SURTSEY RESEARCH

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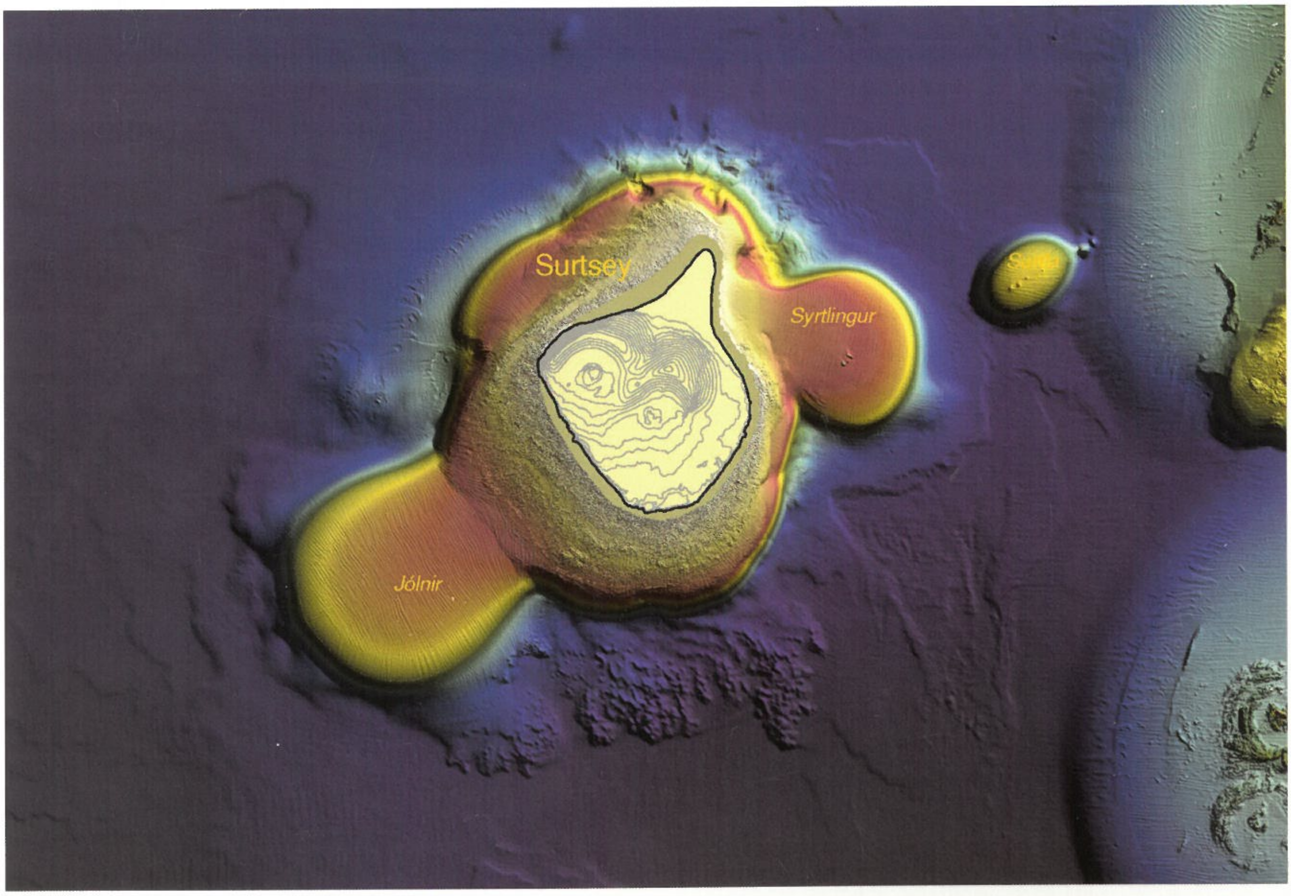

The Surtsey Research Society • Reykjavík

SURTSEY RESEARCH
Volume 12

THE SURTSEY RESEARCH SOCIETY
REYKJAVÍK, 2009

SURTSEYJARFÉLAGIÐ – The Surtsey Research Society
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Surtsey Research is a continuation of Surtsey Research Progress Report I–X

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Printed by ODDI – Reykjavík, Iceland

ISSN 1608-0998

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Introduction

On July 7th, 2008, the volcanic island Surtsey and the surrounding sea was awarded a World Heritage Site status by UNESCO's World Heritage Committee. In the committee's justification for this decision it is found important that scientific work has continuously been carried out on Surtsey from the start of the eruption. Furthermore, it is emphasized and found to be of greatest importance that the island and the surrounding sea has since shortly after the island appeared been declared a nature reserve, and thus been protected from humane impact, as far as possible. This being the first Surtsey Research report after this important recognition, it seems appropriate to review briefly the history of Surtsey and the scientific work on the island.

The submarine eruption which started on the 14th of November, 1963, at Vestmannaeyjar, approximately 20 miles off the southern coast of Iceland aroused great interest among scientists, both in Iceland and abroad, especially after it became likely that the island would last. This led to the National Research Council of Iceland setting up a committee, the Surtsey Research Committee, to coordinate and facilitate the scientific work. There were 11 members, 8 Icelandic scientists, representing different disciplines, two from the United States, and the director of the National Research Council as chairman.

As the scientific interest grew fast, it was felt that more extensive coordination was needed as well as financial support. Therefore, in 1964 the Committee drew up a coordinated plan for scientific work on and around the island. The participants were 21 Icelandic scientists and 13 from abroad. This plan was submitted to various foundations that supported scientific work both in the United States and in Europe. It was well received, but in order to make it possible to receive financial support, especially from abroad, a non-governmental and nonprofit organization had to be created. This led to the foundation of the Surtsey Research Society, May 20th, 1965. Founders were Icelandic scientists, nature enthusiasts and volunteers. Numerous foreign individuals became associate members of the Society. Members are now close to one hundred.

Considerable financial support was received from various institutions and foundations, primarily in the United States, and from the Icelandic Government, as well as important indirect support from scientific institutions in Iceland, United States and Europe through the work of scientists from those institutions on Surtsey. While the activities on Surtsey were at its peak, transportation to the island was mostly by boat from Heimaey, the only inhabited island of Vestmannaeyjar, but after the island became stable the Icelandic Coast Guard has taken care of the transport of one or two scientific expeditions to Surtsey by helicopter every summer.

In 1966 the Surtsey Research Society erected a research station and shelter on the island. It was located on the northern part, close to the shore. That site was gradually destroyed by the ocean breaking down the shore. A new house was built on the eastern part of the island in 1985. That house is maintained by the Society. It has been named "Pálsbaer" (The House of Paul) in honor of the late Professor Paul Bauer of the United States one of the greatest benefactor of the scientific work on Surtsey. A helicopter landing platform was made close to that house in 1993.

In order to protect Surtsey as much as possible from human impact, the National Research Council proposed in 1965 that Surtsey be declared a nature reserve. That was done by the Nature Conservation Council of Iceland and all travel to the island forbidden without permission from the Surtsey Research Society. This was reiterated in 1973 based on a new law on nature conservation. To underline the Government's decision to nominate Surtsey for the UNESCO World Heritage List, a new and revised Declaration for the Surtsey Nature Reserve was issued in January 2006. The boundaries of the Reserve were expanded to ensure the protection of the entire Surtsey volcano, both above and below the sea surface.

After land formed scientists saw a unique opportunity to observe the beginning and development of life on a new and sterile land, especially after the decision was taken to protect it as much as possible from human impact. In the spring of 1964 a meeting was held at the Duke University in the United States to discuss the possibility of extensive scientific studies on Surtsey with participation by scientists from Universities and Institutions in the United States. Participants in that meeting were three from Iceland and several scientists from the United States. The conclusion was that this was not only feasible but also very important. The number of scientists of different disciplines multiplied and so did the activities of the Surtsey Research Society.

Two international conferences have been held. The Surtsey Biology Conference was held in Reykjavik in April 1965. Participants were 22 from Iceland and 16 from abroad. At the conference a "Biological Outline" for research on and around Surtsey was presented. It was "evaluated, scrutinized and accepted", as stated in the minutes from the conference. The second conference, The Surtsey Research Conference, was held in Reykjavik in June 1967. The participants were 36 from Iceland and 40 from abroad. At this conference 17 papers were presented and discussed in five special working groups. Besides those scientific conferences, the thirty and forty years anniversaries of the Surtsey eruption were commemorated by open meetings in Reykjavik where papers were presented on the development of Surtsey. In the fall of 2005 a conference was held in Vestmannaeyjar where scientist outlined the development of Surtsey and the future of the island was discussed.

On behalf of the Surtsey Research Society Surtsey aerial photographs have been taken regularly and maps drawn. This gives a unique record of changes taking place on the island, especially by ocean erosion. In 1967, when its area was the largest, it was 2.65 km^2. It is now close to half that size.

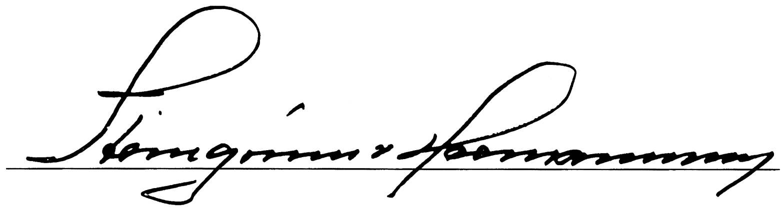
Scientific studies on Surtsey continue with yearly expeditions to the island organized by the Society. It is important to continue this work. Surtsey is far from being fully developed. It yields new knowledge every year. During the eruption scientists from several scientific institutions did work on Surtsey. Since the eruption ceased the work has been primarely in the hands of scientists from three Icelandic institutions, The Icelandic Institute of Natural History, The Agricultural Research Institute and The Marine Research Institute. Furthermore, these institutions, along with the Surtsey Research Society, have during the last 40 years carried most of the expenses of the scientific work with support from the Icelandic Government and the Icelandic Coast Guard.

The bibliography on Surtsey is extensive. Numerous articles and books have been published on the island's development. Of great importance are the publications of the Surtsey Research Society, the Surtsey Research Progress Report (later Surtsey Research). This report, now being published, is the twelfth. Three scientists, Sveinn P. Jakobsson, geology and geophysics, Borgthór Magnússon, terrestrial biology, and Karl Gunnarsson, marine biology, have been in charge of the editing and publishing of this volume. These twelve reports contain 217 papers by scientists who have worked on Surtsey. The Surtsey Research Reports contain the most reliable and comprehensive information available on the island's development and scientific findings.

The Surtsey Research Society has set up a web site (www.surtsey.is) with comprehensive information about the creation and development of Surtsey, its history, the Society, the scientific work on the island and its conservation as a nature reserve. Through that site all the reports published by the Society are accessible.

In historical times several islands have been created on Earth by submarine eruptions but none have been protected from human influence as Surtsey or scientifically observed as thoroughly and continuously from its birth. This is why Surtsey is unique. It has already yielded valuable knowledge about both geological development of a new land and settlement of life on a sterile rock. With uninterrupted scientific work, Surtsey will continue being a source of new knowledge.

For the Surtsey Research Society,



Steingrímur Hermannsson
chairman

GEOLOGY AND GEOPHYSICS

Some aspects of the seafloor morphology at Surtsey volcano: The new multibeam bathymetric survey of 2007

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ABSTRACT

A multibeam bathymetric survey in 2007. which included the area around Surtsey, allows a new interpretation to be made of aspects of the seafloor geology. It also provides support for previous observations and interpretations. The multibeam map brings to light features which the earlier, single beam surveys missed. Here, we describe the nature of the erosional platform around Surtsey, outline an area of probable pillow lava off southern Surtsey, and describe features in deep water (<120 m) which may have been formed by erosion. Sand waves in water depths up to 90 metres support the idea of strong bottom currents. The survey also allows an extrapolation of the known erosion history of Surtsey and surrounding vents (Jólnir, Syrtlingur, and Surtla). Knolls on the tops of Syrtlingur and Surtla are thought to be due to palagonitisation in the vicinity of the volcanic vents. Canyons in the northern submarine slope of Surtsey support previous observations of slope failure and sediment flow to the surrounding seafloor.

INTRODUCTION

A new multibeam bathymetric survey of the Vestmannaeyjar archipelago included the area around Surtsey. The vast improvement in resolution of bottom features displayed by the new dataset offers a fresh opportunity to look at the sea floor around Surtsey and use features observed there to add to, or confirm, the present view of events since November 1963.

The island Surtsey rose from the sea floor in a volcanic eruption lasting from November 1963 to June 1967. The island is the subaerial segment of the complete Surtsey volcano, which forms a line of volcanic features on the sea floor oriented southwest-northeast. At the end of the eruption in June 1967 the length of the volcanic features was 5.5 km and its base area encompassed some 8 km^2. The history of the eruption is well recorded and several aspects of the morphological changes of the volcano have been studied extensively, but in this report we look for fresh information in the new multibeam chart.

Surtsey is part of the Vestmannaeyjar archipelago (Fig. 1) which consists of 18 islands and a number of skerries, and is located on the insular shelf off the south coast of Iceland. Vestmannaeyjar constitutes a discrete volcanic system at the southern end of Iceland's Eastern Volcanic Zone (Jakobsson 1979). A large part of the volcanic system is submarine and investigations indicate that local submarine as well as subaerial volcanism is the source of material building up the Vestmannaeyjar marine shelf (Thors & Helgason 1988). Before we discuss the new chart, it is useful to look at the history of Surtsey and briefly mention some of the research carried out in the area.

BACKGROUND

The Surtsey eruption 1963–1967

The eruption history of the Surtsey volcano is well known (Thórarinsson 1966, 1967, 1969; Thórarinsson *et al.* 1964). The main milestones of that history are listed in Jakobsson & Moore (1982).

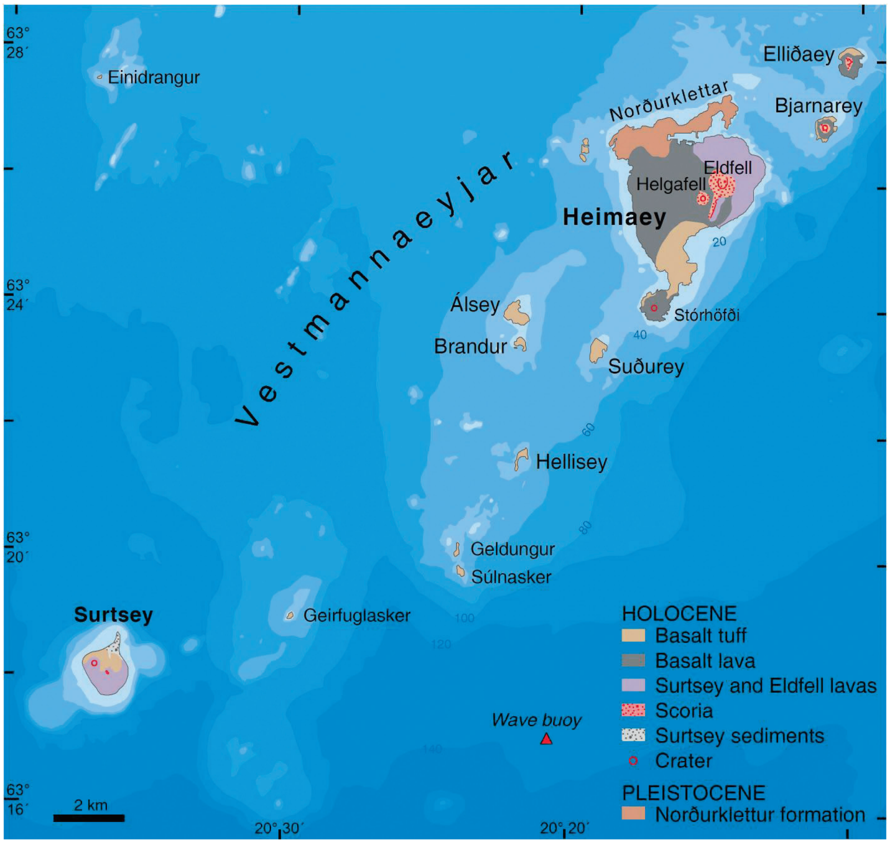


Figure 1. Simplified geological map of the Vestmannaeyjar archipelago. Depth contour lines are in meters. The Surtsey volcano is depicted as in 2007. The coastline of Surtsey island is based on aerial photographs from July 2007. The position of the wave buoy of the Icelandic Maritime Administration is shown.

The visible eruption started with hydromagmatic explosions along a 300–400 long fissure trending 035° on 14 November 1963. Emerging on 15 November 1963, the island grew rapidly in size. On 31 January 1964, eruptions ceased in the eastern vent, and on the following day eruptions broke out in a northeast-trending fissure at the northwest side of that crater, where another crescent-shaped tephra crater formed and finally achieved a maximum height of 173 m above sea level.

Between 28 December 1963 and 6 January 1964, explosive submarine activity was visible about 2.0 km east-northeast of Surtsey. This eruption fissure, estimated 250 m long, created a submarine ridge called Surtla to over 100 m above the sea floor.

On 4 April 1964, the eruption in the western crater switched to an effusive Hawaiian-type lava phase. Effusive lava activity continued in the western crater until 17 May 1965, and gradually a flat lava shield was formed southwards from the crater, while flow-foot breccia was produced at the advancing frontal slope of the lava below sea level.

On 22 May 1965, explosive activity appeared on the sea floor 0.6 km east-northeast of Surtsey. A tephra island, Syrtlingur, was formed and reached a height of 70 m and a maximum area of 0.15 km^2. This island was washed away by wave action a few days after the eruption ceased, on about 17 October 1965. Yet another tephra island, Jólnir, was created by explosive submarine activity about 1 km southwest of Surtsey beginning on 26 December 1965. This island reached a maximum height of 70 m and an area of 0.28 km^2. The eruption ceased on 10 August 1966 and Jólnir had disappeared in late October the same year.

On Surtsey, a new lava eruption started along a SW-NE-striking 220-m-long fissure on 19 August 1966 on the floor of Surtsey's eastern tephra crater. Lava flowed incessantly from this fissure throughout late 1966 and early 1967. Between 12 and 17 December 1966, another short fissure became active in the northwestern inside wall of the eastern tephra crater, producing a small lava flow. Then, during the period of 1–8 January 1967, lava broke through the eastern tephra cone at four additional sites (Fig. 2), but the southernmost eruption site is now covered with sand dunes. Lava was last seen to flow on Surtsey on 5 June 1967.

At the end of the eruption, the Surtsey island had reached a size of 2.65 km^2, and the total amount of eruptive material was estimated 1.1 km^3, about 70% of which was tephra and 30% lava (Thórarinsson 1969). The height of the island at that time was 175 m above sea level, and as the seawater depth before the eruption had been about 130 m, the total height of the volcano was 305 m.

The structure of Surtsey

The structure of Surtsey island is well known through the detailed eruption history summarized

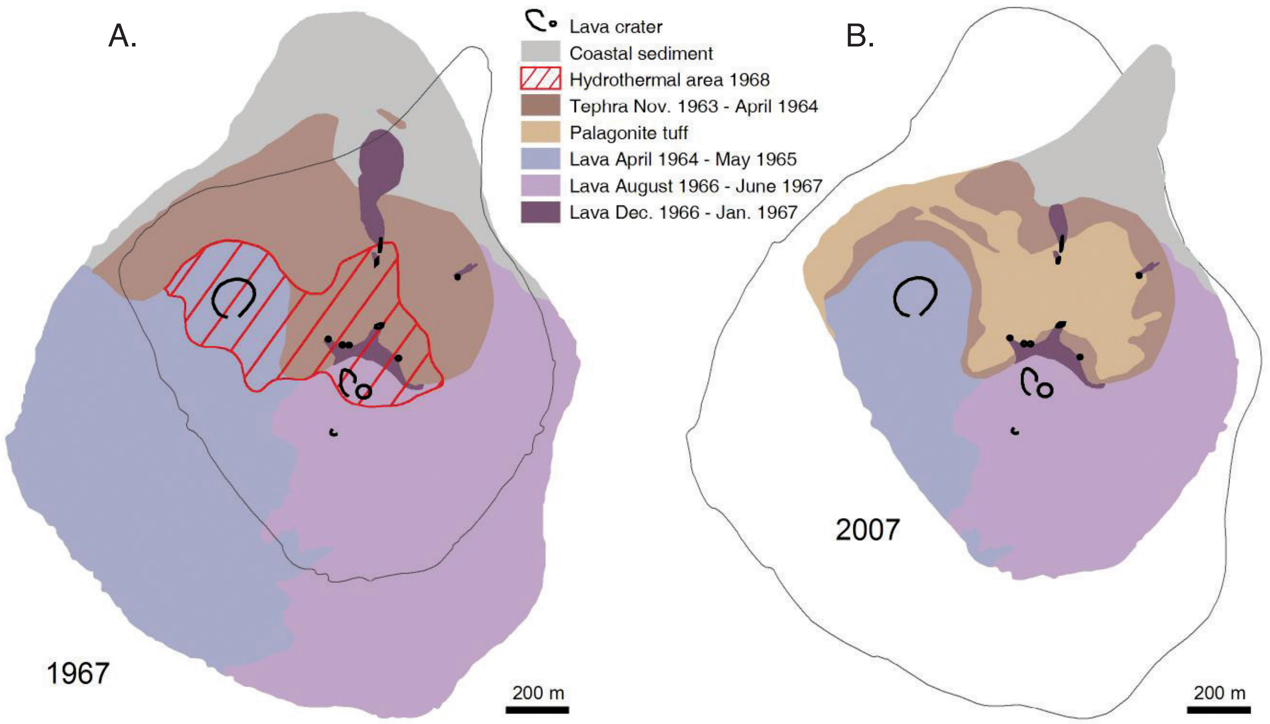


Figure 2. Geological map of Surtsey. A. As in 1967, with approximate extent of the hydrothermal area as in 1968; the outline of the island is based on aerial photographs from August 1967. B. As in 2007; the outline of the island is based on aerial photographs from August 2007. This diagram also illustrates the enormous change in size of the island during the 40 intervening years.

above, studies of the drill core of 1979 (Jakobsson & Moore 1982, 1986), geomagnetic measurements (Sigurgeirsson 1966, 1974) and gravity model studies (Thorsteinsson & Gudmundsson 1999). Besides, the monitoring of the Surtsey volcano since 1967 has provided important clues to its structure, e. g. by monitoring of the development of the hydrothermal system and the transformation of tephra to palagonite tuff within the hydrothermal area (Jakobsson *et al.* 2000), the marine abrasion (Norrman 1980, 1985), and the subsidence of the volcano (Moore *et al.* 1992; Sturkell *et al.* 2009).

Kjartansson (1966) and Thórarinsson (1966) suggested, mainly by analogy, that pillow lava had formed in deep water during the first phase of the Surtsey eruption and formed the base of the volcano. However, the existence of this basal pillow lava was never proven (Jakobsson 1978), and the results of the 1979 drilling operation do not indicate the existence of such a formation (Jakobsson & Moore 1982).

It should be underlined that the three principal geological formations of Surtsey, tephra, lava, and palagonite tuff, react quite differently to erosion (Jakobsson *et al.* 2000). The Surtsey tephra is mainly made up of fine glass shards less than 2 mm in diameter (Sheridan 1972). The tephra formation is therefore very easily eroded by wind, water and wave action. The lava flows are mostly multiple pahoehoe flows, but aa flows are also present (Thórdarson 2000). The lavas have proven to be more easily eroded by marine abrasion than expected. The porous delta formation below the lava is also easily eroded. The palagonite tuff, however, has turned out to be surprisingly resistant to marine abrasion. In 1980–1982 the sea had eroded its way to the tuff core in the northwestern side of the western crater (Fig. 2) and up to 120 m high tuff cliffs were formed. This cliff profile has not changed much since that time.

The structure of Surtla, Syrtlingur and Jólnir

Only tephra was observed having formed during the eruptions of Surtla, Syrtlingur and Jólnir. Scuba divings onto the top platform of Surtla in 1968 (Norrman 1970) and 1981 (Kokelaar & Durant 1983) revealed only loose tephra with angular lava fragments. However, a geomagnetic measurement carried out in 1965 indicated that Surtla has a core of magnetic basalt (Sigurgeirsson 1966). In 1974 a dredge haul was collected from the southeast slope of Surtla; it consisted of fresh, dense scoria fragments (Jakobsson 1982).

Diving at Syrtlingur in 1968 revealed that the top platform was made up of coarse tephra (Norrman 1970). In 1982 two dredge hauls of fresh, dense scoria and vesicular lava fragments were collected on the east and south slopes of Syrtlingur (Jakobsson 1982). The divings to the top platform of Jólnir in 1968 and 1989 (Norrman & Erlingsson 1992) also showed that it was made up of tephra. Although the magnetic measurements of 1965 may have indicated that the core of Surtla is denser than the rest of the mound, there is in fact no evidence for the presence of dense crystalline rock, for example basal pillow lava, at the base of Surtla, Syrtlingur or Jólnir.

Wave climate in the Surtsey region

Surtsey is situated in region of extremes in winter weather and wave climate. Wave data near Surtsey have been recorded by the Icelandic Maritime Administration since 1988. Among other things, the data show that the largest waves in the area come from the southwest. Significant wave heights (the average height of one-third of the waves observed during a given period of time) of over 16 m have been recorded and wave peak periods of up to 20 seconds (Baldursson and Ingadóttir 2007). Waves of these magnitudes obviously have enormous erosion power, and the history of Surtsey reflects this (see Fig. 2, and discussion below).

Previous bathymetric surveys of the Surtsey area

The history of bathymetric surveys of the area around Surtsey is presented in a separate report (Vésteinsson 2009). The first survey was carried out in July 1964 and since then the Surtsey area has been surveyed five times. These surveys have served as a basis for the monitoring of changes of the sea floor and their interpretaion. The multibeam survey of 2007 is the most recent of the surveys, and allows an extrapolation of previous observations to the present day. This will be done in the next chapter.

GEOLOGICAL FEATURES OBSERVED IN THE BATHYMETRIC MAP

Technical notes on map

The new seafloor image of the Surtsey area is presented as Figure 3. (see inset between p.16 and 17) The image was created using the CARIS HIPS Multibeam Professional software, a suite of bathymetry processing tools. CARIS HIPS is used by the ICG Hydrographic Department for processing and preparing hydrographic survey data.

The resolution of the image is variable. In the depth range 0–30 m the resolution is 2 m, in the depth range 30–60 m it is 3 m, 60–95 m it is 5 m and in the depth range 95+ m the resolution of the image is 10 m. The reason for this is the fact that the maximum possible resolution decreases with depth. To get the most out of the seafloor image, in terms of feature detection on shallower areas around Surtsey, this method of variable image resolution was devised. Vertical exaggeration is tenfold (10). This high vertical exaggeration creates wave-like "artifacts" most apparent on smooth surfaces e.g. like the Jólnir mound. These waves are very regular and can be distinguished rather easily from natural features.

Bottom topography through time

The bathymetric surveys of the Surtsey area are illustrated in Figure 4. The first map shows the bathymetry of the area in 1964, during the eruption. Two notable features are the Surtla mound northeast of Surtsey, with a minimum depth of 25 metres, and an appendix extending to the southwest from Surtsey. As discussed below, this is thought to represent pillow lava extruded below sea level.

The 1967 map shows the extent and shape of the Jólnir (to the southwest), and Syrtlingur (northeast) mounds by the end of the eruption. Minimum depths of these features are displayed. The top of Surtla has by now receded by 8 metres.

In 1973 the erosion of the three mounds had proceeded still further. Similarly, this map indicates a marked retreat of the Surtsey shoreline. The 1985 map shows a continuing trend with still increasing depth to Jólnir, Syrtlingur, and Surtla. During the next 15 years, or until year 2000, the powerful southwest waves lashed the island and its submarine siblings to further retreat. The new map, from 2007, suggests that submarine erosion is slowing down, while the southwest coast of Surtsey is still retreating.

Submarine erosion of Surtla, Syrtlingur, and Jólnir

The erosion of the three submarine mounds described above has been discussed previously by Norrman (1970), Jakobsson (1982), Kokelaar & Durant (1983) and Norrman & Erlingsson (1992). As the top sections of Surtla, Syrtlingur and Jólnir are built up of tephra, the submarine erosion has until now been within unconsolidated tephra, excluding the knolls on Syrtlingur and Surtla, see below. Both Kokelaar & Durant (1983) and Norrman & Erlingsson (1992) concluded that the submarine erosion was due to wave and current activity and that the erosion was active on all mounds, the sediments mainly being washed over the sides of the mounds.

In Table 1 the most reliable depth measurements to the top platform of the three mounds are presented, including the new measurements of 2007. The dates of the disappearance of the islands of Syrtlingur and Jólnir from the sea surface are also listed. The data show a particularly fast rate of erosion (Fig. 5), although the rate is slowly decreasing. The erosion has been particularly vigorous at Jólnir which disappeared as an island above sea level in October 1966; in 2007 the depth to the top platform of the mound at this site was 43 m.

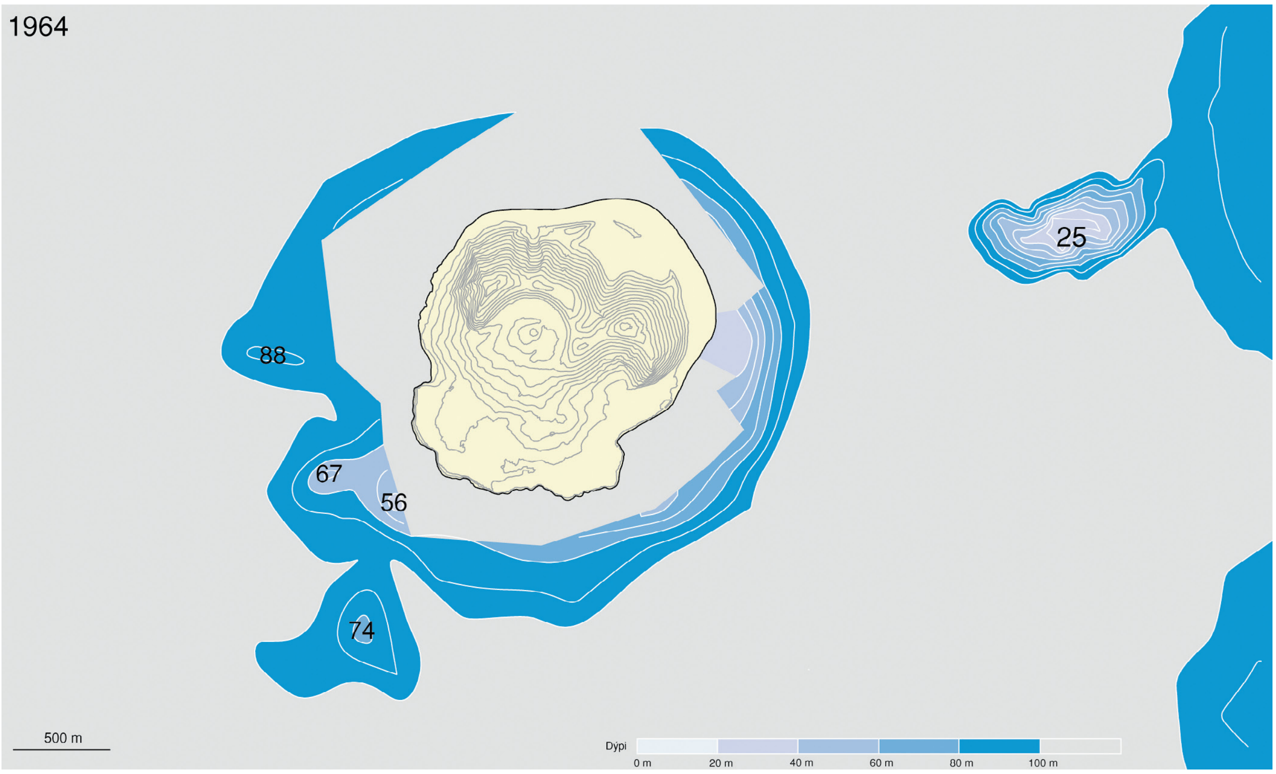
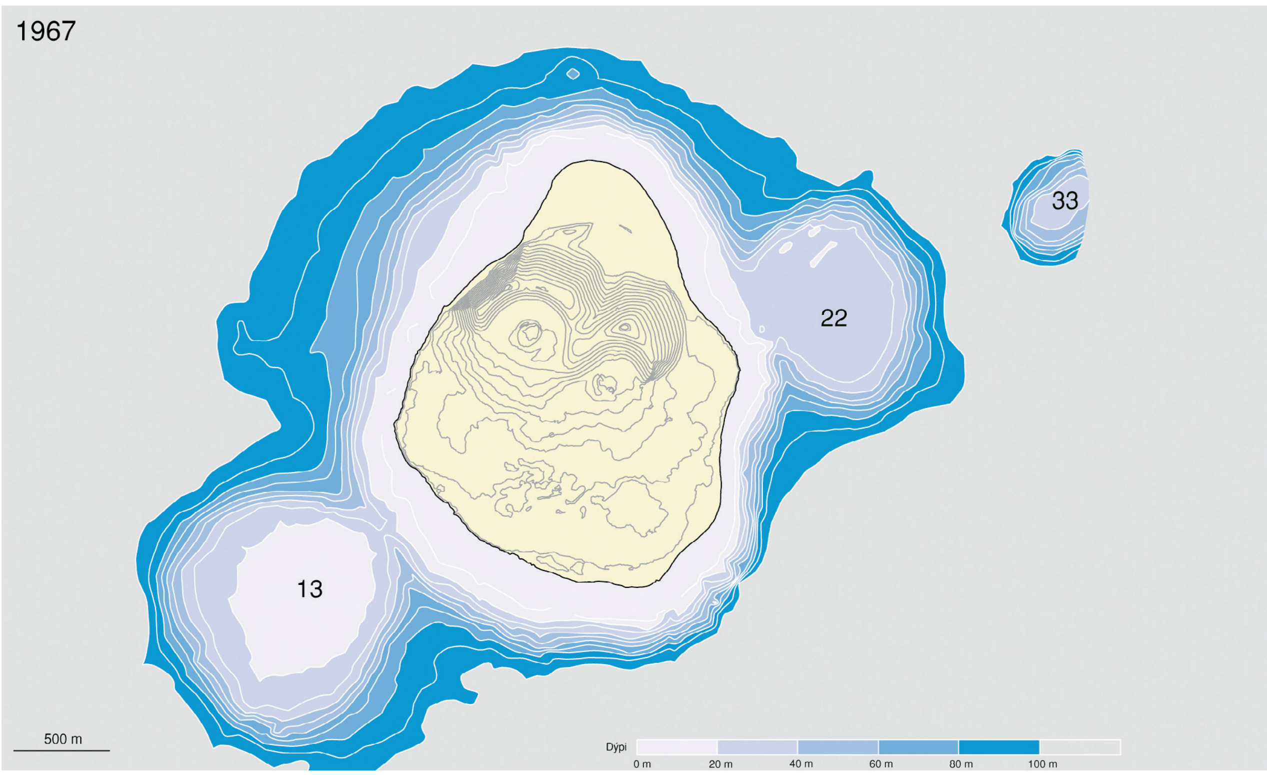
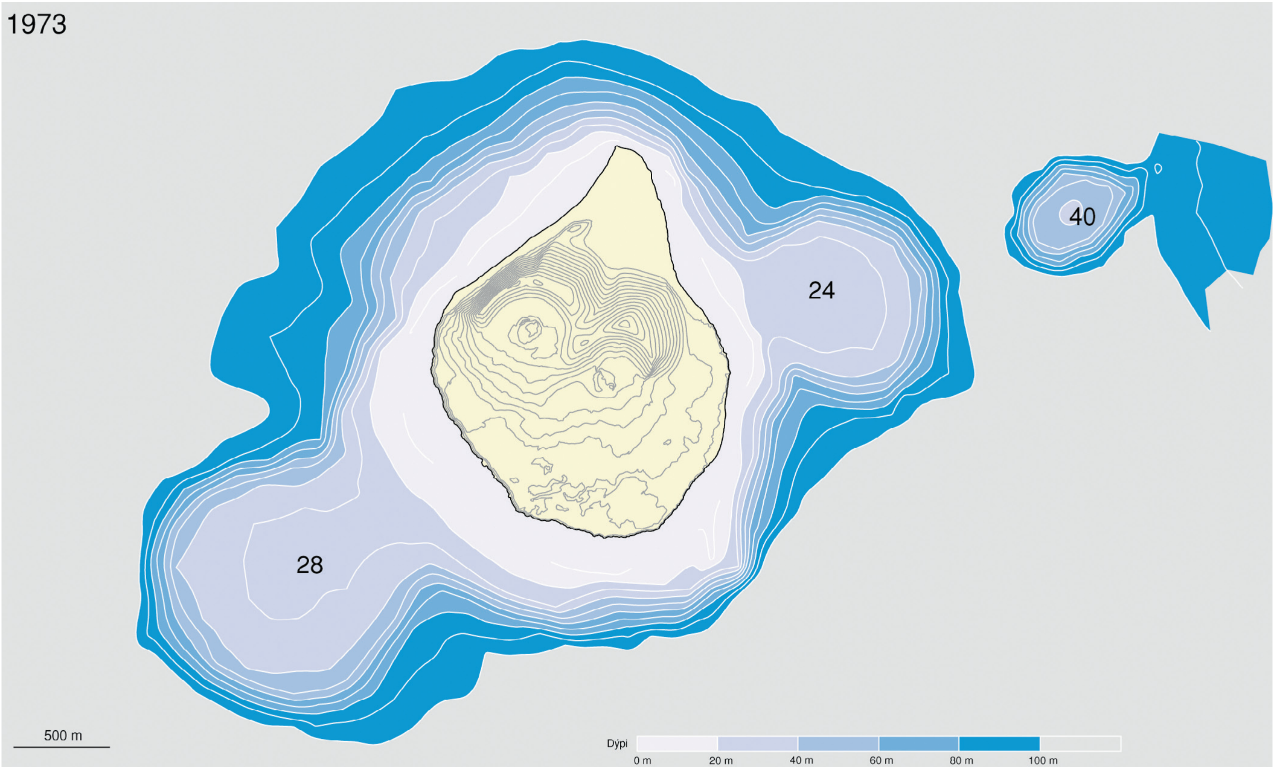


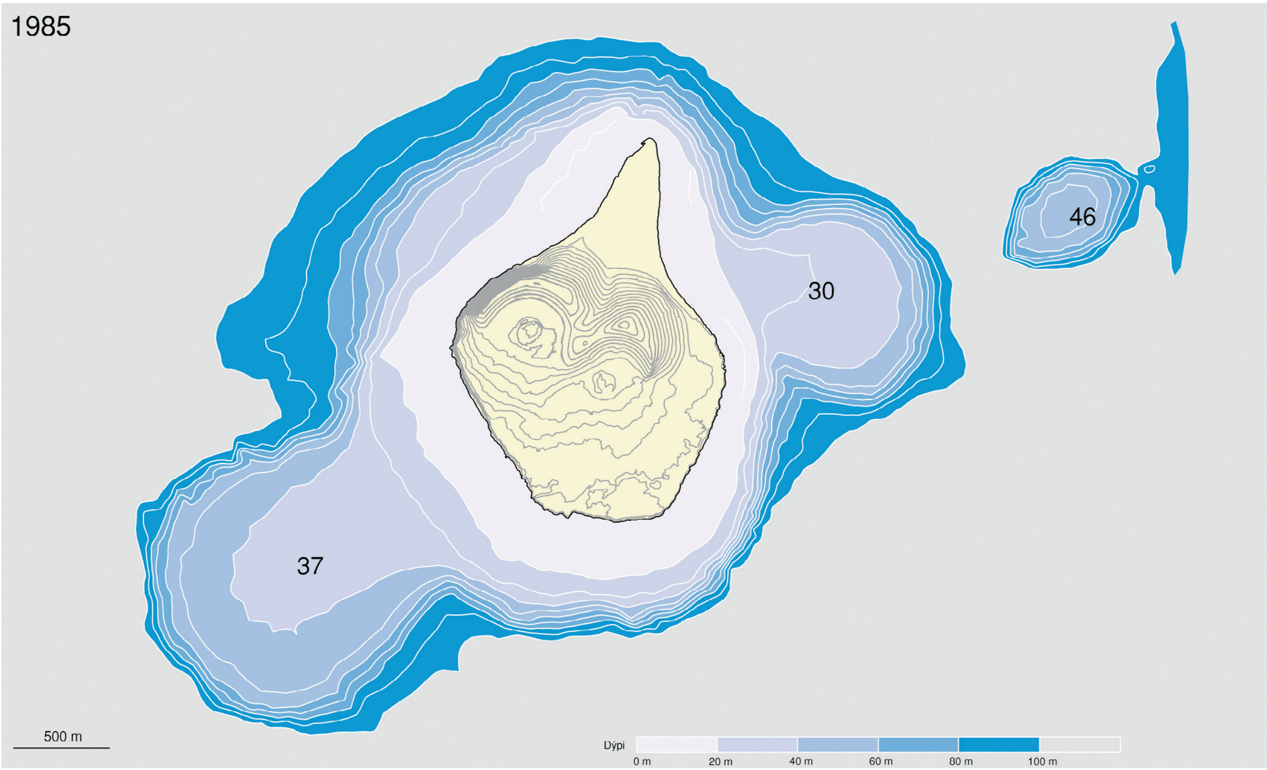
Figure 4. The development of the sea floor topography around Surtsey, 1966–2007. Depth contours at 10 m intervals. See main text for discussion.
A: depth soundings of July–August 1964 (Kjartansson 1966). The topography of Surtsey is based on aerial photographs from August 1964. The irregular shape of Surtla, east northeast of Surtsey, is due to unevenly distributed soundings.



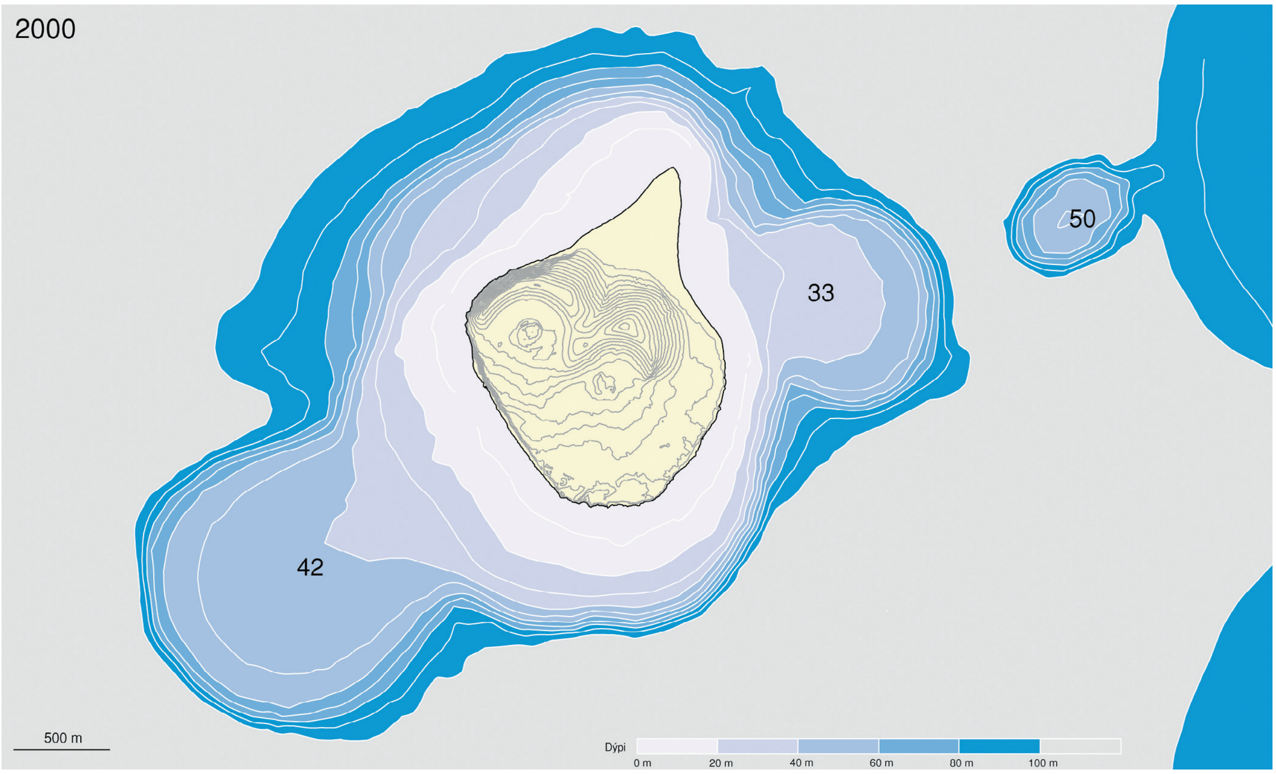
B: depth soundings of July 1967 (Sigurdsson 1968). The topography of Surtsey is based on aerial photographs from August 1967.



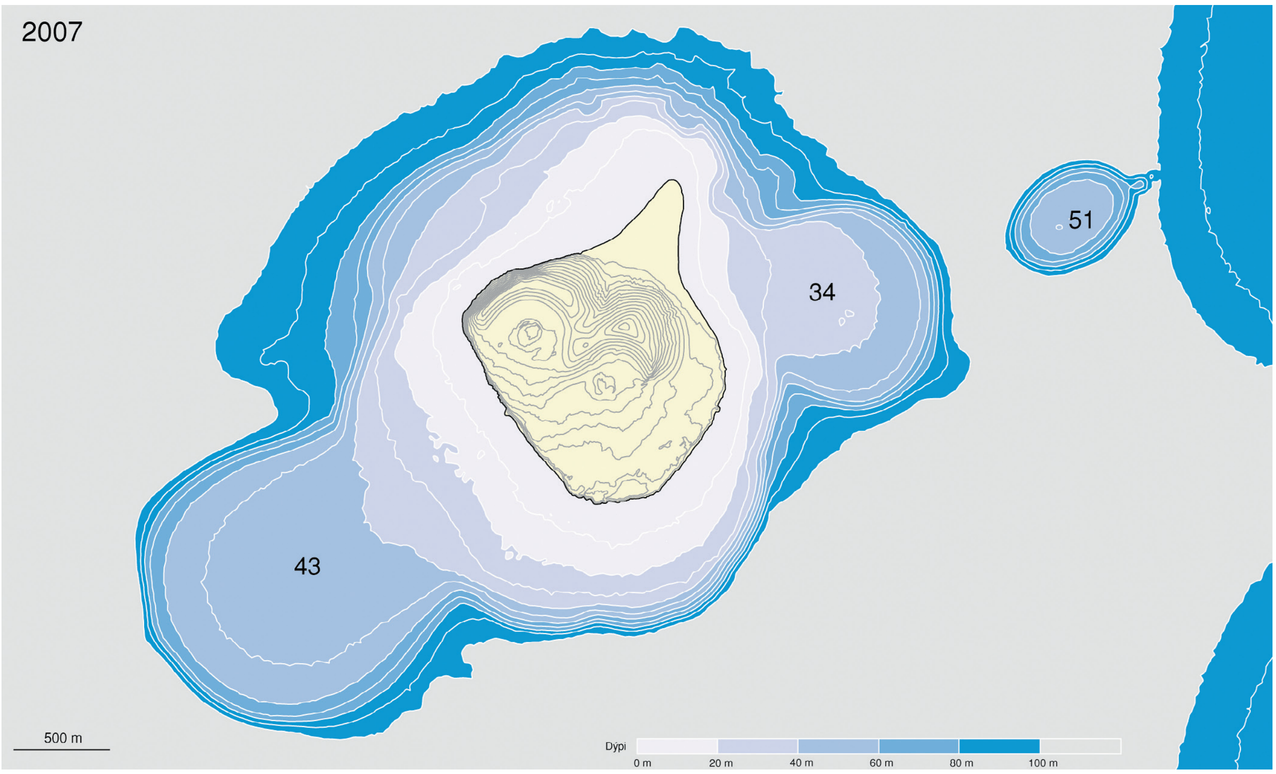
C: depth soundings of July 1973 (Icel. Hydrogr. Service). The topography of Surtsey is based on aerial photographs from July 1975.



D: depth soundings of June 1985 (Icel. Hydrogr. Service). The topography of Surtsey is based on aerial photographs from August 1985.



E: depth soundings of July 2000 (Icel. Hydrogr. Service). The topography of Surtsey is based on aerial photographs from August 2000.



F: depth soundings of July 2007 (Icel. C. G. Hydrogr. Dept.). The topography of Surtsey is based on aerial photographs from August 2007.

