly due to further intake of gas. In small bubbles equilibrium between the gas phases may perhaps be established near the surface but for larger bubbles, that have been formed by coalescence at a greater depth, this will hardly be the case. Their gas will therefore be representative of equilibrium at a greater depth. In sampled gas the components of low solubility will be greatly enriched in relation to the other components.

References

1. Einarsson, Trausti: (1940) The Flowing Lava. Studies of its Main Physical and Chemical Properties. In the Eruption of Hekla 1947-48, IV, 3. Vísindafélag Íslendinga, Reykjavik.

2. Lamb, Horace: (1932) Hydrodynamics. 6th Ed. Cambridge.

3. Fuller, R.E.: (1931) Aqueous chilling of basaltic lava on the Columbia River Plateau. Amer. J. Sci., 5th ser., 21, no. 124, pp. 281-300.

4. Fuller, R.E.: (1934) Structural features in the Columbia River lavas of central Washington. Jour. Ceol. 42, no. 3, pp. 311-328.

5. Einarsson, Trausti: (1962) Upper Tertiary and Pleistocene Rocks in Iceland. Vísindafélag Íslendinga, 36, Reykjavik.

6. Einarsson, Trausti: (1965) Submarine volcanic breccia in the area south of Tjörnes. Vís. Ísl. Greinar IV, 1, pp. 29-47.

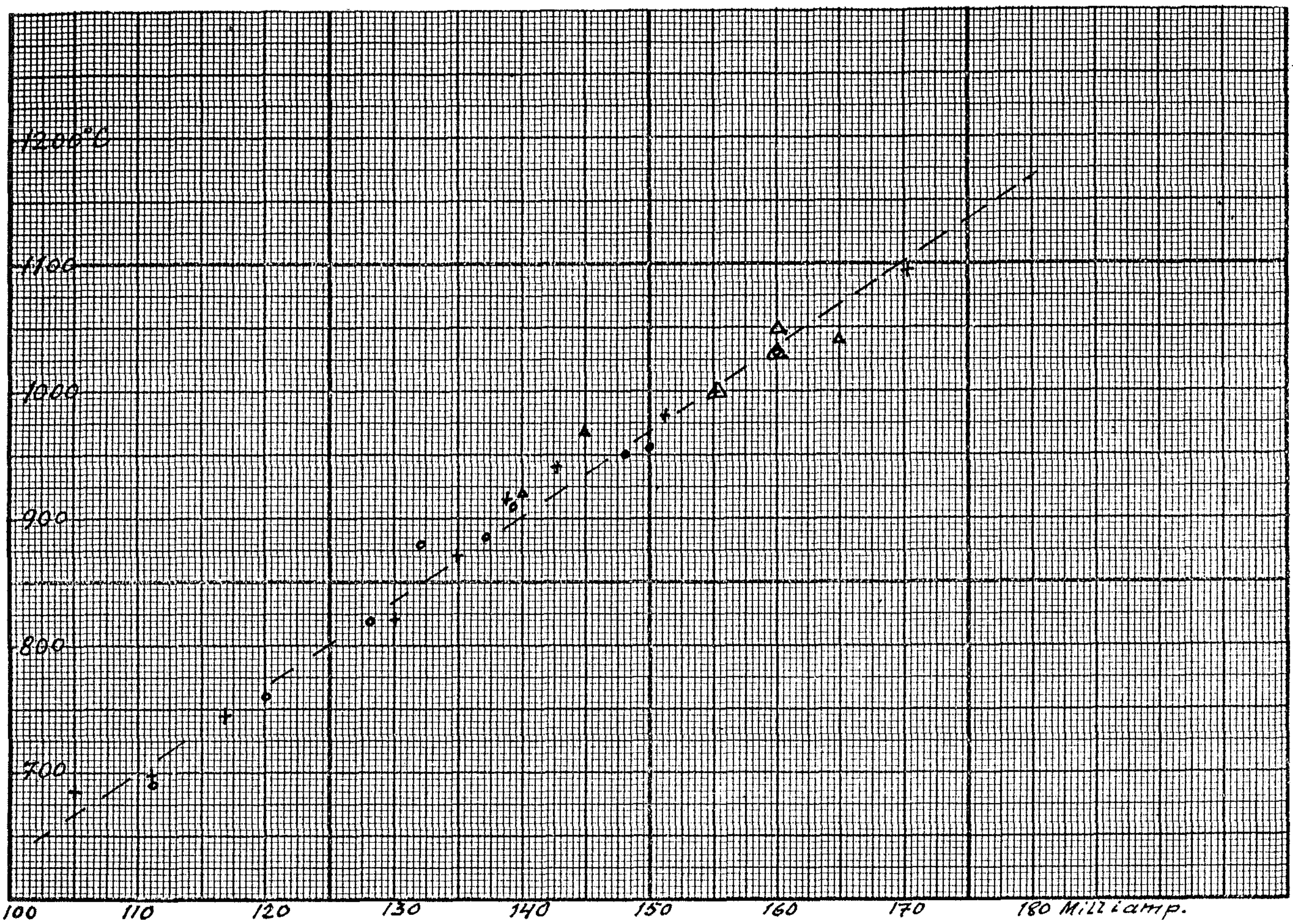


Fig. 1. Three separate comparisons (+, o, Δ) of pyrometer readings (Milliampere) with thermocouple temperature.