Table 1. Depth measurements (m) on Surtla, Syrtlingur and Jólnir, 1964–2007. The dates of disappearance of the islands of Syrtlingur and Jólnir are also listed. See Fig. 5.

Time	Surtla	Syrtlingur	Jólnir	Reference
February 1964	–23			Thórarinsson (1966)
August 1964	–25			Kjartansson (1966)
October 1965		0		Thórarinsson (1969)
October 1966			0	Thórarinsson (1969)
July 1967	–33	–20	–14	Sigurdsson (1968), Norrman (1970)
July 1968		–23	–22	Norrman (1970)
July 1973	–40	–25	–28	Icel. Hydrogr. Service (1973)
June 1985	–46	–31	–36	Icel. Hydrogr. Service (1985)
July 1989	–47	–32	–37	Norrman & Erlingsson (1992)
July 2000	–50	–33	–42	Icel. Hydrogr. Service (2003)
July 2007	–51	–34	–43	Icel. Coast Guard, Hydrogr. Dept. (this report)

The submarine pillow lava field

The deep seafloor immediately to the south of Surtsey is particularly rugged (Fig. 6). The surface is hummocky with small elongated ridges. A hydrographic survey made in July–August 1964 (Fig. 4A) shows topographic highs southwest of Surtsey, and our evidence agrees with suggestions that this feature was formed through submarine extrusion of lava during a period when the western lava crater appeared quiet, between 30 April and 9 July, 1964. This was originally suggested by Einarsson (1965), Kjartansson (1966) and Thórarinsson (1966), and airborne geomagnetic field measurements carried out in 1965 had indicated a magnetized body at this site (Sigurgeirsson 1966). The implication was that the magma had flowed in shallow lava tunnels below the surface of the island. As it degassed on its way it could be extruded as lava on the sea bottom without any explosive activity.

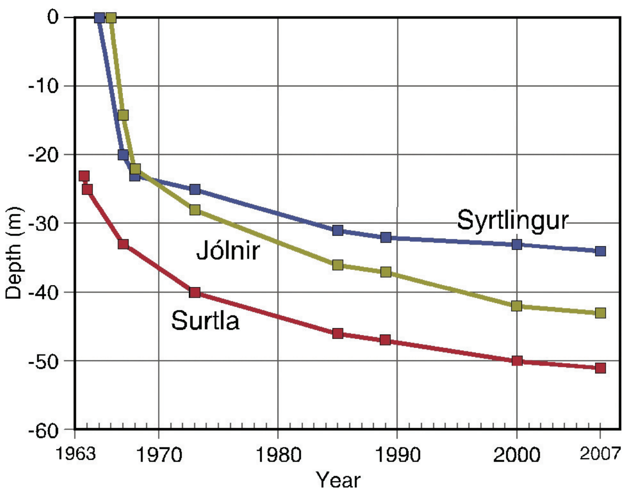


Figure 5. The erosion of the submarine hills of Surtla, Syrtlingur and Jólnir, with reference to mean depth of the top platform, cf. Table 1.

A dredge haul made in 1982 on the flank of the topographic high (Jakobsson 1982) consisted solely of fragments of degassed pillows (Fig. 7). This indicates that the lava was emplaced as pillow lava. A thin section of the lava indicates similarity to the extruded subaerial lavas of 1964 and 1965, which have a higher content of olivine and spinel phenocrysts than the first extrusives of the eruption. This argues against an alternative possibility that this degassed pillow lava was formed on the seafloor at the beginning of the Surtsey eruption in November 1963 (cf. Kjartansson 1966, and Thórarinsson 1966). A seismic reflection profile (Thors & Jakobsson 1982), crosses this area and the younger Jólnir island, showing how the explosive volcanism of Jólnir and its subsequent erosion (see below) have subsequently partly buried the mound of pillow lava. The field of pillow lava, defined by the above evidence (age, dredge sample, magnetic survey), is outlined on Figure 6. It is estimated to have covered an area of 5 km^2 at 74–130 m depth. The pillow lava may possibly reach a thickness of some 60–80 m (see the depth contours of mounds southwest of Surtsey on Figure 4A), but can be estimated to be generally some 20–30 m, indicating a volume of 0.1–0.3 km^3.

Several cases have been described where degassed subaerial lava flows into the sea and continues to flow on the seafloor, in some cases several hundred meters (cf. Moore *et al.* 1973, Moore & Clague 1987). At Thingvellir in the Western Volcanic Zone of Iceland, the postglacial Nesjahraun lava flowed into lake Thingvallavatn and spread out in deep water (Thors 1992).

The erosional platform of Surtsey

The shallow erosional platform around Surtsey is seen (Figs. 3 and 6) to have a rough surface. In the

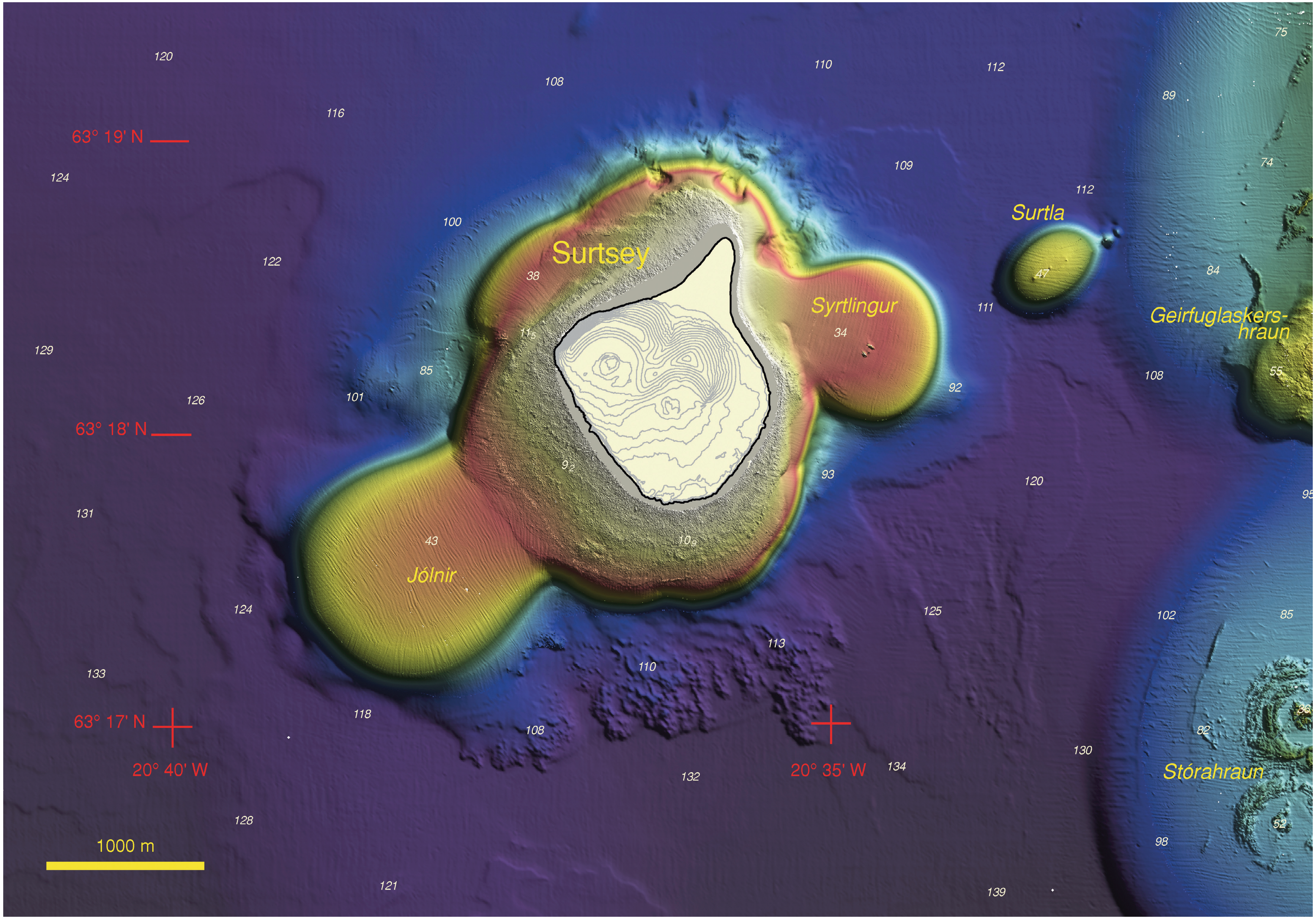


Figure 3. The 2007 bathymetry map of Surtsey volcano and surroundings.

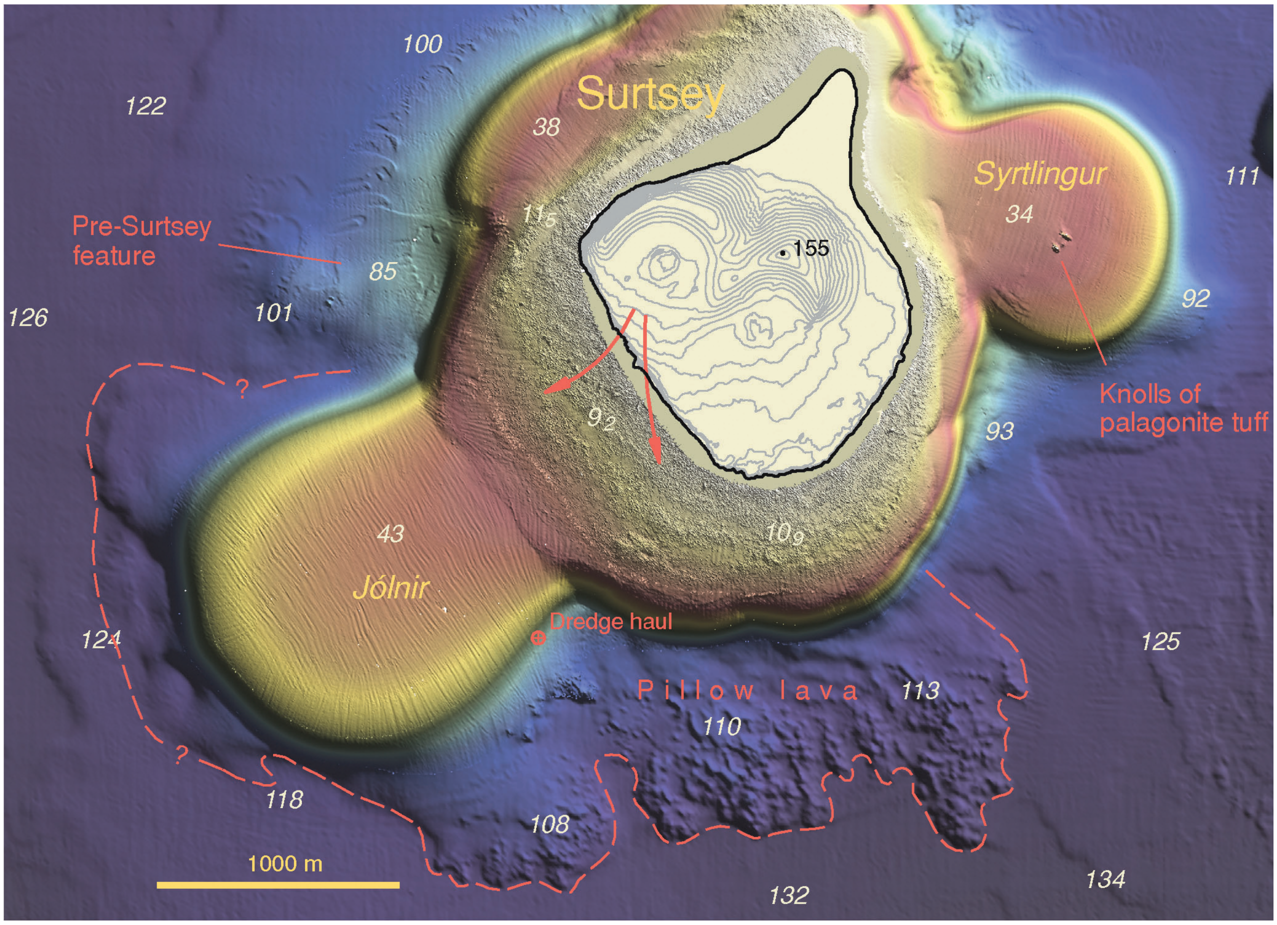


Figure 6. The submarine pillow lava field according to the new map. A cut-out from Figure 3. The estimated extent of the pillow lave is indicated along with flow directions of the lava from the western lava crater Surtungur. The site of the dredge haul of 1982 is shown, taken before the Jólnir mound expanded further due to submarine erosion.

south, this is easy to explain. This is the area where lava flowed into the sea during the eruption, slowly increasing the size of the island. This will have resulted in an accumulation, below sea level, of brecciated and glassy basalt products, while a solid lava was formed above sea level. The submarine material would be easily eroded compared to the lava, and as the post-eruptive coastline was cut back by the enormous waves of winter storms, a spread of large blocks broken from the lava cliffs would be expected on the seafloor, intermixed with the remains of the weaker sublayer.

In the north, lava did not reach the sea during the eruption, so the rough surface of the erosional platform has to be explained partly by blocks and boulders carried from the southern side of the island. In addition to a rocky surface, there appear to be shore-parallel ridge forms in the bottom to the south of the island. These may represent events of erosion, or rocks resistant to erosion.

The rocky nature of the erosional platform underlines the high-energy environment at Surtsey. This is not an area where sediments accumulate in shallow water.

Figure 7. Photograph of a degassed pillow lava fragment, dredged in 1982, sample NI 8068. The position of the dredge is shown in Figure 6.

Slope failure of Surtsey

The northern submarine slope of Surtsey is cut by a few canyons which are indicative of slope failure and sediment transport in the form of debris flow or turbidity currents into deeper water. These features are clearly displayed in Figure 3, which shows three major canyons cut far into the slope. One or two shallower canyons may be identified in the slope.

Although the resolution of the data does not allow one to trace individual sediment flows from shallow to deep water, it seems clear that a number of elongate sediment bodies extend from the bottom of slope out onto the flat seafloor north of Surtsey. This suggests that sediment flow has taken place over a period of time and probably is an ongoing process on the northern submarine slope. The shape of the larger canyons suggests that possibly more than one event of slope failure was responsible for their formation. The easternmost canyon, for example, is a wide, open feature, indicating that initially a large area suffered slope failure. Into the northern part of this feature is cut a smaller canyon which can be traced all the way down slope and into deep water. It seems clear that this is a younger feature, and may serve as a temporary conduit for sediment transport down the slope.

The concentration of submarine canyons at the northern slope calls for an explanation. We suggest that this results from the nature of erosion and resultant sediment transport in shallow water. The chief forces of erosion in Surtsey are the enormous waves occasionally hitting the island from the southwest (cf. above). The erosional debris is washed around the island where some of it goes to the building up, and maintaining, the northern spit. The reminder serves to build up a sediment platform, or terrace. Periods of rapid sedimentation would make the sediment pile unstable and liable to slope failure. Similarly, earthquakes, such as the large ones occurring in southern Iceland in 2000 and 2008 would act as triggers for events of this nature.

This is not the first indication of slope failure at Surtsey. Norrman (1970) described depth measurements off northwestern Surtsey that showed canyons cut into the submarine slope. He also reported on work by a diver, who observed trains of boulders on the slope embedded in sand at the angle of repose. The implication is that this was material waiting for the next event of transport down slope.

Consolidation of the core of Syrtlingur and Surtla

The new bathymetric map shows two prominent knolls on the top platform of Syrtlingur and four on the crest of Surtla (Fig. 3). The Syrtlingur knolls have a length of 40–50 m and rise vertically to a height of 15 m above the surroundings. The Surtla knolls have a diameter of about 20–25 m and appear to rise to a height of 4 m above the surroundings.

The side-scan sonar study of 1989 (Norrman & Erlingsson 1992) had already revealed the presence of these knolls on Surtla and Syrtlingur, although they appeared considerably smaller at that time, due to a lesser degree of erosion of the tephra. A small rock sample was collected from the westernmost knoll on Syrtlingur in 1989 (Norrman & Erlingsson 1992). The sample is of semi-consolidated palagonite tuff. Judging from the degree of palagonitization and formation of secondary minerals, the rock is at the first stage of alteration and consolidation of basaltic tephra to palagonite tuff (Jakobsson 1978, Jakobsson & Moore 1986). The temperature of alteration of the collected sample is tentatively estimated to have been at or below 60 °C. This leads us to conclude that the knolls represent tephra which has undergone palagonitization in the vicinity of the volcanic conduit, and that the higher temperatures caused by this setting led to palagonite-tuff formation to higher level than elsewhere.

The presence of palagonite tuff proves that a hydrothermal system was established in Syrtlingur and Surtla and strongly indicates that the tephra in the core section is consolidated and altered. Norrman & Erlingsson (1992) did not observe any temperature anomalies at Syrtlingur in 1989, so presumably the hydrothermal system had already cooled considerably down at that time. As the other knolls on Syrtlingur and Surtla are of comparable shape and size, it is reasonable to conclude that they are also made up of palagonite tuff. Although no knolls have so far been observed on Jólnir it cannot be ruled that its core is made up of palagonite tuff.

It is of interest to note that an acoustic study in 1989 indicated a prominent seismic reflector in the central parts of Surtla and Jólnir. Norrman & Erlingsson (1992) speculated that this reflector is indicative of a steep temperature gradient, from ambient temperatures to 50–100 °C, at a depth of less than 10 m below the surface. Independently, this could indicate that the lower parts of Surtla and Jólnir are now made up of palagonite tuff. The presence of palagonite tuff in the core section of Syrtlingur, and possibly Surtla and Jólnir, has important implications for the evaluation of the origin of other submarine mounds and ridges which are very common on Vestmannaeyjagrunn (Thors & Helgason 1988).

Erosional (?) features in deep water

The seafloor around Surtsey received a rain of volcanic ash during the eruption and was presumably covered by this material by the end of volcanic activity. One might therefore expect to see around Surtsey a relatively flat seafloor of volcanic sediment, reworked, perhaps, by storm events. The deep bottom (100 to 130 m) illustrated by the bathymetric map is, on the contrary, characterized by low scarps separating relatively flat tracts. Although gradients are very small, some sort of slumping mechanism might be involved. There is, however, no evidence of slumped material down slope from the scarps. Furthermore, the shape of the scarps does not resemble slump scarps. We suggest therefore that the features are erosional in origin.

If the scarps and intervening flat bottom are the result of erosion, it is worth noting that the features appear to be associated with Surtsey, and disappear to the northwest and southeast. This could be taken to stem from stronger currents near the island such as might be expected where a water mass flows around an obstacle.

EVIDENCE OF CURRENT TRANSPORT OF SEDIMENT

The new bathymetric map provides evidence of sediment movement in relatively deep water near Surtsey. Near the northeast corner of the map (Fig. 3) a field of sand waves is seen with wave crests approximately transverse to water movements from the southwest. The sand waves occur in water depths of less than 70 metres to about 90 metres.

ACKNOWLEDGEMENTS

We are most grateful to the Surtsey Research Society for logistic support. Critical reviews of the manuscript by Páll Einarsson and Sigurdur Steinthórsson are greatly appreciated.

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Xenoliths of exotic origin at Surtsey volcano, Iceland

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ABSTRACT

Numerous xenoliths of considerable diversity have been collected from the tephra pile of the Surtsey volcanic island. In total, 102 samples were classified as of foreign origin and studied further. Thin sections were available of 71 samples and they were analysed with the aid of the petrological microscope. The other 31 samples were studied by macroscopic observations. Many of the xenoliths display irregular shapes and have a combination of sharp edges, rough surfaces, and smoothly weathered faces as can be expected from ice-rafted debris (IRD). In addition, the samples are poorly sorted which further suggests IRD origin. Iceberg-producing outlet glaciers north of Iceland are primarily in East Greenland and to a lesser extent on Kvit Øya, Franz Joseph Land, and Novaya Zemlya. By comparing the rock type classification of the samples to bedrock maps of the main iceberg-producing areas, a further indication on origin was established. At least 90% of the samples could be originated from Daugaard-Jensen glacier which is the most fertile iceberg producer north of Iceland and therefore has to be considered the most likely origin of the exotic xenoliths.

INTRODUCTION

Numerous xenoliths have been collected from the volcanic island Surtsey, most of them by scientists at the Icelandic Institute of Natural History. The xenoliths are of considerable diversity, varying from angular basalt rock fragments to well rounded gneiss. More than 100 of the sampled xenoliths are of rock types that cannot be of Icelandic origin.

Rocks of foreign origin in Iceland have for long attracted the attention of nature observers. In the late 18th century, Sveinn Pálsson (1945) noted several rocks around the Iceland coast that he concluded were of foreign origin. Thorvaldur Thoroddsen (1958–1960) observed granite, quartzite and schist on his travel on the North coast of Iceland in 1895. Several other observations of foreign rock types have been documented (Noe-Nygaard 1950, Einarsson 1963, Líndal 1964, Thórarinsson 1966b, Einarsson 1969, Kjartansson 1970, Jóhannesson 2000) and many samples have been collected by scientists at the Icelandic Institute of Natural History (Jakobsson 1982). Clasts of petrological composition foreign to Iceland have been noted in Early Pleistocene rocks in Iceland (e.g. Eiríksson 1981) and in Holocene and Late glacial marine sediments (e.g. Knudsen & Eiríksson 2002, Haflidason *et al.* 2000). It is commonly believed that these rocks were brought to Iceland either as ballast in ships or with icebergs.

This report is based on a B.Sc. thesis submitted at the University of Iceland in the spring 2004 (Reynisson 2004). The aim of the research was to identify the rock types believed to be of foreign origin that were found on Surtsey. Petrological microscopy of thin sections and macroscopical examination of hand specimens were used to classify the rocks and observe morphological properties. The aim was also to propose a likely place of

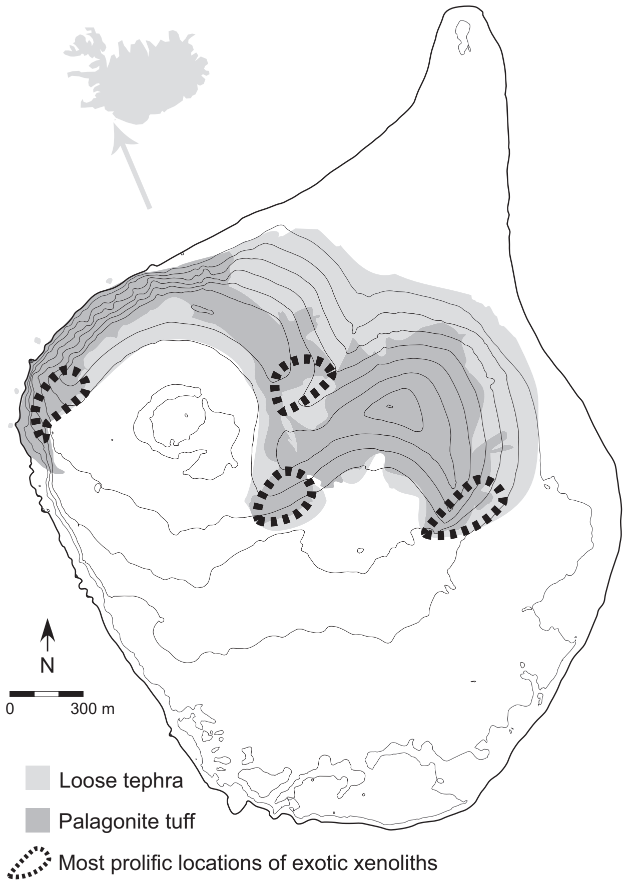

Figure 1. The four most prolific collection areas of exotic xenoliths on Surtsey. All four locations are in the proximity of the border of loose tephra and underlying palagonite tuff. Modified from Jakobsson (2000) and Jakobsson *et al.* (2000).

origin and way of transport for the foreign rock types.

The xenoliths were all found in the tephra (Fig. 1) which formed during the submarine explosive phase of the Surtsey eruption, from November 1963 to April 1964 (Thórarinsson 1966a). The tephra formed two merged crescent-shaped cones. It has been subject to hydrothermal alteration and in 1998 some 80–85% of the remaining tephra pile above sea level had been altered to palagonite tuff (Jakobsson *et al.* 2000).

EXOTIC XENOLITHS ON SURTSEY

All xenoliths from Surtsey which are registered in the rock collection of the Icelandic Institute of Natural History, Reykjavík, were examined and the samples likely to be of foreign origin were analysed further. Coarse-grained rocks apart from gabbro were considered to be of foreign origin, as well as all medium and high grade metamorphic rocks and all sedimentary rocks containing high amounts of quartz or carbonate. A total of 102 samples were classified as of foreign origin. Figure 2 shows some typical samples and variation in kind, shape, and size.

The morphological properties of the chosen samples were examined and classified according to the classification schemes of the British Geological Society (Gillespie *et al.* 1999, Hallsworth & Knox 1999, Robertson 1999). The classification scheme is based as far as possible on actual, descriptive attributes and is essentially non-genetic. The hierarchical approach of the scheme allows a name to be assigned to a rock at the level of the hierarchy most appropriate to the rock type and level of information available. Thin sections were available of 71 samples and they were analysed with the aid of the petrological microscope. The remaining 31 samples were studied by macroscopic observation. Table 1 lists the classification of all the studied samples.

The first sample was found on Surtsey as early as in the summer of 1967 and samples are still being collected. The locations of the findings are very disperse but four areas have been the most prolific (Fig. 1). Most of the xenoliths have been collected immediately under or on the slopes of the two prominent tuff cones. Eolian erosion of both tephra and tuff has been heavy in these areas, leaving xenoliths on the surface.

Sedimentary xenoliths that are believed to be from the ocean floor prior to the eruption have also been found on Surtsey. Observations on fossils from these xenoliths and two carbon age determinations indicate that the xenoliths are Holocene in age (Alexanderson 1972, Símonarson 1974). In addition, about one third of the exotic xenoliths have remnants of a sedimentary coat to some extent. The coat appears to be of the same composition as the sedimentary xenoliths, i.e. volcanic clast. Therefore it is feasible to assume that the exotic xenoliths studied in this report were part of young sediment having accumulated on the sea floor prior to the eruption.

ORIGIN OF THE EXOTIC XENOLITHS

Most of the exotic xenolith samples were classified as pebbles and a few as cobbles (Fig. 3). One sample stands out in terms of size (23x23x17 cm) and is the only exotic xenolith that is big enough to be assumed to be from ballast. All the other samples are too small to be potential ballast. Furthermore it is highly unlikely that a high concentration of ballast is to be found on the ocean bottom in the Surtsey area as it is not close to any harbor.

Icebergs are the main mechanism by which coarse-grained terrestrial debris can be transported to the ocean bottom (Dowdeswell *et al.* 1998, Cofaigh *et al.* 2001). The morphological aspects displayed by the majority of the samples suggest that after they were detached from abraded exposures they were not modified by subsequent abrasion, as can be expected from ice-rafted debris (IRD)

Figure 2. Typical samples of the exotic xenoliths from Surtsey showing the variety in size, shape, and rock type. The top row is a selection of sedimentary rocks, the middle row contains metamorphic rocks and the bottom row represents igneous rocks. Note the irregular shapes and the combination of rough, broken faces and smoothly worn faces. It should be noted that some of the samples have been cut. Numbers are sample numbers of the Icelandic Institute of Natural History, see Table 1.

(Linthout *et al.* 2000). Many samples are of irregular shapes and have a combination of sharp edges, rough surfaces, and smoothly weathered faces. In addition, range of observed sizes is consistent with IRD origin (Dowdeswell *et al.* 1998).

Ocean currents generally control the route icebergs are transported and the drift speed is influenced by winds (Bigg *et al.* 1997). Because ocean currents have not changed much during the Holocene (Bond *et al.* 2001) today's currents are indicative of the routes icebergs have travelled during the Holocene (Fig. 4). Therefore it can be assumed that the origin of the icebergs that deposited the exotic xenoliths is somewhere up-current of the deposition site.

Iceberg-producing outlet glaciers north of Iceland are primarily in East Greenland and to a lesser extent on Kvit Øya, Franz Joseph Land, and Novaya Zemlya (Wadhams 1986). The main contributors to iceberg production in East Greenland are the fast-flowing Daugaard-Jensen and Vestfjord glaciers which calve into Scoresby Sund (Cofaigh *et al.* 2001). Storstrømmen glacier and De Geer glacier are also significant producers of icebergs

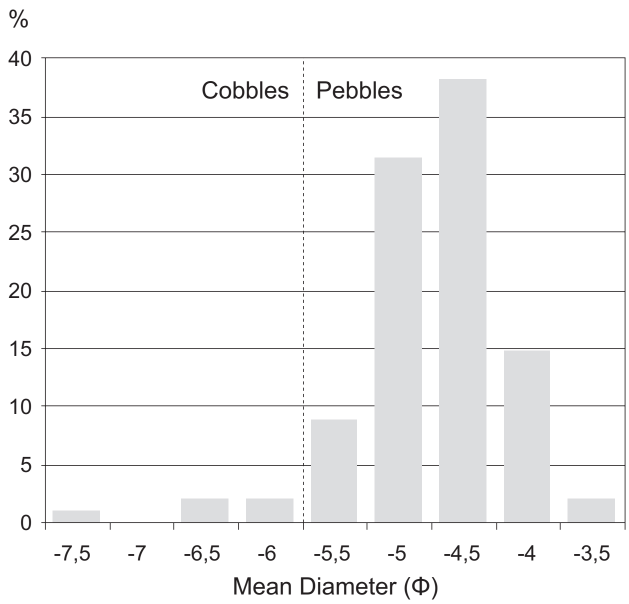

Figure 3. Size distribution of the exotic xenoliths from Surtsey. Most of the samples are pebbles and only a few are cobbles. Vertical axis is percentage of total number of samples. Horizontal axis is the mean diameter of the samples on Phi scale.

Table 1. Principal type classification and assigned rock names of the studied samples. Samples that were studied microscopically have thin section numbers.

Sample No.	Thin Section No.	Principal Type	Rock Name
7971	N-3826	Igneous	Alkali-feldspar-granite
9745	N-1979	Igneous	Alkali-feldspar-granite
9748	N-1981	Igneous	Alkali-feldspar-granite
22960	N-3831	Igneous	Alkali-feldspar-granite
12352		Igneous	Granitic-rock
12356		Igneous	Granitic-rock
9744	N-1978	Igneous	Granodiorite
9753	N-1985	Igneous	Granodiorite
9997		Igneous	Micro-dioritic-rock
10724		Igneous	Micro-dioritic-rock
22877		Igneous	Micro-dioritic-rock
22958		Igneous	Micro-dioritic-rock
9751		Igneous	Micro-granitic-rock
10718	N-3847	Igneous	Micromonzogranite
9756	N-1990	Igneous	Micro-quartz-rich-granitic-rock
9750	N-1986	Igneous	Microsyenogranite
9764	N-1997	Igneous	Microsyenogranite
12375	N-3828	Igneous	Microsyenogranite
13306	N-3861	Igneous	Microsyenogranite
9746	N-3827	Igneous	Monzogranite
11587	N-3851	Igneous	Monzogranite
15381	N-3862	Igneous	Monzogranite
22976	N-3836	Igneous	Monzogranite
9747	N-1980	Igneous	Quartz-alkali-feldspar-syenite
15379		Igneous	Quartz-rich-coarse-grained-crystalline-rock
879	N-1984	Igneous	Syenogranite
7970	N-3845	Igneous	Syenogranite
9743	N-106	Igneous	Syenogranite
9752	N-1983	Igneous	Syenogranite
9763	N-1996	Igneous	Syenogranite
12226	N-2668	Igneous	Syenogranite
13304	N-3859	Igneous	Syenogranite
15387	N-3864	Igneous	Syenogranite
22883	N-3868	Igneous	Syenogranite
22961	N-3835	Igneous	Syenogranite
22968	N-3834	Igneous	Syenogranite
9758	N-1992	Igneous	Tonalite
10723	N-3850	Metamorphic	Biotite-chlorite-garnet-bearing schist
9765	N-1998	Metamorphic	Biotite-muscovite gneiss
15385	N-3863	Metamorphic	Feldspar-amphibole-plagioclase-chlorite-bearing gneiss
20616	N-3865	Metamorphic	Feldspar-plagioclace-epidote-chlorite gneiss
9762	N-1995	Metamorphic	Feldspar-plagioclase-biotite gneiss
9760		Metamorphic	Gneiss
10725		Metamorphic	Gneiss
13308		Metamorphic	Gneiss
12353		Metamorphic	Gneissose granite
10716	N-3828	Metamorphic	Gneissose-biotite-amphibole syenogranite
9766	N-3846	Metamorphic	Gneissose-biotite-myrmekite syenogranite
10717	N-3829	Metamorphic	Gneissose-chlorite-clinopyroxen-muscovite metagranite
9759	N-1993	Metamorphic	Granofelsic-chlorite-bearing metafelsic-rock
9735	N-2007	Metamorphic	Layered-biotite semipelite
13305	N-3860	Metamorphic	Layered-muscovite quartzite
12388		Metamorphic	Lineated semipelite

22957	N-3869	Metamorphic	Lineated-muscovite semipelite
9720	N-2001	Metamorphic	Lineated-muscovite-biotite semipelite
9761	N-1994	Metamorphic	Metacarbonate-rock
10720	N-3849	Metamorphic	Muscovite-biotite-bearing quartzite
22880	N-3867	Metamorphic	Mylonitic-porphyroclastic-muscovite-chlorite-garnet phyllonite
9719	N-1999	Metamorphic	Phyllitic-garnet-bearing semipelite
22966	N-3833	Metamorphic	Phyllitic-muscovite-chlorite semipelite
9757	N-1991	Metamorphic	Porphyroblastic-garnet amphibolite
9721	N-2000	Metamorphic	Pyllitic-muscovite-rich pelite
12355	N-3854	Metamorphic	Quartz-feldspar-muskovite orthogneiss
10726		Metamorphic	Quartzite
12350		Metamorphic	Quartzite
12354		Metamorphic	Quartzite
15384		Metamorphic	Quartzite
15389		Metamorphic	Quartzite
22058	N-3866	Metamorphic	Quartzite
22962		Metamorphic	Quartzite
9755	N-1989	Metamorphic	Quartz-plagioclace-biotite gneiss
21533		Metamorphic	Quartz-rich-medium-grained-crystalline-rock
10719	N-3848	Metamorphic	Slaty-muscovite-epidote semipelite
12368		Sedimentary	Dolomite-sparstone
7973	N-2320	Sedimentary	Dolostone
9723	N-2003	Sedimentary	Dolostone
9727		Sedimentary	Dolostone
11585		Sedimentary	Dolostone
15156		Sedimentary	Dolostone
22977	N-3837	Sedimentary	Feldspathic-wacke
22978	N-3870	Sedimentary	Feldspathic-wacke
11037		Sedimentary	Feldspathic-wacke
12367	N-3856	Sedimentary	Limestone
15157		Sedimentary	Limestone
9732	N-2045	Sedimentary	Lithoclastic feldspathic-arenite
9754	N-1987	Sedimentary	Lithoclastic silicate-mudstone
9733	N-2048	Sedimentary	Organic limestone
9722	N-2002	Sedimentary	Quartz-arenite
9731	N-2006	Sedimentary	Quartz-wacke
12348	N-3852	Sedimentary	Quartz-wacke
12369	N-3857	Sedimentary	Quartz-wacke
9730	N-2005	Sedimentary	Siliciclastic dolostone
11586		Sedimentary	Siliciclastic dolomite-sparstone
9726		Sedimentary	Siliciclastic dolostone
9749	N-1982	Sedimentary	Subfeldspathic-arenite
9734	N-2043	Sedimentary	Subfeldspathic-wacke
15155		Sedimentary	Thin-laminated dolostone
9724	N-2044	Sedimentary	Thin-laminated siliciclastic dolostone
12357		Sedimentary	Very-thin-laminated dolomite-sparstone
12374		Sedimentary	Very-thin-laminated dolostone
22967		Sedimentary	Very-thin-laminated dolostone
9725	N-2004	Sedimentary	Very-thin-laminated siliciclastic dolostone

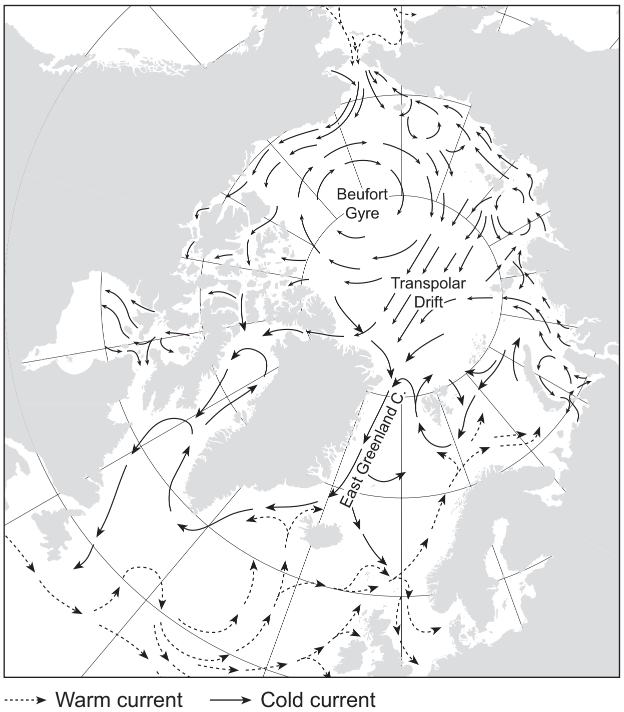

Figure 4. Surface currents in the Arctic region. Modified from AMAP 1998.

in East Greenland (Reeh 2004, Koch 1945). Most icebergs remain at or near their glaciers of origin, because of grounding or because of adverse winds and currents. Fjords which are wide enough to have a gyral circulation can discharge icebergs more easily. Thus the most fertile iceberg-producing fjord in East Greenland is Scoresby Sund. Most icebergs produced on Kvit Øya, Franz Joseph Land, and Novaya Zemlya appear to go aground in the Barents or Kara Seas, and a true iceberg in the ice drift emerging from the Trans-Polar Drift Stream into the East Greenland Current is rare (Wadhams 1986).

By comparing the rock-type classification of the exotic xenoliths from Surtsey to bedrock maps of areas surrounding the aforementioned glaciers, a further indication on origin was established (Escher & Pulvertaft 1995, Dallmann *et al.* 2002, Hjelle 1993, Ministry of Geology of the USSR 1980). The proportion of the exotic xenoliths that can be accounted for in areas surrounding the glaciers of interest, is assumed to be indicative of probable origin of the samples. Figure 5 summarises the results of the comparison. East Greenland offers a wide variety of rock types and the full variation of the samples collected on Surtsey can be traced to rock units exposed in East Greeland. At least 90% of the samples could have originated from Daugaard-Jensen glacier which is the most fertile iceberg producer north of Iceland and therefore that glacier has to be considered the most likely origin of the exotic xenoliths.

ACKNOWLEDGEMENTS

Jón Eiríksson and Sigurdur Steinthórsson are thanked for improvements to this manuscript. We are grateful to the Surtsey Society, Reykjavik, for providing logistic support. Sigurdur Steinthórsson at the University of Iceland and Kristján Jónasson at the Icelandic Institute of Natural History are thanked for valuable assistance in thin section studies and rock type determinations. We are also

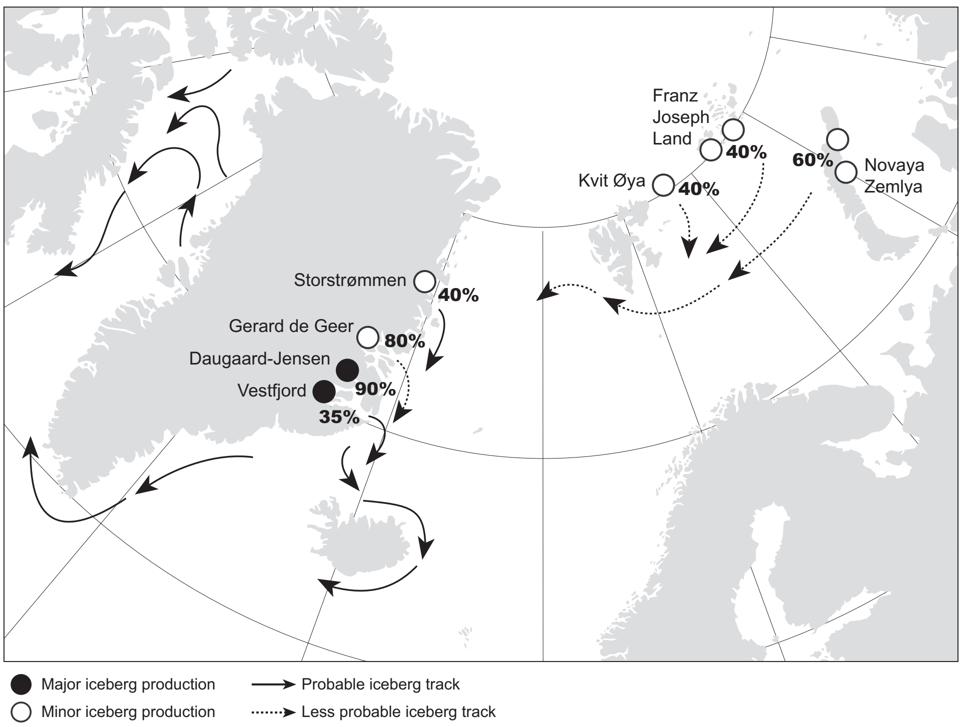

Figure 5. Possible origin of the exotic xenoliths from Surtsey. Numbers refer to the proportion of the exotic xenoliths that match formations shown on bedrock maps of each area. Three distinct factors combine to make Daugaard-Jensen glacier in Greenland the most probable origin of the exotic xenoliths. It is the most productive iceberg producer up-current from Iceland, it calves into Scoresby Sund which is known to release an abundance of icebergs to the East Greenland current and most of the samples from Surtsey can be traced to its surrounding area.

grateful for the help provided by Leifur A. Símonarson at the University of Iceland in identifying fossils from sedimentary xenoliths. We thank Sigurdur Sveinn Jónsson at the Iceland Geosurvey for X-Ray diffraction analysis of one of the samples.

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Chemical composition of hydrothermal water and water-rock interactions on Surtsey volcanic island. A preliminary report

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ABSTRACT

A continuously cored drill hole was drilled on Surtsey in 1979 in order to study the structure of the volcano and the hydrothermal alteration of tephra formed during the Surtsey eruption. The drill hole has provided important insights into the character of the hydrothermal system in the volcano. The basalt tephra in Surtsey has been observed to alter rapidly within the hydrothermal system, concluding with the consolidation of the tephra into palagonite tuff. The temperature in the drill hole has been measured regularly, and samples of water for chemical analysis have been collected occasionally. The composition of the water in the well is basically that of seawater, but shows slight water-rock interaction. In 2002 a hot spring with a temperature of 82°C was discovered on the northwestern shore of the island. The chemical composition of the water in the hot spring shows direct mixing of seawater and rainwater, with some water-rock interaction.

INTRODUCTION

Surtsey island is a part of the Vestmannaeyjar archipelago. It was constructed from the sea floor in a volcanic eruption that lasted from 1963 to 1967 (Thórarinsson 1966, 1969, Thórarinsson et al. 1964). During the hydromagmatic explosive submarine phase of the eruption, from November 1963 to April 1964, basalt tephra was produced. The tephra layers formed two crescent-shaped cones which merged.

The Surtsey eruption evolved from an explosive phase into an effusive phase at the western crater in April 1964. Altogether, seven craters and crater fissures emitted lava between April 1964 and June 1967. The first major effusive phase (1964–1965) produced a lava shield reaching 100 m above sea level, while the second phase (1966–1967) produced a 70 m high lava shield. Together they form a lava field that slopes gently to the south and east. In addition there are five small lava flows on the slopes of Austurbunki (Fig. 1).

Apart from Surtsey, eruptions occurred on the sea floor at three sites. About 2.5 km north-northeast of Surtsey, a submarine tephra ridge, Surtla, was built up in December 1963 and January 1964. At a distance of 0.6 km to the east-northeast of Surtsey, explosive activity formed the island of Syrtlingur in 1965. In 1965–1966 yet another island, called Jólnir, was formed by explosive activity 1 km southwest of Surtsey. Today, however, only submarine platforms remain of these two islands.

Due to heavy marine erosion (Jakobsson et al. 2000), the surface area of Surtsey has been reduced from a maximum of 2.65 km^2 in 1967 to 1.40 km^2 in 2006, and high tuff and lava cliffs have formed. Marine erosion had worn its way to the tuff core at the northwestern cliffs of the island by 1980.

DRILL HOLE SE-1 ON SURTSEY

In the summer of 1979 a continuously cored drill hole was drilled in Surtsey (Jakobsson & Moore 1982). The drill site (Fig. 1) is located at

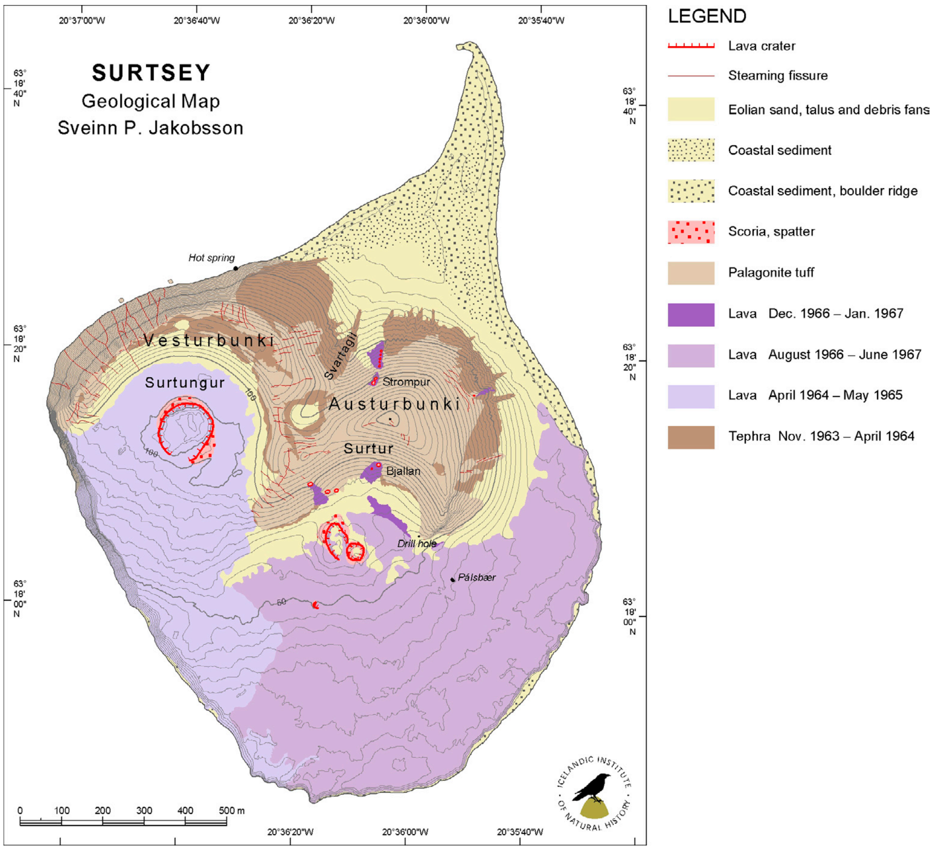

Fig. 1. Geological map of Surtsey, as in 2006. Topography is based on aerial photographs from August 2004. The locations of the drill hole SE-1 and the hot spring are indicated.

Fig. 2. Water sample collected downhole from drill hole SE-1 at Austurbunki in 1990.

the southeastern edge of the Surtur tephra crater, at 58 m above sea level. Figure 2 shows the top of the drill hole in 1990. The total depth of the well was 181 m, and it is believed that the bottom of the hole is only a few meters from the old sea floor. Drilling had to be terminated at this depth due to very loose material from which cores could not be recovered. The well has an steel casing to 165 m depth. The main purpose of the drilling was to obtain a core for studying the structure of the island and the hydrothermal alteration of the tephra formed during the Surtsey eruption. The core has been described in detail by Jakobsson & Moore (1982, 1986).

HYDROTHERMAL ANOMALY

In the spring of 1967, a mild hydrothermal anomaly was discovered at the surface in Austurbunki. The extent of this anomaly is clearly related to the distribution of lava craters (Friedman and Williams 1970). The hydrothermal area at the surface continued to expand until approximately 1979, when the expansion ceased, presumably because tephra consolidation had started to affect the heat flux through the rock. Since about 1995, surface temperatures appear to have been on the decline. Vapour emissions are, however, still visible from many open fissures. In the tuff cones, the highest near-surface temperatures within the hydrothermal area have typically been about 97–

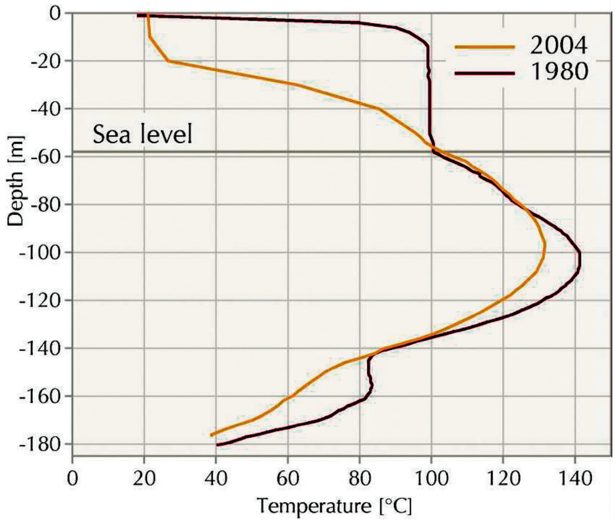

Fig. 3. Temperature measurements in the drill hole in September 1980 and August 2004. The seawater level is at a depth of 58 m. The drill hole is cased down to a depth of 165 m.

100°C, indicating how vapour dominates the heat flux above sea level.

The basalt tephra has been observed to alter rapidly within the hydrothermal portions of Surtsey, concluding with consolidation of the tephra into palagonite tuff, first observed at the surface in 1969. During the alteration process, the original glass shards in the tephra are chemically altered and hydrated to produce palagonite (Jakobsson 1978). A number of chemical elements are released from the original glass in the tephra to form an array of new secondary minerals, which eventually fill the voids in the rock and cement its particles together (Jakobsson & Moore 1986). It is estimated that some 85–90% of the volume of the tephra cones above sea level had been changed to dense palagonite tuff by 2006. Because of this alteration and compaction of the tephra, the rock is considerd to become gradually impermeable, with heat flux mainly taking place along fractures in the rock.

The drill hole has provided important insights into the character of the hydrothermal system in the volcano. These data, along with studies at the surface, strongly suggest that the heat in the hydrothermal system was provided by intrusions which formed both below and above sea level in 1965 and 1966 at Vesturbunki, and in December 1966 and January 1967 at Austurbunki. Lava extrusions in these areas probably contributed as well (Jakobsson & Moore 1982, 1986, Stefánsson et al. 1985, Jakobsson et al. 2000). Temperature logs in the drill hole, shown in Figure 3, indicate a general cooling of the hydrothermal system, with the maximum temperature at 105–110 m depth declining from a calculated value of 154°C in 1966 and 1967 to a measured temperature of 130°C in 2004 (Jakobsson et al. 2000).

Figure 4 shows a cross section of Surtsey, from northwest to southeast. The information on the geometry of the hydrothermal system and the alteration of the tephra is based on observations during the eruption, surface geology, sea floor topography, and drill hole data. It is inferred that cold sea water enters the hydrothermal system through deep porous layers. The water is heated by contact with dikes and intrusions, produces alteration of the tephra, and then rises and presumably flows back into the sea.

In the summer of 2002 a hot spring with a temperature of 78°C was discovered on the northwestern shore (Figs. 5 and 6), where hot water was flowing from a 15–20 m long fissure with a northeasterly trend. In 2006 the temperature was 82°C, but in the summer of 2008 the hot spring proved to be inaccessible, as it was now below sea level, due to marine erosion.

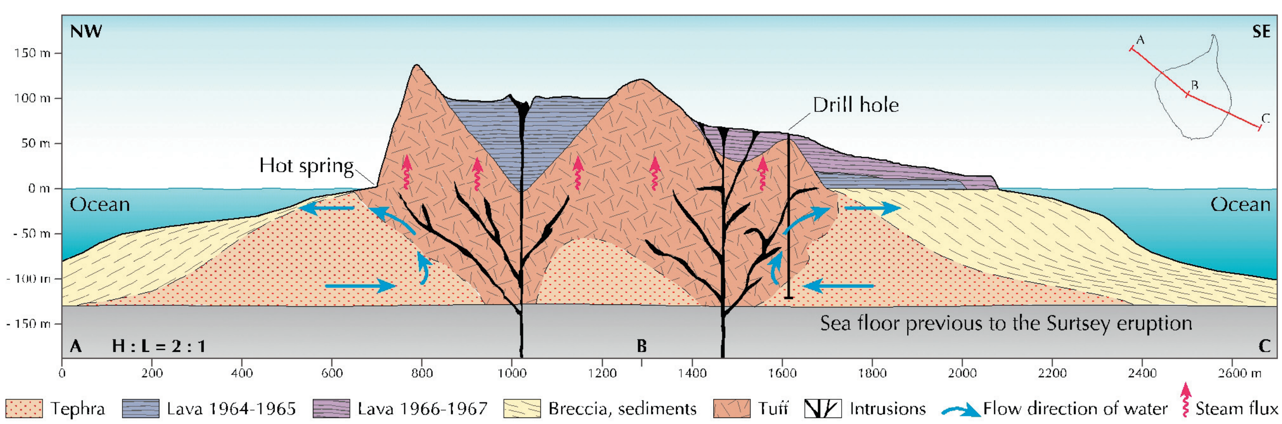

Fig. 4. A cross section through the Surtsey volcano, from northwest to southeast. It is inferred that the tephra within the suggested hydrothermal system is transformed into palagonite tuff.

Fig. 5. The hot spring at the northwestern shore of Surtsey in August 2006. The cliff to the left is made up of palagonite tuff, originally formed as tephra in hydromagmatic explosions in 1964.

Fig. 6. A closer view of the hot spring.

WATER SAMPLES

Sample locations

Samples for chemical analysis of water were collected at several locations on Surtsey from 1985 to 2006. On four occasions samples were collected from drill hole SE-1 (Fig. 2). The samples were collected by a downhole sampler at two depth intervals in the drill hole, at 55 to 65 m depth, close to the water level, and at 167 to 177 m depth, below the well casing. All the samples from the drill hole are listed in Table 1. Water level monitoring has revealed that the tidal amplitude in the well is about 80% of the amplitude in the surrounding ocean.

Table 1. Water samples collected on Surtsey 1985 to 2006.

Sample id.	*Date*	*Depth (m)*	*Sample id.*	*Date*
Drill hole ~ 55 m depth			*Dug pit*	
19850230	1985-08-05	55	19850234	1985-08-06
19850231	1985-08-05	65	19860099	1986-07-17
19850232	1985-08-05	55	19860100	1986-07-18
19860094	1986-07-17	58	19860101	1986-07-18
			19880100	1988-08-11
Drill hole ~ 175 m depth			*Seawater*	
19860095	1986-07-16	167	19850233	1985-08-05
19860096	1986-07-16	170	19880101	1988-08-10
19860097	1986-07-17	177	*Rainwater*	
19880103	1988-08-10	176	19880102	1988-08-10
19900241	1990-09-24	176	*Hot spring*	
			20020204	2002-08-17
			20060517	2006-08-12

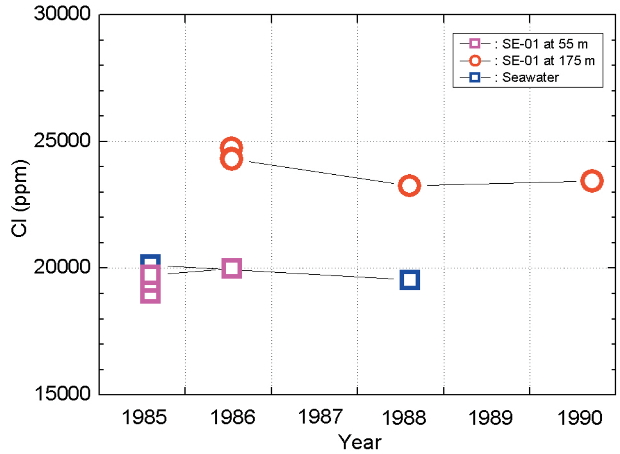

Fig. 7. Chloride content of samples from drill hole SE-1 at the depth intervals 55–65 m and 167–177 m. The concentration of chloride in coastal seawater at Surtsey is shown for comparison.

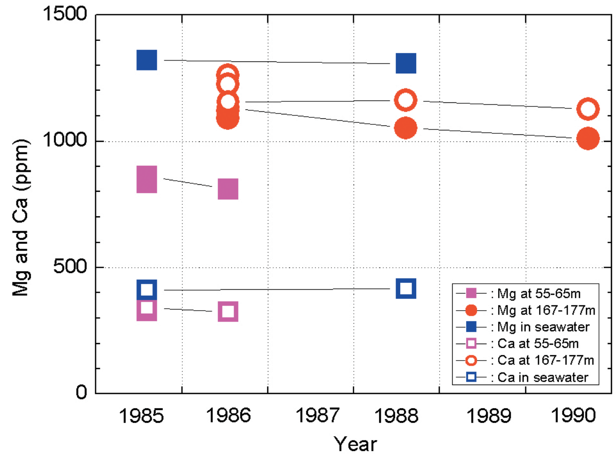

Fig. 8. Magnesium and calcium content of samples from drill hole SE-1 at the depth intervals 55–65 m and 167–177 m. The concentration of these elements in coastal seawater at Surtsey is shown for comparison.

Samples for chemical analysis were also collected from a pit that was dug on the flat northern end of Surtsey. The pit was dug primarily to study the tidal phase delay and amplitude difference between Surtsey and the Vestmannaeyjar harbour. Samples of coastal seawater were also collected, as were samples of rainwater from the roof of the Pálsbaer hut. Finally, two samples from a recently discovered hot spring at Vesturbunki were collected in 2002 and 2006 (Fig. 4). These samples are also listed in Table 1.

The water samples collected on Surtsey were analysed for various elements. Some were analysed for all major elements including pH and carbonates, whereas others were only analysed for salinity and a few other components.

Samples from drill hole SE-1

Water samples for chemical analysis were collected from the drill hole with a downhole sampler in 1985, 1986, 1988 and 1990. Four samples were collected at the depth interval 55 to 65 m, a few meters below the water level in the well. The water at this level is not in any direct contact with the rock, since the drill hole is cased to 165 m, as previously stated. These samples are thus not thought to participate in any water-rock interaction, and they were only collected because of difficulties with

Table 2. Chemical composition of water samples from the drill hole SE-1 at 55 to 65 m depth (ppm).

Sample id.	*19850230*	*19850231*	*19850232*	*19860094*
Date	1985-08-05	1985-08-05	1985-08-05	1986-07-17
Depth (m)	55	65	55	58
SiO_2	11.4	10.2	11.0	7.47
B				5.0
Li				0.27
Na	10940	10970	11033	11210
K	475	493	494	580
Mg	835	861	861	810
Ca	327	346	340	325
Sr				7.34
F	0.69	0.70	0.70	0.63
Cl	19003	19440	19732	19980
Br	68.9	69.9	70.2	
SO_4	1460	1407	1436	1342
Fe				1.04
TDS	35760	36574	36634	36650
$\delta^{18}O$ ‰				6.72

Table 3. Chemical composition of water samples from the drill hole SE-1 at 167 to 177 m depth (ppm).

Sample id.	*19860095*	*19860096*	*19860097*	*19880103*	*19900241*
Date	1986-07-16	1986-07-16	1986-07-17	1988-08-10	1990-09-24
Depth (m)	167	170	177	176	176
pH / °C	8.59/24.1	8.56/23.9	8.12/24.5	8.34/22.6	8.31/23.8
CO_2 (total carbonate)	15.8	15.8	46.5	14.9	8.8
H_2S (total sulphide)	< 0.03	< 0.03	< 0.03	< 0,03	< 0.03
SiO_2	0.99	1.10	9.54	2.47	8.40
B	4.36	4.42	4.54		4.10
Li	0.22	0.20	0.20	0.24	
Na	13291	13426	13245	12715	12337
K	662	679	695	564	520
Mg	1091	1120	1134	1052	1010
Ca	1226	1261	1156	1162	1127
Sr	12.1	11.7	10.1		
F	0.37	0.36	0.48	0.39	0.40
Cl	24322	24745	24296	23250	23440
SO_4	2972	3097	3057	2581	2726
Br				78.9	79.3
Fe	0.20	0.17	0.14	0.025	
TDS	48310	49390	48610	42950	43730
$\delta^{18}O$ ‰	1.37	1.13	1.38	1.25	

sampling the well at deeper levels. However, five samples were collected in the depth interval of 167 to 177 m. The temperature in the upper depth interval is approximately 100°C but the temperature at 167 to 177 m depth is approximately 50 to 70°C, as shown in Figure 3. The results of the chemical analyses from the drill hole are presented in Tables 2 and 3.

The thermal water from the drill hole is seawater with a chloride concentration similar to that of

Table 4. Chemical composition of water samples from the dug pit (ppm).

Sample id.	*19850234*	*19860099*	*19860100*	*19860101*	*19880100*
Date	1985-08-06	1986-07-17	1986-07-18	1986-07-18	1988-08-11
pH / °C	8.30 / 23.9				8.33 / 22.2
CO_2 (total carbonate)	87.5				46.1
H_2S (total sulphide)	< 0.03				< 0.03
SiO_2	4.97	5.41	6.89	6.89	6.38
B		3.30			
Li		0.13	0.04	0.04	0.05
Na	7037	6899	1380	1462	2207
K	319	321	69.8	75.5	106
Mg	847	771	154	154	209
Ca	258	260	46.9	49.1	75.6
Sr		3.92	0.80	0.80	
F	1.22	0.80	1.43	1.43	2.52
Cl	12555	12432	2501	2638	3553
SO_4	1822	1615	342	358	838
Br	44.3				12.1
NO_3					2.13
Fe		0.30			0.025
TDS	24737	24630	4965	5265	7141

Table 5. Chemical composition of samples of seawater and rainwater collected on Surtsey (ppm).

Sample id.	*19850233*	*19880101*	*19880102*
Date	1985-08-05	1988-08-10	1988-08-10
	seawater	seawater	rainwater
pH / °C	8.25/23.3	8.22/22.1	
CO_2 (total carbonate)	102	103	
H_2S (total sulphide)	< 0.03	< 0.03	
SiO_2	0.03	0.27	0.52
Li		19.0	
Na	10757	10836	153
K	452	452	6.28
Mg	1320	1307	17.9
Ca	410	417	7.26
F	0.86	0.63	0.017
Cl	20130	19530	281
SO_4	2684	2738	34.9
Br	70.6	68.1	0.83
NO_3			0.28
Fe	0.17	< 0.025	
TDS	39512	38040	503

the seawater at the island shore. The samples show that the concentration of the major elements at these two depth intervals is relatively stable over the period studied. Figure 7 shows the chloride concentration in the water, and Figure 8 shows the magnesium and calcium content of the water. The content of these elements in seawater at Surtsey are also shown for comparison.

Samples from the dug pit

During the expeditions to Surtsey in 1985, 1986, and 1988, pits were dug into the central part of the peninsula extending north from the main part of the island. The main purpose of the pits was to study differences in tidal amplitude and phase between Surtsey and the Vestmannaeyjar harbour. The pits were deep enough to collect water for chemical analysis, and the results are shown in Table 4. The water samples collected from the pit had chloride content ranging from 2500 to 12500 ppm, which indicated direct mixing between rain water and seawater as discussed below.

Samples of coastal seawater and rainwater

Two samples of seawater were collected on the eastern shore of Surtsey, one in 1985 and another one in 1988. A sample of rainwater was collected from the roof of the Pálsbaer hut in 1988. The results are shown in Table 5. The chloride content of the seawater at Surtsey is slightly higher than that of standard mean ocean water (SMOW), which has a chloride content of 19400 ppm. The rainwater samples displayed a high concentration of dissolved solids, indicating the influence of seawater spray.

Table 6. Chemical composition of water samples from the hot spring (ppm).

Sample id.	*20020204*	*20060517*
Date	2002-08-17	2006-08-12
Flow rate (L/s)	~0.1	~0.1
Temp. (°C)	78.0	82.4
pH / °C		7.53 / 23.9
CO_2 (total carbonate)		30.5
H_2S (total sulphide)		< 0.03
TDS		22410
SiO_2	43.8	25.9
Na	3035	6730
K	134	327
Mg	55.3	261
Ca	386	726
Sr		4.66
F	6.51	2.12
Cl	3160	11360
SO_4	3120	2160
Br	10.2	
Fe		0.0296
Al		0.111
Ba		0.0528
Co		0.00006
Cr		0.00041
Cu		0.00105
Mn		0.0454
Mo		1.03
Ni		0.00051
Pb		0.00033
Zn		0.00211

Samples from the hot spring at Vesturbunki

In the summer of 2002, a hot spring with a temperature of 78°C was discovered at sea level at the nortwestern shore of Vesturbunki. The spring is shown in Figs. 4 and 5. A water sample was collected from the spring, see Table 6. In the summer of 2006, another sample was collected from the same spring. At this time the temperature was found to be 82°C, and the flow rate was estimated as 0.1 L/s. The sampling was difficult, and the chemical analyses show the mixing of seawater and spring water. In the summer of 2008 the hot spring was inaccessible, as it was then below sea level.

CHEMICAL COMPOSITION OF THE WATER SAMPLES

The thermal waters collected on Surtsey are of seawater origin. The chemical composition of some samples can best be explained by the direct

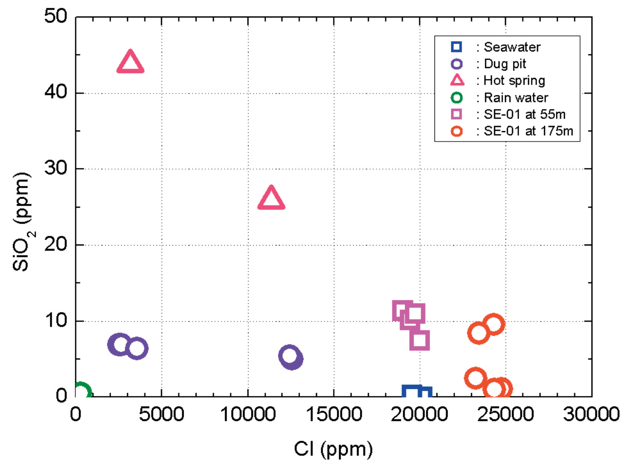

Fig. 9. The relationship between chloride and silica in all water samples.

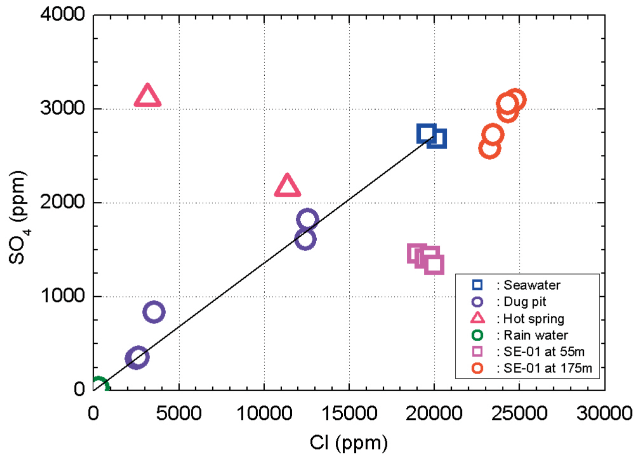

Fig. 10. The relationship between chloride and sulphate in all water samples. The line indicates direct mixing of rainwater and seawater.

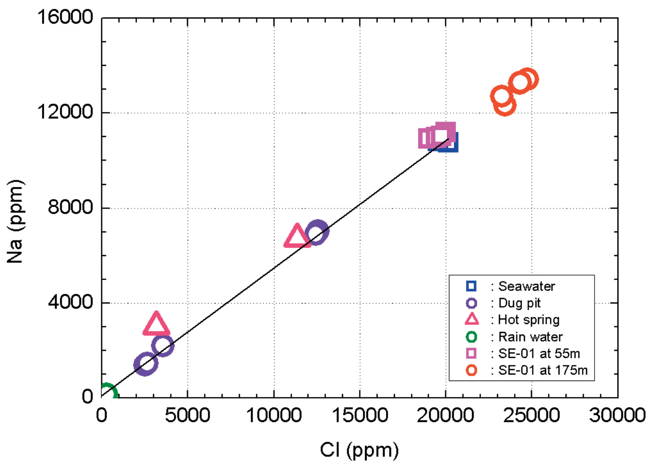

Fig. 11. The relationship between chloride and sodium in all water samples. The line indicates direct mixing of rainwater and seawater.

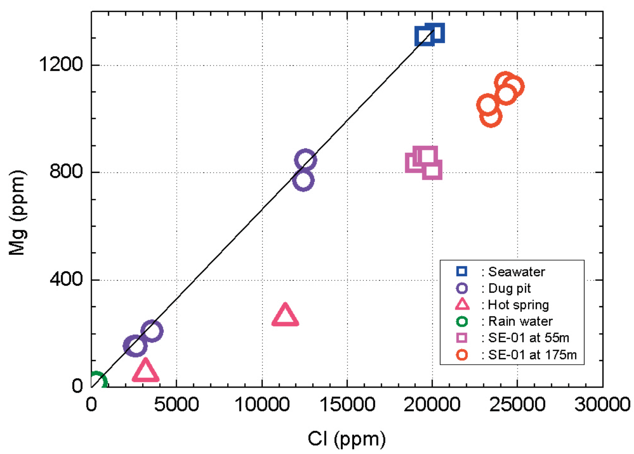

Fig. 12. The relationship between chloride and magnesium in all water samples. The line indicates direct mixing of rainwater and seawater.

mixing of seawater and rainwater. Other samples, however, show evidence of ion exchange with the host rock. This is especially true of the higher temperature waters.

The salinity of the water at the upper depth level, close to the water level in the drill hole, is almost identical to that of the coastal seawater, whereas the samples collected at lower temperature and close to the bottom of the well have approximately 20% higher salinity (Fig. 7).

This increase in salinity is probably an indirect consequence of the palagonitization of the tephra. During the alteration process, hydration of the basaltic glass removes some of the water from the pore fluid, leaving the chloride still dissolved. This, in effect, increases the chloride concentration in the fluid that is in contact with the tephra at the deeper level. The water at the upper depth level is unaffected, however, because it is wholly contained within the casing and has no direct contact with the tephra.

The relationship between chloride and some other major elements in the water samples is shown in Figs. 9 to 14. It is evident from these figures that the chemical composition of waters from the dug pits can best be explained by direct mixing of seawater with rainwater. Waters from drill hole SE-1 and from the hot spring at Vesturbunki show water-rock interactions, however.

The silica content shown in Figure 9 is slightly elevated with respect to seawater in samples from the drill hole, but it is below 10 ppm in all other samples expect the ones from the hot spring. The hot spring samples display an increase in the sulphate concentration, in contrast to the samples from the drill hole (Fig. 10), whose sulphate concentration falls below the mixing line. The concentration of sodium in all water samples (Fig. 11) falls directly on a mixing line between seawater and rain water. Samples from the hot spring and from the drill hole all show a decrease in Mg content (Fig. 12), most likely due to the formation of Mg-rich clays as an

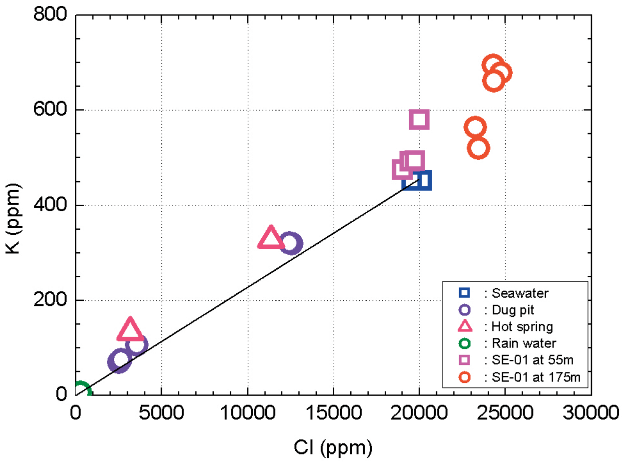

Fig. 13. The relationship between chloride and potassium in all water samples. The line indicates direct mixing of rainwater and seawater.

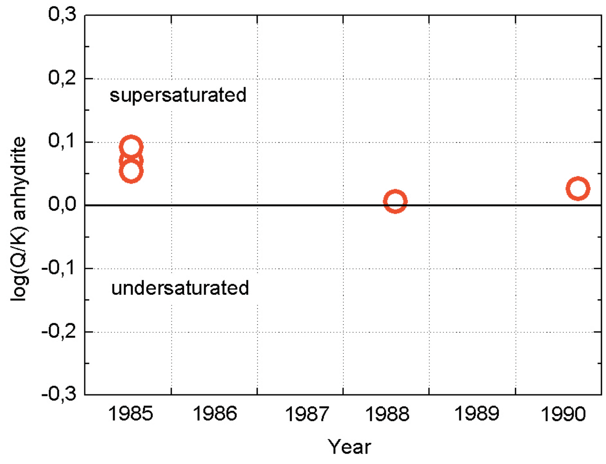

Fig. 15. Saturation index for anhydrite in water samples from 167 to 177 m depth in drill hole SE-1. Reference temperature for calculations is 50°C.

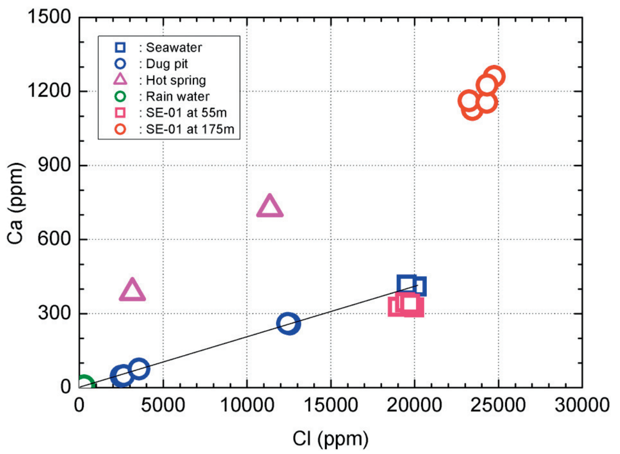

Fig. 14. The relationship between chloride and calcium in all water samples. The line indicates direct mixing of rainwater and seawater.

alteration product in the surrounding rock. There is a slight increase in potassium content compared to direct mixing as shown in Figure 13. The water samples from the lower depth interval in the drill hole and the hot spring samples all have a greatly increased concentration of calcium (Fig. 14).

The saturation index for anhydrite ($CaSO_4$) calculated for the samples from the lower depth interval in the drill hole is shown in Figure 15. The reference temperature is 50°C, which was approximately the temperature at 170 m depth in 1985. The calculations indicate that the water is very close to equilibrium with anhydrite in the rock.

Anhydrite is found scattered throughout the drill core of hole SE-1, and is most abundant near the bottom of the hole where the average alteration temperature of the tephra between 1967–1979 was < 40°C (Jakobsson & Moore 1986). The anhydrite apparently precipitated directly when inflowing sea water was heated, thus lowering the sulfate solubility. Comparable deposition of anhydrite occurs in the Reykjanes thermal brine (Tómasson & Kristmannsdóttir 1972).

ACKNOWLEDGEMENTS

Kristján Hrafn Sigurdsson, Jón Benjamínsson, Jósef Hólmjárn and Reynir Fjalar Reynisson are thanked for collecting water samples from Surtsey and Jón Örn Bjarnason for discussions and improving the manuscript. We are most grateful to the Surtsey Research Society and to the Icelandic Coast Guard for logistic support and to the Icelandic Institute of Natural History, Orkustofnun and Iceland GeoSurvey for financial support. Water samples were analyzed at the Orkustofnun and Iceland GeoSurvey laboratory and stable isotopes at the University of Iceland.

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Chemical composition of hydrothermal water and water-rock interactions on Surtsey volcanic island. A preliminary report

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ABSTRACT

A continuously cored drill hole was drilled on Surtsey in 1979 in order to study the structure of the volcano and the hydrothermal alteration of tephra formed during the Surtsey eruption. The drill hole has provided important insights into the character of the hydrothermal system in the volcano. The basalt tephra in Surtsey has been observed to alter rapidly within the hydrothermal system, concluding with the consolidation of the tephra into palagonite tuff. The temperature in the drill hole has been measured regularly, and samples of water for chemical analysis have been collected occasionally. The composition of the water in the well is basically that of seawater, but shows slight water-rock interaction. In 2002 a hot spring with a temperature of 82°C was discovered on the northwestern shore of the island. The chemical composition of the water in the hot spring shows direct mixing of seawater and rainwater, with some water-rock interaction.

INTRODUCTION

Surtsey island is a part of the Vestmannaeyjar archipelago. It was constructed from the sea floor in a volcanic eruption that lasted from 1963 to 1967 (Thórarinsson 1966, 1969, Thórarinsson et al. 1964). During the hydromagmatic explosive submarine phase of the eruption, from November 1963 to April 1964, basalt tephra was produced. The tephra layers formed two crescent-shaped cones which merged.

The Surtsey eruption evolved from an explosive phase into an effusive phase at the western crater in April 1964. Altogether, seven craters and crater fissures emitted lava between April 1964 and June 1967. The first major effusive phase (1964–1965) produced a lava shield reaching 100 m above sea level, while the second phase (1966–1967) produced a 70 m high lava shield. Together they form a lava field that slopes gently to the south and east. In addition there are five small lava flows on the slopes of Austurbunki (Fig. 1).

Apart from Surtsey, eruptions occurred on the sea floor at three sites. About 2.5 km north-northeast of Surtsey, a submarine tephra ridge, Surtla, was built up in December 1963 and January 1964. At a distance of 0.6 km to the east-northeast of Surtsey, explosive activity formed the island of Syrtlingur in 1965. In 1965–1966 yet another island, called Jólnir, was formed by explosive activity 1 km southwest of Surtsey. Today, however, only submarine platforms remain of these two islands.

Due to heavy marine erosion (Jakobsson et al. 2000), the surface area of Surtsey has been reduced from a maximum of 2.65 km^2 in 1967 to 1.40 km^2 in 2006, and high tuff and lava cliffs have formed. Marine erosion had worn its way to the tuff core at the northwestern cliffs of the island by 1980.

DRILL HOLE SE-1 ON SURTSEY

In the summer of 1979 a continuously cored drill hole was drilled in Surtsey (Jakobsson & Moore 1982). The drill site (Fig. 1) is located at

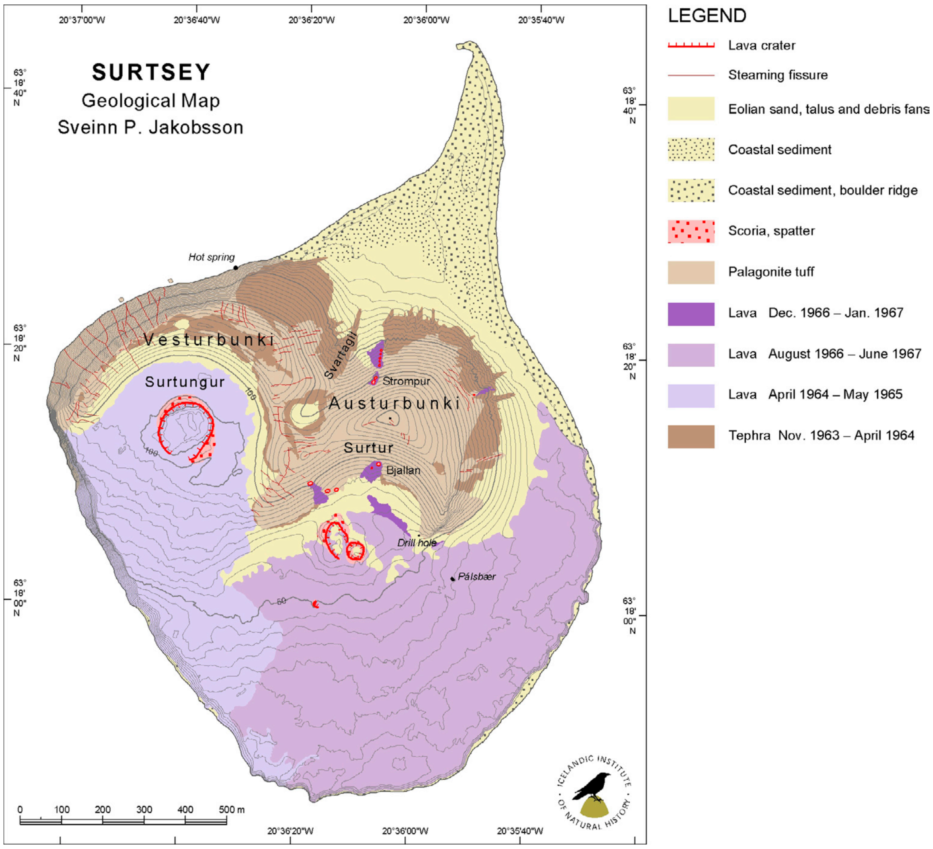

Fig. 1. Geological map of Surtsey, as in 2006. Topography is based on aerial photographs from August 2004. The locations of the drill hole SE-1 and the hot spring are indicated.

Fig. 2. Water sample collected downhole from drill hole SE-1 at Austurbunki in 1990.

the southeastern edge of the Surtur tephra crater, at 58 m above sea level. Figure 2 shows the top of the drill hole in 1990. The total depth of the well was 181 m, and it is believed that the bottom of the hole is only a few meters from the old sea floor. Drilling had to be terminated at this depth due to very loose material from which cores could not be recovered. The well has an steel casing to 165 m depth. The main purpose of the drilling was to obtain a core for studying the structure of the island and the hydrothermal alteration of the tephra formed during the Surtsey eruption. The core has been described in detail by Jakobsson & Moore (1982, 1986).

HYDROTHERMAL ANOMALY

In the spring of 1967, a mild hydrothermal anomaly was discovered at the surface in Austurbunki. The extent of this anomaly is clearly related to the distribution of lava craters (Friedman and Williams 1970). The hydrothermal area at the surface continued to expand until approximately 1979, when the expansion ceased, presumably because tephra consolidation had started to affect the heat flux through the rock. Since about 1995, surface temperatures appear to have been on the decline. Vapour emissions are, however, still visible from many open fissures. In the tuff cones, the highest near-surface temperatures within the hydrothermal area have typically been about 97–

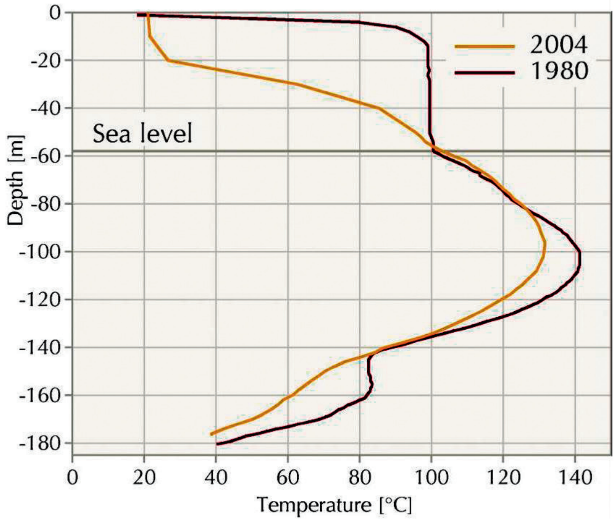

Fig. 3. Temperature measurements in the drill hole in September 1980 and August 2004. The seawater level is at a depth of 58 m. The drill hole is cased down to a depth of 165 m.

100°C, indicating how vapour dominates the heat flux above sea level.

The basalt tephra has been observed to alter rapidly within the hydrothermal portions of Surtsey, concluding with consolidation of the tephra into palagonite tuff, first observed at the surface in 1969. During the alteration process, the original glass shards in the tephra are chemically altered and hydrated to produce palagonite (Jakobsson 1978). A number of chemical elements are released from the original glass in the tephra to form an array of new secondary minerals, which eventually fill the voids in the rock and cement its particles together (Jakobsson & Moore 1986). It is estimated that some 85–90% of the volume of the tephra cones above sea level had been changed to dense palagonite tuff by 2006. Because of this alteration and compaction of the tephra, the rock is considerd to become gradually impermeable, with heat flux mainly taking place along fractures in the rock.

The drill hole has provided important insights into the character of the hydrothermal system in the volcano. These data, along with studies at the surface, strongly suggest that the heat in the hydrothermal system was provided by intrusions which formed both below and above sea level in 1965 and 1966 at Vesturbunki, and in December 1966 and January 1967 at Austurbunki. Lava extrusions in these areas probably contributed as well (Jakobsson & Moore 1982, 1986, Stefánsson et al. 1985, Jakobsson et al. 2000). Temperature logs in the drill hole, shown in Figure 3, indicate a general cooling of the hydrothermal system, with the maximum temperature at 105–110 m depth declining from a calculated value of 154°C in 1966 and 1967 to a measured temperature of 130°C in 2004 (Jakobsson et al. 2000).

Figure 4 shows a cross section of Surtsey, from northwest to southeast. The information on the geometry of the hydrothermal system and the alteration of the tephra is based on observations during the eruption, surface geology, sea floor topography, and drill hole data. It is inferred that cold sea water enters the hydrothermal system through deep porous layers. The water is heated by contact with dikes and intrusions, produces alteration of the tephra, and then rises and presumably flows back into the sea.

In the summer of 2002 a hot spring with a temperature of 78°C was discovered on the northwestern shore (Figs. 5 and 6), where hot water was flowing from a 15–20 m long fissure with a northeasterly trend. In 2006 the temperature was 82°C, but in the summer of 2008 the hot spring proved to be inaccessible, as it was now below sea level, due to marine erosion.

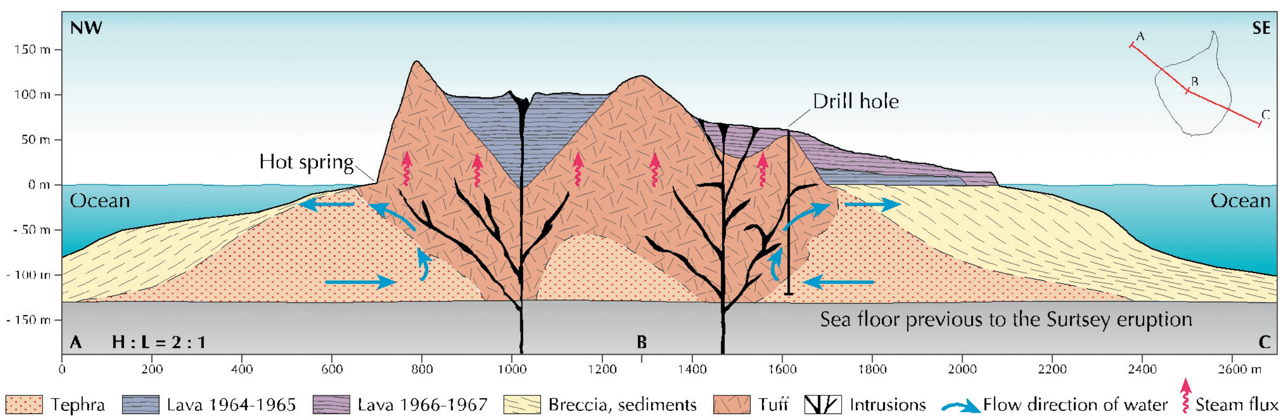

Fig. 4. A cross section through the Surtsey volcano, from northwest to southeast. It is inferred that the tephra within the suggested hydrothermal system is transformed into palagonite tuff.

Fig. 5. The hot spring at the northwestern shore of Surtsey in August 2006. The cliff to the left is made up of palagonite tuff, originally formed as tephra in hydromagmatic explosions in 1964.

Fig. 6. A closer view of the hot spring.

WATER SAMPLES

Sample locations

Samples for chemical analysis of water were collected at several locations on Surtsey from 1985 to 2006. On four occasions samples were collected from drill hole SE-1 (Fig. 2). The samples were collected by a downhole sampler at two depth intervals in the drill hole, at 55 to 65 m depth, close to the water level, and at 167 to 177 m depth, below the well casing. All the samples from the drill hole are listed in Table 1. Water level monitoring has revealed that the tidal amplitude in the well is about 80% of the amplitude in the surrounding ocean.

Table 1. Water samples collected on Surtsey 1985 to 2006.

Sample id.	*Date*	*Depth (m)*	*Sample id.*	*Date*
Drill hole ~ 55 m depth			*Dug pit*	
19850230	1985-08-05	55	19850234	1985-08-06
19850231	1985-08-05	65	19860099	1986-07-17
19850232	1985-08-05	55	19860100	1986-07-18
19860094	1986-07-17	58	19860101	1986-07-18
			19880100	1988-08-11
Drill hole ~ 175 m depth			*Seawater*	
19860095	1986-07-16	167	19850233	1985-08-05
19860096	1986-07-16	170	19880101	1988-08-10
19860097	1986-07-17	177	*Rainwater*	
19880103	1988-08-10	176	19880102	1988-08-10
19900241	1990-09-24	176	*Hot spring*	
			20020204	2002-08-17
			20060517	2006-08-12

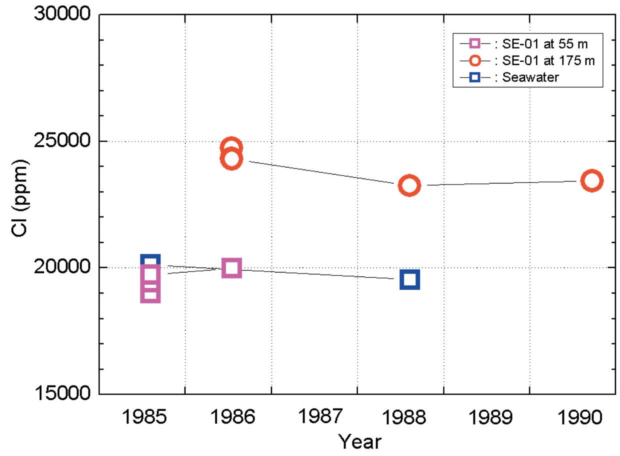

Fig. 7. Chloride content of samples from drill hole SE-1 at the depth intervals 55–65 m and 167–177 m. The concentration of chloride in coastal seawater at Surtsey is shown for comparison.

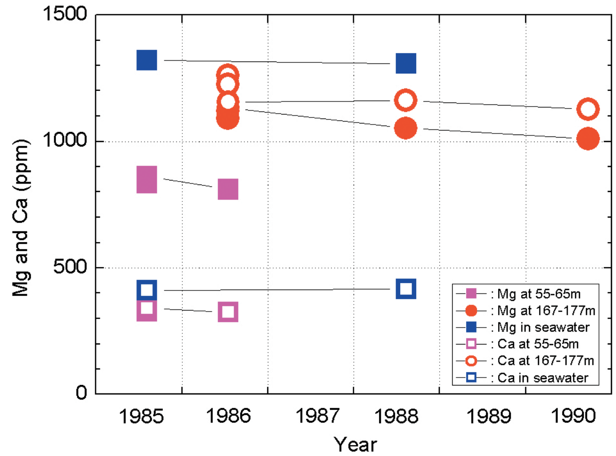

Fig. 8. Magnesium and calcium content of samples from drill hole SE-1 at the depth intervals 55–65 m and 167–177 m. The concentration of these elements in coastal seawater at Surtsey is shown for comparison.

Samples for chemical analysis were also collected from a pit that was dug on the flat northern end of Surtsey. The pit was dug primarily to study the tidal phase delay and amplitude difference between Surtsey and the Vestmannaeyjar harbour. Samples of coastal seawater were also collected, as were samples of rainwater from the roof of the Pálsbaer hut. Finally, two samples from a recently discovered hot spring at Vesturbunki were collected in 2002 and 2006 (Fig. 4). These samples are also listed in Table 1.

The water samples collected on Surtsey were analysed for various elements. Some were analysed for all major elements including pH and carbonates, whereas others were only analysed for salinity and a few other components.

Samples from drill hole SE-1

Water samples for chemical analysis were collected from the drill hole with a downhole sampler in 1985, 1986, 1988 and 1990. Four samples were collected at the depth interval 55 to 65 m, a few meters below the water level in the well. The water at this level is not in any direct contact with the rock, since the drill hole is cased to 165 m, as previously stated. These samples are thus not thought to participate in any water-rock interaction, and they were only collected because of difficulties with

Table 2. Chemical composition of water samples from the drill hole SE-1 at 55 to 65 m depth (ppm).

Sample id.	*19850230*	*19850231*	*19850232*	*19860094*
Date	1985-08-05	1985-08-05	1985-08-05	1986-07-17
Depth (m)	55	65	55	58
SiO_2	11.4	10.2	11.0	7.47
B				5.0
Li				0.27
Na	10940	10970	11033	11210
K	475	493	494	580
Mg	835	861	861	810
Ca	327	346	340	325
Sr				7.34
F	0.69	0.70	0.70	0.63
Cl	19003	19440	19732	19980
Br	68.9	69.9	70.2	
SO_4	1460	1407	1436	1342
Fe				1.04
TDS	35760	36574	36634	36650
$\delta^{18}O$ ‰				6.72

Table 3. Chemical composition of water samples from the drill hole SE-1 at 167 to 177 m depth (ppm).

Sample id.	*19860095*	*19860096*	*19860097*	*19880103*	*19900241*
Date	1986-07-16	1986-07-16	1986-07-17	1988-08-10	1990-09-24
Depth (m)	167	170	177	176	176
pH / °C	8.59/24.1	8.56/23.9	8.12/24.5	8.34/22.6	8.31/23.8
CO_2 (total carbonate)	15.8	15.8	46.5	14.9	8.8
H_2S (total sulphide)	< 0.03	< 0.03	< 0.03	< 0,03	< 0.03
SiO_2	0.99	1.10	9.54	2.47	8.40
B	4.36	4.42	4.54		4.10
Li	0.22	0.20	0.20	0.24	
Na	13291	13426	13245	12715	12337
K	662	679	695	564	520
Mg	1091	1120	1134	1052	1010
Ca	1226	1261	1156	1162	1127
Sr	12.1	11.7	10.1		
F	0.37	0.36	0.48	0.39	0.40
Cl	24322	24745	24296	23250	23440
SO_4	2972	3097	3057	2581	2726
Br				78.9	79.3
Fe	0.20	0.17	0.14	0.025	
TDS	48310	49390	48610	42950	43730
$\delta^{18}O$ ‰	1.37	1.13	1.38	1.25	

sampling the well at deeper levels. However, five samples were collected in the depth interval of 167 to 177 m. The temperature in the upper depth interval is approximately 100°C but the temperature at 167 to 177 m depth is approximately 50 to 70°C, as shown in Figure 3. The results of the chemical analyses from the drill hole are presented in Tables 2 and 3.

The thermal water from the drill hole is seawater with a chloride concentration similar to that of

Table 4. Chemical composition of water samples from the dug pit (ppm).

Sample id.	*19850234*	*19860099*	*19860100*	*19860101*	*19880100*
Date	1985-08-06	1986-07-17	1986-07-18	1986-07-18	1988-08-11
pH / °C	8.30 / 23.9				8.33 / 22.2
CO_2 (total carbonate)	87.5				46.1
H_2S (total sulphide)	< 0.03				< 0.03
SiO_2	4.97	5.41	6.89	6.89	6.38
B		3.30			
Li		0.13	0.04	0.04	0.05
Na	7037	6899	1380	1462	2207
K	319	321	69.8	75.5	106
Mg	847	771	154	154	209
Ca	258	260	46.9	49.1	75.6
Sr		3.92	0.80	0.80	
F	1.22	0.80	1.43	1.43	2.52
Cl	12555	12432	2501	2638	3553
SO_4	1822	1615	342	358	838
Br	44.3				12.1
NO_3					2.13
Fe		0.30			0.025
TDS	24737	24630	4965	5265	7141

Table 5. Chemical composition of samples of seawater and rainwater collected on Surtsey (ppm).

Sample id.	*19850233*	*19880101*	*19880102*
Date	1985-08-05	1988-08-10	1988-08-10
	seawater	seawater	rainwater
pH / °C	8.25/23.3	8.22/22.1	
CO_2 (total carbonate)	102	103	
H_2S (total sulphide)	< 0.03	< 0.03	
SiO_2	0.03	0.27	0.52
Li		19.0	
Na	10757	10836	153
K	452	452	6.28
Mg	1320	1307	17.9
Ca	410	417	7.26
F	0.86	0.63	0.017
Cl	20130	19530	281
SO_4	2684	2738	34.9
Br	70.6	68.1	0.83
NO_3			0.28
Fe	0.17	< 0.025	
TDS	39512	38040	503

Table 6. Chemical composition of water samples from the hot spring (ppm).