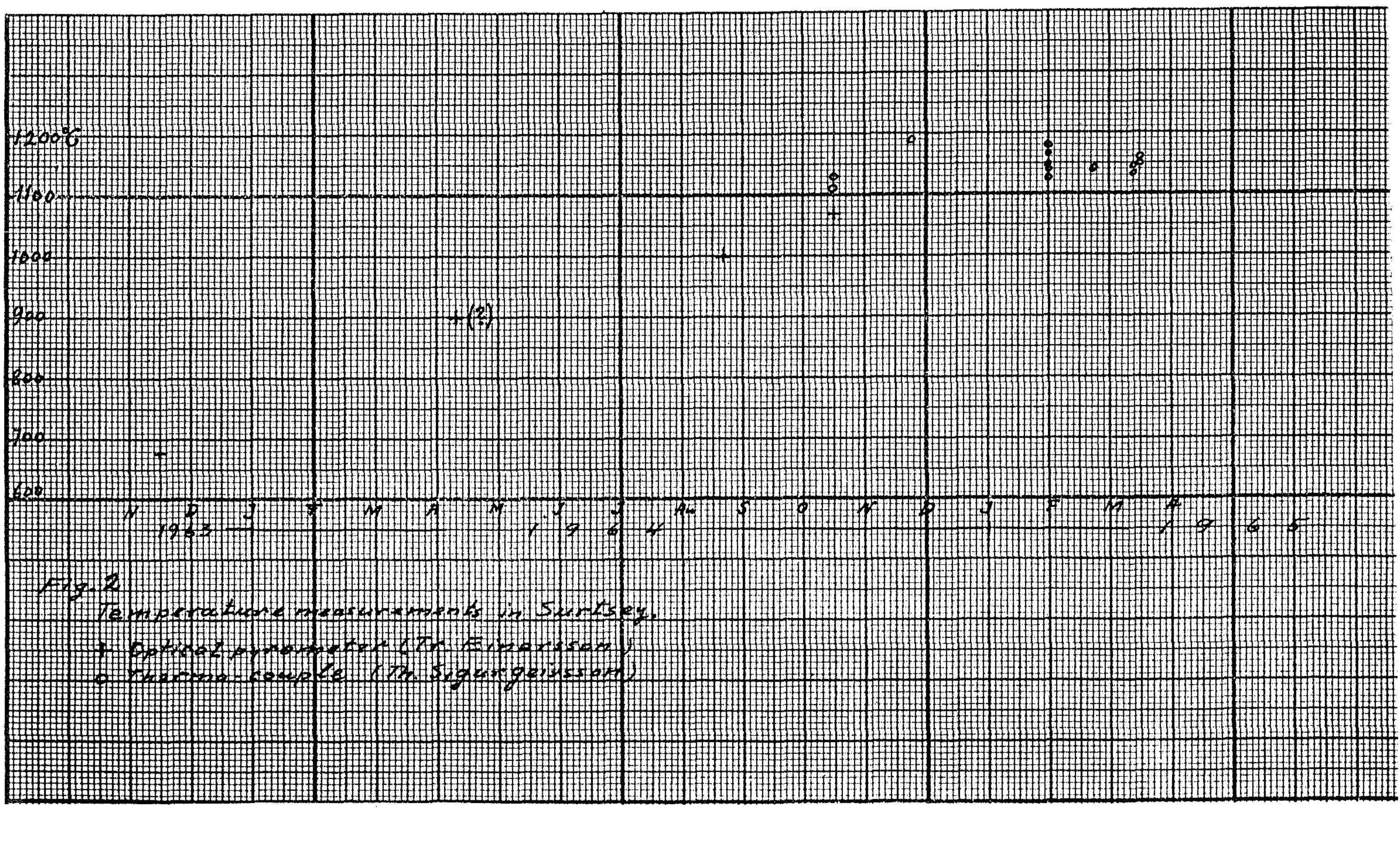


Fig. 2
Temperature measurements in Surtsey.
+ Optical pyrometer (Th. Einarsson)
o Thermo-couple (Th. Sigurgeirsson)