Sample id.	*20020204*	*20060517*
Date	2002-08-17	2006-08-12
Flow rate (L/s)	~0.1	~0.1
Temp. (°C)	78.0	82.4
pH / °C		7.53 / 23.9
CO_2 (total carbonate)		30.5
H_2S (total sulphide)		< 0.03
TDS		22410
SiO_2	43.8	25.9
Na	3035	6730
K	134	327
Mg	55.3	261
Ca	386	726
Sr		4.66
F	6.51	2.12
Cl	3160	11360
SO_4	3120	2160
Br	10.2	
Fe		0.0296
Al		0.111
Ba		0.0528
Co		0.00006
Cr		0.00041
Cu		0.00105
Mn		0.0454
Mo		1.03
Ni		0.00051
Pb		0.00033
Zn		0.00211

the seawater at the island shore. The samples show that the concentration of the major elements at these two depth intervals is relatively stable over the period studied. Figure 7 shows the chloride concentration in the water, and Figure 8 shows the magnesium and calcium content of the water. The content of these elements in seawater at Surtsey are also shown for comparison.

Samples from the dug pit

During the expeditions to Surtsey in 1985, 1986, and 1988, pits were dug into the central part of the peninsula extending north from the main part of the island. The main purpose of the pits was to study differences in tidal amplitude and phase between Surtsey and the Vestmannaeyjar harbour. The pits were deep enough to collect water for chemical analysis, and the results are shown in Table 4. The water samples collected from the pit had chloride content ranging from 2500 to 12500 ppm, which indicated direct mixing between rain water and seawater as discussed below.

Samples of coastal seawater and rainwater

Two samples of seawater were collected on the eastern shore of Surtsey, one in 1985 and another one in 1988. A sample of rainwater was collected from the roof of the Pálsbaer hut in 1988. The results are shown in Table 5. The chloride content of the seawater at Surtsey is slightly higher than that of standard mean ocean water (SMOW), which has a chloride content of 19400 ppm. The rainwater samples displayed a high concentration of dissolved solids, indicating the influence of seawater spray.

Samples from the hot spring at Vesturbunki

In the summer of 2002, a hot spring with a temperature of 78°C was discovered at sea level at the nortwestern shore of Vesturbunki. The spring is shown in Figs. 4 and 5. A water sample was collected from the spring, see Table 6. In the summer of 2006, another sample was collected from the same spring. At this time the temperature was found to be 82°C, and the flow rate was estimated as 0.1 L/s. The sampling was difficult, and the chemical analyses show the mixing of seawater and spring water. In the summer of 2008 the hot spring was inaccessible, as it was then below sea level.

CHEMICAL COMPOSITION OF THE WATER SAMPLES

The thermal waters collected on Surtsey are of seawater origin. The chemical composition of some samples can best be explained by the direct

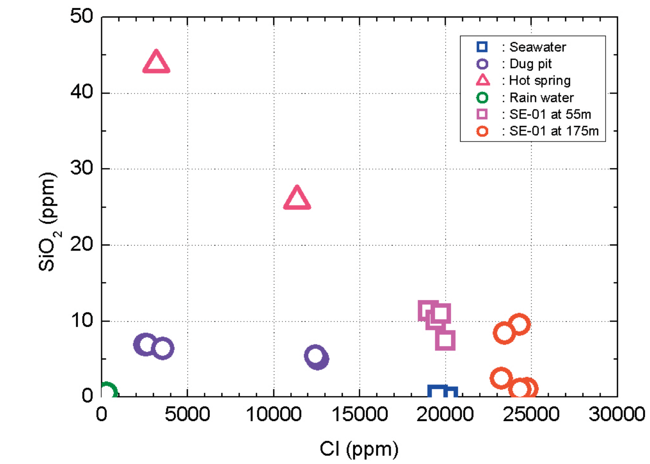

Fig. 9. The relationship between chloride and silica in all water samples.

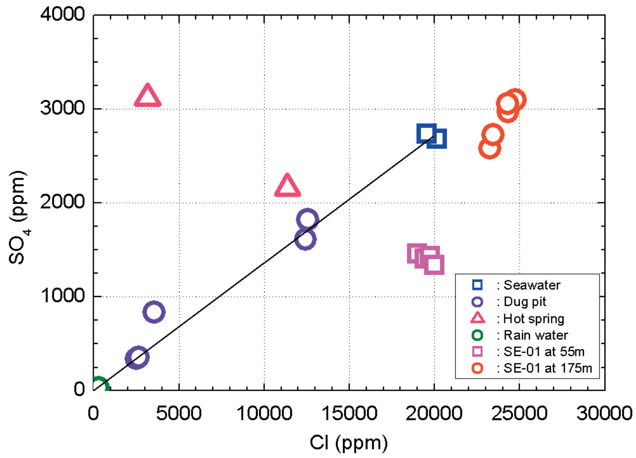

Fig. 10. The relationship between chloride and sulphate in all water samples. The line indicates direct mixing of rainwater and seawater.

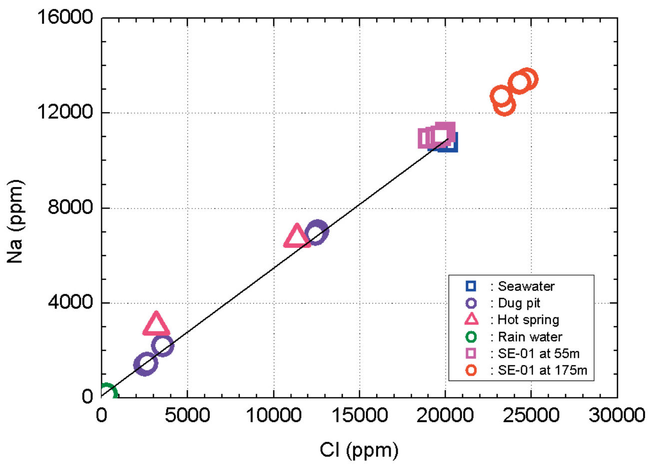

Fig. 11. The relationship between chloride and sodium in all water samples. The line indicates direct mixing of rainwater and seawater.

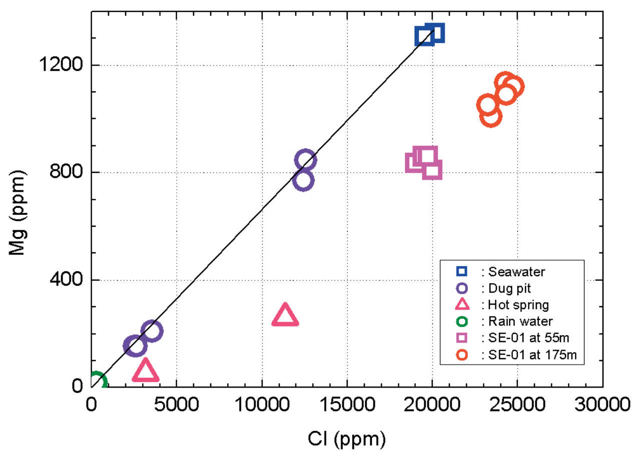

Fig. 12. The relationship between chloride and magnesium in all water samples. The line indicates direct mixing of rainwater and seawater.

mixing of seawater and rainwater. Other samples, however, show evidence of ion exchange with the host rock. This is especially true of the higher temperature waters.

The salinity of the water at the upper depth level, close to the water level in the drill hole, is almost identical to that of the coastal seawater, whereas the samples collected at lower temperature and close to the bottom of the well have approximately 20% higher salinity (Fig. 7).

This increase in salinity is probably an indirect consequence of the palagonitization of the tephra. During the alteration process, hydration of the basaltic glass removes some of the water from the pore fluid, leaving the chloride still dissolved. This, in effect, increases the chloride concentration in the fluid that is in contact with the tephra at the deeper level. The water at the upper depth level is unaffected, however, because it is wholly contained within the casing and has no direct contact with the tephra.

The relationship between chloride and some other major elements in the water samples is shown in Figs. 9 to 14. It is evident from these figures that the chemical composition of waters from the dug pits can best be explained by direct mixing of seawater with rainwater. Waters from drill hole SE-1 and from the hot spring at Vesturbunki show water-rock interactions, however.

The silica content shown in Figure 9 is slightly elevated with respect to seawater in samples from the drill hole, but it is below 10 ppm in all other samples expect the ones from the hot spring. The hot spring samples display an increase in the sulphate concentration, in contrast to the samples from the drill hole (Fig. 10), whose sulphate concentration falls below the mixing line. The concentration of sodium in all water samples (Fig. 11) falls directly on a mixing line between seawater and rain water. Samples from the hot spring and from the drill hole all show a decrease in Mg content (Fig. 12), most likely due to the formation of Mg-rich clays as an

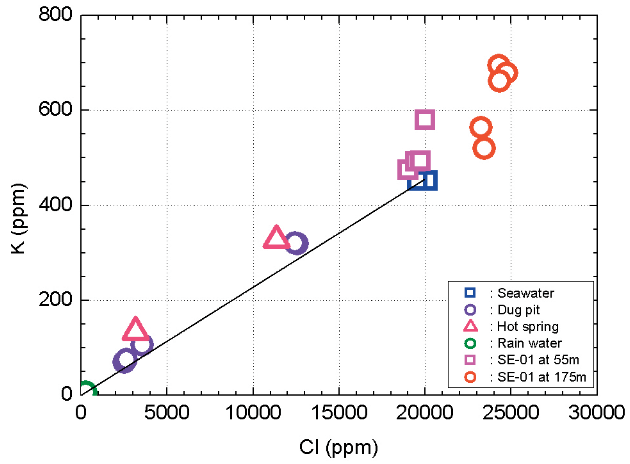

Fig. 13. The relationship between chloride and potassium in all water samples. The line indicates direct mixing of rainwater and seawater.

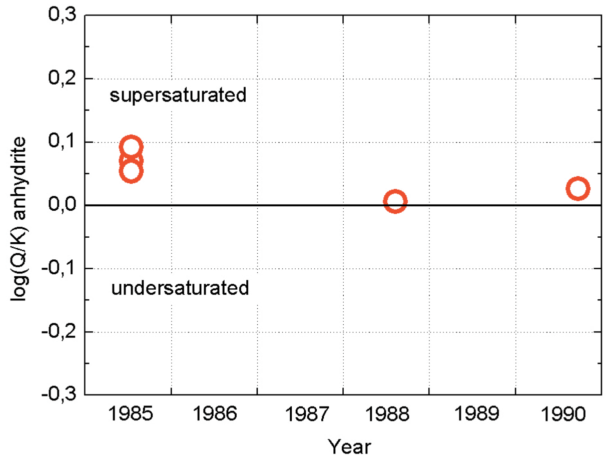

Fig. 15. Saturation index for anhydrite in water samples from 167 to 177 m depth in drill hole SE-1. Reference temperature for calculations is 50°C.

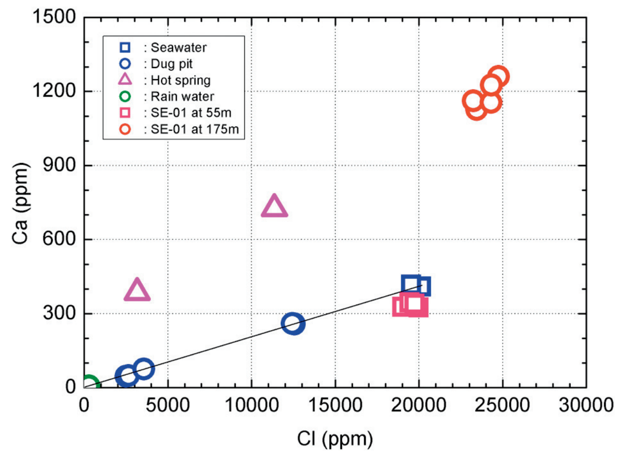

Fig. 14. The relationship between chloride and calcium in all water samples. The line indicates direct mixing of rainwater and seawater.

alteration product in the surrounding rock. There is a slight increase in potassium content compared to direct mixing as shown in Figure 13. The water samples from the lower depth interval in the drill hole and the hot spring samples all have a greatly increased concentration of calcium (Fig. 14).

The saturation index for anhydrite ($CaSO_4$) calculated for the samples from the lower depth interval in the drill hole is shown in Figure 15. The reference temperature is 50°C, which was approximately the temperature at 170 m depth in 1985. The calculations indicate that the water is very close to equilibrium with anhydrite in the rock.

Anhydrite is found scattered throughout the drill core of hole SE-1, and is most abundant near the bottom of the hole where the average alteration temperature of the tephra between 1967–1979 was < 40°C (Jakobsson & Moore 1986). The anhydrite apparently precipitated directly when inflowing sea water was heated, thus lowering the sulfate solubility. Comparable deposition of anhydrite occurs in the Reykjanes thermal brine (Tómasson & Kristmannsdóttir 1972).

ACKNOWLEDGEMENTS

Kristján Hrafn Sigurdsson, Jón Benjamínsson, Jósef Hólmjárn and Reynir Fjalar Reynisson are thanked for collecting water samples from Surtsey and Jón Örn Bjarnason for discussions and improving the manuscript. We are most grateful to the Surtsey Research Society and to the Icelandic Coast Guard for logistic support and to the Icelandic Institute of Natural History, Orkustofnun and Iceland GeoSurvey for financial support. Water samples were analyzed at the Orkustofnun and Iceland GeoSurvey laboratory and stable isotopes at the University of Iceland.

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Precision levelling and geodetic GPS observations performed on Surtsey between 1967 and 2002

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ABSTRACT

The load on the crust from the ~ 0.8 km^3 of eruptive products of the Surtsey eruption is expected to lead to subsidence of the Surtsey island by sagging of the lithosphere, compaction of material, and slumping of the volcanic edifice. Immediately after the eruption ended in the summer of 1967 a levelling line was established across the island to monitor this expected subsidence. The line originally contained 42 benchmarks. As Surtsey is subjected to extensive erosion, in particular in the western and southern parts of the island, the western section of the line has been lost to the sea. In the year 2002 the line ended with benchmark 28. Additional benchmarks were installed 1979, 1982, 1985 and 2002, to fill in gaps in the original line and another profile was installed through the Surtur I crater. Between 1967 and 2002 levelling has been performed eleven times. One benchmark was surveyed with geodetic GPS in 1992. The benchmark was resurveyed in 2000 and 2002 and the GPS network has been extended to comprise four points. In this report we have compiled the levelling data collected on Surtsey so far. Furthermore we present coordinates for the GPS-benchmarks. Continuing subsidence of Surtsey is observed with a decaying rate. The area around the Surtur I crater is the most stable part with a subsidence rate of 0.7 cm/yr in the period 1991–2002. The largest subsidence is observed at the flanks of the island with rates up to 1.4 cm/yr. The excess rate here is most likely caused by slumping of the sides of the island.

INTRODUCTION

The new island Surtsey (Fig. 1), formed in an eruptive episode off the south coast of Iceland in 1963–1967, experiences continuous changes, from its creation during the eruption to the decline by erosion after the termination of the eruption (Jakobsson *et al.* 2000). Compaction of the island started immediately as it was formed, but during the eruption it was not possible to follow this closely. In the summer 1967, shortly after the cessation of the eruption, a levelling line was installed across the island. Repeated levelling has been performed making it possible to monitor the subsidence at Surtsey. In addition, geodetic GPS measurements were initiated on Surtsey in 1992 with the main purpose of tying the vertical displacement of the levelling line to a reference frame outside the island. Levelling has been performed on eleven occasions and geodetic GPS observation has been done three times. The geodetic measurements on Surtsey show continuing subsidence, at a decreasing rate with time. This report gives a complete record of all geodetic measurements performed on Surtsey since 1967.

THE SURTSEY ERUPTION

The eruption was detected on November 14, 1963, at the ocean surface at the southern tip of the Eastern Volcanic Zone but may have started a few days earlier (e.g. Thórarinsson *et al.* 1964, Thórarinsson 1967, Thórarinsson 1964, 1965, 1966, 1969). The water depth was 130 m but a new island, Surtsey, was formed the following day. Four craters were active on a 500 m long, SW-NE striking fissure. The activity gradually concentrated on one crater, Surtur

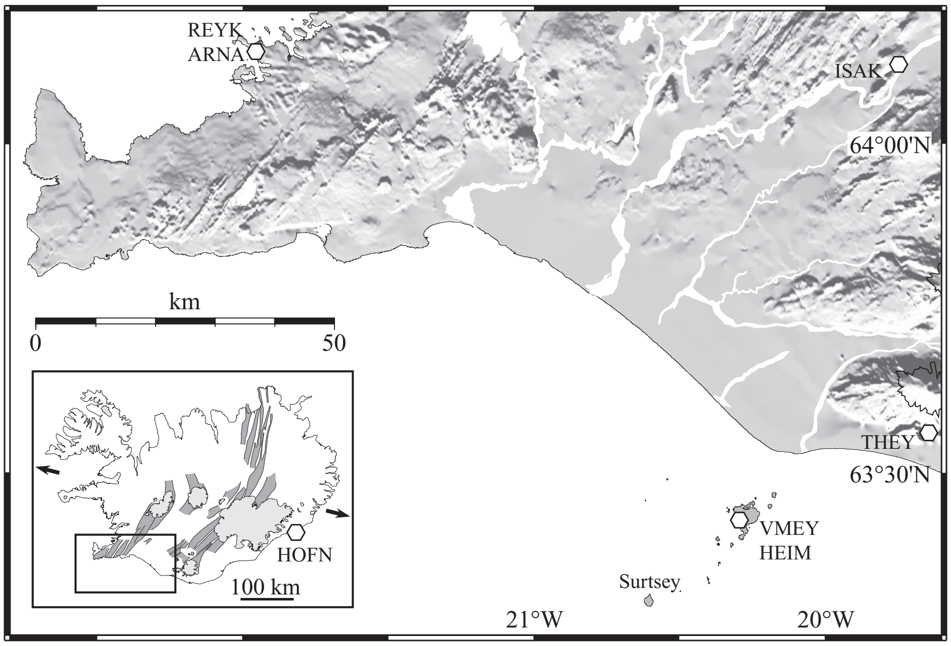

Fig. 1. Map covering the south-western part of Iceland. The hexagons show the location of the GPS points occupied as reference stations during the three geodetic GPS-surveys on Surtsey.

I, and phreato-magmatic activity continued with little changes until the end of January 1964 when it stopped temporarily. A second eruption site was active during this first phase of the eruption, about 2.5 km ENE of Surtsey, producing a submarine ridge, Surtla, almost extending to sea-level. On February 1 a new crater, Surtur II, began erupting. Phreato-magmatic activity continued until April 4, 1964. Then the magma conduit got isolated from the sea water and the activity changed into lava effusion. A lava shield was formed during a period of lava effusion that ended in the middle of May 1965. On May 23, 1965 a new submarine eruption site became active 0.6 km east of Surtsey, building an island in 5 days. The new island, Syrtlingur, had attained an area of 0.15 km^2 and height of 70 m by September 1965. This eruption site became inactive in the middle of October and the island was eroded away in a week. No eruptive activity was spotted for 2 months, but in late December 1965 an eruption began on the ocean bottom 0.8 km SW of Surtsey. The eruption built an island, Jólnir, in about a week. By July 1966 the new island had an area of 0.4 km^2 and a maximum height of 70 m. This eruption ended on August 10, 1966 and by September 20 this new island had also disappeared. On August 19, 1966 a new eruptive fissure opened up within the crater Surtur I. Three craters were active in the beginning but a few days later only one remained. Lava was erupted from this crater until June 5, 1967, building up a flat lava shield and extending the Surtsey island to the east. The eruptive fissure was temporarily extended to the north side of the island on January 1, 1967, producing a small patch of lava. The total volume of erupted material is estimated ~ 0.8 km^3 of solid rock equivalent, all of it basaltic (Jakobsson et al. 2000).

LEVELLING

The data from all the eleven levelling campaigns are given in Table 1. The original levelling line that was installed across the new island (Fig. 2) in 1967 consisted of 42 benchmarks (Tryggvason 1968) spaced approximately 50 m apart. The erosive forces of the sea have shortened this original levelling line by 14 benchmarks. Several benchmarks that are still on land are lost in the drifting sand and have been lost for years. However, some have been found again and their coordinates have now been determined by GPS measurements.

The reference point for the levelling on Surtsey was at first tied to mean sea level. A pond was located in the north part of Surtsey close to the first research hut, which was demolished in the 1980's as the sea erosion had moved the coastline close to the hut. The station HD was at the doorway in the old hut (Fig. 2). The surface of this pond was assumed to be very close to the mean sea level (Tryggvason 1968). The water level in the pond was out of phase with the predicted ocean tide and a delay of more than two hours relative to the predicted ocean tide in Heimaey was observed (Tryggvason 1968). This pond had disappeared in 1969, but, the ground water table was close to the surface and a pit was dug to observe the water table (Tryggvason 1972). The water level corrected for the ocean tide was used as the reference level for the levelling campaigns made in 1967 to 1991. In the 1979 survey Moore (1982) estimated that the average water level in the dug pit was 32±15 cm above the mean sea level. The water level in the pond and dug pits is named WP in Tables 1 & 2 and in Figure 2.

The levelling line was complemented with new points in 1979 (Moore 1982) as the sand drift on

Table 1a. Data for the levelling performed across Surtsey, including 1967 to the 2002 survey. All values are given in meters. The 1967 to 1991 surveys are referenced to the WP point. As the WP point could not be located in 2002, benchmark 621 was used as reference. The 621 benchmark is the GPS point SURS.

Site	1967A	1967B	1968	1969	1970	1979	1982	1985	1988	1991	2002
WP	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
601	8.7880	8.9050	8.9050	8.6090	8.5280	8.2950					
602	10.8996	11.0115	10.9983	10.6910	10.6025						
603	12.4895	12.5993		12.2636	12.1710						
604	15.4782	15.5832									
605	18.7406	18.8434	18.7995	18.4696	18.3664						
606	21.0478	21.1506	21.1037	20.7723	20.6679	20.3160	20.2100	20.0590	19.9500	20.0170	-30.4137
607	23.7212	23.8137	23.7398	23.4001	23.2908	22.8920	22.7720	22.6200	22.5140	22.5780	-27.8517
608	23.3581	23.4407	23.3378	22.9884	22.8741						
609	24.3543	24.4492	24.3739	24.0334	23.9214	23.5090	23.3970			23.2330	-27.1674
610	25.6973	25.8029	25.7742	25.4493	25.3457						
611	28.6667	28.7754	28.7499	28.4305	28.3343						-22.5233
612	30.9279	31.0358	31.0113	30.6897	30.5926		30.2300	30.1220	30.0270	30.1130	-20.2579
613	33.2649	33.3642	33.3360	33.0097	32.9115						
614	34.1049	34.2112	34.1893	33.8667	33.7723						
615	35.1394	35.2459	35.2169								
616	42.3743	42.4681	42.4285	42.0971	41.9940						-8.7601
617	43.9742	44.0339	43.8992	43.5699	43.4588						-7.2849
618	47.1692	47.2624	47.0210	46.6601	46.5523						
619	48.8669	48.9049	48.6913	48.3211	48.1996						
620	51.3190	51.4262	51.3971	51.0743	50.9791						
621	51.1409	51.2333	51.1750	50.8494	50.7541		50.4970	50.4130	50.3060	50.3910	0.0000
622	52.1904	52.2887	52.2346	51.8928	51.7902			51.4410	51.3330	51.4160	1.0359
623	52.4808	52.5728	52.4782	52.1057	51.9911			51.6250	51.5130	51.6000	1.2247
624	53.6409	53.7266	53.5830	53.1882	53.0606			52.6690	52.5580	52.6460	2.2748
625	56.3717	56.4421	56.1665	55.7002	55.5426			55.1020	54.9970	55.0810	4.7078
626	55.1859	55.2680	55.0945	54.6815	54.5441			54.0770	53.9660	54.0520	3.6750
627	46.8897	46.9858	46.8916	46.5231	46.4004			45.9180		45.8930	-4.4940
628	38.9433	39.0473	38.9879	38.6328	38.5142			38.0000	37.8690	37.9700	-12.6068
629	32.2679	32.3762	32.3373	31.9936	31.8784			31.3320	31.1860	31.2990	
630	30.9129	31.0229	30.9944	30.6573	30.5450			29.9860	29.8390	29.9430	
631	30.6739	30.7840	30.7594	30.4282	30.3215			29.7960			
632	32.1005	32.2099	32.1832	31.8525	31.7475			31.1960			
633	33.3989	33.5086	33.4820	33.1517	33.0472			32.4800			
634	33.2734	33.3819	33.3511	33.0155	32.9085						
635	37.2355	37.3432	37.3114	36.9699	36.8604						
636	33.2752	33.3811	33.3322	32.9901	32.8798						
637	31.7889	31.8949	31.8562	31.5224	31.4127						
638	30.3638	30.4712	30.4409	30.1092	30.0016						
639	26.7511	26.8596	26.8369	26.5095	26.4062						
640	22.3683	22.4780	22.4598	22.1383	22.0399						
641	20.6012	20.7121	20.7003	20.3848	20.2936						
642	15.8768	15.9931	15.9519	15.6581							

Surtsey had buried some of the original benchmarks. The levelling in 1979 tied the drill hole (SHD-1) with a water-level pit (WP). Also a new loop containing 10 benchmarks (512–520) through the Surtur I crater, and two benchmarks (510 and 511) in the beginning of the original levelling line (Fig. 2) were installed by J. G. Moore in 1982.

During the levelling in 2002 two new benchmarks (NE09 and NE10; Fig. 2) were installed in the line because benchmarks 618 and 619 were not found. To bridge the 250-m gap, two new benchmarks were installed. Also a benchmark (NE07) was installed in the centre of the helicopter landing platform and this was tied to the levelling line.

In addition to the precision levelling performed, several control points (white paintings on rocks) were installed in 1968 and levelled for a detailed photogrammetric mapping of the island (Norrman

Table 1b. Data for the levelling performed across Surtsey, including 1979 to the 2002 survey. All values are given in meters. The 1979 to 1991 surveys are referenced to the WP point. As the WP point could not be located in 2002, benchmark 621 was used as reference.

Site	1979	1982	1985	1988	1991	2002
WP	0.0000	0.0000	0.0000	0.0000	0.0000	
510		14.7830	14.6440	14.5430	14.6180	-35.8001
511		15.8350	15.6890	15.5800	15.6530	-34.7775
512		61.9490	61.8820	61.7910	61.8770	11.5149
513		66.5630	66.4960	66.4070	66.4880	16.1256
514		70.2780	70.2100	70.1210	70.2010	19.8338
515		70.9210	70.8570	70.7670	70.8480	20.4786
516		70.7470	70.6800	70.5890	70.6700	20.3002
517		65.5100	65.4390	65.3410	65.4240	15.0473
518		67.9900	67.9200	67.8270	67.9080	17.5320
519		61.7790	61.7050	61.6040	61.6850	11.3074
520		53.7760	53.6960	53.5930	53.6770	3.2922
P-1					4.8870	
S-1	27.1570	27.0720	26.9560	26.8670	26.9550	
S-2	34.8270	34.7320	34.6320	34.5390	34.6300	-15.7358
S-3	41.1830	41.0800	40.9880	40.9020	40.9910	-9.3649
S-4	57.3390	57.2140	57.1360	57.0460	57.1340	6.7705
S-6	3.3410	3.3060				
S-7	4.1660	4.1310	4.0150	3.9150	4.0280	
SDH-1	58.7540	58.6290	58.5560	58.4590	58.5470	
SDH-2		5.6910	6.1670	6.4890		
NE07						-16.1630
NE09						-0.6930
NE10						-0.1400
ALP	10.3810					
HD	7.0570					
IS	8.7300	8.6850				
LMI	3.387					
SW	15.9050					
TW	49.4420	49.3290	49.2480	49.1570	49.2460	

1970). During the kinematic GPS-survey in Surtsey 1992 three new benchmarks were installed to complement the net of ground control points for aerial photography and mapping purposes (Einarsson *et al.* 1994).

COORDINATES FOR THE LEVELLING POINTS ON SURTSEY

The original levelling line was installed in the summer of 1967 by Tryggvason (1968), and the coordinates for the benchmarks were presented by Tryggvason (1970). In 1994 a kinematic GPS-survey was performed (Einarsson *et al.* 1994) of 14 of the originally 42 benchmarks. Twelve benchmarks (631 to 642) had been destroyed by coastal erosion in 1992. Sixteen benchmarks were not found during the 1992 survey as the drifting sand had buried them. In the 2002-survey cracks around benchmark 628 indicated that it was the next one to be lost into the sea (Figs. 2 & 3). In this survey fifteen benchmarks were found in the original Tryggvason levelling line, three in addition to what was found in 1992 as the sand continuously changes. The coordinates were measured with a hand-held GPS in 2002. The coordinates presented by Tryggvason (1970) were used to calculate the positions for the benchmark, which had not been positioned by GPS in 1992 and 2002. The coordinates from Tryggvason have the origin at benchmark 601. The GPS-survey presented by Einarsson *et al.* (1994) gave positions in longitude and latitude, which were transferred to UTM coordinates. Point 621 was chosen as the origin in both nets (the net from Tryggvason 1970, Einarsson *et al.* 1994) and the co-ordinates of point 621 were set to 0,0. Benchmark 621 was chosen to be the origin because of its central location in the line and because it is the benchmark used for geodetic GPS measurements. Thirteen points were measured both by Tryggvason (1970) and Einarsson *et al.* (1994), which were used to determine the rotation angle between the two co-ordinate sets. The average angle was 0.4° anticlockwise so the co-ordinates given by Tryggvason (1970) had to be rotated –0.4° around point 621. After the rotation

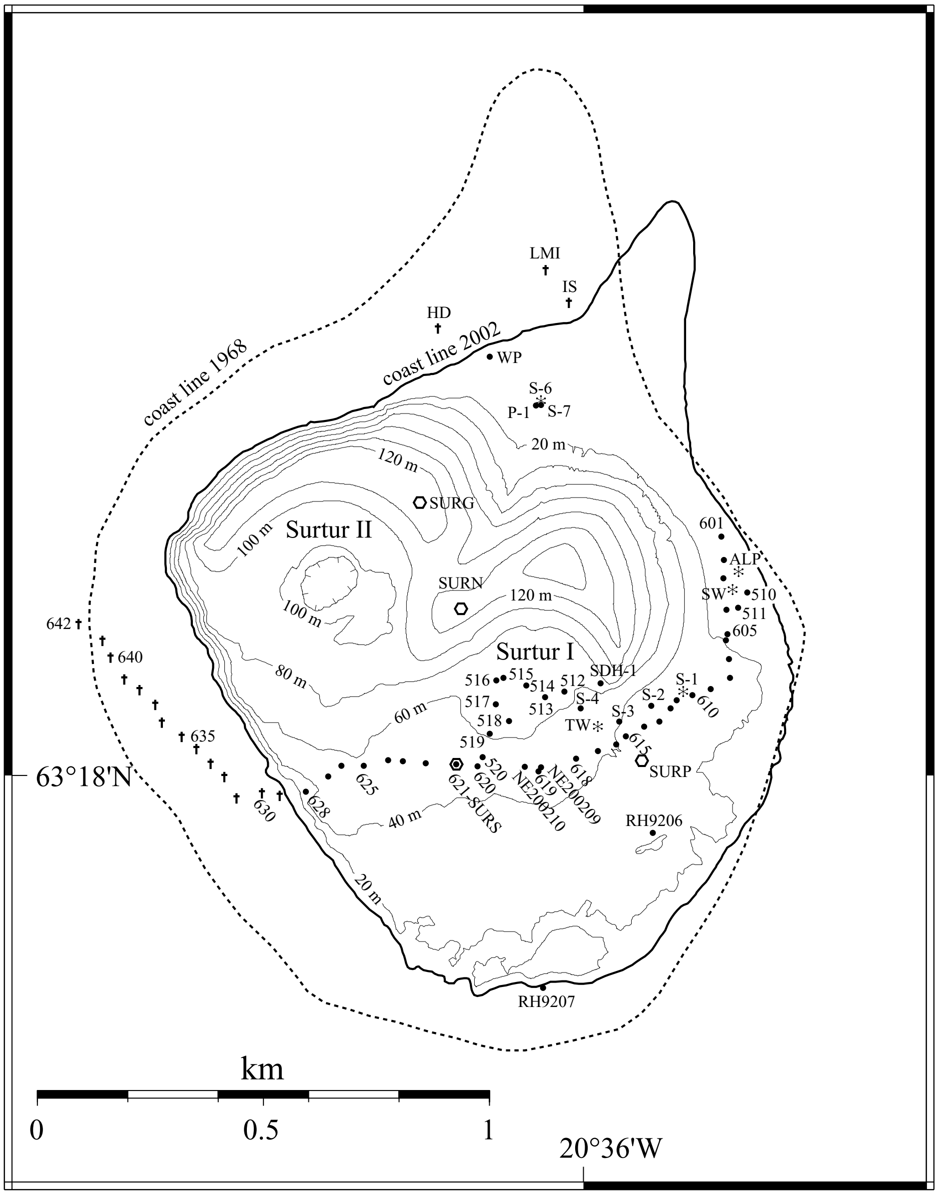

Fig. 2. Map of Surtsey with the 1968 coastline adapted from Norrman (1970) and the coastline 2002 (Sveinn Jakobsson pers. com. 2008). The benchmarks with coordinates (Table 2) are marked with filled circles. The benchmarks lost due to sea erosion are marked with crosses. The benchmark HD was located in the doorway of the first hut. Markings and benchmarks (S-1, S-6, ALP, SW and TW) not found or without any documented coordinates are marked with stars The GPS benchmarks are shown with hexagons. The levelling line is connected to the GPS measurements at BM 621 by the GPS site SURS. The topography is shown by 20 m elevation contours (Sveinn Jakobsson pers. com. 2008).

Fig. 3. Levelling performed in 2002, with the invar rod at benchmark 628. This is probably the last picture of that benchmark as the ground is cracked and the sea erosion will consume it.

Table 2. Measured and calculated coordinates for all benchmarks found and with reported coordinates. The prefix PE indicates that the coordinates (±1m) originate from Einarsson et al. (1994), the HG prefix indicates coordinates (±3m) obtained in 2002, and the remanding are coordinates (±1m) ET/ES calculated (marked ET/ES) from Tryggvason (1970). These coordinates are only for locating the points and should not be used for geodetic purposes.

Site	Longitude	Latitude	Origin
601	-20.59396	63.30470	ET/ES
602	-20.59384	63.30423	ET/ES
603	-20.59386	63.30388	ET/ES
604	-20.59374	63.30326	ET/ES
605	-20.59370	63.30278	ET/ES
606	-20.59376	63.30266	PE
607	-20.59363	63.30229	PE
608	-20.59359	63.30192	ET/ES
609	-20.59442	63.30170	PE
610	-20.59522	63.30158	ET/ES
611	-20.59591	63.30148	ET/ES
612	-20.59617	63.30132	ET/ES
613	-20.59668	63.30106	ET/ES
614	-20.59734	63.30096	ET/ES
615	-20.59798	63.30076	ET/ES
616	-20.59855	63.30061	PE
617	-20.59936	63.30048	ET/ES
618	-20.60032	63.30033	ET/ES
619	-20.60196	63.30008	ET/ES
620	-20.60462	63.30018	ET/ES
621	-20.60556	63.30022	PE
622	-20.60689	63.30024	PE
623	-20.60788	63.30027	PE
624	-20.60854	63.30030	PE
625	-20.60960	63.30019	PE
626	-20.61058	63.30019	PE
627	-20.61117	63.29998	PE
628	-20.61213	63.29968	PE
629	-20.61329	63.29963	PE
630	-20.61407	63.29969	ET/ES
631	-20.61518	63.29959	ET/ES
632	-20.61571	63.30001	ET/ES
633	-20.61632	63.30027	ET/ES
634	-20.61693	63.30056	ET/ES
635	-20.61757	63.30080	ET/ES
636	-20.61844	63.30108	ET/ES
637	-20.61874	63.30143	ET/ES
638	-20.61943	63.30172	ET/ES
639	-20.62010	63.30193	ET/ES
640	-20.62068	63.30236	ET/ES
641	-20.62104	63.30269	ET/ES
642	-20.62209	63.30302	ET/ES
642	-20.62209	63.30302	ET/ES
510	-20.59283	63.30360	HG
511	-20.59322	63.30330	HG
512	-20.60081	63.30165	HG
513	-20.60167	63.30154	HG
514	-20.60250	63.30177	HG
515	-20.60348	63.30192	HG
516	-20.60380	63.30187	HG
517	-20.60381	63.30140	HG
518	-20.60325	63.30107	HG
519	-20.60409	63.30082	HG
520	-20.60441	63.30036	HG
WP	-20.60408	63.30824	PE
P-1	-20.60206	63.30728	PE
S-2	-20.59702	63.30137	HG
S-3	-20.59843	63.30106	HG
S-4	-20.60011	63.30132	HG
S-7	-20.60184	63.30728	PE
RH9205	-20.60536	63.30328	PE
RH9206	-20.59695	63.29887	PE
RH9207	-20.60176	63.29582	PE
NE09	-20.60184	63.30016	HG
NE10	-20.60256	63.30017	HG

Table 3. Description of lost stations from Moore (1982).

Site	Notes
ALP	Base of bent aluminium peg (not found recently)
HD	Threshold in the doorway of the old hut (destroyed)
IS	Iron stake in a small tuff hill, which is eroded today (destroyed)
LMI	Iron stake north of the former small tuff hill (destroyed)
SW	White painted square with a yellow inner circle (not found recently)
TW	White triangle painted on the lava (not found recently)
SDH-2	The top of pipe at the WP site (not found recently)

the difference between co-ordinate pairs from the two sets was 1 meter or less. Finally the generated UTM co-ordinates for the "missing" points were transferred to longitude and latitude form and are presented together with the positions given by Einarsson *et al.* (1994) in Table 2.

This work presents co-ordinates for all benchmarks except three, which might surface in the future as the windblown sand is ever shifting. Those are benchmarks S-1, S-6 and ALP. They are indicated in Figure 2 with stars, as their position is not well known.

In the 1979 survey (Moore 1982) only a few of the original benchmarks were found (Table 1), and the drill-hole elevation was determined relative to a five days average of the water level in the pit (WP in Fig. 2). In this survey several new benchmarks were installed and other markers with less long-term stability were also used. Most of these are lost forever but the two stations that were painted on lava might be re-discovered (Table 3).

GPS MEASUREMENTS

Three campaigns with geodetic GPS measurements have been performed on Surtsey, in 1992,

Table 4. The sites surveyed in the 1992 Surtsey GPS campaign.

Site	Start	End	Receiver	Antenna	Slant height [m]
SURS	221	222	Trimble 4000 SST	TRM 14532.00	1.247
HEIM/0S24	221	222	Trimble 4000 SST	TRM 14532.00	1.142
ISAK/0S13	213	229	Trimble 4000 SST	TRM 14532.00	1.025
ARNA	205	216	Trimble 4000 SST	TRM 14532.00	1.059

Table 5. The sites surveyed in the 2000 Surtsey GPS campaign.

Site	Start	End	Receiver	Antenna	Slant height [m]
SURS	195	197	Trimble 4000 SSI	TRM 33429.20	0.931
SURN	197	198	Trimble 4000 SSI	TRM 33429.20	0.987

Table 6. The sites surveyed in the 2002 Surtsey GPS campaign.

Site	Start	End	Receiver	Antenna	Slant height [m]
SURS	228	230	Trimble 4000 SSI	TRM 33429.20	1.032
SURN	228	230	Trimble 4000 SSI	TRM 33429.20	1.038
SURG	230	231	Trimble 4000 SSI	TRM 33429.20	1.028
SURP	230	231	Trimble 4000 SSI	TRM 33429.20	0.995

2000 and 2002. In the 1992 survey kinematic GPS was also carried out at a number of points, see Einarsson *et al.* (1994). Geographic descriptions of the GPS points are given by Ólafsdóttir *et al.* (2003), who also include a complete list of the major campaigns in which some of the GPS measurements on Surtsey were included. In the first GPS-measurements, in 1992, only benchmark number 621 was occupied, now called SURS and it was re-measured in the year 2000. A new GPS-point was measured on benchmark RH9205 named SURN and it is situated in palagonite tuff in the saddle between the two main peaks (Fig. 2). During the 2002 survey SURS and SURN were re-occupied and two new points were added, one in palagonite tuff on the crest of the western mountain, called SURG, with the inscription NE08 (Fig. 4), and a second in the centre of the helicopter platform (SURP, inscription NE07). The purpose of a GPS-point in the helicopter platform is mainly for aerial photography as the concrete plate makes an excellent aerial marker.

Fig. 4. Measurements of the GPS station SURG.

In Tables 4–6 we list the measured sites for each campaign, the start and end day (UTC days), receiver type, antenna type and the slant antenna height. Naming conventions of receiver and antenna type are according to the manufacturer. The original GPS point SURS (benchmark 621) has three different names throughout time: In 1992 it was called S621, in 2000 SURM and in 2002 SURS.

GPS DATA PROCESSING

GPS-data were processed with the Bernese GPS software package (Beutler *et al.* 2000), versions 3.5, 4.0 and 4.2. The data were collected at 15-second intervals during three 8 hours sessions at each site during the 1992 and 2000 campaigns and in the 2002 campaigns the session length was 24 hours. The processing procedure is described by Sturkell *et al.* (2003). Geocentric coordinates for the points in the three different surveys are presented in Tables 8–10.

A slight matter of complication arises from the choice of reference stations for the Surtsey campaigns. In 1992 station ISAK was intended as the reference station, in 2000 REYK was intended as the reference station and ISAK not observed simultaneously, and in 2002 both ISAK and REYK were running during the Surtsey campaign as parts of the continuous GPS network in Iceland (Geirs-

Table 7. Tie coordinates between ARNA and REYK (after Hreinsdóttir 1999, p. 59).

Station name	x(m)	y(m)	z(m)
REYK	2587384.501	–1043033.496	5716563.974
ARNA	2587441.511	–1042831.287	5716573.510

Table 8. Geocentric coordinates for the Surtsey sites in 1992 (campaign SUD92).

Station name	x (m)	y (m)	z (m)
ISAK	2627583.7742	–943252.6850	5715821.0363
ARNA	2587441.6610	–1042831.2440	5716573.5550
0S24	2684307.3194	–990924.4230	5681354.0879
SURS	2689701.8356	–1011290.2930	5675194.9495

Table 9. Geocentric coordinates for the Surtsey sites in 2000 (campaign SURT00).

Station name	x (m)	y (m)	z (m)
HOFN	2679690.2241	–727951.2181	5722789.1977
REYK	2587384.6616	–1043033.4437	5716564.0364
SURS	2689701.8852	–1011290.1472	5675194.8866
SURN	2689453.8128	–1011186.0329	5675421.3052
THEY	2681807.1338	–957239.1215	5688292.0480
VMEY	2683329.9906	–992250.9465	5681548.1928

Table 10. Geocentric co-ordinates for the Surtsey sites in 2002 (campaign SURT02).

Station name	x (m)	y (m)	z (m)
ISAK	2627583.7742	–943252.6850	5715821.0363
HOFN	2679690.2241	–727951.2181	5722789.1977
REYK	2587384.5923	–1043033.4748	5716563.9524
SURS	2689701.8430	–1011290.1442	5675194.7997
SURN	2689453.7723	–1011186.0243	5675421.2133
THEY	2681807.0966	–957239.1163	5688291.9778
VMEY	2683329.9532	–992250.9413	5681548.1164
SURG	2689228.7345	–1011198.5186	5675527.3505
SURP	2689831.5096	–1010904.3236	5675183.9268

son *et al.* 2006). Ultimately we would like to have a single reference station for all the campaigns. To achieve this goal we note that in 1992 station ISAK was observed between days 213 and 229 and station ARNA was observed between days 205 and 216 (Table 4). Therefore, we can make ties between ARNA and ISAK and effectively use ARNA as the reference site for the 1992 survey. In 1998 a tie was made between ARNA and REYK (Hreinsdóttir 1999; Table 7) and this tie we use to effectively have the 1992 results referred to the REYK station. Therefore, we can compare the reuslts from 1992, 2000 and 2002 as if the same reference station, REYK, had been used for all campaigns. The REYK station is known to follow well the movements of the North-American plate and it is subsiding by a rate of about 3 mm/yr in a global reference frame (Sella *et al.* 2002, Geirsson *et al.* 2006). It is therefore straightforward to obtain the absolute horizontal and vertical motions of the Surtsey points. For future reference we recommend that the continuous GPS station on Heimaey (VMEY) will be used as a reference site. VMEY was included in the processing of the 2000 and 2002 data.

CONCLUSIONS

The vertical displacement signal gives most information on the processes that are currently active on Surtsey. A levelling dataset, extending back to 1967, and the later GPS data are compiled and gives good opportunity to unravel the different processes currently active on the island. The GPS data improve the possibility to tie the vertical displacements to a reference frame outside the island and thus reduce the uncertainties in the absolute height determinations.

The data presented here are used to assess different processes responsible for vertical displacements in Surtsey in particular during the 1991–2002 period (Sturkell *et al.* 2009). The main conclusions are the following: Surtsey subsided rapidly during the first 10–15 years and later with a decaying rate. This decay was confirmed by GPS during 1992 to 2002. In the period 1992–2000 the rate was approximately 1 cm/yr, and for the 2000–2002 period approximately 0.5 cm/yr. The deformation processes currently active on Surtsey are compaction of the volcanogenic material, slumping of the flanks of the island, lithosphere sagging due to load of the erupted material and possible compaction of the seabed sediments. Palagonitization of the tephra causes consolidation by growth of secondary minerals and thereby counteracts the compaction. During the first years, thermal contraction of the lava fields may have contributed to the subsidence signal, but probably decayed away in less than 20 years. Between 1991–2002 largest amount of subsidence is observed (15 cm in 11 years) along the sides of the tuff cones where the lava overlays the delta and the central part of the island has subsided by 8–10 cm during the same period.

Because of the current magnitude of the vertical deformation signal and its decay with time, we suggest that in the future the GPS sites and the levelling line be reoccupied at 5–10 year intervals.

ACKNOWLEDGEMENTS

We are most grateful to the Surtsey Research Society, Sveinn P. Jakobsson and to the Icelandic Coast Guard for support. We also thank Freysteinn Sigmundsson, Ingvar Magnússon and Vala Hjörleifsdóttir for their help in earlier GPS surveys and all other people that have helped with the measurements over the years. This work was supported by a grant from the Icelandic Research Council RANNÍS. Reviews by Hjálmar Eysteinsson and the editor, Sveinn P. Jakobsson, greatly improved the paper.

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Surveying and charting the Surtsey area from 1964 to 2007

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ABSTRACT

The history of hydrographic surveys in the area around Surtsey reveals considerable submarine erosion. The first survey was carried out in July 1964. Since then the Surtsey area has been resurveyed five times. The latest one, a multibeam survey, was carried out in July 2007 by the Hydrographic Department of the Icelandic Coast Guard (ICG). The 1967 survey was carried out after volcanic activity had stopped. The least depth on the Jólnir shoal at that time was 15 m. In 2007 it was 43 m. Depth had increased by 28 m in 30 years.

ERUPTION OFF THE SOUTH COAST

The November issue of Icelandic Notices to Mariners in 1963 is a rare one, if not unique, in the history of NMs worldwide. Notice No. 19 carried the information that a submarine volcanic eruption had started on 14 November SW near Geirfuglasker off the south coast of Iceland and that on 22 November an island had emerged from the sea 700–800 m in diameter and rising to 80 m above sea level (Fig. 1). Mariners were warned to keep clear of the area between 63°17.8'N – 63°18.2'N and 20°36.1'W – 20°36.9'W, southwest of the Heimaey island.

In the early morning of 14 November 1963 at approx. 07:15, fishermen from the Heimaey island

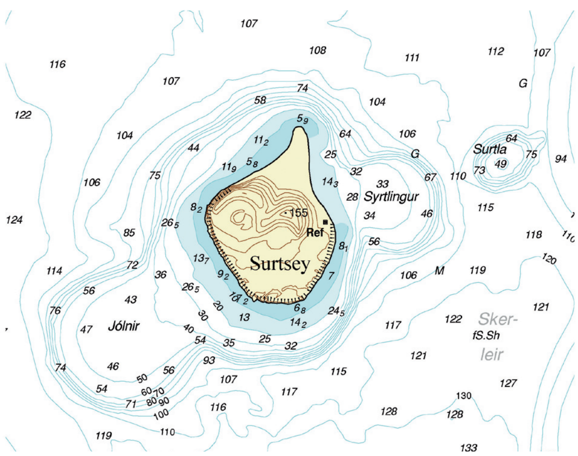

Figure 1. Surtsey as depicted on the latest edition (2002) of the chart Vestmannaeyjar, No. 321, scale 1:50,000.