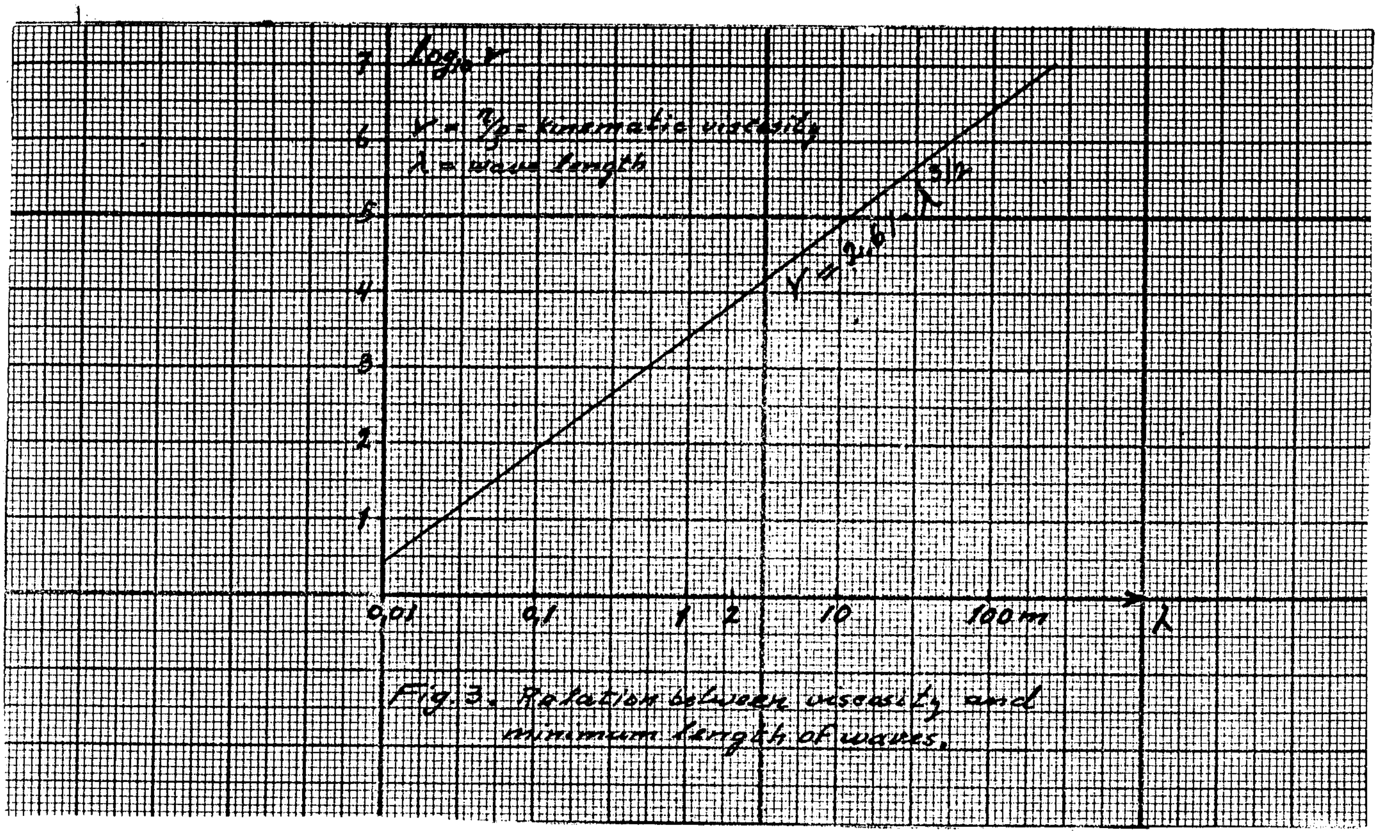


Fig. 3. Relation between viscosity and minimum length of waves.

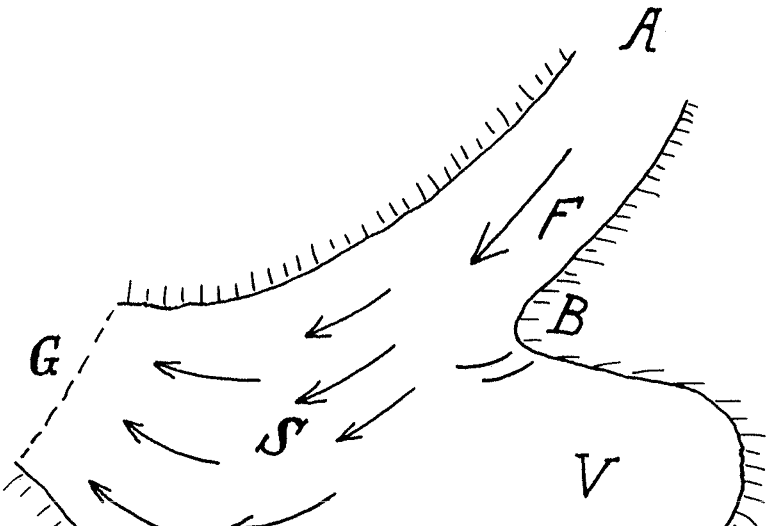


Fig. 4. Main stream of lava, F-S-G, and formation of waves at B.

Geophysical Measurements in Surtsey Carried Out During the Year of 1965

by

Thorbjörn Sigurgeirsson
University of Iceland, Physical Laboratory

Geomagnetic field measurements.

Repeated measurements at the two fixed magnetic stations, Surtsey I (20° 36' 30" W, 63° 18' 22" N) and Surtsey II (20° 36'30" W, 63° 18' 32" N), have given the following results:

Surtsey I

Date	U. T.	F (γ)	H (γ)	Z (γ)	D
1964, Aug. 19	14:45	51487			
1964, Sept. 12	10:50	51453.3	12784.8	49839.7	336° 19'.1
1965, March 14	10:30	51387.4			
1965, Sept. 4	17:00	51404.2	12824.8	49779.3	336° 01'.4

Surtsey II

Date	U. T.	F (γ)	H (γ)	Z (γ)	D
1964, Sept. 12	13:30	51461.9	12848.2	49832.5	336° 44'.8
1965, March 14	9:55	51453.2			
1965, Sept. 4	14:26	51569.7			

Simultaneous field values have been read from the recordings of Leirvogur Magnetic Observatory. The differences in magmetic field components are the following:

	Date	ΔF (γ)	ΔH (γ)	ΔZ (γ)	ΔD
Surtsey I	1964, Aug. 19	525			
	1964, Sept. 12	509	783	329	- 29'.6
	1965, March 14	429			
	1965, Sept. 4	377	710	212	- 41'.4
Surtsey II	1964, Sept. 12	512	831	320	- 0'.3
	1965, March 14	497			
	1965, Sept. 4	510			

The results at Surtsey II show no indication of a changing magnetic field. The closest distance to the lava is here 400-500 m. At Surtsey I there is a continuous change in the magnetic field. The place is on the tephra formation only 100 m from the edge of the lava and 200 m from the lavacrater. The decrease in total field intensity is caused by increasing magnetization of the lava due to cooling. This decrease is shown graphically in Fig. 1.