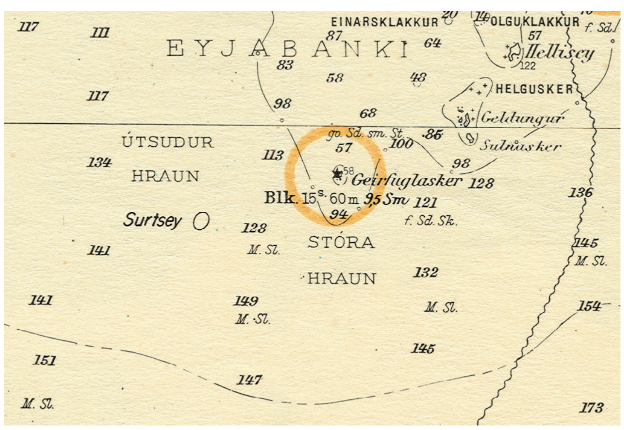

Figure 2. The Surtsey island was first shown on the Icelandic chart Dyrhólaey – Reykjavík, No. 31, scale 1:250,000, printed in January 1964

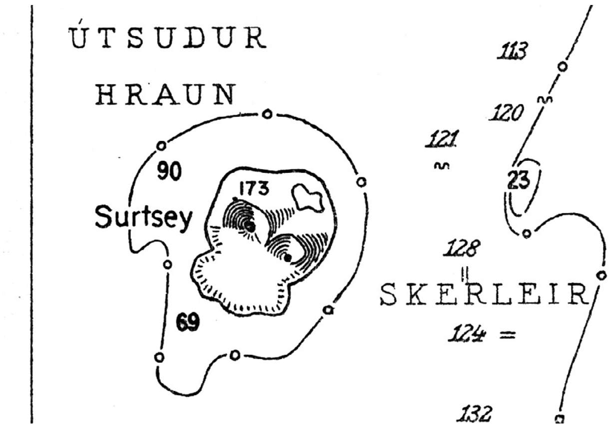

Figure 3. Part of the 1964 NM block for chart No. 33 – scale 1:100,000

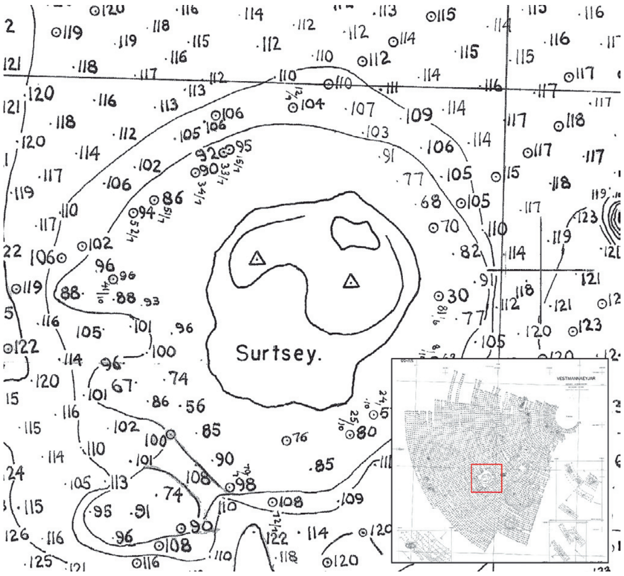

Figure 4. The 1964 survey showing depths around Surtsey.

saw black smoke not far from where they were fishing. The eruption site was a place of rich fishing grounds with depths of 120–130 m. At daybreak they saw that the sea was muddy and bubbling. This was the first sight of the Surtsey volcanic eruption.

FIRST NAUTICAL CHART SHOWING SURTSEY

The Surtsey island was first shown on an Icelandic nautical chart printed early 1964 (Fig 2.), only some two months after the eruption started.

Hydrographic surveys, in Table 1, around Surtsey island have been carried out five times by the Icelandic Hydrographic Service (IHS).[1] A further survey was made in 1967 by the United Kingdom Hydrographic Office (UKHO). The surveys are:

Survey No.	Sheet scale	Date
SV-055	1:40,000	1964, July, August
SV-060	1:10,000	1967, July
SV-089	1:15,000	1973, July
SV-146	1:10,000	1985, June, July
SV-172d	1:10,000	2000, July
SV-216	Multibeam survey	2007, July

FIRST HYDROGRAPHIC SURVEY

After the first survey was carried out in July and August 1964 a Notice to Mariners was issued, including chart inserts (Fig. 3) for the different scale charts covering the area, showing the new island.

The 1964 survey (Fig. 4) was the first echo sounder survey of the area SW of the Heimaey island. The existing lead line survey dated back to 1901. The scale of the survey sheet is 1:40,000, giving survey line spacing of approx. 400 m (not very detailed depth information).

[1] Icelandic Coast Guard – Hydrographic Department from 2005

NEW NAUTICAL CHART

Early in 1966 the chart Vestmannaeyjar – Selvogsbanki, No. 33, scale 1:100,000, was updated and printed showing the current status (Fig. 5) in the area around Surtsey island. Volcanic activity was ongoing close SW of Surtsey island where the small island Jólnir existed for a while. The chart bears a note: ***GOS (Vol)***, "gos" meaning a volcanic eruption. Chart No. 33 is the first and only Icelandic chart (to date) to carry a note of this kind.

In October 1966 a new Icelandic chart (Fig. 6) Selvogur – Vestmannaeyjar, part of the Coastal Chart series at scale 1:100,000, was published. Volcanic activity at Jólnir had ceased. The small island had been washed away leaving a shoal of uncertain depth shown in blue bounded by a black line.

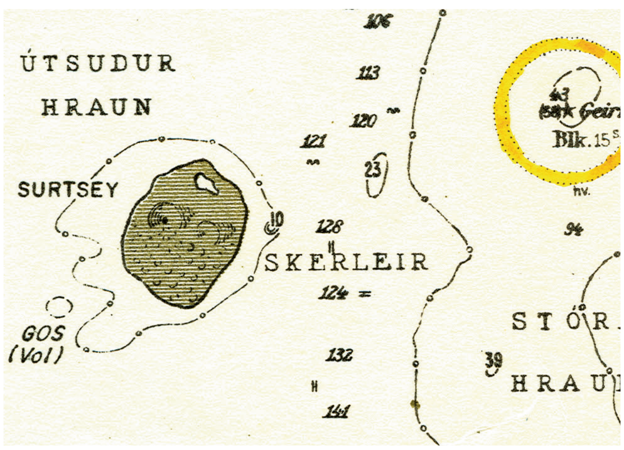

Figure 5. Volcanic activity close southwest of Surtsey as shown on the chart Vestmannaeyjar – Selvogsbanki, No. 33, in 1966.

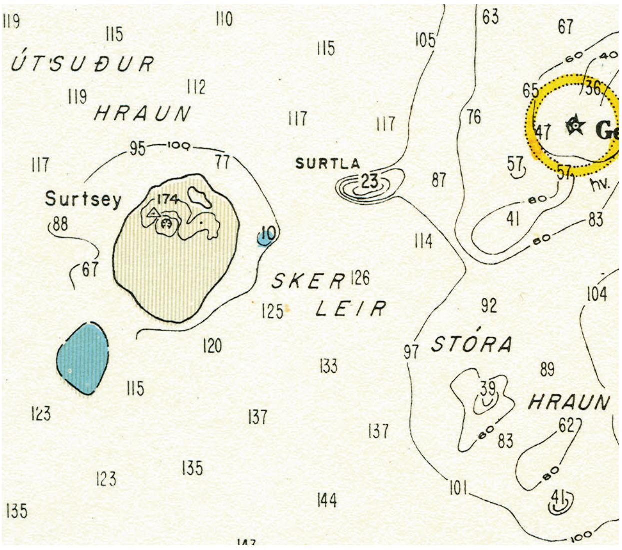

Figure 6. A cut-out from the first edition of the new chart Selvogur – Vestmannaeyjar, No. 16, published in October 1966.

FIRST SURVEY AFTER ERUPTION ENDED

The Surtsey volcanic eruption came to an end in June 1967. The area was surveyed (Fig. 7) the following month by the UKHO. The 1967 survey had a varying line spacing of 40–200 m because the survey was planned in this circular star radiating manner. This gave a good picture of the configuration of the seafloor around the island.

LATER HYDROGRAPHIC SURVEYS

The 1973 survey (Fig. 8) was again carried out in July which is high summer in Iceland and the most likely time of the year to give a favourable weather and sea state for hydrographic surveying. The density of depth data collected was considerably less than in the 1967 survey but gives very valuable information on submarine erosion around Surtsey island between 1967 and 1973. Least depth on the Jólnir shoal had by then increased by 15 m to a striking 28 m.

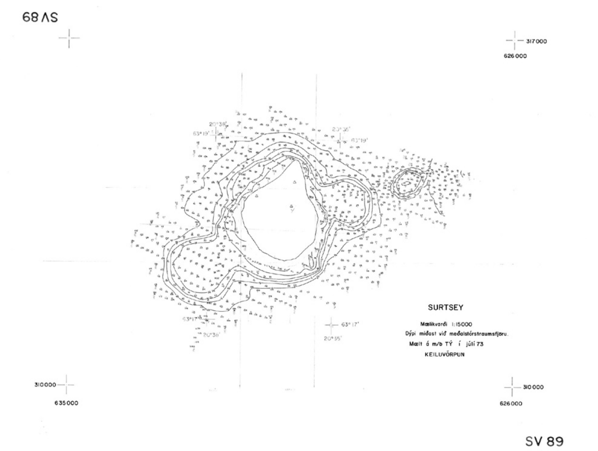

Figure 8. The 1973 survey. Least depth on the Jólnir shoal had increased from 13 m in 1967 to 28 m in 1973.

The next time Icelandic hydrographic surveyors paid the island a visit (Fig. 9) was in 1985. The elements had shaped the island and its surroundings for almost 20 years. It became evident, when the soundings were plotted on the survey sheet and compared to previous survey of 1973 that the submarine erosion had continued as expected. Least depth on the Jólnir shoal had increased to 37 m.

Fifteen years passed but in July 2000 surveyors came to the island once again. The survey (Fig. 10) was planned in a circular manner similar to the 1967 survey. Least depth on the Jólnir shoal had now increased by 5 m to 42 m.

FIRST MULTIBEAM SURVEY

The latest survey (Fig. 11) was carried out in July 2007. It was the first multibeam echo sounder survey around Surtsey island (seafloor coverage

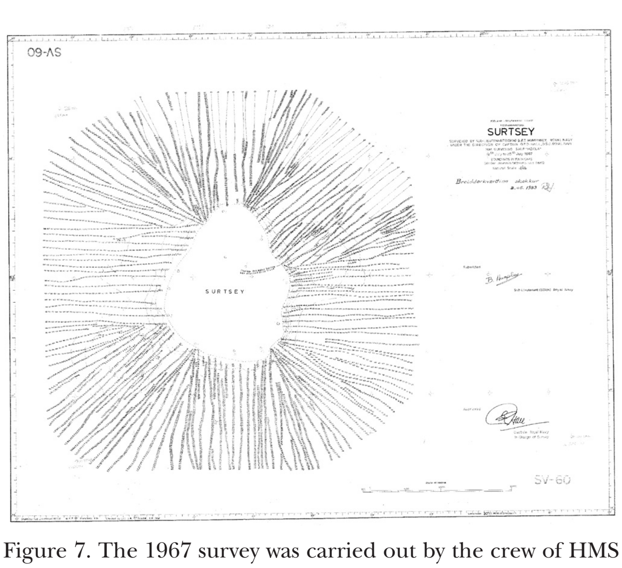

Figure 7. The 1967 survey was carried out by the crew of HMS Hecla, a UKHO survey vessel.

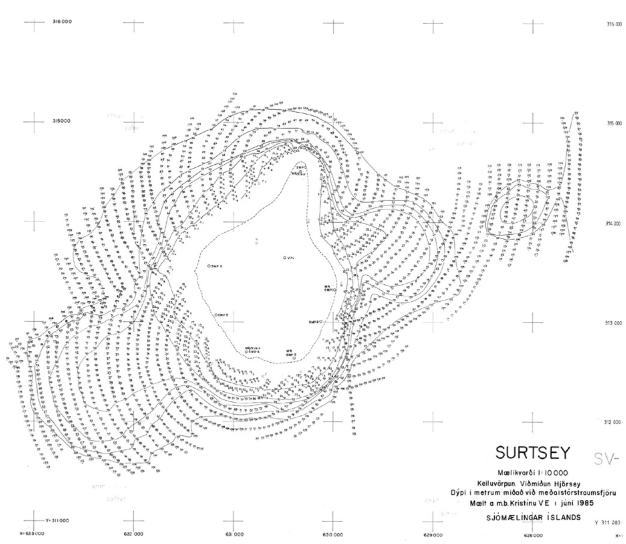

Figure 9. The 1985 survey of the Surtsey area.

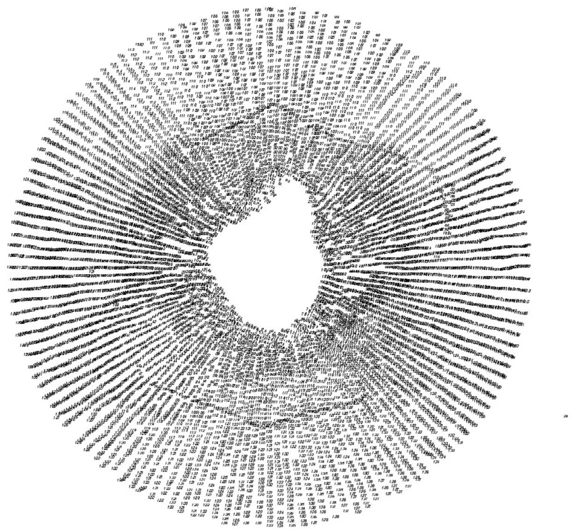

Figure 10. The July 2000 survey has a certain technical beauty, because of its circular shape.

100%) and it revealed details of underwater landscape never seen before.

The sea floor image of the Surtsey area (Fig. 12) was created using the CARIS HIPS Multibeam Professional software (a suite of bathymetry processing tools). ICG Hydrographic Department uses CARIS HIPS for processing hydrographic survey data.

The resolution of the image ranges from 2 m to 10 m in four depth zones (0–30 m, 2 m, 30–60 m, 3 m, 60–95 m, 5 m and 95 m+, 10 m). The reason for this is the fact that as depth increases the maximum possible resolution decreases. To get the most out of the sea floor image, in terms of feature detection on shallower areas around Surtsey island, this method of variable image resolution was used.

Vertical exaggeration is tenfold (10). This large vertical exaggeration creates wavelike "artefacts" most apparent on smooth surfaces e.g. like the Jólnir shoal. These artificial waves are very regular and can be differentiated rather easily from natural features. Erosion on the Jólnir shoal seemed to be slowing down as the least depth was 43 m, an increase of only 1 m the past 7 years.

ACKNOWLEDGEMENTS

The author would like to thank Kjartan Thors and Sveinn P. Jakobsson for their constructive comments on the final draft of the paper and the colleagues at Hydrographic Department of the Icelandic Coast Guard for their contribution to the paper.

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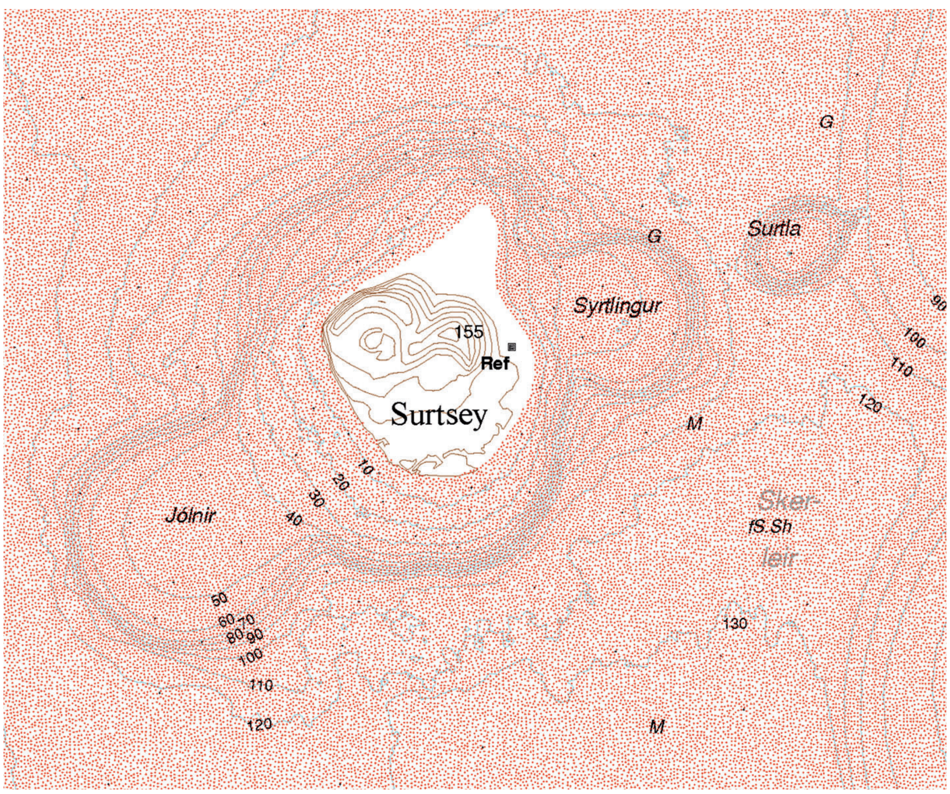

Figure 11. The 2007 multibeam data set reduced to 20 m sounding spacing.

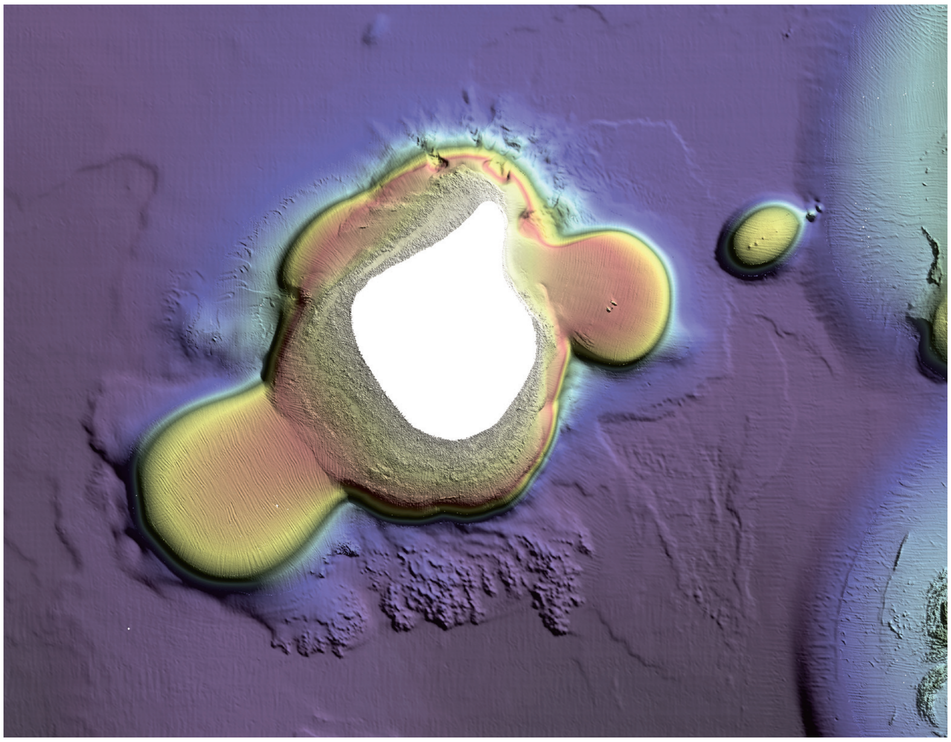

Figure 12. Sea floor image created using the 2007 multi-beam survey full data set.

Icelandic Hydrographic Service 1973. Survey Sheet SV-89, Scale 1:15,000.
Icelandic Hydrographic Service 1985. Survey Sheet SV-146, Scale 1:10,000.
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Developments in plant colonization and succession on Surtsey during 1999–2008

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ABSTRACT

Plant immigration on Surtsey continued during 1999–2008 and 69 vascular plant species had colonized the island by 2008. That year 63 species were recorded, of which 32 had formed viable populations. Birds were considered the main agents of seed dispersal to the island, having dispersed 75% of the species, while 16% were wind dispersed and 9% by sea from 1965.

Plant succession was studied in permanent plots. Barren areas were starkly distinct from a gull colony area affected by breeding seagulls from 1985. Average breeding density by plots within the gull colony was 4 nests 1000 m^{-2} during 2003–2008. Species richness, plant cover and biomass remained low in the barrens. Here two communities, a *Honckenya peploides* community on tephra sand and a gravel flats community with *Silene uniflora* as the indicator species, had developed. Carbon and nitrogen content of soil in barrens was very low and pH relatively high. By 2008, plant species richness in the gull colony was considerably higher than in the barrens and average plant cover and biomass was from 10 to 40 times greater. Soil within the colony area had a relatively high C and N content, and pH was lower than in the barren area. Two forb-rich grassland communities had developed within the colony. On lava, a *Puccinellia distans/ Sagina procumbens* community composed mainly of ruderal species, and a community with the perennial grasses *Poa pratensis*, *Leymus arenarius* and *Festuca richardsonii* as dominants on sand and lava. With the closing of the grassland sward, species richness had declined, reflecting developing dominance.

In 2008 the forb-rich grassland of the gull colony had expanded to about 10 ha in area. It had become a foundation of an abundant invertebrate life and a small community of land birds developing on the island from 1996. Seabirds (primarily gulls) have become increasingly important in shaping and driving the ecosystem development on Surtsey through their nutrient transfer from sea to land and by dispersal of seeds to the island. Puffins have recently started breeding on the island and they are expected to affect further development of the ecosystem.

INTRODUCTION

Colonization by vascular plants on Surtsey has been followed since the formation of the island. In the early years studies focused mainly on dispersal to the island, and the establishment and spread of the pioneer species (Einarsson 1967a,b, 1973, Fridriksson & Johnsen 1968, Fridriksson 1978, 1982, 1992). Special attention was paid to the flora and fauna of the neighbouring volcanic islands that may give an indication of the long-term development on Surtsey (Fridriksson & Johnsen 1967, Fridriksson *et al.* 1972). A study of colonization and species distribution continues to the present day. As species richness and plant cover increased over the last two decades, permanent plots were established to monitor development in more detail (Magnússon *et al.* 1996, Magnússon & Magnússon 2000). These plots have also been used for studies of the invertebrate fauna and ecosystem functions (Ólafsson & Ingimarsdóttir

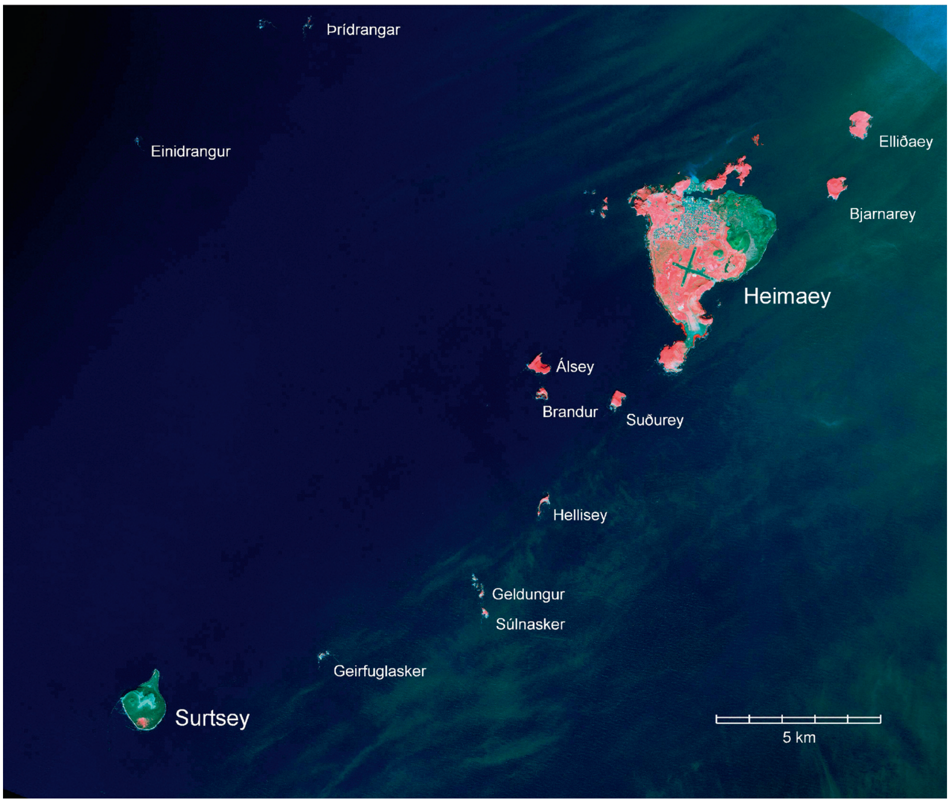

Fig. 1. Surtsey and the Vestmannaeyjar islands on an infra-red SPOT 5 image from July 16, 2003. Areas with dense vegetation appear in red colour, note the gull colony area on southern Surtsey. The Eldfell-volcano and the dark lava from the 1973 eruption give a striking contrast on Heimaey.

2009, Sigurdsson 2009, Sigurdsson & Magnússon 2009).

The importance of seabirds in ecological functions has been increasingly acknowledged in recent years. They can be viewed as chemical and physical engineers that affect terrestrial vegetation through nutrient transport from sea to land, seed dispersal and physical disturbance (Ellis 2005, Ellis *et al.* 2006, Sekercioglu 2006). Breeding seagulls have had great influence on plant colonization and vegetation development on Surtsey since 1985 (Magnússon & Magnússon 2000, Magnússon & Ólafsson 2003).

In the present paper, we provide an account of plant colonization and succession on Surtsey over the last 10 years and the changes that have occurred from earlier years. To our previous study in permanent plots (Magnússon & Magnússon 2000) we have added regular measurements of plant biomass and gull nesting density and their results are presented. We summarise main steps in ecosystem development on the island.

STUDY AREA

Surtsey formed during a volcanic eruption that lasted from November 1963 to June 1967. At the end of the eruption, the island had reached 2.7 km^2 in total area. During the eruption, large tephra cones were built up on the middle of the island by the two main craters. The cones were gradually transformed into denser palagonite tuff as years passed. The highest point on the island is 155 m above sea level. The southern part of Surtsey was formed by lava flows that descended from the craters. The rough lava has, to a large extent, been filled in by drifting tephra and sand from the hills above. The lava on the south-eastern-most part of the island remains mostly free of sand but airborne dust has filled hollows and fissures. The northern-most part of Surtsey is a low spit formed by eroded coastal sediments deposited leeward of the island. In occasional heavy winter storms, the spit has been flooded by extreme surf. Coastal erosion has taken its toll of the island and by 2004 it had been reduced to 1.4 km^2 (Jakobsson *et al.* 2007).

Surtsey is the southern-most of the Vestmannaeyjar islands, which are 7–33 km off the south coast of Iceland (Fig. 1). The climate in the area is mild

Table 1. Mean annual temperature and mean total precipitation at Heimaey weather station (Stórhöfdi) during 1961 – 2006 (Icelandic Meteorological Office).

Period	Temperature (°C)	Precipitation (mm)
1961–1970	5,0	1455
1971–1980	4,8	1713
1981–1990	4,7	1598
1991–2000	5,0	1473
2001–2006	5,8	1718
1961–2006	5,0	1580

and oceanic. At the Heimaey weather station, 19 km from Surtsey, the mean annual temperature during 1961–2006 was 5.0 ˚C and the mean annual precipitation 1580 mm (Icelandic Meteorological Office). A warming trend has been experienced in the area over the last few years as in other parts of Iceland, while precipitation has remained relatively high (Table 1). The Vestmannaeyjar area is generally frost free from the first week of May until the middle of October (Einarsson 1976).

METHODS

Plant colonization and survival

During the study period covered in this paper, annual visits to the island during mid-July continued. During each visit, all portions of the island were thoroughly searched to update survival and colonization of vascular plant species. Since 1998, the location of the first individuals of species new to Surtsey was recorded by GPS. It has also been useful to mark locations of earlier colonists that are limited to a single or very few individuals. Field markers have been left next to plants that are hard to relocate. From this work, an unbroken record on colonization and survival of vascular plant species on Surtsey exists from 1965 when the first plant was found.

Permanent plots study

The study of plant succession in permanent plots that began in 1990 on the island has been continued. Twenty-five plots, 10x10 m in size, were initially established and completed by 1995. The location of the plots was chosen subjectively with respect to substrate type and influence of gulls on vegetation development on the island (Magnússon *et al.* 1996, Magnússon & Magnússon 2000). A few of the plots have been decommissioned and new ones established because of plot destruction or revision of the sampling method. After establishment the whole set of plots was sampled for the first time in 1996 and every second year after that. In 2008, there were 25 plots in active sampling on the island (Fig. 2, Table 2). In all years, the sampling has been carried out in the middle of July.

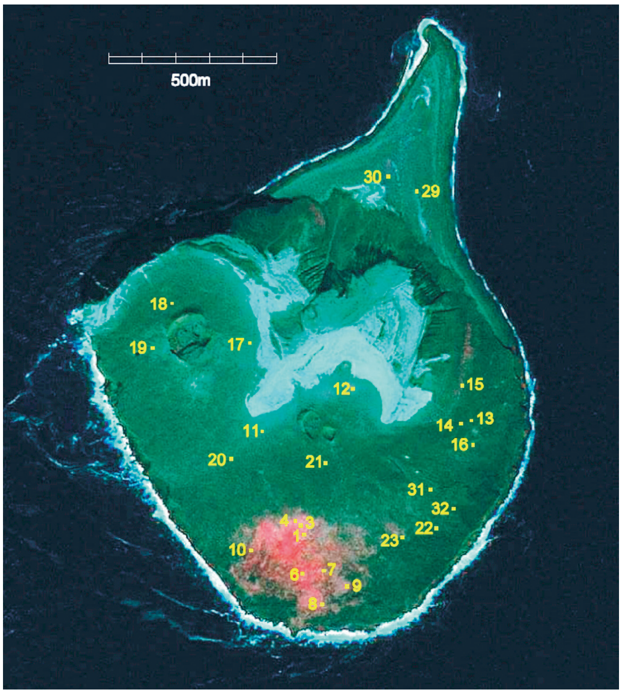

Fig. 2. Location of permanent plots on Surtsey, infra-red SPOT 5 image, July 16, 2003. Gull colony area on the southern island appears in red colour.

Vegetation

The permanent plots were sampled with line-transects (Magnússon & Magnússon 2000). Five 10 m transects were laid across each plot, parallel at 1, 3, 5, 7 and 9 m from their reference edge. Plant cover was determined by line-intercept method. All vascular plant species intercepting the line were recorded separately for each meter along the line, as well as the total cover of mosses, lichens and bare ground. Additional vascular species within the plots not intercepted by the line were also recorded. In the analysis, they were given the lowest possible intercept value of 1 cm equivalent to 0.02% cover.

Table 2. Permanent plots on Surtsey in use in 2008, year of establishment, substrate type, number of sampling and relative influence of breeding gulls.

Plot no.	First sampled	Substrate type	No. of samples	Influence of gulls
1,3,4	1990	sand-filled sheet lava	10	high
6–10	1994	sheet lava	8	high
11–14, 16, 18,19	1994	sand-filled sheet lava	8	low
15,17	1994	tephra hill site	8	low
20,21	1995	sand-filled sheet lava	8	low
22,23	1995	sheet lava	8	moderate
29,30	2005	coastal sand	3	low
31,32	2008	block lava	1	low

Soil

In 2008, soil sampling was carried out in the plots as in 1998 (Magnússon & Magnússon 2000). Four random samples were taken in each plot with a 7 cm wide soil corer down to a 10 cm depth. The samples were mixed in the field to make a composite sample for each plot. In the laboratory, the samples were dried at room temperature and sieved through a 2 mm mesh, for determination of pH, carbon (C) and nitrogen (N). pH was measured in a mixture of 5 g of dried soil and 25 ml of deionzied water after 2 hours shaking, following the methods of Blakemore *et al.* (1987). C and N content of soils was measured in a Vario MAX CN – Macro Elementar Analyzer (Elementar Analysensysteme GmbH), using 1.5–4 g samples depending on the organic matter content. The samples were ground in a ball mill and dried at 105 ˚C before the analysis. All soil analyses were done by the Keldnaholt chemical laboratory. The analytical methods differed and the limits of quantification were lower for C and N than in 1998 (Magnússon & Magnússon 2000).

Plant biomass

In 1999, vegetation was harvested for the first time at the permanent plots for determination of plant biomass. The sampling was repeated in 2003 and 2007. As the sampling was destructive, it was carried out in a 10x10 m area adjacent to each permanent plot. Four samples were harvested at random coordinates within the plots. The vegetation was cut at ground level along a 2 m line, using electric grass clippers with a 7.5 cm wide cut. All vegetation, live and standing dead, was collected. In the laboratory, the samples were dried at 60 ˚C to a constant oven dry weight.

Density of gull nests

To get an indication of the influences of the breeding seagulls on plant succession on the island a nest count in and around the permanent plots was started in 2003 and then repeated annually. This was done by inspecting carefully a 1000 m^2 circular plot with a centre in the middle of a permanent plot. A team of 4–5 researchers, spread out a long the 17,85 m long radius line, walked in a circle within the nest-counting plot. All gull nest bowls that appeared to have been occupied in the current season were counted. A record was also kept of older nests. It is the great black-backed gull (*Larus marinus*), herring gull (*L. argentatus*) and lesser black-backed gull (*L. fuscus*) that breed in great numbers upon the island (Magnússon & Magnússon 2000, Magnússon & Ólafsson 2003, Petersen 2009). Their nests have been counted but they were not separated to a species as the chicks had left the nests when the counting was carried out (mid July). A few fulmar nests (*Fulmarus glacialis*) were also encountered within the surveyed plots and they were also included.

Data analysis

We used DECORANA-ordination (Hill 1979a) to investigate vegetation similarity between individual plots and trends in plant succession. Data from the different sampling years was included for all the 25 plots in use in 2008, which gave a total of 182 plots and 26 plant species for the different sampling years. A square root transformation was performed on the cover data and downweighting of rare species was selected in the ordination procedure. A TWINSPAN-classification (Hill 1979b) was also carried out using only the 2008 data from the plots. This left 23 plant species in the analysis. The square root values were also used and the cut levels were set as 0, 1, 2, 4 and 7. The ordination and classification were run in the PC-ORD 5-package (McCune & Mefford 2006).

RESULTS

Plant colonization and survival

In 2008, the number of vascular plant species found on Surtsey from the first colonization in 1965 had risen to 69. Of those species 63, or 91%, were found alive in that season (Fig. 3, Appendix 1). The first decade of plant colonization on the island was characterised by shore plants. Survival of entering species was high and most of them formed viable populations within a few years. This period was in comparison followed by a relative stagnation during the next decade, 1975–1984, when relatively few new species entered the island and survival dropped. This was to change after 1985, following the sharp increase in number of gulls and formation of a dense breeding colony on the southern part of the island. The gulls facilitated a wave of new plant invasion and survival on the island that is still in force. From 1990–1998 there was a steady

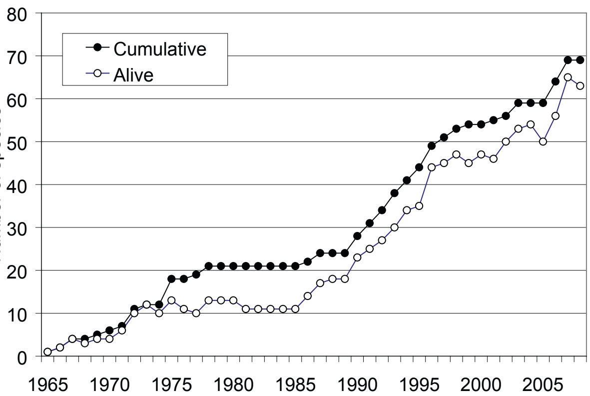

Figure 3. Number of vascular plant species found on Surtsey during 1965–2008.

Table 3. Vascular plants recorded on Surtsey from 1965 and their status in 2008. Species were considered to have formed viable populations if they had spread on the island and were found in at least 5 locations.

			Species status in 2008		
		First colonization	Alive	Viable population	Within permanent plots
Pterydophytes					
1	*Equisetum arvense*	1975	X		
2	*Cystopteris fragilis*	1971	X	X	
3	*Gymnocarpium dryopteris*	2007	X		
4	*Polypodium vulgare*	1996	X		
Monocots					
	grasses				
5	*Agrostis capillaris*	1992	X	X	X
6	*Agrostis stolonifera*	1987	X	X	X
7	*Agrostis vinealis*	1993	X		
8	*Alopecurus geniculatus*	1992	X	X	
9	*Alopecurus pratensis*	2007	X		
10	*Anthoxanthum odoratum*	1996	X		
11	*Calamagrostis stricta*	2007	X		
12	*Deschampsia beringensis*	1993	X		
13	*Festuca richardsonii*	1973	X	X	X
14	*Festuca vivipara*	2006	X		
15	*Leymus arenarius*	1966	X	X	X
16	*Phleum pratense*	1994	X		
17	*Poa annua*	1987	X	X	X
18	*Poa glauca*	1994	X		
19	*Poa pratensis*	1975	X	X	X
20	*Puccinellia distans*	1972	X	X	X
	sedges and rushes				
21	*Carex maritima*	1972	X	X	
22	*Eleocharis quinqueflora*	1993	X		
23	*Juncus alpinus*	1995	X		X
24	*Juncus arcticus*	1991	X		
25	*Luzula multiflora*	1990	X		
26	*Luzula spicata*	1997	X		
	orchids				
27	*Platanthera hyperborea*	2003			
Dicots					
	forbs				
28	*Achillea millefolium*	2007	X		
29	*Alchemilla vulgaris*	1990	X		
30	*Angelica archangelica*	1972	X		
31	*Armeria maritima*	1986	X	X	X
32	*Atriplex longipes*	1977			
33	*Atriplex sp.*	2006	X		
34	*Cakile arctica*	1965	X	X	
35	*Capsella bursa-pastoris*	1990			
36	*Cardaminopsis petraea*	1978	X	X	X
37	*Cerastium fontanum*	1975	X	X	X
38	*Cochlearia officinalis*	1969	X	X	X
39	*Epilobium collinum*	2007			
40	*Epilobium palustre*	1990	X		
41	*Euphrasia frigida*	2001	X	X	
42	*Galium normanii*	1995			
43	*Galium verum*	2003	X		
44	*Honckenya peploides*	1967	X	X	X
45	*Leontodon autumnalis*	1996	X	X	
46	*Matricaria maritima*	1972	X	X	X
47	*Mertensia maritima*	1967	X	X	X
48	*Montia fontana*	1994	X		X
49	*Myosotis arvensis*	1997	X		
50	*Oxyria digyna*	1998	X		
51	*Plantago lanceolata*	2004	X		
52	*Plantago maritima*	2002	X		
53	*Polygonum aviculare*	1991			
54	*Potentilla anserina*	1996	X	X	
55	*Ranunculus acris*	1992	X	X	
56	*Rhodiola rosea*	2006	X		
57	*Rumex acetocella*	1978	X	X	X
58	*Rumex acetosa*	1991	X	X	X
59	*Rumex longifolius*	1996	X	X	
60	*Sagina procumbens*	1986	X	X	X
61	*Saxifraga caespitosa*	2006	X		
62	*Silene uniflora*	1991	X	X	X
63	*Stellaria media*	1970	X	X	X
64	*Taraxacum spp.*	1991	X	X	X
	shrubs				
65	*Empetrum nigrum*	1993	X	X	X
66	*Salix herbaceae*	1995	X	X	
67	*Salix lanata*	1999	X		
68	*Salix phylicifolia*	1998	X		
69	*Thymus praecox*	2006	X	X	
			63	32	23

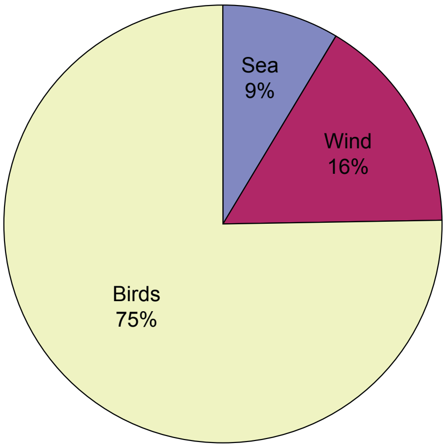

Figure 4. Probable route of dispersal by colonizing species found on Surtsey in 1965–2008.

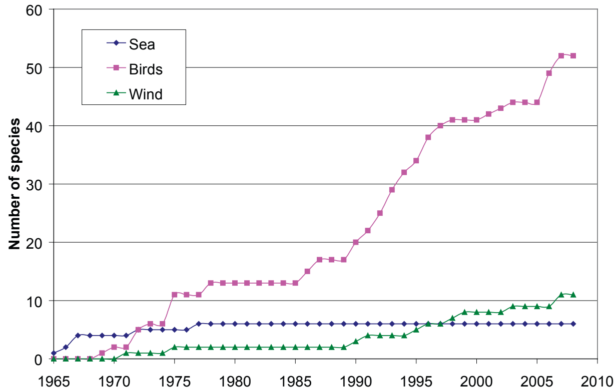

Figure 5. Cumulative curves of dispersal routes to Surtsey considered used by the different vascular plant species during 1965 – 2008. Based on dispersal-mode spectra of the flora and sites of establishment on the island (see also Appendix 1).

increase with 2–5 new species entering every year. During 1999–2005, colonization declined to 0–3 species per year indicating that it was levelling off. This was however followed by a sharp increase in 2006 and 2007 with 5 new species found on the island each year. In addition, a few species, which had been unsuccessful colonizers on the island in the past, have invaded the island again (Fig. 3).

The colonization sequence and location of first encounter of the different species indicates that about 9% were brought by sea currents to the island, 16% by wind and 75% by birds (Fig. 4. Appendix 1). The six species brought in by the sea are all coastal plants adapted to sea dispersal, e.g. *Cakile arctica, Leymus arenarius* and *Honckenya peploides*. They were the first species appearing on the sandy, northern shores. The eleven species considered wind dispersed are all adapted to that mode of transportation. They have small spores or light, hairy seeds easily carried by wind. Examples of these are the fern *Cystopteris fragilis, Taraxacum* sp., the three *Salix* species found on the island and the first orchid *Platanthera hyperborea*. The remaining 52 species were probably brought by birds to the island, either internally or externally. The first encounter of most of these species has been upon the island within or at the edge of the gull colony indicating birds as carriers. The first species considered carried by birds to the island was *Cochlearia officinalis* (Appendix 1). During the first decade dispersal by sea was most important but has not added significantly to the flora after that. Bird dispersal became important a few years later and has continued as the main gateway. Wind dispersal has on the other hand gained increasing importance after 1990 (Fig. 5).

Table 4. Viable plant populations within the main plant taxonomic groups on Surtsey in 2008 in proportion to the number of colonizing species of each group.

Plant group	Viable populations %
Pterydophytes	25
Grasses	56
Sedges & rushes	17
Forbs	51
Shrubs	60

Of the 69 colonizing species during 1965–2008, there were 4 pterydophytes, 16 grasses, 6 sedges and rushes, 1 orchid, 37 dicot forbs and 5 shrubs (Table 3). All species of these groups were alive in 2008 except the orchid and 5 species of dicot forbs, which was by far the largest group. Of the colonizing species, 32 had spread on the island and formed viable populations in 2008 (Table 3). Looking at the assemblage of plants in 2008 grasses, forbs and shrubs were relatively successful in establishing on the island while pterydophytes and the sedges and rushes met greater obstacles (Table 4). Thus, *C. fragilis* was the only pterydophyte widely distributed in 2008 and of the sedges and rushes, only *Carex maritima* had a viable population (Table 3).

The key players in plant colonization on Surtsey during the first two decades were mainly species adapted to relatively infertile habitats along the sandy shores and barren inland areas. Examples of these species are *H. peploides, L. arenarius, Mertensia maritima, C. maritima, Festuca richardsonii* and *Rumex acetosella,* which all became established and started spreading within a few years of first colonization. All are clonal perennials and stress tolerant species with relatively large seeds. The species assemblage changed considerably after 1985. With improved soil conditions came denser vegetation in the area affected by gulls. Plant species that were more nutrient demanding or had more complex requirements for establishment came to dominate. Thus *Poa annua, P. pratensis, Sagina procumbens, Stellaria media, Rumex acetosa, Ra-*

Table 5. Results of analysis of soil samples taken in permanent plots in Surtsey in 2008. Plots 1–10 and 23 were within the gull colony but plots 11–22 and 29–32 were outside it. Averages ± se. are shown below for each set of plots. C and N: total content in oven dry wt.

Plot	pH	C %	N %	C/N
1	7.25	1.26	0.098	12.93
3	7.31	0.56	0.051	10.84
4	7.40	0.49	0.047	10.49
6	6.43	4.28	0.302	14.16
7	6.51	4.72	0.400	11.81
8	7.14	2.28	0.189	12.06
9	7.33	1.79	0.163	10.94
10	7.40	0.95	0.076	12.42
11	8.64	0.03	0.004	7.63
12	8.55	0.05	0.006	7.62
13	8.25	0.03	0.005	5.19
14	8.14	0.02	0.004	4.74
15	7.92	0.02	0.004	4.36
16	7.87	0.06	0.007	7.57
17	8.52	0.03	0.005	5.47
18	8.15	0.03	0.004	6.25
19	7.83	0.03	0.006	5.82
20	8.62	0.03	0.005	6.00
21	8.39	0.02	0.004	3.81
22	6.84	0.27	0.028	9.57
23	7.07	0.24	0.025	9.64
29	8.95	0.01	0.001	8.33
30	9.39	0.03	0.003	8.67
31	7.59	0.08	0.009	9.01
32	7.73	0.19	0.019	10.05
Average:				
1–10 & 23	7.09 ± 0.12	1.84 ± 0.55	0.150 ± 0.043	11.7± 0.46
11–22, 29–32	8.24 ± 0.15	0.05 ± 0.02	0.007 ± 0.002	6.88±0.48

nunculus acris, and *Taraxacum* sp. became firmly established in the wake of the gull invasion. Among latecomers into the developing plant community in the last 15 years were a hemiparasitic species, *Euphrasia frigida,* and an orchid, *Platanthera hyperborea.* The recent invasion of shrubs to the island (Table 3) is also of interest. The three *Salix* species that occur, all wind dispersed, reached the island in 1995–1999.

PERMANENT PLOT STUDY

Density of gull nests

Gull nests were found at 9 of the 25 permanent plots from 2003 (Fig. 6). Most of the plots with nests were within the gull colony on the southern part of the island (plots 1–10) or at its expanding fringe (plot 23) (Fig. 2). In 2006 a nest was also encountered at plot 16 that was outside the main gull colony. A few scattered nests of the great black-backed gull have been on that part of the island and out to the northern spit since 1974. At plot 7 within the gull colony, 1–2 fulmar nests were found in 2003–2008 and they were included with the gull nests.

A total of 27–50 nests were found at the plots in the different years, with a low in 2003 and a high in 2008. The average number was 3.0–5.6 nests 1000 m^{-2} in a year and 4.1 nests 1000 m^{-2} over the whole period, by plots where they were encountered. The highest nest density throughout the period was at plots 9 and 10 (Fig. 6) that were at the fringe of the gull colony when they were set up. In the older part of the colony (plots 1–7), nest density was on the other hand lower.