The map on Fig. 2 shows the location of magnetic profiles measured with a proton precession magnetometer. Profile designations are in continuation of those reported in a previous progress report (Surtsey Research Progress Report I).

Fig. 3 shows the magnetic field intensity along profile D. This profile starts in an early crater just outside the edge of the lavastream. The low field intensity at the beginning of the profile is caused by the edge of the lava. The extensive minimum near the western end of the profile may be due to heating from flowing lava although it is not visible at the surface. The high value at the western end of the profile is due to the fact that it is on the top of a cliff.

Profile E, shown in Fig. 4, was measured on March 3 from a rubber boat. The route runs from east to west about 300 m from the southern coast of Surtsey without any accurate positioning. The depth along the route is not known accurately, but it is believed that the magnetic anomailies are caused by basalt which the eruption has deposited on a flat sedimentary seabottom.

Profile F in Fig. 5 was measured on June 6 from a small boat across the submarine hill of "Surtla" from south to north. This hill was formed at the end of 1963 by a submarine eruption which was only visible at the surface for one or two weeks, but an island was never formed. A bottom profile, taken by means of an echo sounder, is shown below the magnetic profile. The results show that this hill contains some core of magnetized basalt although most of it may be nonmagnetic material as in the northern part of Surtsey.

On August 31 an aeromagnetic survey was carried out over Surtsey from a helicopter at an altitude of 200 m with the proton precession probe hanging 20 m below the helicopter. Measurements were automatically made every 3 seconds and recorded on a film. At the same time another camera takes photographs straight down for positioning. In all 28 profiles were flown, all crossing the island in different directions. The map has not yet been worked out, but one profile flown from southwest to northeast is reproduced in Fig. 6 and shown on the map as profile G. The cross section of the island and the seabottom profile are taken from the Icelandic Geodetic Survey map from August, 1965, and the Icelandic Hydrographic Survey map from July, 1964. The bottom profile close to the shore is uncertain.

The magnetic profile indicates a magnetized body at the bottom of the sea southwest of Surtsey. It also shows that the sourhern part of the island is strongly magnetic, while the northern part hardly causes any anomaly in the magnetic field.

Temperature measurements.

Temperature measurements were continued using the same thermometer as previous year. The results are the following:

Feb. 20, 1965	Flowing lava SSE from crater 50-100 m from the sea.	1139°C 1141°C
	Flowing lava S of crater 50-100 m from the sea.	1139°C 1141°C
March 13, 1965	Small lavatongue SSE of crater. 50 m from the sea.	1144°C 1145°C
	Same place. Lava emerging from a small opening.	1137°C
	Same place. Open lavastream 1-2 m broad. Lava velocity 0,5 m/sec.	1133°C 1134°C 1141°C
	Same place. Lava emerging from a small hole.	1134°C
	Same place. Small lavastream	1132°C
March 14, 1965	Lava in crater	1151°C 1162°C

During the last measurement in the small lavastream it was noted that while the thermometer was at rest the temperature only went to 1117°C, but when it was slowly withdrawn and moved back and forth close to the surface of the lava the temperature rose to 1132°C. Possibly the rise in temperature was due to oxidation of the lava. The temperature quoted is always the maximum temperature found in each place and may not be the true temperature of the lava.

On March 14th the lava was high enough in the crater so the thermometer could reach it from the edge. The thermometer was thrown out from the edge into the crater and pulled back by the leads connecting its cold end to the voltmeter, until the cold junction was about 1 m up on the edge of the crater. A second observer watched the voltmeter and when it stopped rising the thermometer was pulled up. It was important not to keep the thermometer too long in the crater as it then would stick to the edge. Two measurements were made. One gave an e.m.f. of 46,40 mV with a cold junction temperature of 16°C, the other 46,74 mV with a cold junction temperature of 18°C. According to tables of thermoelectric e.m.f. for chromel-alumel thermocouples this corresponds to 1151 and 1162°C respectively.