Soil

A considerable difference was found in soil pH, C and N between plots in 2008. The pH was determined in the range of 6.4–9.4, C content 0.01–4.72%, N content 0.001–0.400 and C/N ratio 4.5–14.2 (Table 5). The soil was poorly developed

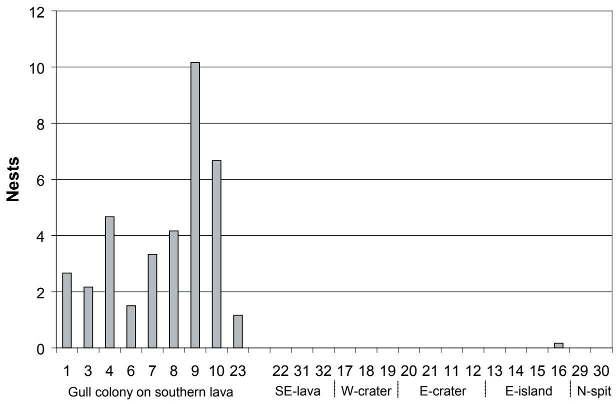

Figure 6. Average number of gull nests counted at permanent plots in 2003–2008. Nests were counted in a 1000 m^2 circle area around each plot. Plots are grouped according to location, from the gull colony on the southern lava, south eastern lava, area around the western crater, eastern crater, eastern part of the island to the northern spit, see also Fig. 2.

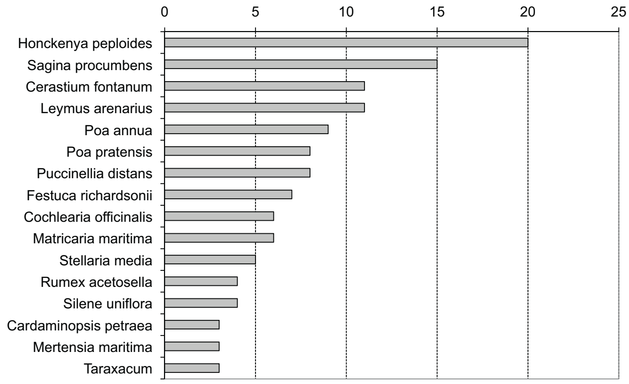

Figure 7. Relative frequency of vascular species in the 25 permanent plots in Surtsey in 2008. Species occurring in ≥ 2 plots are shown, other species occurring were *Rumex acetosa, Agrostis stolonifera, A. capillaris, Armeria maritima, Empetrum nigrum, Juncus alpinus* and *Montia fontana*.

in the barrens outside the gull colony and had a very low C and N contents, and C/N ratio and a relatively high pH (Table 5). In this area the soil was poorest (C < 0,02%) in plots 14, 15, 21 and 23, which all had a very sparse cover of *H. peploides* on coarse sand substrate. Soil from plots within the gull colony had distinctly lower pH and higher C and N contents and C/N-ratio (Table 5). In that area the soil from plots 6 and 7 was highest in C and N content and had the lowest pH. Both plots were on sheet lava and had dense grass cover and root mats. In plots 1–4, which were also in the centre of the gull colony, the soil had, on the other hand, higher pH and a lower C and N contents although their vegetation cover and biomass was comparable. These plots were in an area of sand-filled lava with high content of coarse ash in the upper soil.

Species richness and plant cover

Twenty-three vascular plant species were recorded within the permanent plots in 2008. The most frequent species were *H. peoploides, S. procumbens, Cerastium fontanum* and *L. arenarius*, all found in over 10 plots (Fig. 7). There was a great difference between plots as species richness varied from 1 to 16 (Fig. 8). In the barrens outsite the gull colony area 1–7 species were found per plot. There species richness was highest in plots 18 and 19, by the western crater (Fig. 2, 8), where species like *Armeria maritima, Cardaminopsis petraea, Rumex acetosella* and *Silene uniflora* had spread during the study period. The poorest plots (17 and 21) of the barrens still contained only one species in 2008. They were covered in tephra sand and had a very sparse cover of *H. peploides.* Within the gull colony area (plots 1–10, 23) species richness was relatively high by comparison, or 4–16 species per plot. In plots (1–6) in the centre of the colony species richness had declined in the last few years as their vegetation had become very dense. In plots (7–10, 23) along the edge of the colony, species richness had on the other hand increased. Species richness was highest in plot 10 (Fig. 8), which had a mixture of rough lava surfaces and sandy depressions within it, creating more diverse conditions than generally found in the other plots.

There was almost a two hundred-fold difference in plant cover between plots with the lowest and highest cover in 2008, as the cover range was 0.6–116% (Fig. 9). Development of cover in plots in the barren areas was very limited and in most of them it remained extremely low. In all the plots cover was less 30% in 2008, but the average cover was 7%. In the barrens cover was highest in plots (29 and 30) on the northern spit that had large patches *H. peploides.* In the two plots (31 and 32) set up in the block lava on the eastern part of the island in 2008, vascular plants were very scarce. There *Stereocaulon* lichens and *Racomitrium* mosses were most prominent and made up the cover (Fig. 9). In plots within the gull colony the average cov-

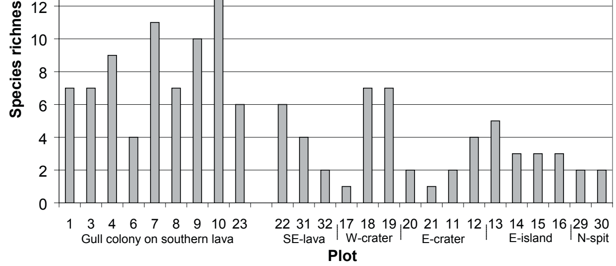

Figure 8. Species richness of vascular plants in permanent plots in 2008.

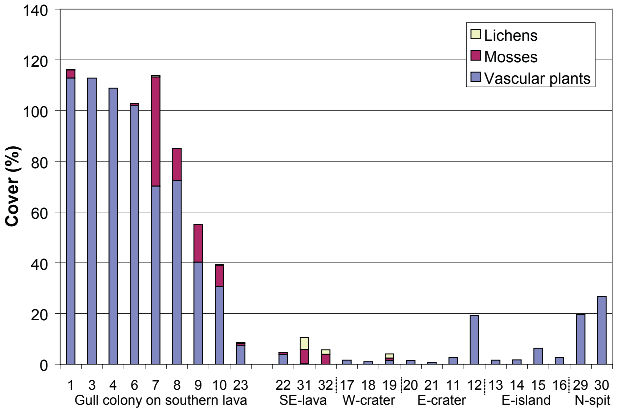

Figure 9. Total cover of vascular species, mosses and lichens in permanent plots in 2008.

er had reached 83% in 2008. In plots (1–7) in the centre of the colony the cover had reached 100% or more while it was lower in plots (8–23) at the fringe where the vegetation development had not gone as far (Fig. 9).

Plant biomass

In 2007 plant biomass within the permanent plots ranged from 0.3 to 856 g m^{-2}. Biomass was very low in plots in the barren areas and a trend in its development was not observed during 1999–2007. The average biomass of the barrens was 10 g m^{-2} and 9 g m^{-2} in 1999 and 2007 respectively, for plots measured in both years. In 2007 biomass in these areas was highest in plots (29, 30) on the northern spit which reflected their relatively high cover (Fig. 9, 10). Plant biomass was high in plots within the gull colony and there was a steady increase from the first sampling in 1999 (Fig. 10). This reflected the development in plant cover (Fig. 9). In 1999 the average biomass in plots within in the colony was 146 g m^{-2} and it had risen to 401 g m^{-2} by 2007. The biomass was highest in plots 1–6 (Fig. 9) in the centre of the colony where lush grassland had developed. The biomass was markedly lower in plots near the fringe of the colony (Fig. 10).

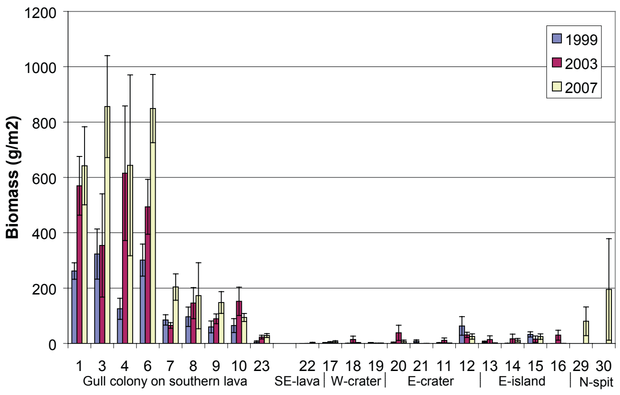

Figure 10. Average plant biomass (± s.e.) within permanent plots in 1999, 2003 and 2007. Living green and standing dead material, dry weight.

Plant succession and communities – multivariate analysis

Ordination

The indirect ordination results revealed the relative vegetation changes which had occurred in the permanent plots since they were set up. On the first axis (eigenvalue 0.627) there was a separation of plots with sand as main substrate to the left of the axis and lava plots without sand on the right (Fig. 11). In the middle of the axis was plot 10 that had both types of substrate as previously described. The second axis (eigenvalue 0.371) was related to temporal vegetation change and indicated the main trends in the plant succession. At the bottom of the axis were the oldest bare lava plots representing the first stages of colonization whereas plots with more developed vegetation were higher up on the axis. Sitting highest on the second axis was plot 6 that had become an outlier in the last sampling years indicating a relatively abrupt change in vegetation composition.

The main cluster of plots to the left of the ordination diagram represented sand plots outside the gull colony. In these plots plant colonization and succession was very slow over the sampling period and limited changes in vegetation composition occurred. All the plots to the right of the cluster on the diagram were from the gull colony where significant changes occurred both on sand and lava substrate (Fig. 11). The difference and changes in species composition, plant cover and species richness of the plots in space and time explained the main trends further (Fig. 12, 13).

The key species in colonization of tephra sand areas, *Honckenya peploides*, was present in all plots in the main cluster, in most cases in a low abundance (Fig. 12, 16). With the influence of gulls in these areas *H. peploides* responded by increasing greatly in cover. This change was followed in plots 1–4 from 1990 and onward (Fig. 11,12). *H. peploides* continued increasing in cover until 2000 but declined thereafter with increased abundance of other species colonizing the plots. The first followers were the annuals *Poa annua* and *Stellaria media* along with *Cerastium fontanum*. These species also declined after 2002 when the perennial grasses *Poa pratensis* and *Leymus arenarius* became dominant in these plots (Fig. 12, 13, 18). *Matricaria matitima* increased in the gull colony after 2000 both on sand and lava. It had a rather scattered distribution and its abundance was relatively low within permanent plots (Fig. 7, 12). *Mertensia maritima*, a shore species and early colonizer of Surtsey, as *H. peploides* and *L. arenarius*, did not respond to the gull invasion.

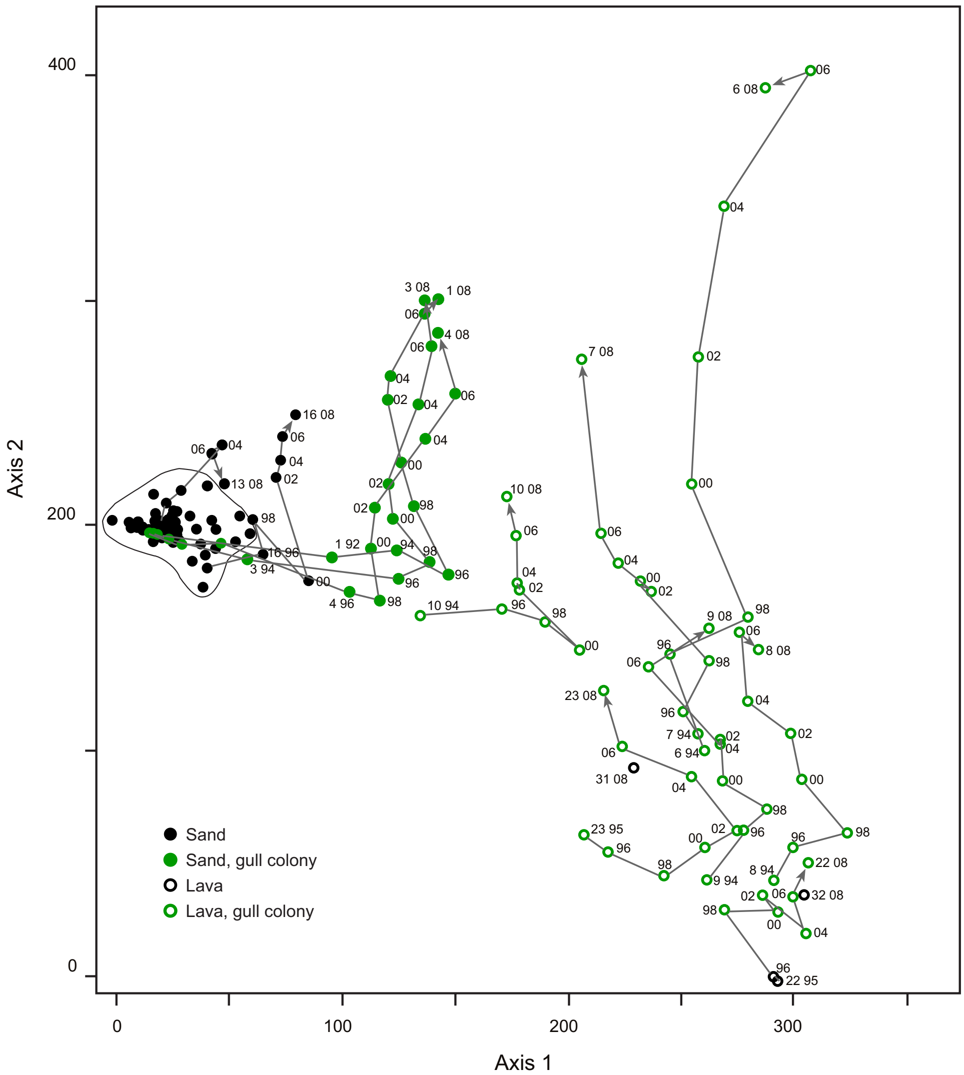

Figure 11. DECORANA-ordination results for permanent plots in the different sampling years. Lines connect the same plots and indicate relative vegetation changes and their direction between sampling years. The cluster to the left represents mainly plots 11–21 and 29–31 in the different years and plots 1, 3 and 4 at their earliest stages.

Its abundance has remained low and distribution limited (Fig. 7, 12). With the gradual rise in plant cover following the gull invasion, species richness in the sand plots increased to start with and peaked around 2000 (plots 1–4). After that it has declined with the closing of bare ground and dominance of the perennial grasses in recent years (Fig 13, 14).

On the lava within the gull colony area the key species of the first colonizing stages were different from the sand areas (Fig. 17). There *Sagina procumbens* was the first colonizer followed by *Puccinellia distans* and *Cochlearia officinalis* (Fig. 12). The species were able to grow on the sheet lava and did not require deep soil for root establishment. In the centre of the gull colony, where changes had gone furthest (plots 6–9), the abundance of these species declined with the colonization and increase of the grasses *P. pratensis* and *Festuca richardsonii* (Fig 12, 14). *P. annua, C. fontanum and Matricaria maritima* also colonized these plots (Fig. 12) and a few other species in low abundance. Plot 6 was positioned in the centre of the gull colony, at the site where the first small patch of vegetation was found in the breeding area in 1986. At the time a crust of moss (*Bryum argenteum)* with *S. procumbens* was found in the patch. When the plot was set up in 1994 there were 8 species recorded within it and *P. distans* and *P. annua* were dominant with 26% and 15% cover respectively. In that year *F. richardsonii* was found within the plot and was registered with the lowest cover of 0.02%. From that time the cover increased year by year by vegetative expansion and it formed a dense, continuous mat. In 2000 *F. richardsonii* had become dominant in the vegetation and gained 49% cover, and in 2006 the cover had reached 99% that the species maintained in 2008 (Fig. 12, 14, 19). A decline in abundance and a loss of other species occurred at the same time in the plot. The species richness peaked at 9 species in 1996–2000 but in 2008 it had declined to 4 species with the gradual overtaking by perennial grasses in the lava plots as in the sand plots. These changes were evident in the ordination results (Fig. 11–13.). Examples of species changes within selected plots occurring under the different substrate conditions and gull influence are given in Fig. 14.

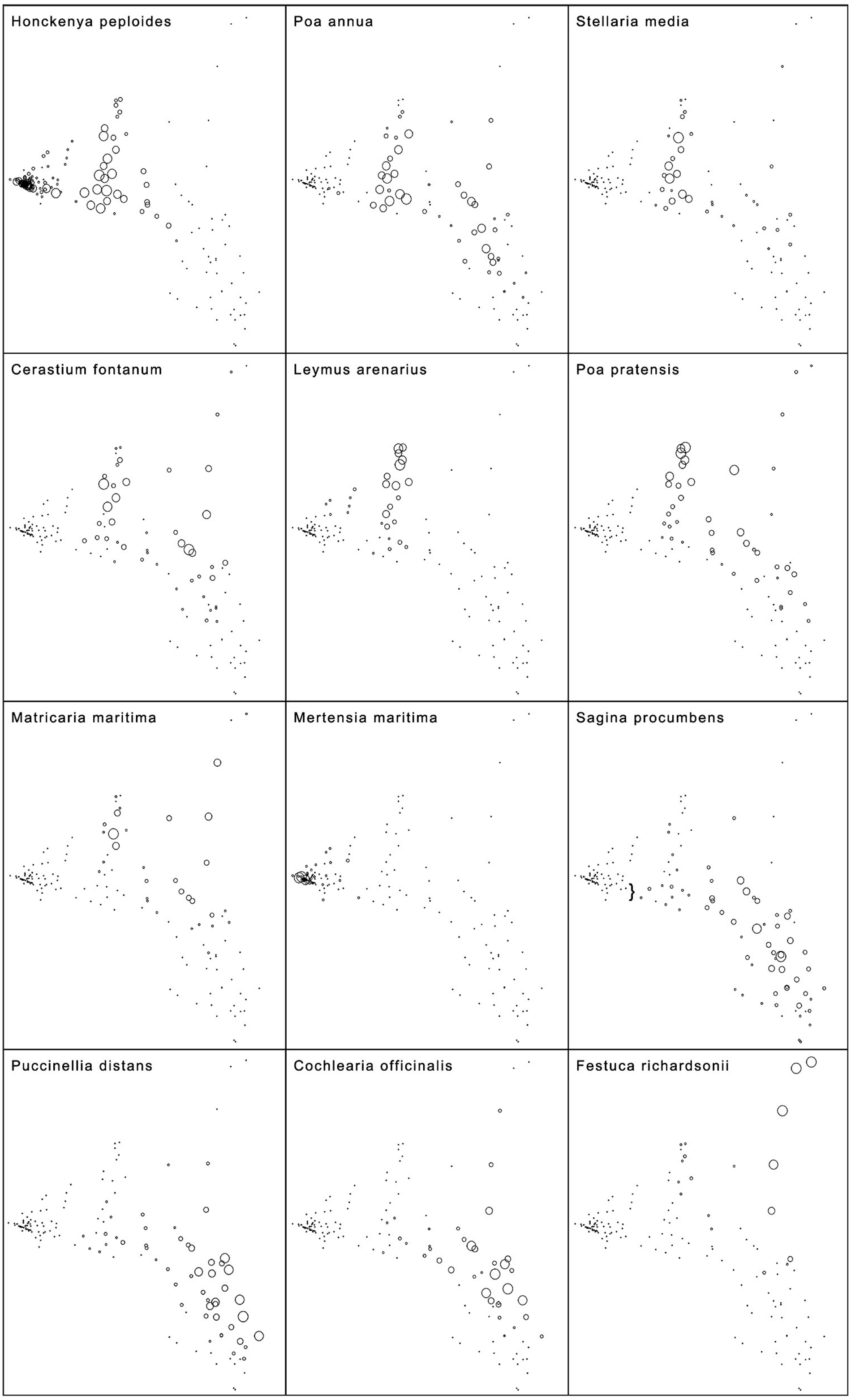

Figure 12. Relative abundance of selected species in permanent plots on Surtsey shown in relation to ordination results. Plots have the same position as shown in fig. 11; horizontal axis separated plots from sand and lava areas while main successional changes occurred along vertical axis. Bubble size reflects species cover, dots absence of species.

Classification

In a divisive polythetic classification (i.e. Twinspan) of the permanent plots data from 2008, four groups were formed (Fig. 15), and further classification is not shown. In the first division all lava plots and plots within or at the edge of the gull colony area (groups I & II) were separated from the sand plots outside the area (groups III & IV). *Poa pratensis* and *Puccinellia distans* were indicator species in the division and present in plots in groups I and II. *Honckenya peploides* was the most abundant species in plots in groups III and IV but was not confined to them. In the second division lava plots at an early succession stage (group I) separated from plots at a later stage and positioned in the centre of the gull colony area (group II). *P. distans* was the

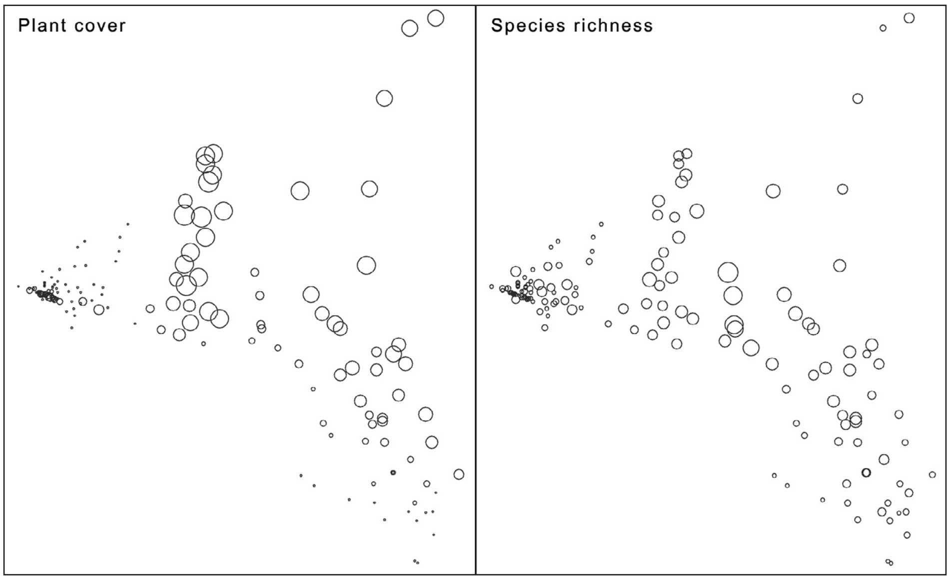

Figure 13. Relative plant cover and species richness in permanent plots on Surtsey shown in relation to ordination results. Plots have the same position as shown in fig. 11.

main indicator for group I but *Festuca richardsonii, Leymus arenarius* and *Poa pratensis* for group II. In the third division of plots outside the gull colony, a separation of plots occurred with the pioneer *H. peploides* as the only or dominant species (group III) and plots with more diverse vegetation (group IV). *Silene uniflora* was the indicator species of the division and it occurred in plots in group IV. *Cardaminopsis petraea, Rumex acetosella* and *Armeria maritima* were also among the species in the group.

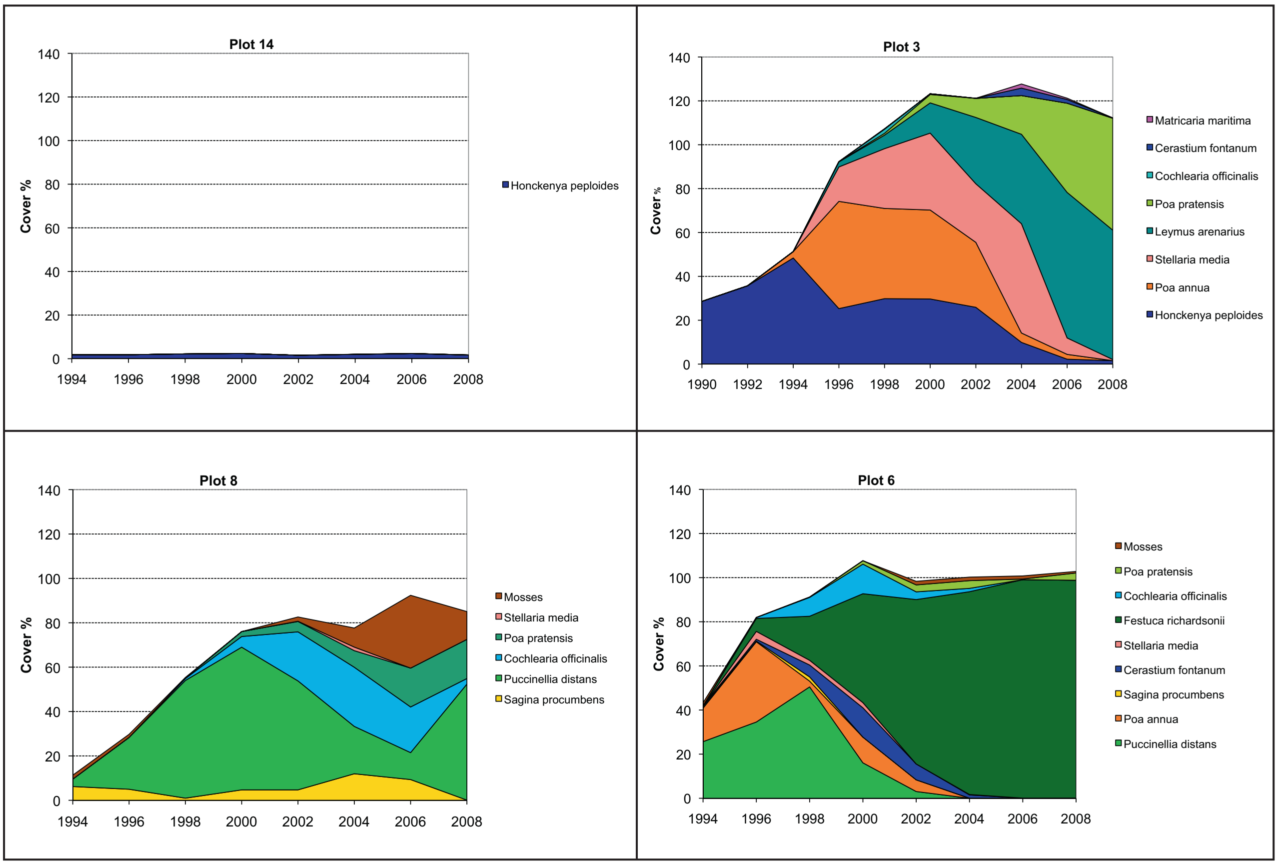

Figure 14. Examples of changes in species cover in selected permanent plots (14, 3, 8 and 6) over the study period 1990/1994–2008. Plots 14 and 3 were on sand-filled lava outside and inside the gull colony area respectively. Plot 8 and 6 were on lava pavements inside the gull colony are. Only species with > 1% cover area shown on the diagrams.

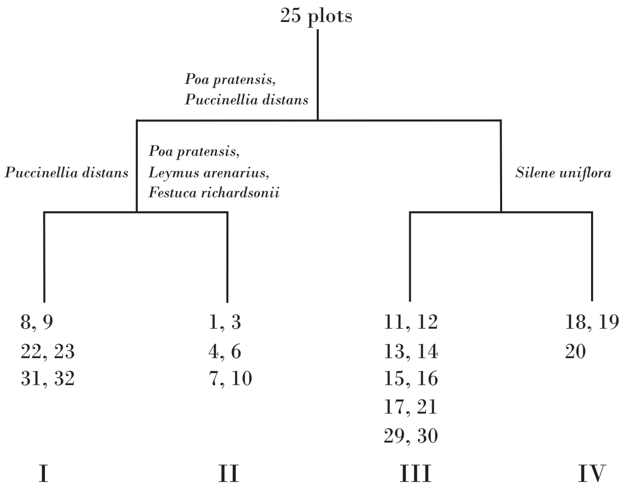

Figure 15. A TWINSPAN-classification of permanent plots based on vegetation composition in 2008. Species most decisive (indicators) of each division are shown.

DISCUSSION

Colonization

The second wave of invasion on Surtsey by vascular plant that followed the formation of a gull colony in 1985 (Magnússon & Magnússon 2000) was still in progress during this study period. In 2008 there were 63 plant species found alive on the island. Most of the species are common elsewhere on Vestmannaeyjar islands, the likely source of most species colonizing Surtsey (Fig. 1). The Icelandic mainland has every plant species that has been found on Surtsey. While Surtsey is the southernmost island of Iceland and in the pathway of migratory birds, there has been no indication of species colonizing the island from distant sources. The vascular flora of Heimaey, the largest of the Vestmannaeyjar islands (13,4 km^2), contains some 160 species (Eythor Einarsson, personal communication). Other islands, on the other hand, harbour only 2–30 species, corresponding to their area, which ranges from 0.01–0.46 km^2 (Fridriksson & Johnsen 1967). All the species recorded on the smaller islands with the exception of two (*Ranunculus repens* and *Saxifraga rivularis*), had colonized Surtsey by 2008 and most of them had formed viable populations. Two species (*Eleocharis quinqueflora* and *Gymnocarpium dryopteris*) present on Surtsey in 2008 have not been recorded elsewhere on the islands but are both found upon the mainland

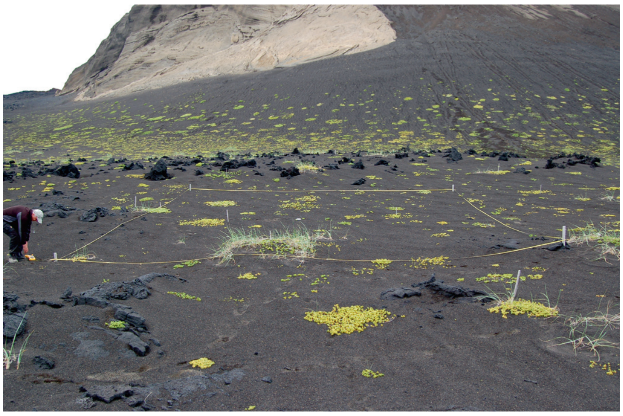

Fig. 16. *Honckenya/Leymus*-community on tephra sand in 2008, plot 14.

Fig. 18. *Leymus/Poa*-grassland on sand within gull colony in 2008, plot 3.

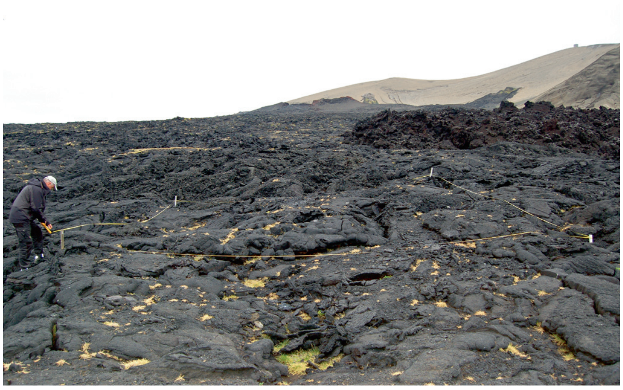

Fig. 17. *Puccinellia/ Sagina*-pioneer community on lava in 2008, plot 22.

Fig. 19. *Festuca*-grassland on lava within gull colony in 2008, plot 6.

(Kristinsson 1986). The number of species growing on Surtsey has long surpassed that of the smaller neighbouring islands. This may be explained by Surtsey's considerably larger size and its greater diversity of habitats compared to the other volcanic islands, which are much older and more eroded. It is likely that total species richness of Surtsey will continue increasing during the next few decades and peak at about 80–100 species, after which it is expected to decline with the continual erosion, shrinking of the island and increasing dominance by a few species.

Our study indicates that transport of birds has by far been the most important pathway of new vascular plant introductions to Surtsey. The lesser black-backed gull and the herring gull in particular appear to have played a major role as can be seen by the sudden rise in new colonization after their invasion of the island (Magnússon & Magnússon 2000, Magnússon & Ólafsson 2003). These species visit and feed more frequently in inland areas than the great black-backed gull does, which depends more on marine food (Götmark 1982). The lesser black-backed gull and the herring gull are therefore more likely to carry seeds. Dispersal of seeds by gulls and other birds to islands and other distant areas has been reported in several other studies (Gilham 1956, Morton & Hogg 1989, Nogales *et al.* 2001, Ellis 2005, Abe 2006) and it has also been demonstrated that predatory birds may act as secondary seed dispersers (Nogales *et al.* 2002). Snow buntings (*Plectrophenax nivalis*) have bred on Surtsey since 1996. The species feeds mostly on insects during summer when insects are abundant but on seeds during the rest of the year. The snow buntings may therefore have carried new plants to Surtsey (Fridriksson & Sigurdsson 1968). In addition, the graylag goose (*Anser anser*) bred on the island for the first time in 2002 and may be in a position to import new species. Ravens (*Corvus corax*) have frequented Surtsey from the early years and may have dispersed seeds of upland species as well.

Other factors than increased visits by birds on Surtsey have probably also played part in maintaining the high rate of plant colonization and survival on the island in recent years. The gradual warming in Iceland in the last 10 years and relatively high precipitation (Björnsson *et al.* 2008) may have positively affected the continued colonization of Surtsey and ecosystem development. However, the improved nutrient conditions of soil on the island and expansion of vegetation in the gull colony has been of the greatest importance. In the colony, the platform with favourable growing conditions for new colonists has increased in area year by year. The fungal succession is also of interest here. Studies of the fungi of Surtsey and the colonizing vascular plants indicate developmental stages from non-dependent to facultative or dependency on arbuscular mycorrhizal fungi (AMF) in the early years (Greipsson & El-Mayas 2000) to the presence of ectomycorrhizal fungi in later years (Eyjólfsdóttir 2009). A development similar to that described during succession on Mount St. Helens (del Moral *et al.* 2005). The late establishment of *Salix* species on Surtsey may have been caused by the lack of ectomycorrhizal soil fungi in the earlier years. The same applies to the orchid, *Platanthera hyperborea,* found on the island for the first time in 2003. As discussed by Thornton (1997) the minute orchid seeds are very light and widely dispersed. The small seeds have no food reserve and require mycorrhizal fungi for germination and establishment. In 2001 *Euphrasia frigida,* the first hemiparasitic species, was found on Surtsey. It has spread in the grassland in the gull colony and established a viable population. The species is a facultative root hemiparasite and plants are known to connect to a variety of hosts, including grasses (Seel & Press 1993, Nyléhn & Totland 1999).

With a record of plant colonization on Surtsey extending over more than 40 years a clear pattern of dispersal routes and their relative importance in time has emerged (Fig. 5). It has similarities to the dispersal pattern obtained in long-term studies of the colonization of Krakatau after the explosion in 1883 (Whittaker et al. 1992, Thornton 1997). There dispersal by sea was important in the early years but then stabilized, as has been found on Surtsey. In addition, dispersal by animals on Krakatau got a later start than sea dispersal. This was attributed to lack of vegetation that attracted animals, which is similar to the experience from Surtsey. On both islands animal dispersal has continued. The main difference in the pattern is wind dispersal which was important from the beginning on Krakatau and has been the most effective of the three main dispersal routes. On Surtsey on the other hand wind dispersed species were scarce in the flora over the first 30 years but have been increasing from that time. This difference probably reflects the contrasting floras and climate of the two areas. In the cool sub-arctic climate of Iceland soil and ecosystem development is very slow in comparison to the tropical environment of Krakatau. Seeds of common wind dispersed species have probably landed on Surtsey throughout the history of the island. However, conditions for establishment were not favourable until after the gull invasion of the island. Wood & del Moral (1987) demonstrated in experiments in the early years of their research on Mount St. Helens that high-dispersal species had low tolerances on the barren substrates and apparently required site amelioration prior to establishment.

Density of gull nests and soil conditions

The distribution and density of gull nests were reflected in the soil and vegetation development on Surtsey. The overarching influence of gulls and other seabirds on environment within their breeding colonies has been emphasised (Sobey & Kenworthy 1979, Hogg & Morton 1983, Mizutani & Wada 1988, Ellis 2005). At their breeding sites the birds deposit faeces and regurgitate pellets, fish and marine invertebrates are spilled on the ground during feeding of chicks and corpses of birds that die within the colony decompose. Nest material may also be brought into the sites. The most significant of these in the soil enrichment and vegetation development are the faeces that have a relatively high content of nitrogen, phosphorus, potassium and minerals (Sobey & Kenworthy 1979), which are of great importance in primary succession.

We have not attempted to measure the nutrient input from the gulls into their breeding area on Surtsey but it is substantial as indicated by the vegetation development and biomass. Nutrient loading in freshwater habitats from water birds has been estimated for the Netherlands using excretion and food models (Hahn *et al.* 2007). A seasonal estimate of a family unit (parents and offspring) for the lesser black-backed gull and the herring gull was around 0.6 kg N season^{-1} and 0.12 kg P season^{-1}. If these values are used to estimate nutrient inputs in the gull colony area on Surtsey, they give about 25 kg N ha^{-1} and 5 kg P ha^{-1} in a season, based on the nest counts at the permanent plots in 2003–2008 (4 nests 1000 m^{-2} or 40 nests ha^{-1} on the average). Taking into account the variation in nesting density between plots during 2003–2008 (1–10 nests 1000 m^{-2}) the nutrient input would be estimated as 6–60 kg N ha^{-1} and 1.2–12 kg P ha^{-1}. This is a conservative estimate because a correction is not made for the great black-backed gull which is the largest of the gulls on Surtsey and a substantial part of the breeding population with the other two species (Petersen 2009).

The results of the soil sampling in the permanent plots in 2008 indicated that C and N content of soil within the gull colony area had increased from 1998 (Magnússon & Magnússon 2000). In the barrens outside the area the contents remained extremely low. In mature, freely drained grassland soils in Iceland organic carbon is commonly in the range of 5–15% (Helgason 1968). According to Arnalds (2004) the brown andosols (BA) of Iceland have a carbon content of 2–7% in the in the top 50 cm. The highest carbon values (4.3–4.7%) determined in Surtsey in 2008 are therefore approaching levels encountered in mature soils. The results from Surtsey show clearly the importance of nutrient input for the ecosystem development.The role of the gulls on Surtsey is in many ways comparable to that of the nitrogen-fixing *Lupinus lepidus* in the plant succession on Mount St. Helens following the eruption in 1980 (del Moral & Rozzell 2005, del Moral 2009).

Plant succession and community development

The substrate conditions of the sand and lava areas on Surtsey differed greatly (Fig. 16, 17). However, similarities can be seen in the succession. In the centre of the gull colony area where plant succession has gone furthers it was mainly ruderal species (Grime *et al.* 1988) that responded to the increased nutrient input to start with and gained high abundance in the vegetation. Examples of these were *Poa annua*, *Stellaria media*, *Sagina procumbens*, *Puccinellia distans* and *Cochlearia officinalis* (Fig. 12). At the fringe of the expanding colony this stage in the vegetation development is still represented on the island and will probably be for the next few decades. With further development the ruderal species however lost ground to more competitive species that responded more slowly to start with but have become dominant in the last few years. The most prominent of these are the perennial grasses *Leymus arenarius, Poa pratensis* and *Festuca richardsonii* that have become dominant in the grassland in the centre of the gull colony area (Fig. 18, 19). They have all formed mats of relatively dense canopy of leaves by extensive lateral spread above and below ground, a character of competitive species (Grime *et al.* 1988). Mixed in the grassland are forb species like *Cerastium fontanum* and *Matricaria maritima* that are more competitive and stress tolerant than the pioneer, ruderal species.

The plant biomass, in the densely vegetated grassland plots within the gull colony area in 2007 was very high (642–856 g m^{-2}, Fig 10). It had reached similar or higher levels than lowland grasslands in Iceland where plant biomass is commonly in the range of 100 – 300 g m^{-2} in autumn but may reach ~500 g m^{-2} in the productive *Deschampsia caespitosa*-grasslands (Magnússon & Magnússon 1990, Magnússon *et al.* 1999). Further substantial increases in plant biomass in the most densely vegetated plots on Surtsey are not expected to continue as the dominant grasses have reached full cover.

The vegetation within the gull colony of Surtsey is in floristic composition and species dominance becoming more and more similar to that of the neighbouring islands (Fig. 1). On the other islands lava and sand areas along with their habitats and flora no longer exist. Most of the bedrock consists of palagonite tuff and remains of craters overgrown with vegetation. Seabirds are very abundant on the islands. Puffin (*Fratercula arctica*) is most numerous and nests in the grassland on top of the islands while guillemots, kittiwakes and fulmars inhabit the cliffs. On the islands Fridriksson & Johnsen

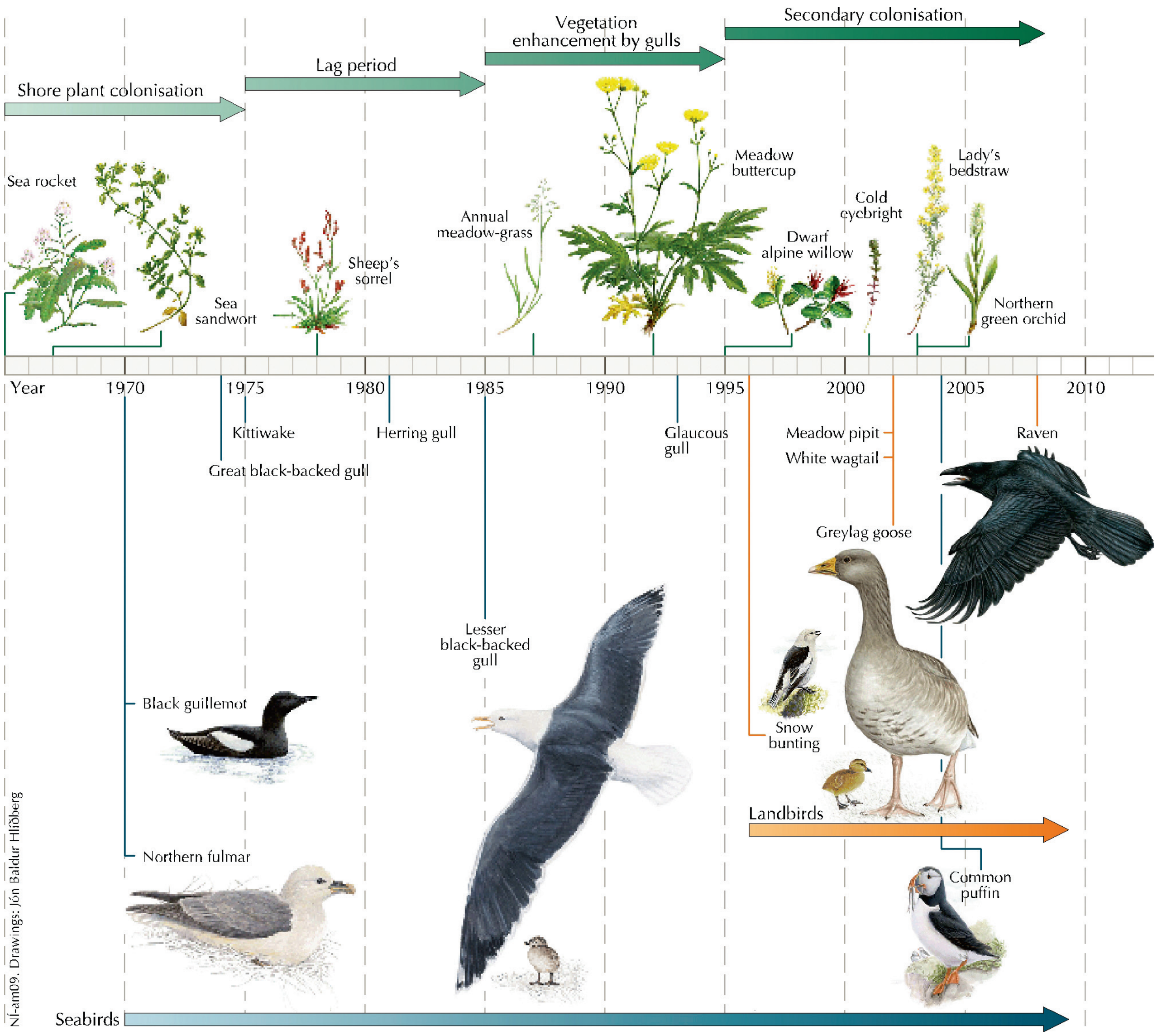

Figure 20. Main steps in species colonisation and ecosystem development of plant communities and birdlife on Surtsey. A large increase in the number of breeding seagulls on the island following 1985 improved soil nutrient status and facilitated dispersal of new plant species to the island. This was followed by enhanced development of vegetation and invertebrate communities, enabling land birds to settle on the island ten years later. Diagram made by Anette Th. Meier; drawings of plants and birds by Jón Baldur Hlídberg.

(1966) described three main plant communities: a) The puffin colony vegetation with *Festuca rubra (= richardsonii)* as the dominant species; b) Dry meadow land vegetation with *F. rubra* and *Poa pratensis* as dominants; c) The coastal cliff vegetation with *Puccinellia maritima* and *Cochlearia officinalis* as the most predominant. In general the vegetation of the larger islands was dominated by grasses, especially *F. rubra*. The vegetation development on Surtsey in recent years indicates very clearly a formation of a grassland community within the gull colony. The key players are the same species as on the neighbouring islands and so are most of the associated species.

Ecosystem development

The colonization and ecosystem development of terrestrial biota on Surtsey has been followed for 45 years (Fridriksson 1975, 2005, Magnússon & Ólafsson 2003, Jakobsson *et al.* 2007). Throughout the period new colonizers have been discovered on the island. The simple ecosystem of the early years has become more complex with the formation of communities, food webs and species interactions. The different studies of recent years indicate that the island is still going through a colonization phase that will prevail for the next few decades. This is evident for the vascular plants, lichens (Kristinsson & Heidmarsson 2009), fungi (Eyjólfsdóttir 2009), invertebrates (Ólafsson & Ingimarsdóttir 2009) and birds (Petersen 2009). Surtsey has shed a light on the formation of the neighbouring volcanic islands and their fate caused by oceanic erosion. On Surtsey we are also witnessing how they were colonized and the rise and fall of their ecosystem.

The initial colonization of shore plants on Surtsey during the first decade was followed by a lag period (Fig. 3) during which few new species colonized the island and survival was low. Further development was limited by infertility of the young soil and low rate of dispersal and colonization. With the large gull invasion of the island starting in 1985, the barrier to succession was breached and the development lepted forward. From that time forward, the gulls have been the driving force behind the changes and will probably continue to be for the near future. The gull case from Surtsey is a good example of the effects marine birds can have on terrestrial ecosystems (Ellis 2005, Ellis *et al.* 2006) and the varied roles birds can play in ecological functions (Sekercioglu 2006). On Surtsey the most important functions have been nutrient input from sea to land and seed dispersal. In the stepwise colonization and ecosystem development of Surtsey the initial importance of the shore plants should not be downplayed. They were the pioneers that later attracted the birds to breed upon the island. We see the main periods and most important steps in the development as follows (Fig. 20, 21):

- **1965–1974. Shore plant colonization:** Shore plants invade the northern shore and expand onto the sand-filled lava on the eastern part of the island. *Honckenya peploides* is most successful, forms small patches and starts producing seeds. The first pair of great black-backed gulls (GBBG) breeds on the island towards the end of the period and uses *H. peploides* plants as the main nesting material.
- **1975–1984. Lag period:** Vascular plant invasion slows, survival of colonizers is poor. Further establishment and expansion of shore plants, mainly *H. peploides* and *Leymus arenarius*. Gradual increase in nesting gulls (GBBG), nest and seek shelter in developing patches of shore plants and enhance their growth. First pair of herring gulls (HG) breeds on the island.
- **1985–1994. Gull invasion and vegetation enhancement:** The lesser black-backed gull (LBBG) invades the island. A dense gull colony is formed on the barren southern lava. The moss *Racomitrium* is the main nest material as nest material is scarce. Rapid increase in gull population with over 100 breeding pairs of LBBG, HG and GBBG at the end of the period. Gull invasion is followed by a great increase in new plant colonizers that are mainly dispersed by the gulls to the island. Arbuscular mycorrhizal fungi (AMF) are found, colonizing plant species are non-dependent, facultative or dependent on AMF. A great increase in cover of established species and fast colonization and spread of ruderal species, e.g. *Poa annua, Stellaria media* and *Sagina procumbens,* within the gull colony where the first extensive patches of vegetation are formed. Vegetated area on southern lava covers 3 ha at the end of the period.
- **1995–2008: Secondary plant colonization and establishment of land birds:** Continued colonization of new plant species and expansion of vegetation driven by the gulls, while several wind dispersed species also colonize the island. Development of a forb-rich grassland with *Poa pratensis*, *Festuca richardsonii* and *L. arenarius* as dominants. Vegetated area on southern lava occupies about 10 ha at the end of the period. Marked increase in soil organic matter and plant biomass within the gull colony. Willows establish on the island, as do a hemiparasitic species (*Euphrasia frigida)* and the first orchid (*Platanthera hyperborea*). Several ectomycorrhizal fungi are found in association with willows. Increase in number of invertebrate species

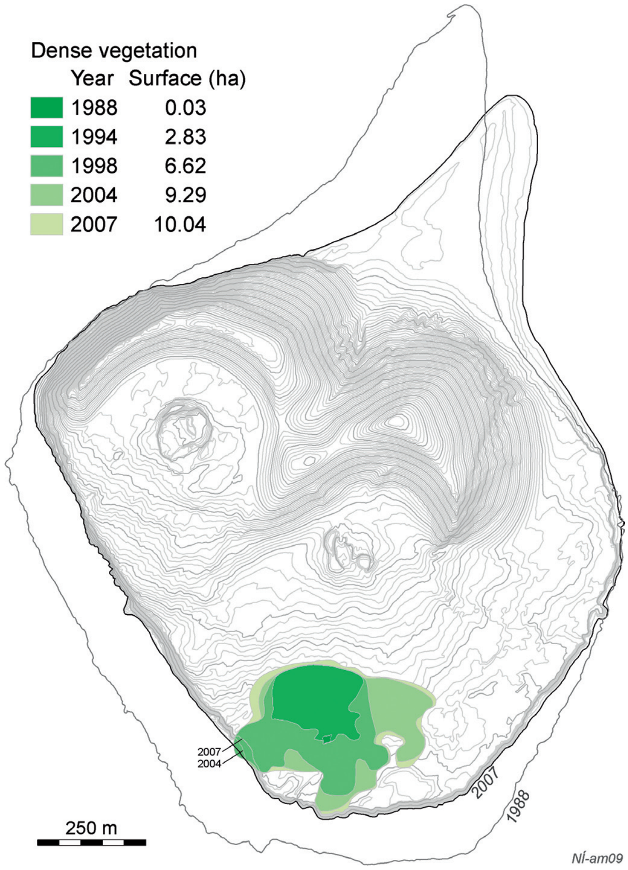

Figure 21. Expansion of dense vegetation within gull colony on Surtsey during 1988–2007. Approximation from aerial photographs, drawn by Anette Th. Meier. Note erosion of the island over the period.

and abundance on the island. Snow bunting, the first land bird species, starts breeding on the island, followed by the white wagtail and the meadow pipit, all passerine species that feed their young on insects. Greylag geese start nesting, grazing on the grassland in the gull colony. The first pairs of puffins start breeding in the cliffs. Increase in breeding gulls and expansion of colony. Ravens breed on the island at the end of the period. This omnivorous bird and a top predator, feeds its chicks mainly on eggs and the young of fulmars, gulls and kittiwakes.