Fig. 1

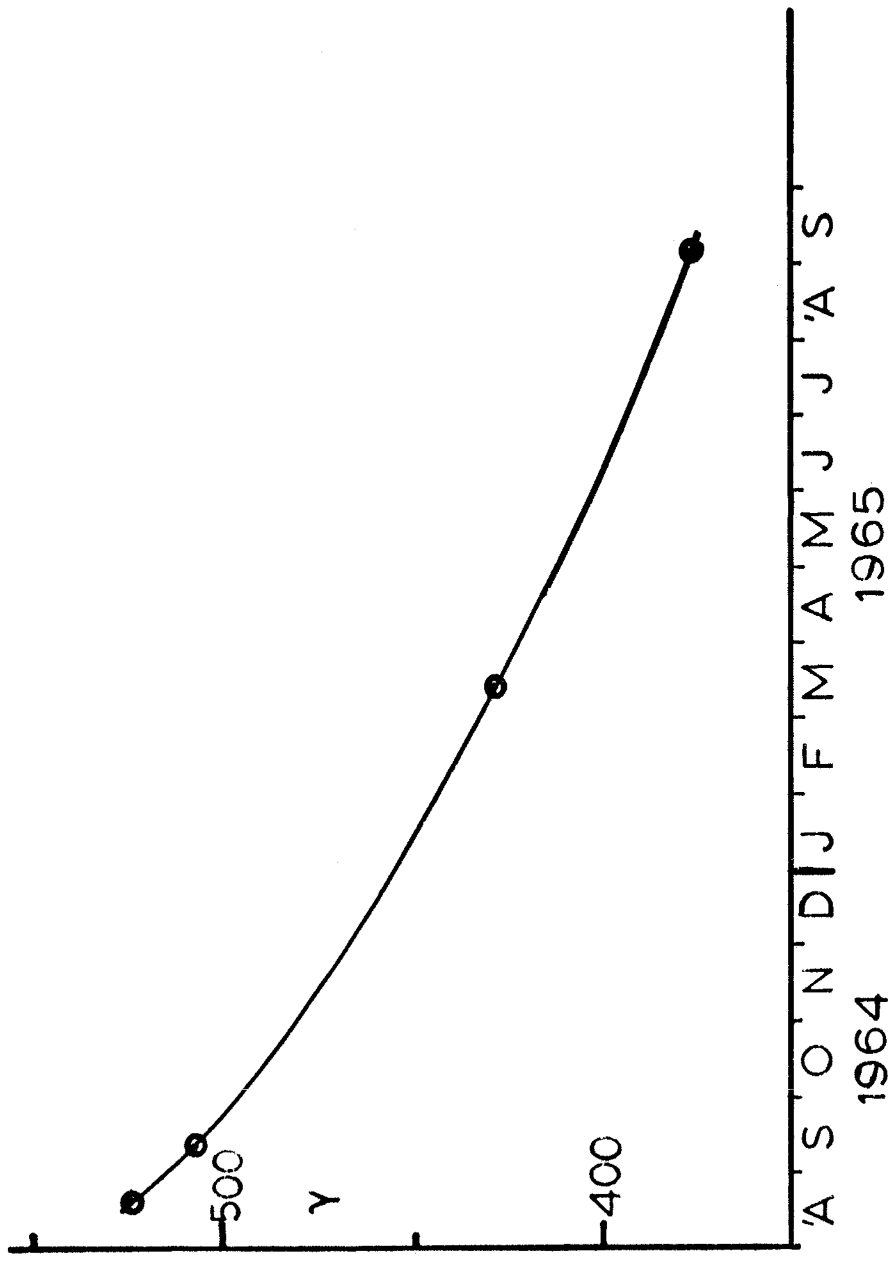


Fig. 2