We predict that during the next few decades the development on Surtsey will continue along these lines, with an increase in species richness of plants and birds, though at a slower rate. Expansion of vegetated areas will continue with associated soil development, invertebrate- and bird-life. The puffin is the most numerous and characteristic birds of the Vestmannaeyjar islands where it breeds in great numbers in the grasslands upon the islands. In the grasslands it acts as an ecosystem engineer (Sekercioglu 2006) with its burrowing activity and transfer of nutrients from sea to land. The puffin has recently started breeding in hollows and cracks in the cliffs of Surtsey. It is still confined to the cliffs but prospecting burrows have been found in the developing grassland. We expect the puffin to start breeding in the grassland within two decades and become a key species in further ecosystem development. In the longer run the erosion of the island, with a loss of habitats and encroachment of vegetation will lead to a decline in overall species richness of plants and animals and the ecosystem will become similar to that of the neighbouring islands. *Cakile arctica* was the first plant to colonize the shores of Surtsey in 1965. Of the established plant populations on the island it might also become the first victim of extinction with the disappearance of the northern lowland spit.

ACKNOWLEDGEMENTS

The Surtsey Research Society has provided logistic support for the study and transport to the island was carried out by the Icelandic Coastguard. The initiation of the project was funded by the Icelandic Research Council. Toyota Iceland supported biological research on Surtsey in 2007 and 2008. Anette Th. Meier, Sigurdur K. Gudjohnsen and Olga Kolbrún Vilmundardóttir made diagrams and maps, drawings of birds and animals were made by Jón Baldur Hlídberg. Roger del Moral and Bjarni D. Sigurdsson made valuable comments and corrections on the manuscript.

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Appendix 1. Record of vascular plant species found on Surtsey during 1965–2008 (65–08). Probable route of dispersal (D) is shown in third column. S: sea, B, b: birds, W, w: wind; capital letter denotes that species is adapted to the dispersal, but lower case that the dispersal route was most probable.

	Species	D
1	*Cakile arctica*	S
2	*Leymus arenarius*	S
3	*Honkenya peploides*	S
4	*Mertensia maritima*	S
5	*Cochlearia officinalis*	B
6	*Stellaria media*	b
7	*Cystopteris fragilis*	W
8	*Angelica archangelica*	S
9	*Carex maritima*	b
10	*Puccinellia distans*	b
11	*Matricaria maritima*	b
12	*Festuca richardsonii*	b
13	*Cerastium fontanum*	b
14	*Equisetum arvense*	W
15	*Silene uniflora*	b
16	*Juncus arcticus*	b
17	*Poa pratensis*	b
18	*Sagina procumbens*	b
19	*Atriplex glabriuscula*	S
20	*Rumex acetosella*	b
21	*Cardaminopsis petraea*	b
22	*Armeria maritima*	b
23	*Poa annua*	b
24	*Agrostis stolonifera*	b
25	*Alchemilla vulgaris*	b
26	*Epilobium palustre*	W
27	*Capsella bursa-pastoris*	b
28	*Luzula multiflora*	b
29	*Taraxacum*	W
30	*Rumex acetosa*	b
31	*Polygonum aviculare*	b
32	*Agrostis capillaris*	b
33	*Alopecurus geniculatus*	b
34	*Ranunculus acris*	b
35	*Deschampsia beringensis*	b
36	*Empetrum nigrum*	B
37	*Agrostis vinealis*	b
38	*Eleocharis quinqueflora*	b
39	*Phleum pratense*	b
40	*Montia fontana*	b
41	*Poa glauca*	b
42	*Juncus alpinus*	b
43	*Salix herbacea*	W
44	*Galium normanii*	b
45	*Potentilla anserina*	b
46	*Anthoxanthum odoratum*	b
47	*Leontodon autumnalis*	b
48	*Rumex longifolius*	b
49	*Polypodium vulgare*	W
50	*Luzula spicata*	b
51	*Myosotis arvensis*	B
52	*Salix phylicifolia*	W
53	*Oxyria digyna*	b
54	*Salix lanata*	W
55	*Euphrasia frigida*	b
56	*Plantago maritima*	b
57	*Platanthera hyperborea*	w
58	*Galium verum*	b
59	*Plantago lanceolata*	b
60	*Thymus praecox*	b
61	*Saxifraga caespitosa*	b
62	*Rhodiola rosea*	b
63	*Festuca vivipara*	b
64	*Atriplex sp.*	b
65	*Achillea millefolium*	b
66	*Alopecurus pratensis*	b
67	*Calamogrostis stricta*	b
68	*Gymnocarpium dryopteris*	W
69	*Epilobium collinum*	W

Ecosystem carbon fluxes of *Leymus arenarius* and *Honckenya peploides* on Surtsey in relation to water availability: a pilot study

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ABSTRACT

Large parts of Surtsey are covered by sparse plant communities, with *Honckenya peploides* and *Leymus arenarius* as the key species. The objective of the present pilot study was to investigate ecosystem fluxes of moist and dry areas covered by those two species. Light saturated gross photosynthesis (GPP), expressed on soil surface area basis, was 45% higher in *L. arenarius* at dry sites, but similar for both species at moist sites. This may indicate that *L. arenarius* is better adapted to habitats with low water availability. When carbon fluxes were compared at moist and dry conditions across both species, it was clear that both ecosystem respiration and GPP were much higher at the moist site. This may indicate that periodic water stress due to low water holding capacity of the young volcanic ash may be an important limiting factor for biological activity on Surtsey, in addition to the low nutrient availability.

INTRODUCTION

Surtsey is a volcanic island that emerged from the North Atlantic Ocean in 1963. Vascular plants have dominated the primary succession on the island, and their colonisation and succession has been intensively studied (*e.g.* Fridriksson 1966, Magnússon 1992, Magnússon & Magnússon 2000, Magnússon, Magnússon & Fridriksson 2009).

The first twenty years after Surtsey appeared were characterised by colonisation and succession of costal plants, with *Honckenya peploides* and *Leymus arenarius* as key species, forming sparse vegetation cover on sandy areas of the island (Fridriksson 1992). During the past 15 years swards of grasses and forbs have formed on the southern part of the island, after colonisation by seagulls (*Larus* sp.). The gulls have carried seeds of new plant species and fertilized the sterile soil with their droppings and food brought to the nest sites from the sea. Vegetation development on other parts of the island have on the other hand remained slow by comparison. There the *H. peploides* and *L. arenarius* are the key plant species in most cases, along with e.g. *Mertensia maritime* and *Cardaminopsis petraea* (Magnússon & Magnússon 2000, Magnússon, Magnússon & Fridriksson 2009).

Biological activity of terrestrial ecosystems can be indirectly measured as CO_2 being taken up and emitted from the soil surface (Larcher 2003). As soil organic matter is decomposed CO_2 is released. Hence, CO_2 efflux from the soil surface may partly indicate the decomposition rate and activity of soil organisms (bacteria, fungi and soil fauna). The second major contributor of CO_2 to the atmosphere from the soil surface is the metabolism of living plant roots. Together these two fluxes are termed soil respiration (R_s). When aboveground parts of living plants are included in respiration measurements, the process is often termed ecosystem respiration (R_e). The rate of R_e depends therefore on plant growth and maintenance respiration and soil decomposition activity. Gross photosynthesis (GPP) is only a measure of plant activity and represents the first step in their growth process (Larcher 2003).

Ecosystem function has not been studied as much on Surtsey as the ecosystem structure. In the early years Henriksson & Rodgers (1978) and Henriksson & Henriksson (1982) studied terrestrial nitrogen cycle. Frederiksen et al. (2000) studied soil development on Surtsey. Klamer et al. (2000) also studied the amount of microbial activity in unvegetated and vegetated soil. Magnússon (1992) studied how soil respiration changed with increasing cover of *L. arenarius* and *H. peploides* on the island. He found that respiration rates were related to differences in vegetation cover and root biomass. Since these early measurements, no gas exchange measurements have been made *in situ* on Surtsey until the present study. The objective of the study was to compare patches of *H. peploides* and *L. arenarius* found at dry and moist conditions to test if soil humidity was important for ecosystem fluxes on Surtsey.

MATERIAL AND METHODS

Surtsey is the southernmost of the Vestmannaeyjar islands. The climate is mild and oceanic, with annual mean temperature of 5.0 °C and mean annual precipitation of 1576 mm during 1965 – 2005, as recorded on the Heimaey weather station 15 km to the northeast of Surtsey (Icelandic Meterological Office).

To test if soil humidity was important for ecosystem fluxes on Surtsey, measurements were made on 19 July 2006 on patches with 100% surface cover of *L. arenarius* and *H. peploides* on two permanent plots, where the volcanic ash profile was freely drained and discharge was not likely to be substantial (Fig. 1 – plots 3 and 17; Magnússon & Magnússon 2000). For comparison, patches with

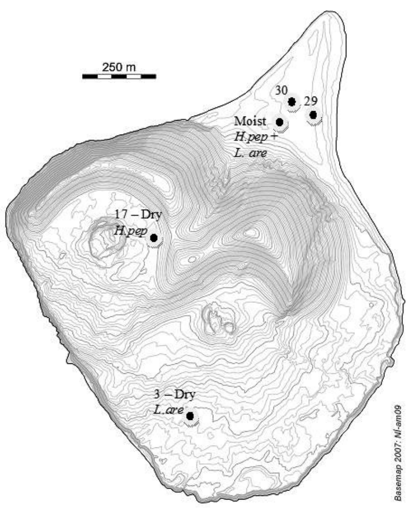

Figure 1. Location of the dryer permanent vegetation plots no. 3 and 17 covered by *Leymus arenarius* and *Honckenya peploides*, respectively, and the place at the low ness where the two species grew at more moist conditions. Also shown are the permanent plots no. 29 and 30.

Table 1. Soil acidity (pH, in water), total carbon (SOC,%), total nitrogen (N, %) and the soil C/N ratio of permanent survey plots on Surtsey used in the present study. Data from Magnússon, Magnússon & Fridriksson (2009).

Plots No	Soil depth	pH	N	SOC	C/N ratio
3	> 35	7.3	0.051	0.56	10.8
17	> 35	8.5	0.005	0.03	5.5
29	> 35	8.9	0.001	0.01	8.3
30	> 35	9.4	0.003	0.03	8.7

100% surface cover of the same two species were measured at the edge of the lowland ness, just below a relatively large discharge area formed by the two craters of Surtsey (ca. 80–130 m SW of plots 30 and 29; Fig. 1). There the volcanic ash profile was humid and ground water was found at ca. 30 cm depth. Both species showed clear signs of more favorable growing conditions at the more humid site, as they were darker green in color and had denser foliage. The area at the ness had, however, less soil nitrogen than the two dryer sites (Table 1). The dryer *L. arenarius* plot (no 3) was found within a seagull colony that had greatly increased the soil fertility, while the dry *H. peploides* plot (no 17) was not much affected by the seagulls (Magnússon et al. 2009).

EMG-4 infrared gas analyser and a CPY-2 transparent cuvette (PP Systems) were used to measure the carbon fluxes. First, the transparent chamber was fitted to the surface of the dense patches and net ecosystem exchange (NEE) was measured. Then, the chamber was covered with black cloth and the measured was repeated at the same spot in total darkness, yielding ecosystem respiration (R_e). Gross photosynthesis (GPP) was then estimated as:

$$GPP = NEE + R_e \qquad (1)$$

All carbon flux measurements took place during daytime hours in high solar radiation and 3–5 measurements were made for each vegetation type. The average solar radiation during the measurements was ca. 1400 µmol m^{-2} s^{-1} PAR and the average soil temperature at 10 cm depth was 16.5 °C.

RESULTS

When carbon fluxes were compared at moist and dry conditions across both species, it was clear that light saturated carbon uptake (GPP) was substantially higher under the more moist conditions (+115%; Fig. 2). The relative change in R_e, which indicates respiration and decomposition activity, was even stronger at the moist site (+665%). The

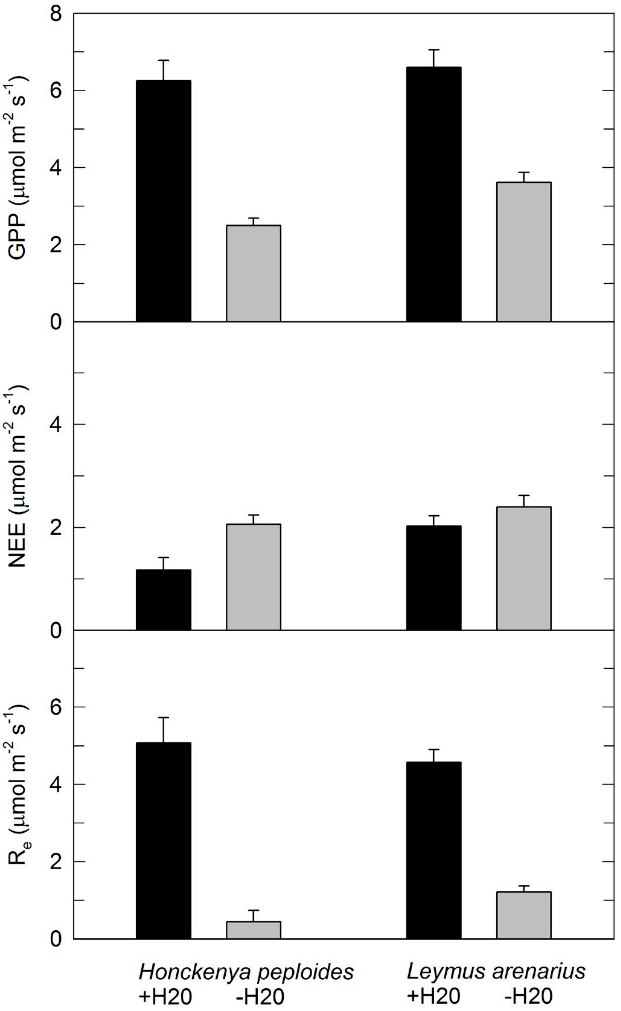

Figure 2. Gross photosynthesis (GPP), net ecosystem exchange (NEE) and ecosystem respiration (R_e) in a moist area (+H20) and dry area (-H20) on Surtsey in July 2006. Means and SE of 3–5 measurements per site.

large increase in R_e led to 28% lower NEE under the moist conditions. The net effect was therefore that 18% more carbon was accumulating in the dry patches when the measurements took place than in the moist ones, even though their uptake rate was much lower.

The GPP was similar for the two species when they were growing under more moist conditions, or 6.2 and 6.6 μmol CO_2 m^{-2} s^{-1} for *H. peploides* and *L. arenarius*, respectively (Fig. 2). However, when the two species were compared at drier conditions, the *L. arenarius* had 45% higher uptake rate than *H. peploides*. Ecosystem respiration was slightly higher in the *H. peploides* than the *L. arenarius* at moist conditions (+11%), but much lower at dry conditions (–36%; Fig. 2). This led to the instantaneous carbon accumulation (NEE) in the two species was higher for *L. arenarius* both under moist and dry conditions (+73% and +17%, respectively).

DISCUSSON

Comparison to earlier measurements on Surtsey

Magnússon (1992) used an alkali absorption method to measure R_s in areas with three different surface types, bare sand, 13% *H. peploides* cover and 21% *L. arenarius* cover. This method does not give absolute values but rather a relative measure of respiration intensity between sites (Reiners 1968; Magnússon 1992). The difference of the alkali method from true respiration is dependent on the flux rate, but typically it overestimates respiration at low rates (Óskarsson 1998). When converted to molar units, Magnússon (1992) found on average 0.55, 0.70 and 1.78 μmol CO_2 m^{-2} s^{-1} R_s from the bare, *H. peploides* and *L. arenarius* surfaces. These R_s rates are similar as the measured R_e at the dry sites in the present study (0.4–1.2 μmol CO_2 m^{-2} s^{-1}) where the plant cover was 100%.

Differences between Leymus *and* Honckenya

The two plant species chosen for the present study (*Leymus arenarius* and *Honckenya peploides*) were the most successful colonizers during the first 20 years of primary succession on Surtsey (Fridriksson 1992). Both have seeds that tolerate submergence in sea water and are common in costal plant communities in Iceland (Kristinsson 1987), both tolerate sand blaster and allocate much of their resources to root growth and are therefore well adapted to survive the infertile conditions (Fridriksson 1992; Magnússon & Magnússon 2000).

The present study showed that *L. arenarius* maintained higher GPP than *H. peploides* under dry conditions on the island, even if their GPP was not much different under moist conditions. This is in line with a difference in their growth habitats in Iceland, but *H. peploides* rarely grows above the coastline while *L. arenarius* can also grow on dry inland sandy sites (Greipsson 1994). A controlled drought experiment on *H. peploides* and another *Leymus* species, *Leymus mollis*, at Hudson Bay, Canada, showed that *L. mollis* maintained higher survival under drought stress (Gagné & Houle 2002). The observed difference in GPP may therefore possibly indicate that the *L. arenarius* is better adapted to survive where water availability is scarce, e.g. due to deeper root system.

The comparison between the two dryer sites in the present study is, however, complicated by their difference in soil fertility (Table 1). The relatively higher GPP in *L. arenarius* than *H. peploides* at the dry site could therefore also be a result of higher photosynthetic capacity per surface area, a well known response of plants to fertilization (Larcher 2003).

Differences between moist and dry sites

When carbon fluxes were compared under moist and dry conditions across both species, it was clear that light saturated carbon uptake (GPP) and ecosystem respiration (R_e) were much higher at the moist sites, indicating that water stress may be important factor limiting plant growth on Surtsey. Further, the higher R_e indicated more biologic activity in the moist soil. Earlier studies that have studied biological activity of soils from Surtsey with various methods have not reported on the importance of soil moisture (Frederiksen et al. 2000; Klamer et al. 2000).

It has to be stated that other environmental factors than water availability alone may have differed between the moist and dry sites in the present study. The moist sites were found closer to the sea and it could be expected that they had benefitted from sea-derived organic matter washed onshore. In the earlier mentioned experiment on *H. peploides* and *L. mollis*, both species were shown to respond strongly to nutrient availability, but they did not significantly differ in their response (Gagné & Houle 2002). When the soil nutrient status in different permanent plots on Surtsey was investigated in 2006 (Magnússon et al. 2009; also see Table 1), soil nitrogen was found to be lower in nearby permanent plots at the ness than in the two plots at the dryer sites. Apparently it was therefore not higher soil nutrient status that explained the higher carbon uptake, soil activity and more vigorous growth in the moist area.

More research should be conducted on which environmental factors limit biological activity on Surtsey, where direct measurements of soil water content and nutrient status should be part of the experimental setup.

ACKNOWLEDGEMENTS

The Surtsey Research Society, Institute of Natural History and the Icelandic Coast Guard provided logistic support for the present study. Borgthór Magnússon assisted with the fieldwork and Anette T. Meier with graphic work, and both Borgthór and Sigurdur H. Magnússon gave valuable comments on earlier versions of this article.

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Colonization of lichens on Surtsey 1970–2006

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ABSTRACT

A list of lichen species from the volcanic island Surtsey is presented. A total of 87 species have been recorded since the first three species appeared in 1970. Notes on distribution and short description of the main lichen communities are given. Possible colonization routes to the island are discussed. Four of the species treated are new to Iceland, *Gyalidea fritzei* and *Psilolechia clavulifera* and two species, one *Lecanora* and one *Stereocaulon* which probably are new to science. Two further species belonging to *Lecanora*, provisionally determined as *L. albescens* and *L. semipallida*, are probably new to Iceland.

The primary colonization resembles what has been recorded on other lava fields in Iceland. Lichen species established very slowly on Surtsey with relatively few species found during the first two decades, in 1984 only 17 species had been recorded. That number almost doubled during the next six years, 31 species had been recorded on the island by 1990 and there has been a constant accumulation of species since then. The lichen colonization benefitted from the activity of gulls. Many species were probably dispersed by the trampling birds and colonized the naked lava rock around the breeding area. Later soil formation started in connection with the gull colony and the first colonizers were replaced by other species. The palagonite tuff has only recently been colonized by lichens and on the coastal rocks of the island only one lichenized species has been found so far.

INTRODUCTION

Surtsey (Fig. 1), formed by volcanic eruption in the years 1963–1967, has been carefully studied by scientists in order to monitor its colonization by organisms. Since 1965 the island has 15 times been visited for studies of the colonization and the development of lichen communities in different habitats. No traces of lichens were found in the first three visits, in 1965, 1967 and 1968 (Kristinsson 1970a). The first lichen species to be discovered on Surtsey was *Trapelia coarctata*, first seen in 1970 (Kristinsson 1972). It had by then already formed a more or less continuous cover of white to grey thalli with numerous ascospore-producing apothecia on steep lava rocks covering the outside wall of the Surtungur crater. The site of the lichen regularly received warm steam that kept the wall more or less constantly wet, depending on the wind direction.

In addition to this first mature colonizer, sterile initial stages of two other species were discovered in the Surtsey lava in 1970, *Placopsis gelida* and *Stereocaulon vesuvianum.* These two species together with *Stereocaulon capitellatum* increased greatly and later became the most successful colonizers everywhere in the lava fields throughout the island together with the mosses *Racomitrium ericoides* and *R. lanuginosum. Acarospora smaragdula* soon appeared on the elevated crater margin and outcrops in the lava fields. Light green patches widely distributed on overhanging rocks, in rifts and cave mouths, originally recorded as *Lepraria* and described in detail by Kristinsson (1974), turned later out to be *Psilolechia leprosa.*

Figure 1. Aerial photograph of Surtsey in 2007.

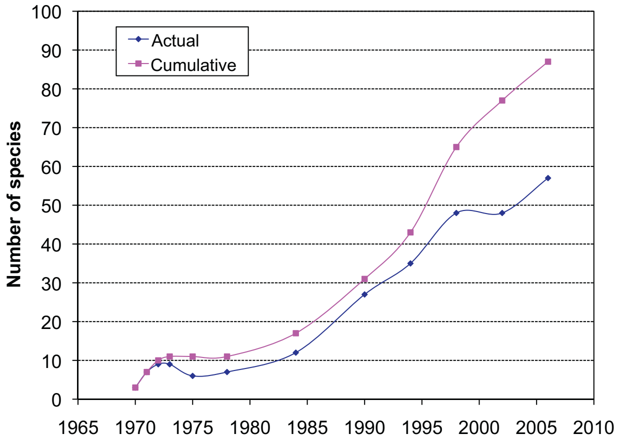


Figure 2. Number of lichen species found in Surtsey 1970–2006.

On the first visits the main emphasis was on a careful search for initial stages of lichens in all the different habitats found on the island. Later, when colonization had started, the distribution of the lichen species was recorded on the basis of a 100 x 100 m grid system.

The purpose of this paper is to give a preliminary list of all species identified from the island, together with notes on their frequency, distribution, and where feasible to consider possible colonization routes. Information on the colonization is compiled (Fig. 2) and the observed development of lichen communities in different habitats is described.

METHODS

During each visit to the island different habitats were carefully searched in order to record all visible lichen species. Common species were recorded on basis of the 100 x 100 m grid system that had been laid over the island for monitoring the distribution of vascular plants (Fridriksson *et al.* 1972). Distribution maps of common lichens based on that grid were already published (Kristinsson 1974). Samples were collected of new or unidentified species for microscopical identification in the laboratory. The chemical content of the specimens was studied using spot tests or thin layer chromatography. The nomenclature follows Santesson *et al.* (2004) for species listed there. All specimens are kept in the herbarium of the Icelandic Institute of Natural History, Akureyri Division (AMNH) and other data are kept in a digitalized database containing known distribution of Icelandic species of plants and fungi. All photos are taken by Hördur Kristinsson unless otherwise stated.

DEVELOPMENT OF LICHEN VEGETATION

Colonization of lichens in different habitats on Surtsey has followed a certain pattern, both regarding the habitat selection of different species and the time scale optimal for different communities. The development of the lichen vegetation often depends on weathering of the substrates, the erosive forces of the wind and sea together with the activity of other organisms colonizing the island.

The first lichen colonization took place around spots where steam condensed directly on the lava rock, a condition only present in the first years before the underlying lava cooled down. Next species to arrive were known primary colonizers in lava fields. However, unexpected they colonized first the youngest aa lava at the eastern side of the island that apparently was more favourable for the colonization than the oldest pahoehoe lava. Certain species preferred the peaks and outcrops in the lava, and others caves, rifts and overhanging rock. Unusual conditions were found in the sheltered area inside the Surtungur crater. The coastal rocks were broken down every year, thus marine lichens of the littoral zone like *Lichina confinis*, *Verrucaria maura* and *V. mucosa* were unsuccessful in colonizing. With the activity of the breeding gulls in the southern part of the island, new conditions were created on the rocks frequently visited by birds. They were colonized by crustose rock lichens probably carried around by the birds' feet, and by coprophilous lichens benefitting from nutrient enrichment by bird dung. Thin soil that slowly formed on these lava blocks created favourable conditions for many terricolous and muscicolous lichens. The thicker soil and grassland that followed destroyed their habitat again, but offered still some conditions for fruticose and foliose lichens like *Cladonia* spp. and *Peltigera* spp. The erosive forces prevented lichen colonization on the palagonite tuff on the top of Austurbunki and Vesturbunki for a long time, but when they had stabilized enough after some 35 years, lichen colonization began. The steep slopes of the tuff cones are still too unstable for lichen colonization, except around the small lava outlets in the slopes (Bjallan, Strompur), where fulmars have nested. Finally, the manmade substrate concrete of the helicopter platform was colonized by lichens. Here, six different lichen habitats have been recognized on Surtsey, i.e. steam holes, lava fields, Surtur crater, seashore, the colony of breeding gulls and the palagonite tuff of Austurbunki. These different habitats will be described in more detail below.

The steam holes

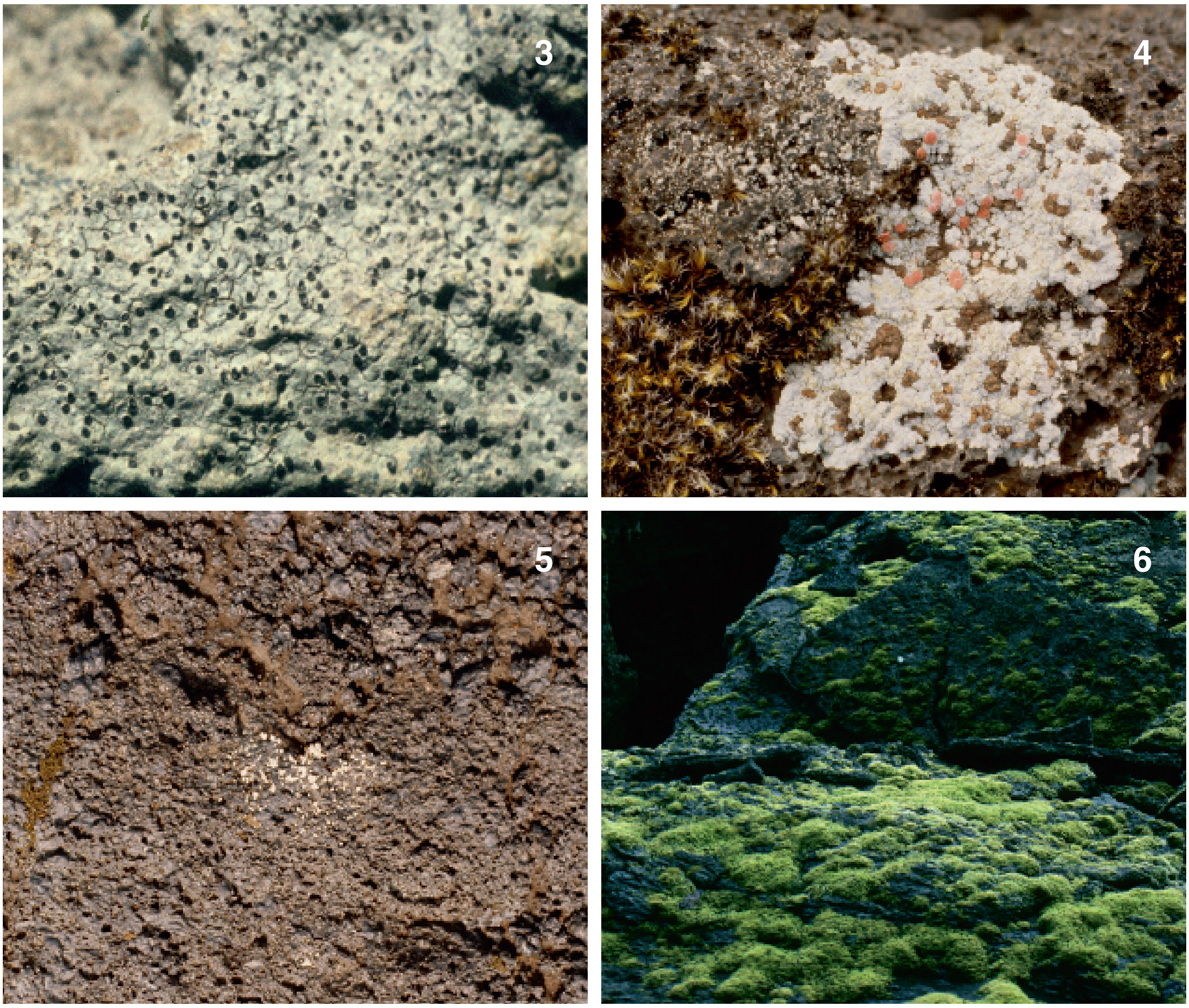
Thermal heat occurred widely in the first years after the Surtsey eruption, especially in the neighbourhood of the craters (Magnússon *et al.* 1970). Warm steam escaped through small openings in the lava surface. The steam was blown along the surface by the wind and maintained surrounding tephra and lava rock wet. The surface water stabilized the blowing tephra sand that became a suitable substrate for colonization of cyanobacteria and bryophytes (Behre & Schwabe 1970, Jóhannsson 1968) mainly *Anabaena variabilis*, *Bryum argenteum*, *Funaria hygrometrica* and *Schizothrix lardacea*. Lichens were not able to colonize these habitats except where the steam was blown over bare rock. Such habitats were mainly found near the Surtungur crater, especially on the outside of the western wall, but also in the surrounding lava fields. These habitats were mainly colonized by two species, *Trapelia coarctata* and *Psilolechia leprosa*. The former species was a very successful and rapid colonizer especially on the rather steep outside walls of Surtungur, facing northwest (Fig. 3). In 1970 and the following years these walls were more or less constantly kept moist by steam escaping through numerous steamholes. When first discovered, in 1970, *T. coarctata* had already formed an extensive cover of richly fertile thallus on these walls (Kristinsson 1972). Later it was also found in other localities under similar conditions. It was still present at number of sites throughout the island in 2006, long after the steam emission ceased, but much less abundant than in 1970. *Psilolechia leprosa* colonized the crater walls a little later and was very abundant in 1975 as minute, sterile thalli with granular surface. It was never seen fertile or covering large areas here as it was later on the overhanging walls in the rifts of the lava field. *Placopsis gelida* also colonized this habitat. As the years passed these habitats changed as they slowly cooled down and the steam disappeared. As those slopes dried out, *Trapelia coarctata* became less vigorous and *Psilolechia leprosa* almost disappeared, but *Placopsis gelida* survived like in the surrounding lava fields.

Primary colonization in the lava fields

The primary colonization in the lava fields of Surtsey resembled other lava fields in Iceland. The first stages have been described in details by Kristinsson (1974). Five species played a main role in this colonization (Fig. 4): the lichens *Placopsis gelida*, *Stereocaulon capitellatum*, *S. vesuvianum* and the mosses *Racomitrium ericoides* and *R. lanuginosum.* These lichens contain cephalodia with cyanobacteria besides the green algae. They start growing within tiny cavities on the lava surface originally formed by air bubbles in the molten lava. These cavities accumulate dust and diaspores of organisms that are captured and settle down in the holes and they also retain some water for longer periods than the smooth lava surface (Kristinsson 1970b). They serve as suitable growth chambers for different kinds of diaspores, such as fungus spores, lichen soredia, cyanobacteria and green algal cells (Kristinsson 1974). Minute thalli of each of the three lichen species develop separately from many adjacent cavities forming a circular colony of 2–4 cm in diameter (Fig. 5), and later on coalescing to form one lichen thallus. In many of the cavities cephalodia containing cyanobacteria can be observed already at initial stages of the lichen growth. In the case of *Placopsis gelida,* this gives rise to a single white thallus with many small cephalodia as is characteristic for the Surtsey lava (Fig. 4), while in older habitats *Placopsis* thalli usually contains one large cephalodium in the center of the thallus.

From the beginning of the lichen colonization in the lava fields all members of the characteristic community were evenly distributed throughout the lava fields all over the island. This distribution pattern indicates wind dispersal. Since all remained sterile and without apothecia for many years, the diaspores must have been dispersed by long distance dispersal at least from the neighbouring islands or the mainland of Iceland.

Initially the growing conditions for lichens were best in depressions in the aa lava on the eastern side of the island, and inside the Surtungur crater. The growth was much slower at exposed sites and in the pahoehoe lava in the centre and on the western side of the island even though those lava flows are older. This was probably both due to the smooth surface structure and less favourable mois-



Figures 3–6. Fig. 3. *Trapelia coarctata* on the outside of the Surtungur crater in 1971. Fig. 4. Primary colonizers in the lava fields of Surtsey 1975. Center: The lichen *Placopsis gelida* with numerous, brown *Nostoc*-cephalodia and a few pink apothecia. Upper left: *Stereocaulon vesuvianum* with white pseudopodetia and black *Stigonema*-cephalodia. Lower left: the moss *Racomitrium lanuginosum*. Fig. 5. Initial stage of *Stereocaulon capitellatum* on lava surface in Surtsey. Typical group of separate thalli each developing from single small cavity on the surface, later coalescing to form one large thallus. Fig 6. *Racomitrium* carpet in the bottom of the Surtungur crater in 1978.

ture conditions, as well as infrequent but rather strong wind erosion occurring there.

Later three other species of *Stereocaulon* appeared in the lava fields, all with more limited distribution. *S. vanoyei* and *S.* sp. were relatively frequent in a limited area on the pahoehoe lava in the eastern part of the island, while *S. spathuliferum* established scattered populations in a few localities. A few *Porpidia* species appeared also quite early. *P.* cf. *crustulata* appeared first and had the widest distribution, and two sorediate species also became rather common, *P. melinodes* and *P. soredizodes*. *Lichenomphalia* cf. *velutina* was seen several times among the primary colonizers in the lava fields. It is a mushroom previously included in the genus *Omphalina* forming a green-algal thallus of *Botrydinia*-type around the base and growing directly on the rock already colonized by *Racomitrium*.

Protruding lava peaks, shady caves and rifts, offered some habitat diversity within the lava fields. The peaks were quite early colonized by *Acarospora smaragdula*. *Arthonia lapidicola*, *Catillaria chalybeia* and *Scoliciosporum umbrinum* also colonized similar habitats, but were less frequent. The overhanging rock in caves and rifts was mainly colonized by *Psilolechia leprosa*, a rapidly spreading species that was found in almost all suitable sites throughout the island, a fact that strongly suggests dispersal by wind.

During the first ten years of lichen establishment in the lava fields their distribution increased and the most favourable sites became mostly covered by bryophytes and lichens, mainly the five species mentioned above. After this period, a deterioration was noticed, especially noticeable during the visit in 1984 and partly also in 1990. Apparently severe erosion had taken place, probably either caused by excessive drought or strong winds. The *Racomitrium* carpets were partly dead or worn away from the rock, some were partly filled with sand and the lichens had detoriated. Some of these sites recovered after 1990 and then some regions also experienced a new change due to the increasing activity of gulls.

The characteristic bryophyte and lichen communities of the lava fields are also severely affected by the closeness of the sea. They are poorly developed in the first 100–200 m from the edge of the seacliffs. In the same way, well developed lava communities that have been formed further inland, deteriorate again when the seacliffs are broken down and the ocean spray approached. *Stereocaulon* disappeared, both the *Racomitrium* species retreat or are replaced by yellowish brown bryophyte communities mainly dominated by *Schistidium maritimum*.

Sheltered habitats in the Surtungur crater

As mentioned earlier the community development in the lava fields was more pronounced in sheltered habitats. The most sheltered location on the whole island was inside the Surtungur crater, the bottom of which was surrounded by steep cliffs on all sides. It had been noticed, that the growth of lichens and bryophytes characteristic for the lava fields was most advanced here. This was the first locality where patches of closed carpets of *Racomitrium lanuginosum* were formed (Fig. 6). In addition to the primary colonizers several crustose lichens, including *Rhizocarpon lavatum*, *Porpidia* cf. *crustulata* (Fig. 7), *P. melinodes* and later *P. flavicunda*, appeared, first inside the crater but later in various locations in the surrounding lava fields. Apart from these rather common species, several very rare species appeared in this crater. Among these were *Gyalidea fritzei*, *Hymenelia arctica*, *Pilophorus cereolus*, *P. dovrensis*, *Psilolechia clavulifera* and *Stereocaulon* cf. *tornense*.

Several soil lichens were first found in the slope below the western wall inside the Surtungur crater, below some unsuccessful nesting attempts of a raven. Among these were *Collema tenax*, *Leptogium lichenoides*, *Peltigera didactyla*, *P. venosa* and *Solorina bispora*. An unidentified species probably belonging to the genus *Micarea* was found growing on rock in this locality.

The first closed moss carpets in the Surtungur crater also provided a substrate for the first specimens of *Peltigera canina* (Fig. 8), *Protopannaria pezizoides* and *Stereocaulon alpinum*.

The seashore

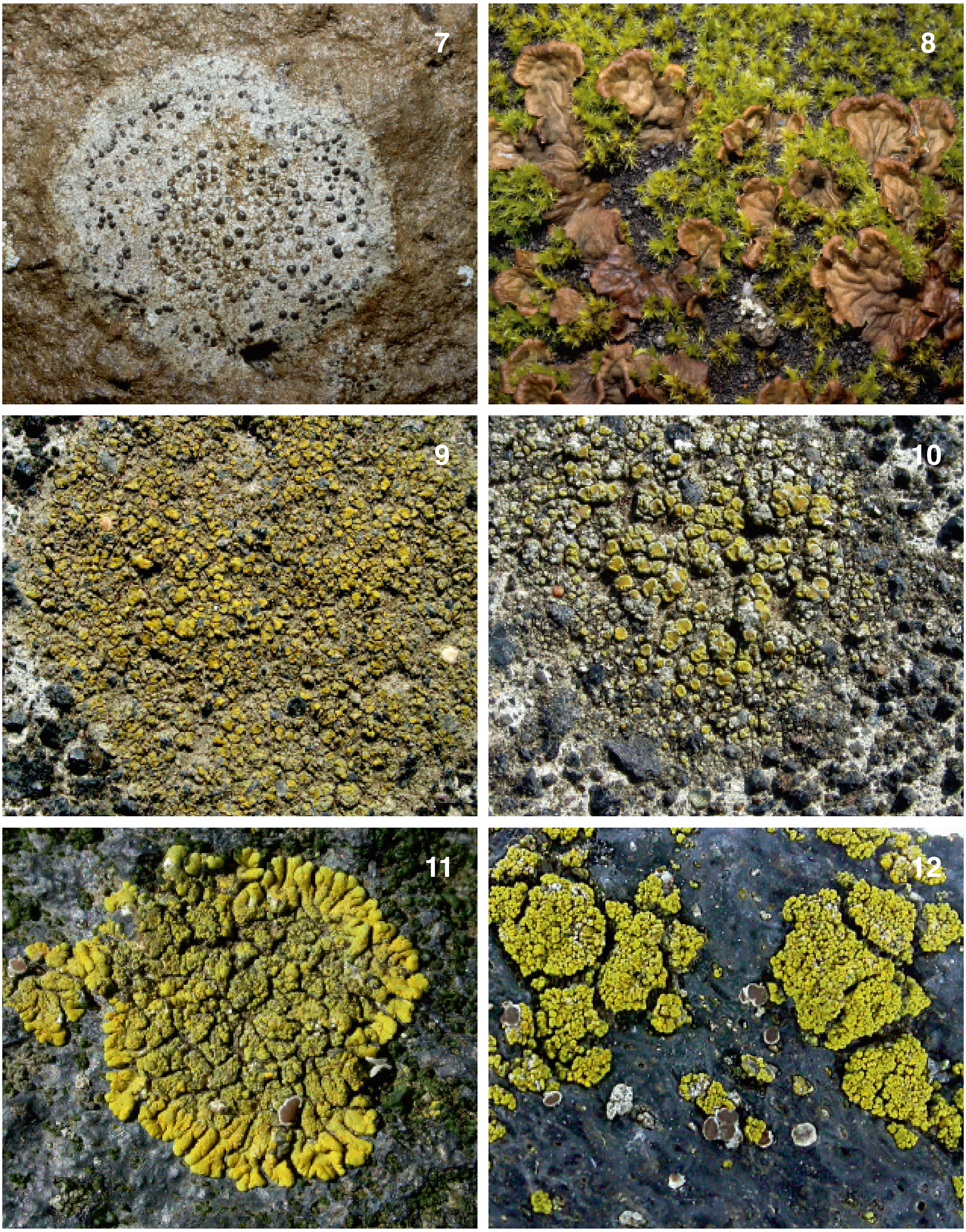
The coastline of Surtsey has changed much over the years due to sea erosion and the island has continued to decrease in size. The lava has been broken down to boulders and smaller particles and these have been rolled up and down the shore, successively getting more or less round. As a result of the sea currents a spit has formed on the northern side of the island. Because of the eroding sea-waves the coastal rocks around the island are very unstable habitats preventing the establishment of marine *Verrucaria* species, such as *V. maura* and *V. mucosa*, which are generally abundant on coastal rocks around Iceland. A similar tendency can be observed in the seaweed flora of the littoral zone which mainly consists of annuals (Jónsson & Gunnarsson 2000). The first, and so far the only, lichenized species growing directly on coastal cliffs was discovered in 2002. It was *Collemopsidium halodytes*, a species that can either grow on coastal rocks or on shells of *Balanus* spp.

Four species of seashore lichens growing above the *Verrucaria*-zone on coastal cliffs have been recorded on Surtsey, *Caloplaca verruculifera*, *Lecanora poliophaea*, *L. salina* and *Rinodina gennarii*. These species grow out of the reach of the ocean waves but they are more or less influenced by spray of seawater, especially during the winter storms.

The colony of the breeding gulls

In 1986 the first lesser black-backed gulls (*Larus fuscus*) were observed nesting on Surtsey. In the following years three other gull species started nesting, viz. herring gull (*L. argentatus*), glaucous gull (*L. hyperboreus*) and great black-backed gull (*L. marinus*). These gulls have formed a relatively dense colony on the island and the nutrient enrichment caused by the faeces of the gulls has triggered a vegetation succession and soil formation within the colony differing from the rest of the island (Magnússon & Magnússon 2000). This succession and subsequent soil formation have formed a habitat for several lichen species which could not grow on Surtsey earlier, such as some *Cladonia* and *Peltigera* species. We can distinguish between two different types of lichen habitat created by the gulls:

1. Blocks of naked lava frequently traversed by the birds. These are colonized by crustose and foliose lichens that are probably brought in and dispersed mainly by the birds themselves. The main species belonging here are *Lecania subfuscula* and an unnamed *Lecanora* sp. which cover most of the blocks. Furthermore, *Lecanora salina*, *Lecanora poliophaea* and *Rinodina gennarii* are frequently found in this habitat, and more sparsely *Candelariella coralliza*. Following these are the bright yellow *Caloplaca verruculi-*



Figures 7–12. Fig. 7. The crustose lichen, *Porpidia* cf. *crustulata*, in the Surtungur crater 1994. Fig. 8. The lichen *Peltigera canina* growing in a carpet of *Racomitrium ericoides* in the bottom of the Surtungur crater in 1990. Fig. 9. *Caloplaca citrina* on palagonite tuff on top of Austurbunki in 2006. Fig. 10. *Candelariella aurella* on the helicopter platform in 2006. Fig 11. *Caloplaca verruculifera* on lava rock near the gull colony in 2006. In the lower part the lichen has grown around a brown apothecium of *Lecanora* sp. Fig. 12. *Candelariella coralliza* on lava rock in the gull colony in 2006. Brown apothecia with white margin belong to *Lecanora* sp.

fera, *Xanthoria candelaria* and *X. parietina*, and the gray-coloured *Phaeophyscia orbicularis*, *Physcia caesia* and *Physcia tenella*. As the succession proceeds and the flat lava blocks get covered by soil and grassland, this community survives only on lava peaks protruding out of the vegetation.

2. Blocks with thin soil formation, first colonized by the vascular plants *Poa annua, Sagina procumbens, Stellaria media* and the agaric *Omphalina rustica* leading later to thicker soil dominated by grasses. The first stages of the soil formation are favourable for many lichens including *Baeomyces rufus*, *Cladonia chlorophaea*, *C. furcata*, *C. macroceras*, *C. pocillum*, *C. symphycarpia*, *Collema tenax* and *Leptogium lichenoides*. Some of these, especially the *Cladonia* species, also survive partly in the third stage of the succession, characterized by thick soil and grassland dominated by dense stands of grasses and other vascular plants. Lichens are not prominent in the grassland, apart from *Cladonia* species and some species of *Peltigera*, especially *P. canina* and *P. neckeri*.

The palagonite tuff of Austurbunki

For many years the volcanic cones, Vesturbunki and Austurbunki, made of loose tephra, were unfavourable for lichen colonization. They were not firm enough and eroded too quickly. First in 2002 it was noticed, that lichen colonization had started on the top of Austurbunki and a little later on the little lower southeast shoulder of the same mountain. The first species seen on this substrate were *Caloplaca citrina* (Fig. 9), *Lecanora* cf. *albescens* and *Lecanora* cf. *semipallida*. In 2006, *Caloplaca crenularia* and *Verrucaria muralis* were also recorded there.

Man-made substrate, concrete

In 1993 a helicopter platform made of concrete was built. In 2006 three lichen species had established on the platform, viz. *Candelariella aurella* (Fig. 10), *Lecanora* cf. *albescens* and *Lecanora* cf. *semipallida*.