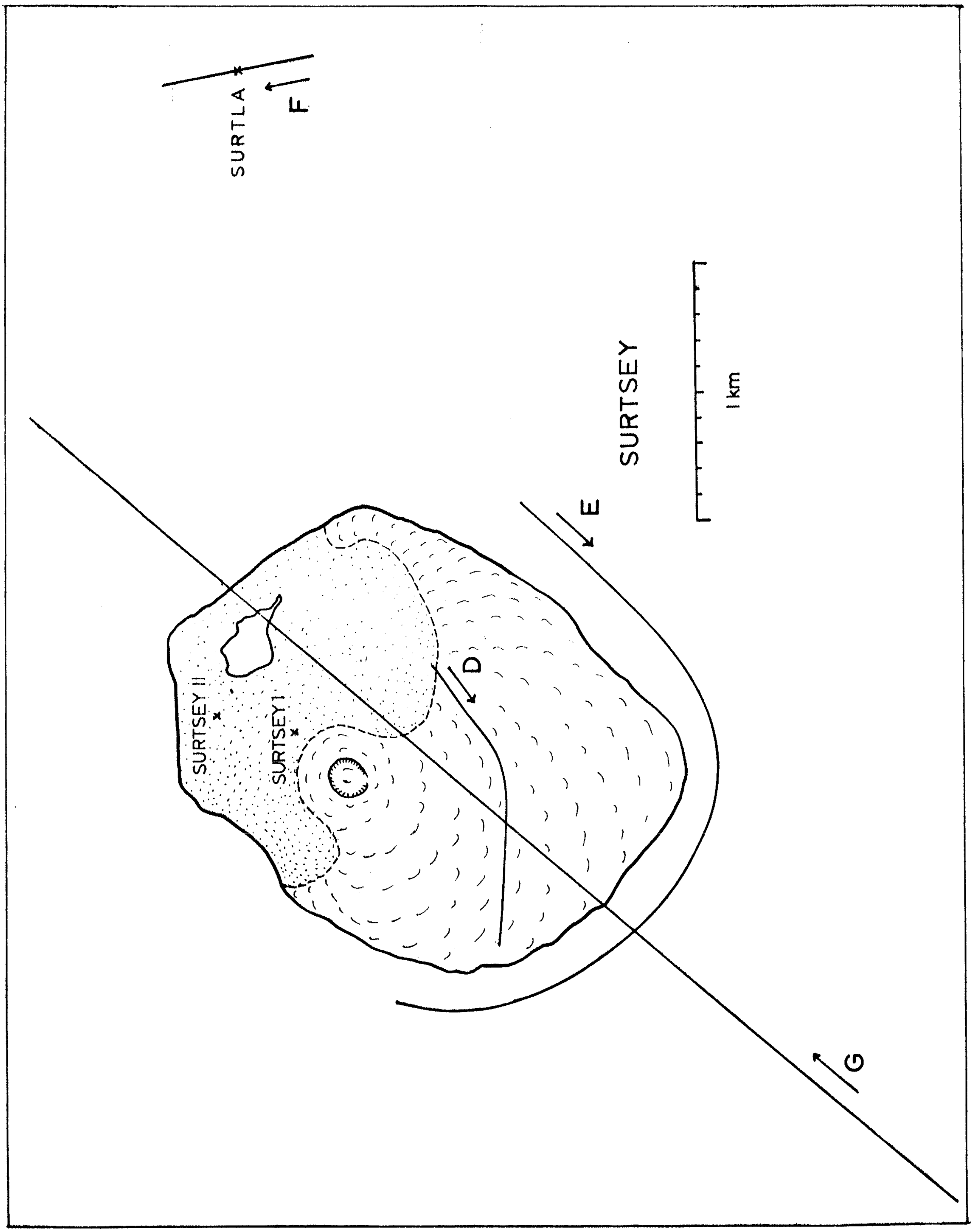


Fig. 3

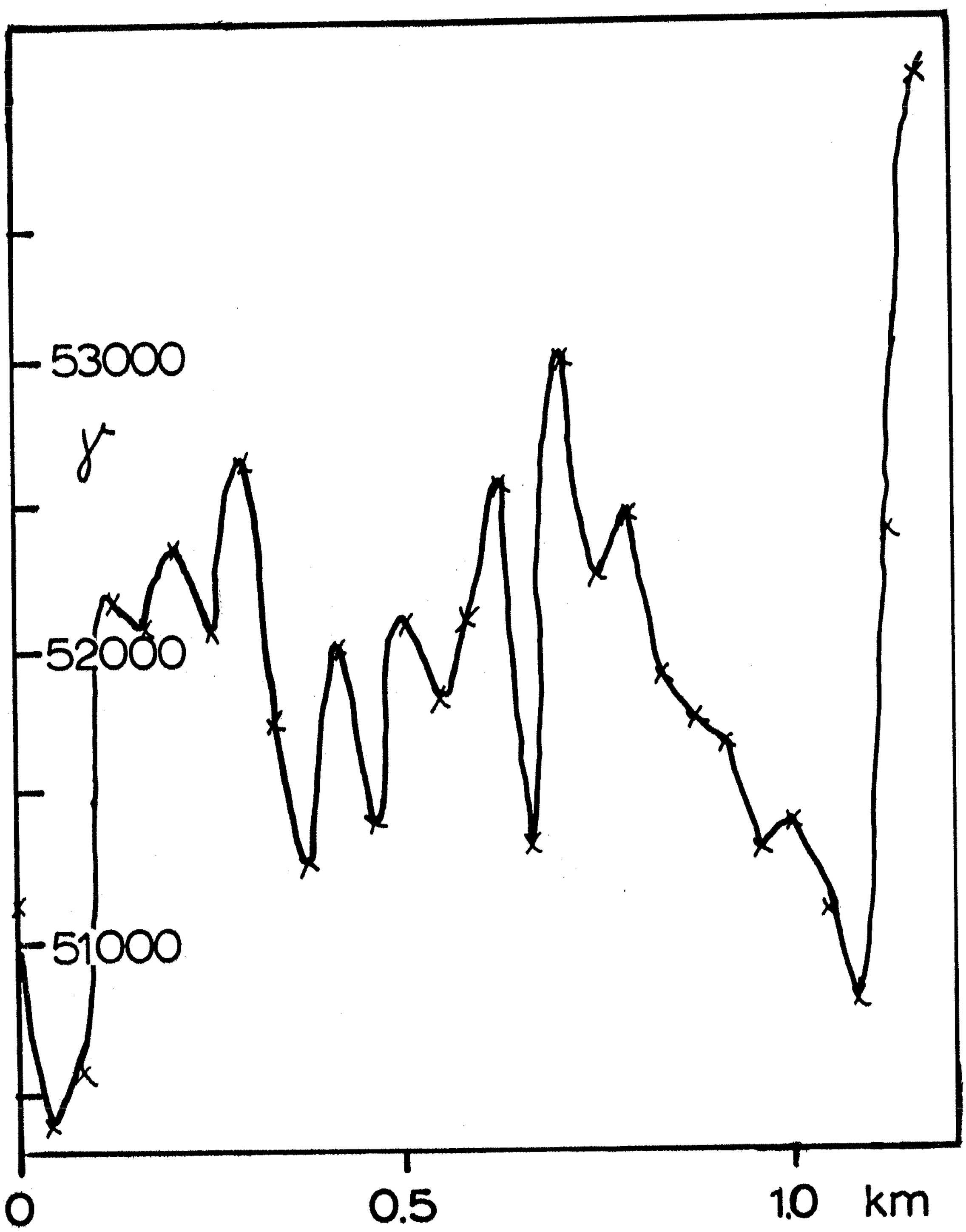
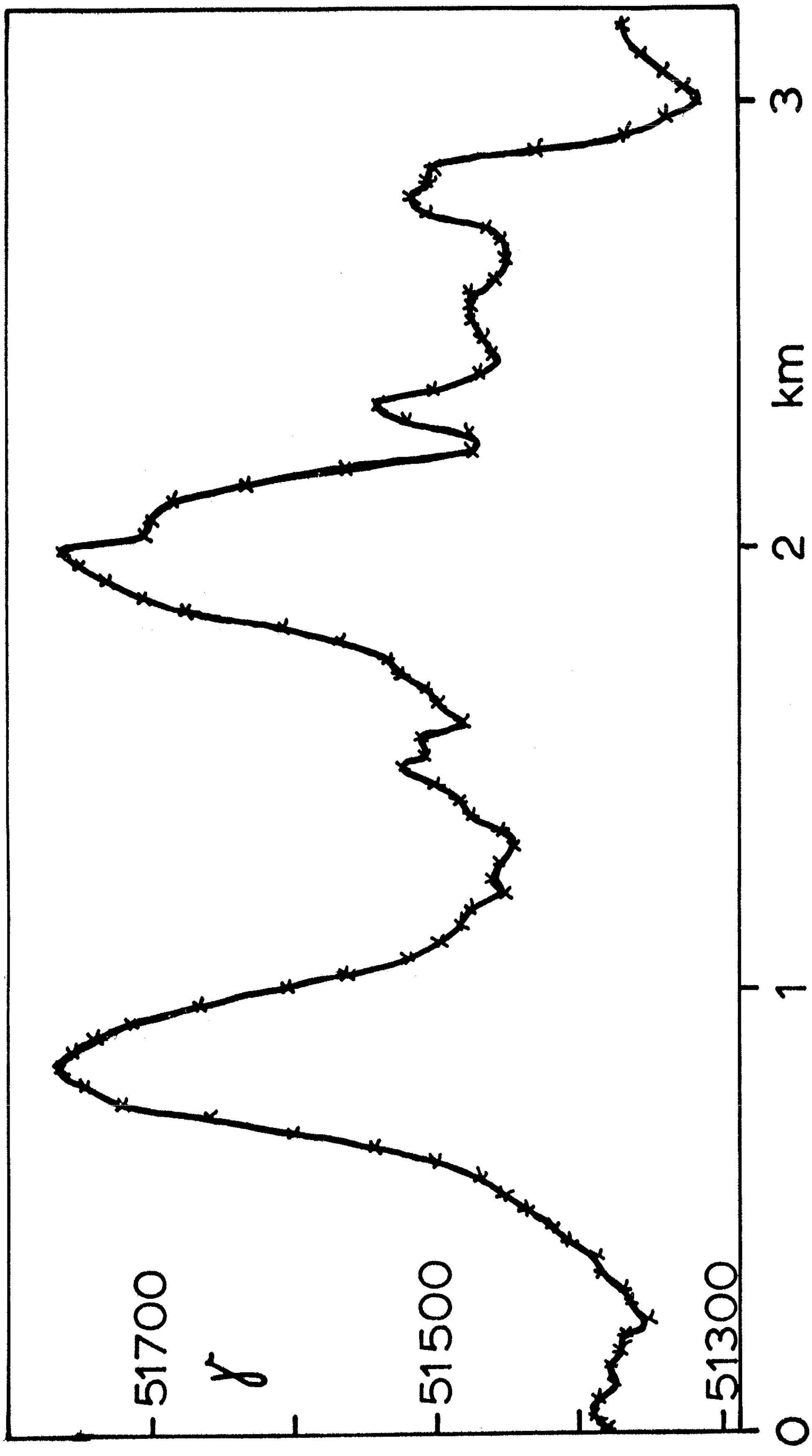


Fig. 4



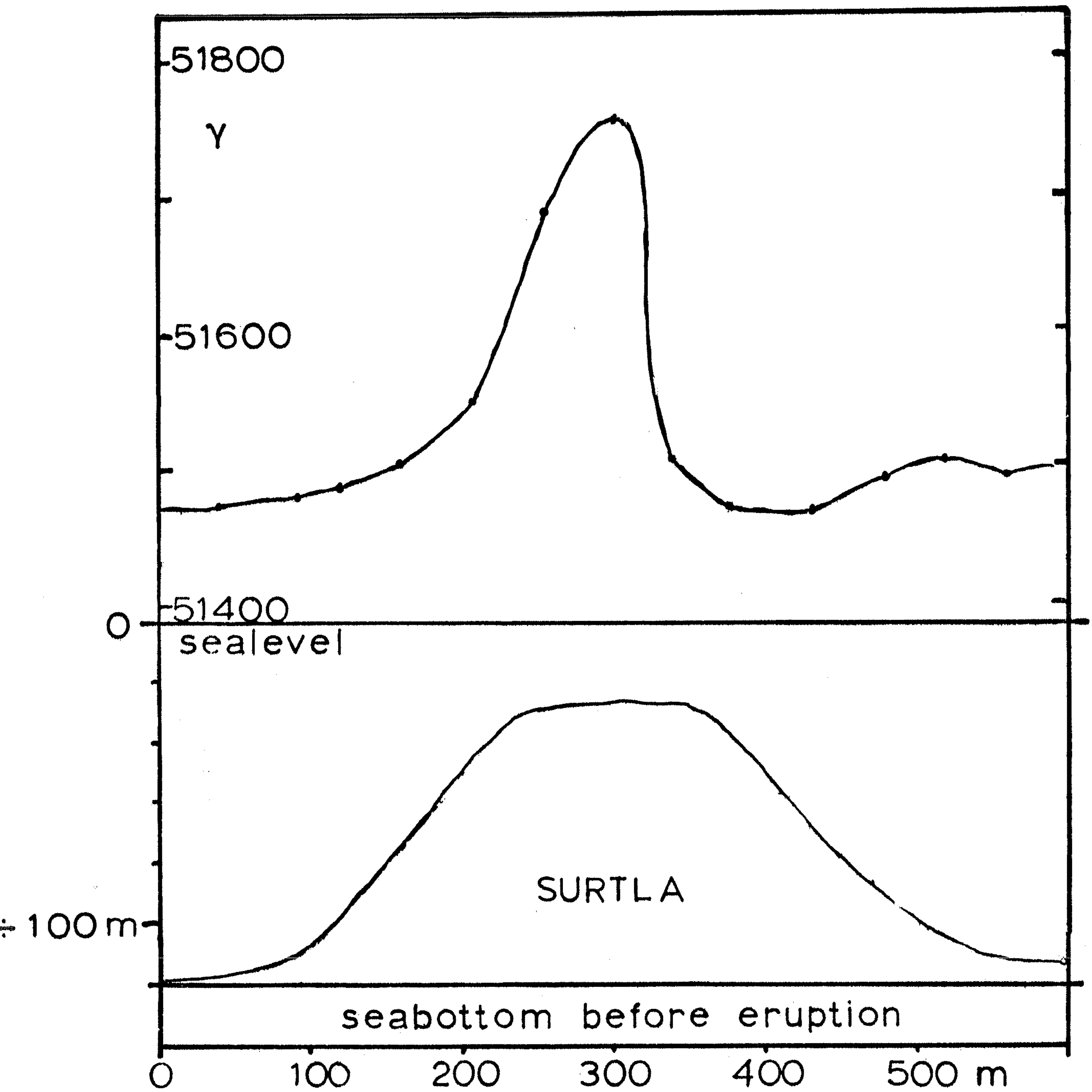
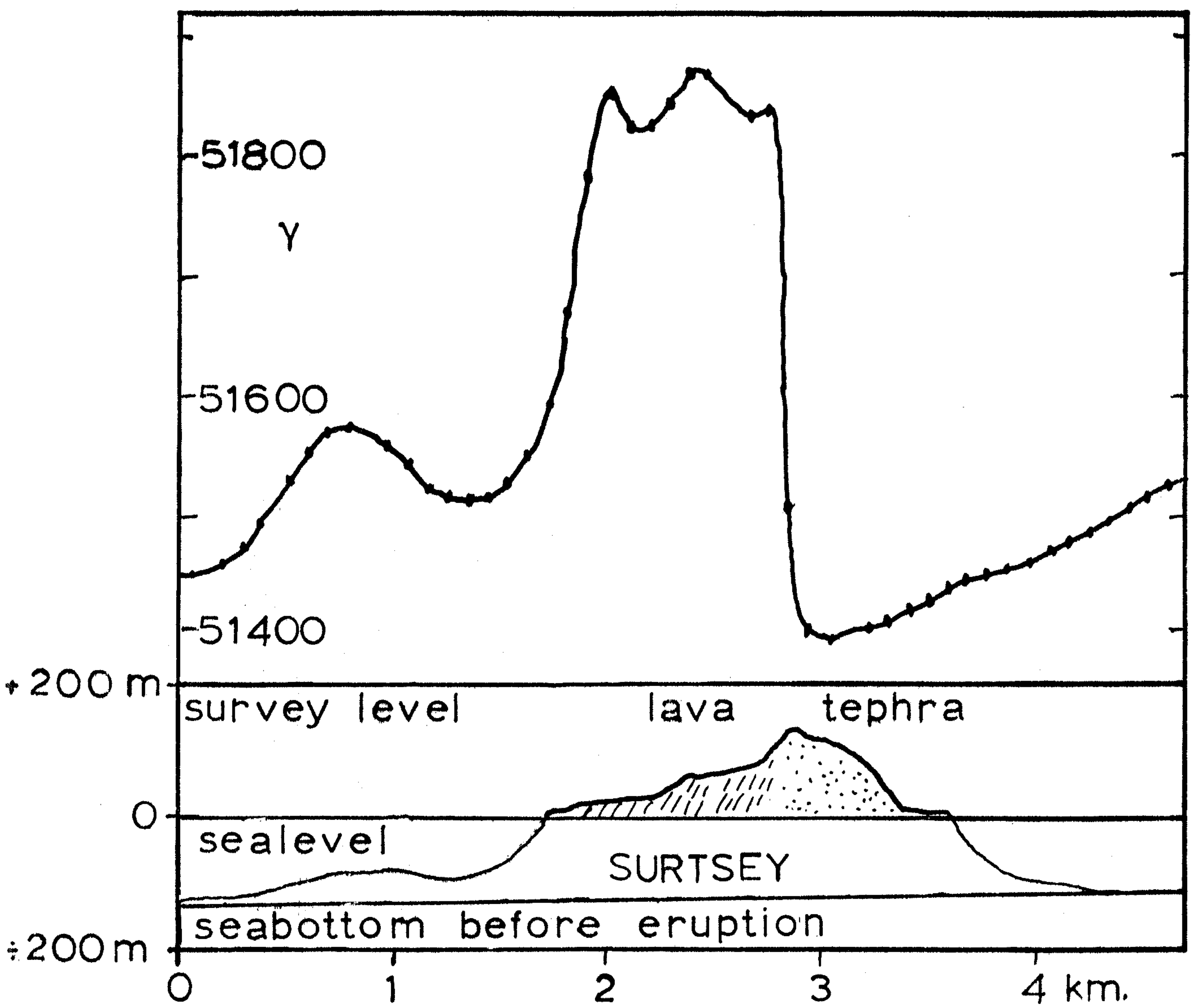

51800
γ
51600
51400
0
sealevel
SURTLA
÷ 100 m
seabottom before eruption
0
100
200
300
400
500 m

Fig. 6



51800
γ
51600
51400
+200 m
survey level
lava
tephra
0
sealevel
SURTSEY
seabottom before eruption
÷200 m
0
1
2
3
4 km.