ANNOTATED LIST OF SPECIES

All species of lichenized and lichenicolous fungi recorded on Surtsey are presented below in alphabetical order. Their occurrences on Surtsey and in other parts of Iceland are described. Lichenicolous species are marked with an asterisk (*). Figure 2 shows the number of species found 1970–2006, together with the accumulated number of species recorded over the same period. In Table 1 the species are listed in the order they were discovered on Surtsey.

Acarospora smaragdula *(Wahlenb.) A.Massal.*

Common in the more oceanic parts of Iceland, in the South and along the western and eastern coasts. It is characterized by light brown or gray-green, very pale, rather dispersed thallus lobes of 0.5–2 mm diameter. The apothecia are immersed, light to dark brown, one to several on each thallus lobe. In the more continental regions of the North and Northeast of Iceland it is more or less replaced by *Acarospora veronensis*.

On Surtsey *A. smaragdula* was first seen in 1971 and again 1972 on the elevated margin of the Surtungur crater. In 1973 it was seen in several localities, mainly on peaks in the lava fields (Kristinsson 1974, as *Acarospora*). In 1978 the species was already very widely distributed on lava surfaces but also on vertical rock faces and shelves. Even though *A. smaragdula* requires an oceanic climate, it obviously tolerates drier habitats than most other lichens on Surtsey. Most other lichens on Surtsey express more vigorous growth in the lower sites between the peaks where moisture conditions are more favourable.

A few *Acarospora* specimens on Surtsey deviate from the typical *A. smaragdula* by having more or less continuous, areolate thallus and larger apothecia with more raised margin. The colour of the thallus has often an orange tint. These specimens were collected on the lava fields around the gull colony in 1994 and 1998, and might belong to *A. amphibola*.

Arthonia gelidae *R.Sant.*

A lichenicolous fungus growing on *Placopsis*. Collected on Surtsey in 1998, growing on *Placopsis* beneath a bird's nest on the inside wall of the Surtungur crater. This species has only been recorded once before in Iceland by Berger (2000) who found it growing on *Placopsis gelida* at Landmannalaugar in the southern part of the Central Highlands of Iceland.

Arthonia lapidicola *(Taylor) Branth & Rostr.*

Very small and inconspicuous species, rarely collected. The thallus is very thin and concoloured with the rock, the apothecia black and only 0.2 mm diameter, barely visible to the naked eye. In Iceland it is usually found on small pebbles lying on the ground, especially on moderately moist gravel flats or old river beds.

This species was first found on Surtsey 1973 growing on a lava outcrop below a top with *Acarospora* (mentioned in Kristinsson 1974 as *Arthonia*). Later it was also found in a sample of *Hymenelia arctica* collected 1998 on basalt on the bottom of the Surtungur crater. It is probably more common on Surtsey than these two records suggest.

Table 1. Lichen species found on Surtsey during the years 1970–2006. Filled squares indicate that the species was seen that year.

Species	1970	1971	1972	1973	1975	1978	1984	1990	1994	1998	2002	2006
Placopsis gelida	■	■	■	■	■	■	■	■	■	■	■	■
Stereocaulon vesuvianum	■	■	■	■	■	■	■	■	■	■	■	■
Trapelia coarctata	■	■	■	■	■	■		■	■	■	■	■
Acarospora smaragdula		■	■	■	■	■	■	■	■	■	■	■
Lichenomphalia cf. *velutina*		■			■	■						
Psilolechia leprosa		■	■	■	■	■	■	■	■	■	■	■
Stereocaulon capitellatum		■	■	■	■	■	■	■	■	■	■	■
Lecania subfuscula			■	■			■	■	■	■	■	■
Porpidia cf. *crustulata*			■				■	■	■	■	■	■
Xanthoria candelaria			■	■				■	■	■	■	■
Arthonia lapidicola				■						■		
Porpidia soredizodes							■	■	■	■	■	■
Rhizocarpon lavatum							■	■	■	■	■	■
Stereocaulon alpinum							■		■	■	■	■
Stereocaulon glareosum							■				■	
Stereocaulon spathuliferum							■	■				
Caloplaca verruculifera								■	■	■	■	■
Cladonia furcata								■		■	■	■
Cladonia macroceras								■	■			■
Cladonia symphicarpia								■		■		
Gyalidea fritzei								■	■	■	■	■
Gyalidea sp.								■				
Hymenelia arctica								■		■		■
Lecanora sp.								■	■	■	■	■
Lecidea lapicida var. *pantherina*								■		■		
Micarea sp.								■				
Peltigera canina								■	■	■	■	■
Porpidia melinodes								■	■	■		■
Porpidia tuberculosa								■	■		■	
Rhizocarpon expallescens								■	■	■	■	■
Rhizocarpon petraeum								■	■	■	■	
Scoliciosporum umbrinum								■	■	■	■	■
Stereocaulon cf. *tornense*								■	■			
Stereocaulon sp.								■	■	■		■
Xanthoria parietina								■		■		■
Cladonia chlorophaea									■			■
Collema tenax									■	■	■	■
Lecanora salina									■		■	
Leptogium lichenoides									■	■	■	■
Peltigera didactyla									■	■	■	■
Pertusaria sp.									■	■		
Protopannaria pezizoides									■			
Rhizocarpon reductum									■	■	■	
Stereocaulon arcticum									■	■	■	■
Stereocaulon rivulorum									■	■		
Stereocaulon vanoyei									■		■	■
Trapelia involuta									■			■
Arthonia gelidae										■		
Baeomyces rufus										■		■
Calvitimela armeniaca										■		
Candelariella coralliza										■		■
Catillaria chalybeia										■	■	■
Cladonia pocillum										■	■	■
Cladonia rangiformis										■		■
Lecanora poliophaeae										■	■	■
Lecidea sp.										■	■	
Peltigera venosa										■	■	
Pilophorus cereolus										■	■	
Placopsis lambii										■	■	
Polyblastia sp.										■		
Porpidia flavicunda										■		■
Solorina bispora										■		
Stereocaulon tomentosum										■	■	■
Verrucaria aquatilis										■	■	■
Verrucaria muralis										■		■
Caloplaca citrina											■	■
Cladonia islandica											■	
Collemopsidium halodytes											■	■
Lecanora cf. *albescens*											■	■
Lecanora cf. *semipallida*											■	■
Peltigera neckeri											■	■
Peltigera praetextata											■	
Pilophorus dovrensis											■	
Psilolechia clavulifera											■	
Pyrenidium hyalosporum											■	
Rinodina gennari											■	■
Verrucaria sp.											■	■
Arthonia phaeobaea												■
Caloplaca crenularia												■
Candelariella aurella												■
Endococcus fusiger												■
Peltigera rufescens												■
Phaeophyscia orbicularis												■
Physcia caesia												■
Physcia dubia												■
Physcia tenella var. *marina*												■
Porpidia speirea												■

Arthonia phaeobaea *(Norman) Norman*

Considered common all around Iceland on coastal rocks. Sigrídur Baldursdóttir (1985) studied marine and maritime lichens in six localities from Hvalfjördur in the southwest to Hornafjördur in the southeast and found *A. phaeobaea* in all localities.

It was first discovered on Surtsey in 2006, growing on the lava surface. The thalli of the specimens are richly fertile and contain a great number of pycnidia.

Baeomyces rufus *(Huds.) Rebent.*

Very common in all parts of Iceland, usually growing on bare soil and peat. First found on Surtsey in a few localities on thin soil around the gull colony in the southern part of the island in 1998. Fertile samples, growing directly on weathered lava rock, were collected 2006 inside the Surtungur crater.

Caloplaca citrina *(Hoffm.) Th.Fr.*

Common on and around bird cliffs along the southern coast of Iceland. It has a sorediate surface, with particles that will easily attach to and be carried around by birds' feet.

First seen and collected on Surtsey in 2002 on palagonite tuff on top of Austurbunki, which is the highest top of the island. It was accompanied by a species of *Verrucaria*. In 2006 it was seen again on the southeastern ridge of Austurbunki, growing on the same substrate (Fig. 9). It is one of very few species that have managed to colonize the secondary rock formed by consolidation of the tephra.

Caloplaca crenularia *(With.) J.R.Laundon*

Rather frequent on rock along the western and southern coasts of Iceland, but not in other regions. It was first discovered on Surtsey in 2006, growing together with *Caloplaca citrina* (see above) on palagonitized tephra on top of the southeastern ridge of Austurbunki. It has a white thallus with orange to rusty brown apothecia. So far it is known only from this single locality on Surtsey.

Caloplaca verruculifera *(Vain.) Zahlbr.*

Common on coastal rocks all around Iceland except on the sandy southern coast. First seen on Surtsey in 1990 within the gull colony, like *Xanthoria candelaria* mainly growing on lava peaks and blocks visited by birds (Fig. 11). There is little doubt that *Caloplaca verruculifera* has been transported to the island by the birds like *Xanthoria candelaria*. Both produce soredia, which are easily attached to the bird's feet, and both are only found in the regions with the highest activity of the seabirds. However, in the central part where the colonization started, their habitat is deteriorating because of the rapid thickening of the soil and expansion of the grassland. However, their distribution extends towards the margins where new areas are colonized by birds.

Calvitimela armeniaca *(DC.) Hafellner*

Only seen on a sample collected in 1998 in a depression in the lava flow east of the hut, Pálsbaer. Four separate, sterile thallus areolae on a sample of *Porpidia soredizodes* had the characteristic colour of this species, with very pronounced, black hypothallus around them. Spot tests also showed the characteristic red reaction by K and KC generally found by *C. armeniaca*. Since this species is absent from the whole southern part of Iceland and common only in the North and the Central Highlands, this record from Surtsey should be treated with caution.

Candelariella aurella *(Hoffm.) Zahlbr.*

Probably very common in all regions of Iceland on various substrates. It is, however, rarely collected since it mainly grows on man-made substrates like monuments, concrete walls and pavements, and it is not easily distinguished from *C. vitellina*. It was found on Surtsey in 2006 growing on the concrete of the helicopter platform (Fig. 10).

Candelariella coralliza *(Nyl.) H.Magn.*

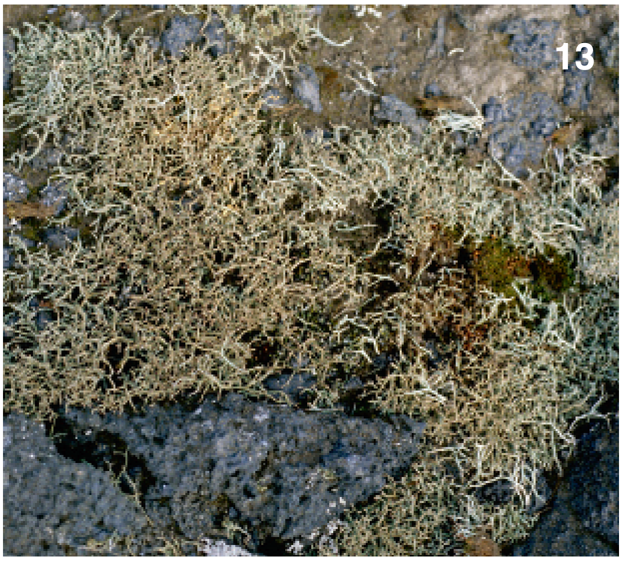
Common in Iceland growing on rock as well as on soil, peat and mosses. First seen on Surtsey 1998 on lava rocks in the gull colony, growing together with *Acarospora smaragdula*, *Lecanora* sp., *Psilolechia leprosa* and *Stereocaulon vesuvianum*. It is still rare there, but was seen again in 2006 growing directly on lava rock (Fig. 12).

Catillaria chalybeia *(Borrer) A.Massal.*

Widely distributed along the western, southern and eastern coast of Iceland. It forms thin, blackish, areolate crusts with small, black apothecia. It was found on Surtsey in 1998 on lava blocks frequently visited by birds east of the Pálsbaer. In 2002 and 2006 it was collected in a few other localities, at the western margin of the Surtungur crater and in the lava fields. It is probably rather widely distributed on the island but easily overlooked because of its dark colour.

Cladonia chlorophaea *(Flörke ex Sommerf.) Spreng.*

Very common all over Iceland. Well developed and typical specimens with podetia were first recorded on Surtsey in the year 1994. They were found growing on soil in the gull colony. Primary squamules of *Cladonia* containing fumarprotocetraric acid that was found as early as 1990 might well belong to this species but it has not been possible to identify them with certainty. Since the spe-



Figures 13–15. Fig. 13. *Cladonia furcata* on thin soil over lava rock near the gull colony in Surtsey in 1998. Fig. 14. *Cladonia macroceras* over mosses in the gull colony in 1994. Plants of *Sagina procumbens*, a rapid colonizer in the early soil formation, are seen at the upper margin. Fig. 15. *Cladonia rangiformis* in Surtsey in 2005 (Photo: Sigurdur H. Magnússon).

cies generally grows on soil it had no suitable habitat on Surtsey until soil had been formed in the gull colony.

Cladonia furcata *(Huds.) Schrad.*

Very common in all parts of Iceland. On Surtsey it was one of the first lichens to colonize the thin soil formed around the gull colony together with *Cladonia macroceras*. First seen in 1990 in a depression in the lava field very close to the first plants of *Alchemilla filicaulis*. The thalli of this first sample are more slender than usually, a growth form frequently found in the southeastern part of Iceland. It has been seen frequently in recent years and can now be regarded as very common in the area affected by the gulls (Fig. 13).

Cladonia islandica *Kristinsson & Ahti*

Widely distributed in Iceland, although not very common. Although known for many years, it was first recently formally described (Kristinsson & Ahti 2009). It is related to *Cladonia subulata* and has fumarprotocetraric acid as the sole secondary lichen compound. It differs from that species in having podetia that are densely squamulose in the lower part and usually more or less decorticated in the upper part, without soredia.

This species is probably rare on Surtsey and has been collected only once in 2002, when it was found growing on soil in a lava channel on the northwest side of the gull colony.

Cladonia macroceras *(Delise) Hav.*

Rather common in all regions of Iceland and seems to prefer tops of cairns or hills or rather fertile heathland. Like *Cladonia furcata* this species was first found on Surtsey in 1990 when the soil formation around the gull colonies had started. It is more frequent than *C. furcata*, and has been recorded on every visit since it was first discovered. Already in 1994 it had a wide distribution and formed well developed, rather large specimens (Fig. 14). *Cladonia furcata* and *C. macroceras* are the most common fruticose lichens on Surtsey. According to our observations *C. macroceras* is more coprophilic and more attracted by the bird colonies than *C. furcata*.

Cladonia pocillum *(Ach.) Grognot*

This is one of the most common *Cladonia* species in Iceland. Generally it is a primary colonizer of disturbed sites, growing on soil or peat, but it is not always easily identified, least of all in its younger stages. Some unidentified specimens collected or seen on Surtsey already in 1978 may belong to this species. There were, however, no suitable habitats until 1990 and later when some soil had been formed in the gull colony. Good samples were collected in 1998, both under the western cliffs inside the Surtungur crater and also in the gull colony in the southern part of the island, where it was widely distributed and common in 2002.

The specimens here referred to as *Cladonia pocillum* differ somewhat from the typical *C. pocillum* as it appears in Iceland. The podetia are low, rarely exceeding 5 mm in height, with broad cups up to 7 mm in diameter. The particles covering the surface inside the cups vary from corticated, bullate granules up to 0.5 mm diameter to fine grained soredia. The primary squamules are neither as thick nor as coalescent as in typical specimens, but rather erect, concave and partly with a shiny surface. The specimens collected on Surtsey are very uniform in this respect. Most of these deviating characters agree with those of *Cladonia monomorpha* Aptroot, Sipman & van Herk. (Aptroot *et al.* 2001), except that many of the cups have sorediate inside.

Cladonia rangiformis *Hoffm.*

Relatively common in coastal districts all around Iceland. Rare on Surtsey, first detected 1998 growing on the soil formed in the gull colony, and again seen both in 2005 (Fig. 15) and 2006. Morphologically rather similar to *Cladonia furcata* but contains atranorin. Some of the Surtsey specimens are more prostrate and less branched than normal *C. rangiformis,* belonging to a morphotype frequently found in exposed habitats in Vestmannaeyjar Islands and some other localities along the southern coast.

Cladonia symphycarpia *(Flörke) Fr.*

Fairly common in Iceland, but overlooked since it only forms primary squamules without podetia. It was already among the primary colonizers in the gull colony in 1990 and collected again 2006. The samples contain atranorin and trace of norstictic acid. The psoromic acid strain (*Cladonia dahliana* Kristinsson), which is characteristic for snow rich habitats in Iceland, has not been found on Surtsey.

Collema tenax *(Sw.) Ach. em. Degel.*

Common in Iceland, growing on soil and over mosses. First discovered on Surtsey 1994 on a rocky slope on the inside of the Surtungur crater below a raven's nest. It was growing over mosses on rocks. The same year it was also seen over mosses on a vertical wall of a lava channel in the gull colony, as well as directly over the thin soil already formed in the colony. Since 1998 it has been found to be common and widely distributed around and in the colony forming well developed specimens and some even with apothecia.

Collemopsidium halodytes *(Nyl.) Grube & B.D.Ryan*

Probably common on the Icelandic coasts although rarely collected. First discovered on Surtsey in 2002, on coastal rocks on the eastern coast of the island. Seen again in the same area 2006. This is the first lichen limited to coastal cliffs found on Surtsey. *Verrucaria maura* and *V. mucosa* which are very common around the Icelandic coast have not yet been seen on Surtsey, mainly because most of the coastal rocks are constantly being broken down by the ocean every winter so these lichens do not have sufficient time to become established.

****Endococcus fusiger*** *Th.Fr. & Almq.*

A rare lichenicolous fungus which was found growing on *Rhizocarpon lavatum* on Surtsey in 2006. The species has previously been found at one locality in northern Iceland (Svane & Alstrup 2004).

Gyalidea fritzei *(Stein) Vězda*

First collected on Surtsey in 1990 and again in 1994 in the bottom of the Surtungur crater. It was apparently rather widely distributed within the crater, on sloping faces of basalt rock and also on vertical walls in a rift in the crater bottom. In 1998 and 2006 the species was also collected in lava fields outside the crater (Fig. 16). It is a very inconspicuous species, with a thallus concolorous with the basalt and the dark apothecia very small, 0.2–0.4 mm in diameter. The species has not been recorded from Iceland before but is probably overlooked. We have seen one further specimen collected by Svanhildur Svane in 1992 in Streitishvarf, East Iceland.

Gyalidea sp.

Another species of *Gyalidea* was collected in the Surtungur crater 1990, and again in the aa lava about 100 m south of Pálsbaer. This species has a white apothecial margin. None of these samples had mature asci or ascospores. Some *Gyalidea* species have whitish apothecia, like for instance *Gyalidea praetermissa* Foucard & G.Thor.

Hymenelia arctica *(Lynge) Lutzoni*

Rather rare species found in different regions of Iceland but appears to be especially common in the southern part of the Central Highlands. A well developed specimen of this species was collected in 1998 in the bottom of the Surtungur Crater, on basalt rock. It was richly fertile with orange, shining apothecia. A sample collected 1990 on the western edge of the eastern crater (Surtur I) probably also belongs to this species but it is poorly fertile and not as characteristic.

***Lecania subfuscula** (Nyl.) S.Ekman*

In the herbaria there are only a few collections of this species from Iceland. These records suggest, however, that it might be common in some specialized habitats, like near bird cliffs. In one case it has been collected growing directly on the excrements of geese.

On Surtsey it was first discovered in 1972, growing on a rock on the outside of the elevated margin of the Surtungur Crater together with *Acarospora smaragdula* and *Trapelia coarctata.* This sample was recorded and illustrated in a previous paper (Kristinsson 1974), as nr. 7, *Bacidia*, occurring very sparsely. It has not been seen again in that locality.

In 1984 it was found again in two other localities on Surtsey, one at the side of white-painted square used as landmark for air photography, and the other in a place where activity of birds had triggered soil formation. The white square attracted birds just as the water tubs did before, and the lichen was growing on the surrounding rocks that were trampled and defecated by birds, probably mainly gulls.

After 1990 this species has become the main colonizer of all rock faces within and around the gull colony. It covers more or less the whole territory inhabited by the gulls along with the *Lecanora* sp. mentioned below, occurring on various substrates, directly on lava rock, on soil or over mosses.

***Lecanora** cf. **albescens** (Hoffm.) Branth & Rostr.*

The first lichens growing directly on palagonitized tephra were collected 2002 and again 2006 on the top of Austurbunki. Among them was a species of the *Lecanora dispersa*-group which seems to belong to *L. albescens.* If correctly identified, this is a new record for Iceland. Similar thalli were found growing directly on the concrete basis of the helicopter platform in 2006 (Fig. 17). In both cases the species was growing together with the following species, *L.* cf. *semipallida.*

***Lecanora poliophaea** (Wahlenb.) Ach.*

Common on maritime rocks around Iceland, usually growing together with *Lecania aipospila*, *Lecanora helicopis* and other species just above the *Verrucaria maura* zone. Characteristic for the species is very pronounced, areolate, grey thallus, the areolae with warted surface. The apothecia are brown with whitish margin.

On Surtsey it was first found in 1998, growing very sparsely on lava rock in the gull colony. It was more widely distributed in 2006 but still only within the gull colony (Fig. 18).

***Lecanora salina** H.Magn.*

Very small and inconspicuous with apothecia in small groups, 0.3–0.6 (–0.8) mm in diameter, light yellowish brown with lighter margin, and concolourous, hardly visible thallus.

Only detected in few samples from Surtsey, the first ones collected in the western slope of the Surtungur Crater in 2002 and in Strompur, a small lava outlet on the inside of Austurbunki. Later on it was also detected in an older sample from 1994 collected in the lava fields around the gull colony (Fig. 19). This species has been recorded only once from Iceland before (Kristinsson 1999) and is probably overlooked because of its small size and obscure colour.

***Lecanora** cf. **semipallida** H.Magn.*

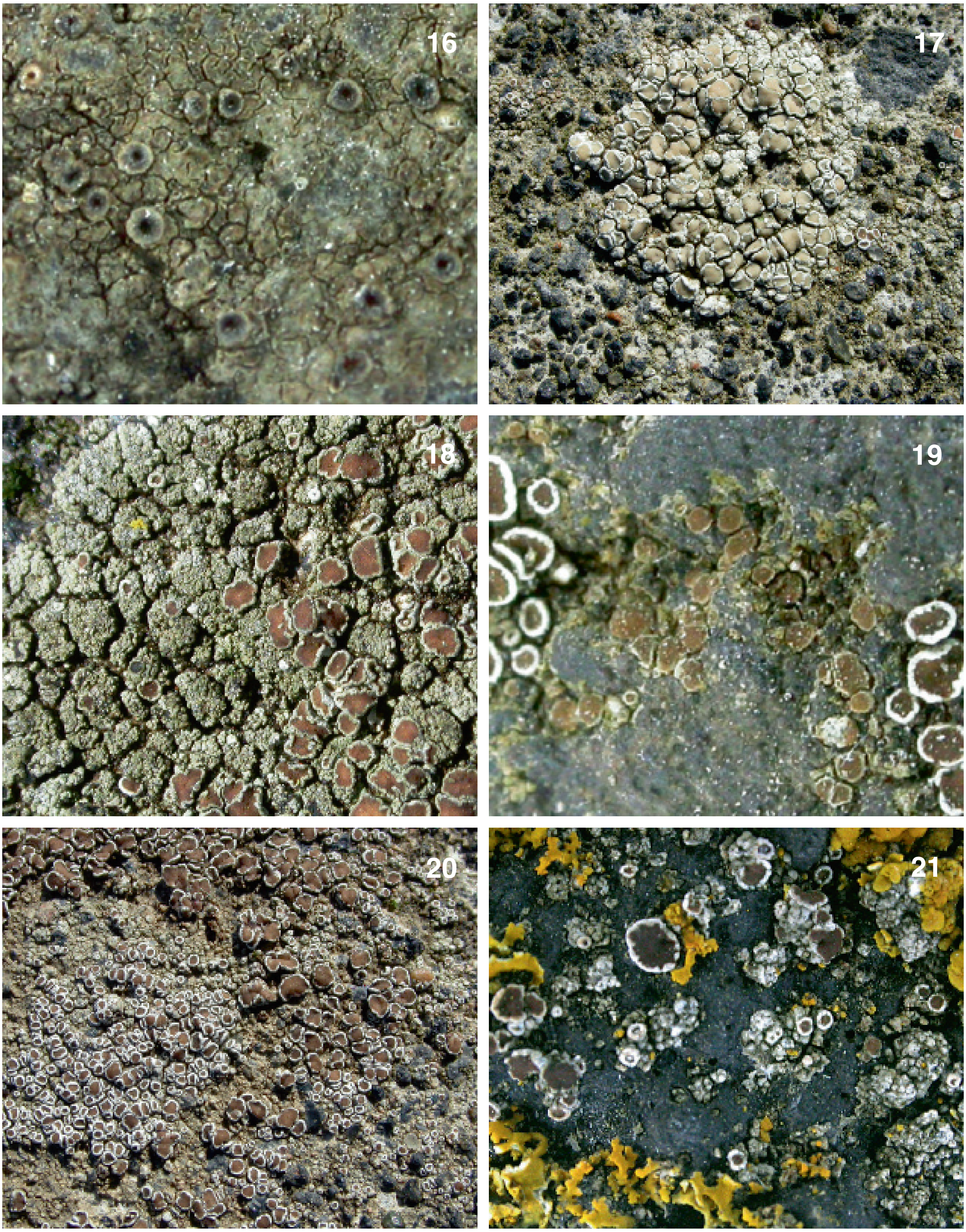
Collected on the top of Austurbunki 2002 and on the helicopter platform in 2006 (Fig. 20). At the first locality it was growing directly on palagonite tuff together with *Caloplaca citrina* and *Lecanora* cf. *albescens.* In the second locality it was associated with *Candelariella aurella* and *Lecanora* cf. *albescens.* This species was recently redelimited by Śliwa (2007a, 2007b). The specimens from Surtsey fit well her description except that the apothecial margin shows negative reactions to K and C. The identification needs to be confirmed when more material becomes available.

Neither *L. albescens* nor *L. semipallida* have been recorded from Iceland before even though they must certainly be rather common on concrete. They are probably included in older records under the names *Lecanora dispersa* or *L. hagenii* but the *L. dispersa* group in Iceland has not yet been revised.

Lecanora sp.

One of the two most successful colonizers on the lava rock around the gull colony was a *Lecanora* species which has not yet been identified. The other equally successful colonizer of this habitat was *Lecania subfuscula.* These two species almost fully covered the rock faces regularly tramped by the gulls. They retreated as soil and dense grass vegetation developed. They retained their habitat only on single peaks of lava rocks protruding through the vegetation cover.

This *Lecanora* mainly consists of a great number of apothecia, often without a visible thallus. When present the thallus is white, with verrucose surface, partly formed by primordial stages of apothecia (Fig. 21). Mature apothecia are brown to dark brown with rather thick, white thalline margin, relatively large, 0.5–2.5 mm in diameter, constricted at the base and often incised, more or less flexuose with age. The apothecia are similar to those of *Lecanora poliophaea.* The species differs from *L. poliophaea* by lacking the characteristic dark grey, ver-



Figures 16–21. Fig. 16. *Gyalidea fritzei* in Surtsey in 1994. Fig. 17. *Lecanora* cf. *albescens* on the helicopter platform in 2006. Fig. 18. *Lecanora poliophaea* on lava rock in the gull colony in 2006. Fig. 19. *Lecanora salina* (small apothecia in the center) on lava rock in the gull colony. *Lecanora* sp. is seen on the left and the right side with white margin. Fig. 20. *Lecanora* cf. *semipallida* on the helicopter platform in 2006. Fig. 21. *Lecanora* sp. (white thallus with dark brown apothecia) between thalli of *Xanthoria candelaria* (lower left) and *Caloplaca verruculifera* (upper right).

rucose thallus of that species. If present, the thallus is white rather than grey.

A specimen of this *Lecanora* was sent to Ulf Arup in Lund, Sweden for further investigation and DNA-analysis. His results indicate that this is a new species with the closest relationship to *Lecanora beringii* Nyl., an arctic species known from the Beringian Islands, the Canadian Arctic and Greenland.

Lecidea lapicida *(Ach.) Ach. var.* ***pantherina*** *Ach.*

One of the most common species on basaltic rocks in Iceland. Rarely seen on Surtsey, first observed inside the Surtungur Crater in 1990 and again 1998. It has also been found on the aa lava near the eastern coast.

Lecidea sp.

An unidentified species of *Lecidea* was collected on basalt rock on Surtsey 1998. It has a white, relatively thick thallus with a glossy surface, and black apothecia with a dark brown hypothecium. All thallus reactions are negative, including the I-reaction of the medulla.

Leptogium lichenoides *(L.) Zahlbr.*

This is the most common species of the genus *Leptogium* found all over Iceland. It grows over mosses on soil and cliffs. It is a foliose lichen with very small, crowded, brown, incised lobes, c. 0.5 mm broad.

It was first found on Surtsey in the inside slopes of the Surtungur Crater below the raven's nest site in 1994. In the same year the first specimens were also detected near the gull colony, on soil frequently trampled by birds, growing together with *Bryum argenteum.* Since then this species has been seen frequently as primary colonizer over the mosses following the soil formation in the gull colony. Like the mosses it retreats again as the succession continues and their habitat gets converted into grassland.

Lichenomphalia *cf.* ***velutina*** *(Quél.) Redhead et al.*

In 1971 the first mushrooms were discovered on Surtsey apparently growing directly out from the lava rock, often accompanied by mosses mainly of the genus *Racomitrium* (Fig. 22). Several collections of the species are from 1975 and 1978. On closer observation a *Botrydina*-type thallus was observed around its base, so this mushroom turned out to be lichenized *Omphalina*, now usually referred to the genus *Lichenomphalia.* This species has been found now and then in the following years growing in the lava fields, often accompanied by the usual colonizers like *Racomitrium lanuginosum* and *Stereocaulon vesuvianum.* Rarely seen in the later years, but the darker brown mushroom *Omphalina rustica* is very common on soil in the gull colony.

Micarea *sp.*

An unidentified specimen probably belonging to the genus *Micarea* was collected on rock below the nesting site of a raven in the inside slope of the Surtunger crater in the year 1990. It has not been seen again.

Peltigera canina *(L.) Willd.*

One of the most common species of this genus in all regions of Iceland. It was also the first species of *Peltigera* found on Surtsey, on the bottom of the crater Surtungur in 1990 (Fig. 8), growing on a continuous carpet of *Racomitrium ericoides.* The lichen had already reached considerable size so it must have been growing there for some years although it was not found in 1984. In 1994 and thereafter the species has also been found in depressions and rifts in the lava fields in the southern part of the island. Since 1998 it has been considerable common on soil inside the gull colony.

Peltigera didactyla *(With.) J.R.Laundon*

Frequent colonizer on soil in relatively moist, disturbed areas in Iceland. It was found in several locations inside the Surtungur crater in 1994 and again in the same localities 1998 and 2002. It was most frequent on the western slopes under the inside cliffs, and also in rifts on the bottom of the crater.

Peltigera neckeri *Hepp. ex Müll.Arg.*

This is the most common species of the *Peltigera polydactyla*-group in Iceland and the first to be seen on Surtsey. A large specimen was found in the northwestern part of the gull colony in 2002. Four years later, in 2006, well developed thalli appeared to be rather widely distributed in the gull colony.

Peltigera praetextata *(Flörke ex Sommerf.) Zopf*

Rather widely distributed throughout Iceland, but more common in the South than in other parts of the country. Two young specimens of this species were collected on Surtsey in 2002. They were first thought to be *Peltigera canina* since the main characters distinguishing *P. praetextata*, the isidia on the margin and along cracks on the surface were hardly visible. But the venation on the lower side and the appearance of the upper surface strongly suggest that these specimens belong to *P. praetextata.* Both locations were within the gull colony.

Peltigera rufescens *(Weiss) Humb.*

Very common in all regions of Iceland, especially abundant at higher elevations and in the North. Not seen on Surtsey until 2006 when a very characteristic and well developed specimen was collected growing on mossy soil in a lava channel south of the Pálsbaer.

Peltigera venosa *(L.) Hoffm.*
Common in all regions of Iceland, especially found under soil banks or on steep or overhanging cliffs. Very young specimens were first discovered on Surtsey 1998, and were again seen 2002 in the same locality as *Peltigera didactyla* below the cliffs in the Surtungur Crater. Only small, infertile lobes were seen.

Pertusaria sp.
Samples of a sterile, crustose species with white thallus growing on rock were collected in 1994 and 1998 on the bottom of the Surtungur Crater. The thallus is thin and has coarsely granular soralia. Neither the thallus nor the soralia react with Pd, K or C. The specimens resemble *Pertusaria aspergilla* morphologically but that species is Pd+ orange-red. Another possibility would be *P. albescens* but that species is usually more or less dark grey, not fitting the Surtsey specimens.

Phaeophyscia orbicularis *(Neck.) Moberg*
Rather common along the western and southern coasts of Iceland near sea bird cliffs, rare elsewhere. First found on Surtsey 2006 on lava rock in the eastern part of the gull colony. The specimen was small but had well developed lobes with soralia.

Physcia caesia *(Hoffm.) Fürnr.*
Distributed all over Iceland and the second most common *Physcia* after *P. dubia*. A quite well developed specimen, about 3 cm across and with abundant soralia was found on Surtsey in 2006, growing in the eastern part of the island on lava peaks north of the gull colony.

Physcia dubia *(Hoffm.) Lettau*
Very common all over Iceland, growing in a similar habitat to *Xanthoria candelaria*, i.e. on rock outcrops, fence posts and other sites frequently visited by birds. First seen on Surtsey 2006 on lava outcrops near the gull colony.

Physcia tenella *(Scop.) DC. var.* ***marina*** *(E.Nyl.) Lynge*
This species is common in the coastal districts of Iceland but rare further inland. It was not found on Surtsey until 2006 (Fig. 23), very close to the locality of *Physcia caesia*. The small samples have the characteristic marginal cilia distinguishing it from the other *Physcia* species. Moberg (2002) considers this variety to be merely a habitat-induced modification.

Pilophorus cereolus *(Ach.) Th.Fr.*
Rare in Iceland, most records from the southwestern region. First collected in 1998 on Surtsey on light reddish brown rock southeast of the Surtungur Crater. The specimen has a crustose, K+ yellow thallus with black cephalodia and some sorediate warts and is apparently a young, immature thallus of *Pilophorus cereolus*. Two specimens were found in new localities in 2002. One of them was well developed and typical with mature pseudopodetia, growing on the western inside slope of Surtungur crater. The other one was at a similar early stage as the one from 1998, found on the mountainside of Austurbunki above Strompur, growing on palagonite tuff.

Pilophorus dovrensis *(Nyl.) Timdal, Hertel & Rambold*
Can be regarded as common in the neighbourhood of the glaciers in the Central Highlands and in high mountain areas in the northern Iceland, but rather rare in other regions. First recorded from Surtsey in 2002, growing on a rock in the southern part of the Surtungur crater. Richly fertile.

Placopsis gelida *(L.) Linds.*
Very common in the more oceanic parts of Iceland. In the more continental regions it is rare except at higher elevations, where it apparently enjoys higher moisture than in the lowlands. It is one of the main colonizers of lava fields in Iceland along with *Stereocaulon capitellatum, S. vesuvianum, Racomitrium ericoides* and *R. lanuginosum*.. It was one of the three lichen species first observed on Surtsey in 1970, in the lava fields north of Surtungur where some steam kept the surface moist. In the following years it was found everywhere in the lava fields and in the Surtungur crater. This simultaneous appearance almost everywhere in the lava fields can be seen as evidence of dispersal by air currents. In the Surtungur crater, in sheltered, moist habitats, it was often richly fertile with large, pink apothecia.

Placopsis lambii *Hertel & V.Wirth*
This species, described by Hertel and Wirth in 1987 (Wirth 1987), was overlooked in the Nordic countries, until Moberg and Carlin (1996) clarified its status in those countries. Morphologically *P. lambii* and *P. gelida* are not easily distinguished, although typical specimens can be recognized in the field. The safest way of recognizing *P. lambii* is by TLC, as the species differs from *P. gelida* in having 5–0-methylhiascic acid. Only four specimens of *P. lambii* have been collected on Surtsey, the first in 1998, but it is possible that some of the field observations of *P. gelida* refer to *P. lambii*.

Polyblastia *sp.*

The lichen genus *Polyblastia* has been circumscribed as having muriform spores, either hyaline or brown. The genus has recently been revised by Savić *et al.* (2008) who showed that *Polyblastia* as traditionally circumscribed is polyphyletic. The specimen from Surtsey was collected in 1998 on basalt and belongs to *Polyblastia* s.str. as delimited by Savić et al (2008).

Porpidia *cf* ***crustulata*** *(Ach.) Hertel & Knoph*

This is by far the most common species of the genus *Porpidia* on Surtsey (Fig. 7). The identification has been very problematic and we must still look at this as a species group which we have not been able to separate in a reasonable way. Most of the specimens have epilithic, moderately thick, white thallus, thicker than is usual for *P. crustulata.* For this reason it was first identified by morphology alone as *Porpidia cinereoatra* but since it either contains stictic acid as the main substance or lacks substances, this possibility was excluded. Of the *Porpidia* species containing stictic acid, *P. crustulata, P. macrocarpa* and related species seem to fit most of the specimens best. The separation of these two species has long been very problematic, the main characters separating them being the spore size and the size of apothecia. *P. crustulata* should have apothecia less than 1.5 mm in diameter, and ascospores 12–16 µm long, while in *P. macrocarpa* the apothecia are up to 2–3 mm in diameter, and the ascospores 16–23 µm long. In the material from Surtsey both the size of the apothecia and the ascospores is very variable (the ascospores 12–22.5 µm and the apothecia 1–2.5 mm). Most probably both *P. crustulata* and *P. macrocarpa* are present in the material, but it would seem rather arbitrary to try to separate them solely on the basis of these characters, especially since they are inconsistent.

Some of the specimens have pruinose apothecia which might indicate that *Porpidia platycarpoides* is also involved. That species has not been recorded in Iceland but Friday (2005) lists it both from the British Isles and North America. The recently described *Porpidia islandica* (Fryday 2005) might also be included in the collected material. In our opinion it is hardly possible to separate the Surtsey material of this group sufficiently without a revision of the large Icelandic collection of the whole group at the same time.

The species complex described above was first seen on Surtsey 1972, recorded as No. 8 *Lecidea* in Kristinsson 1974. It was seen again in 1975 and after that in increasing number at each visit. Today it is common in the lava fields and in the craters of Surtsey.

Porpidia flavicunda *(Ach.) Gowan*

Very common in Iceland. It is generally characterized by a dark orange thallus without soredia, much darker than *Porpidia melinodes.* Specimens assigned to this species in Iceland have recently been separated into two species, *P. flavicunda* and *P. flavocruenta* (Fryday 2005) but the relationship between the two species has not yet been clarified in Iceland.

Porpidia flavicunda s. lat. was first noticed on Surtsey in 1998 at four different localities, growing on lava rock. The Surtsey specimens have not quite as dark colour as is usually seen in Icelandic material of this species.

Porpidia melinodes *(Körb.) Gowan & Ahti*

Equally common in Iceland as *P. flavicunda*, occurring from the lowlands to the alpine zone. It is lighter in colour, always with dark grey soredia, sometimes also fertile. On Surtsey it has mainly been recorded since 1990 in both of the craters and elsewhere on lava blocks (Fig. 24). A sample collected already in 1972 on the outside wall of Surtungur crater, a site that was long supplied by warm steam, is probably also *P. melinodes.* It was mentioned in Kristinsson 1974 as No. 9 *Lecidea.* At present it is widely distributed throughout the lava fields in favourable sites.

Porpidia soredizodes *(Lamy ex Nyl.) J.R.Laundon*

Sterile and sorediate species with a non-amyloid (I–) medulla. It is widely distributed in Iceland and rather common on blocks in the lava fields of Surtsey and in the craters. It was first identified in a sample from 1984.

Porpidia speirea *(Ach.) Kremp.*

Rather common on rocks in Iceland, preferable shaded side. Easily recognized by the pronounced white thallus and the black, more or less immersed, often pruinose apothecia. Rare on Surtsey, first collected in 2006 on rock in the lava field.

Porpidia tuberculosa *(Sm.) Hertel & Knoph*

Sterile and sorediate species with an amyloid (I+) medulla. Widely distributed in Iceland, but probably less frequent than *P. soredizodes.* Rare species on Surtsey, found only in a few places in the lava fields, first collected 1990.

Protopannaria pezizoides
(Weber) P.M.Jørg. & S.Ekman

Very common growing on soil all around Iceland. Very rare on Surtsey, only seen once in 1994 in a cleft of the lava field in the bottom of the Surtungur crater. It has not been seen again.

Figures 22–27. Fig. 22. *Lichenomphalia* cf. *velutina* among young *Racomitrium* plants in the Surtsey lava in 1971. (Photo: Erling Ólafsson) Fig. 23. The first specimen of *Physcia tenella* seen in Surtsey in 2006. Fig. 24. *Porpidia melinodes* on the lava fields in Surtsey in 2006. Fig. 25. *Rhizocarpon expallescens* in the Surtungur crater in 1990. Fig. 26. *Rhizocarpon lavatum* in the lava fields of Surtsey in 2006. Fig. 27. *Rhizocarpon petraeum* in Surtsey in 1998.

Psilolechia clavulifera *(Nyl.) Coppins*

Very rare, only found once in the Surtungur crater in 2002. Apothecia barely visible as black dots, only 0.2 mm in diameter on colourless thallus growing on bare rock. Found in a sample of *Placopsis* and *Rhizocarpon lavatum*. This is the first record of the species in Iceland.

Psilolechia leprosa *Coppins & Purvis*

Very few records from Iceland, but locally apparently quite common, e.g. in the lava fields around Laki in the southern part of the Central Highlands.

On Surtsey this species was one of the very early, successful colonizers in the lava fields, occurring mainly in rifts, caves and other shady places and in the craters. It was first discovered in 1971, found in sites where warm steam kept the rocks constantly wet, as on the western outside wall of the Surtungur crater, where also *Trapelia coarctata* was first found. Very soon *P. leprosa* had colonized crevices and caves throughout the island. Thus, it was most likely dispersed to the island by wind. In the beginning it formed a sterile, sorediate crust, but after a few years abundant, pale brown or pinkish, globose apothecia developed. The thallus is white, at first with a warted, cauliflower-like surface, but soon becoming sorediate-leprose.

In Kristinsson (1974) it was recorded as *Lepraria incana* since it resembled a *Lepraria* when lacking apothecia. True *Lepraria* spp. have not yet been verified in samples from Surtsey.

****Pyrenidium hyalosporum***
Alstrup, D.Hawksw. & R.Sant.

First recorded in Iceland by Svane & Alstrup (2004), growing on *Placopsis gelida* collected in Mýrdalur, South Iceland. It was found on Surtsey in two localities in 2002, also growing on *Placopsis.*

Rhizocarpon expallescens *Th.Fr.*

Small, crustose species with thin, grey to whitish thallus and black apothecia, ascospores one-septate, colourless. Probably widely distributed in Iceland but rarely collected because of its small size. First collected on Surtsey 1984 from the lava fields near the east coast. Most of the samples collected later are from within and on the outside walls of the Surtungur crater (Fig. 25).

Rhizocarpon lavatum *(Fr.) Hazsl.*

Similar to *Rhizocarpon expallescens* but with larger apothecia with a thicker margin and containing muriform, hyaline spores later becoming dark. Common in Iceland, more collected in the southern part than in the North.

First seen in the eastern part of Surtsey in 1984, later found to be rather common, especially in the Surtungur crater but also widespread in the lava fields (Fig. 26). These two species of *Rhizocarpon* are now very common on Surtsey, but none of the yellow species of *Rhizocarpon*, most frequent in Iceland, have yet been found on the island.

Rhizocarpon petraeum *(Wulfen) A.Massal.*

Considered common on rock all over Iceland (Ihlen 2004). First detected on Surtsey in a sample from 1990 on the western outside wall of the Surtungur crater. It was found in numerous places in the lava fields in 1994 and 1998 (Fig. 27). The Surtsey specimens have characteristically rather thick, areolate thallus with innate apothecia. The thallus shows very slow Pd+ orange reaction, indicating the presence of stictic acid.

Rhizocarpon reductum *Th. Fr.*

Common in Iceland according to Ihlen (2004). First found in a Surtsey sample from 1994 from the margins of both the large craters, Surtungur and Surtur. In 1998 and 2002 it was also collected in the lava fields on the eastern side of the island. The specimens are morphologically rather variable but contain stictic acid and have shorter ascospores than *R. petraeum* (20–30) µm versus (26–38 µm).

Rinodina gennarii *Bagl.*

Common in Iceland, especially along the coast. Not seen on Surtsey until 2002 when it was discovered on the western outside walls of Surtungur and also sparsely in the gull colony. It was already rather common and abundant on rock in the lava fields around the gull colony in the next visit in 2006. It appears from this, that it arrived late on Surtsey but once there, it rapidly colonized the gull colony.

Scoliciosporum umbrinum *(Ach.) Arnold*

Common in Iceland, but not yet recorded in the Vestfirdir region. It has usually been found growing on rock but also on other substrates.

First collected 1990 on Surtsey, growing on fish bone in the lava field apparently carried by birds, either from the coast or from outside the island. It was collected again in several localities in 1998 and 2002, generally growing directly on basalt on the top of lava peaks or on the elevated crater margins.

Solorina bispora *Nyl.*

Common on soil all over Iceland. Found on Surtsey 1998 in the slope under the raven's nest on the inside wall of the Surtungur crater. That was also the first locality of several other soil lichens on Surtsey like *Collema tenax*, *Leptogium lichenoides*, *Peltigera didactyla* and *P. venosa*. The species has not been seen on Surtsey again.

Stereocaulon alpinum *Laurer*

One of the most common *Stereocaulon* species in the heath vegetation of Iceland. First collected on Surtsey in 1984, growing in a carpet of *Racomitrium lanuginosum* in the Surtungur crater. It is rare on Surtsey, not seen with certainty outside the crater (Fig. 28). Samples which morphologically resemble this species elsewhere in the lava fields have turned out to contain stictic acid and have subsequently been referred to *S. tomentosum* as *S. alpinum* contains lobaric acid.

Stereocaulon arcticum *Lynge*

Common in Iceland, both as primary colonizer on bare soil and river flats, where it often is found together with *Stereocaulon glareosum*, and also forming cheese–like cushions on volcanic gravel deserts in the Central Highlands. On Surtsey it was first seen in 1994 as primary colonizer on the soil formed around the gull colonies. In 2002, it was widely distributed at the margin of that area. At that time it was also found in a shady cleft in the Surtungur crater.

Stereocaulon capitellatum *H.Magn.*

Rather rare in Iceland, but scattered throughout the country. On Surtsey it was a very active primary colonizer, appearing almost everywhere in the lava fields together with *Placopsis gelida* and *Stereocaulon vesuvianum* from 1971. The first stages consisted of circular colonies of separate, erect lobes arising from air bubbles on the lava surface (Fig. 5). The marginal tip of these primary phyllocladia formed soredia. First a few years later the lobes gradually formed pseudopodetia with capitate soralia as characteristic for the species, and brown cephalodia with *Nostoc* (Kristinsson 1974, Fig. 29). From the beginning these small thalli could be identified as *S. capitellatum* because of the characteristic lichen substances, perlatolic, anziaic and miriquidic acids. In the later years this species has gradually retreated from the lava fields and currently only found in scattered but well developed colonies.

Stereocaulon glareosum *(L.I.Savicz) H.Magn.*

Common in Iceland as primary colonizer on river flats and on open soil. It forms a crust of white, cylindrical isidia with brown tips, interspersed with large, pinkish brown cephalodia. On Surtsey it was first discovered in 1984 on tephra between lava ropes, but later it became rather common on the soil formed in the gull colony. Apart from its first locality, it has only been found in regions where some soil formation has taken place.

Stereocaulon rivulorum *H.Magn.*

Common all over Iceland, usually growing on gravel and in screes. First seen on Surtsey in several localities in 1994, growing on volcanic slag or sand in the lava fields and in the Surtungur crater.

Stereocaulon spathuliferum *Vain.*

Relatively rare in Iceland, but found scattered throughout the country, more frequent at higher elevations than in the lowland. It was first discovered on Surtsey in 1984 growing on a rock in the lava field on the eastern side of the island. Later, similar specimens were found west of the Surtungur crater but the specimens collected there were not so typical and may belong to other species. It is still a rare species on Surtsey, found mainly in two areas.

Stereocaulon tomentosum *Fr.*

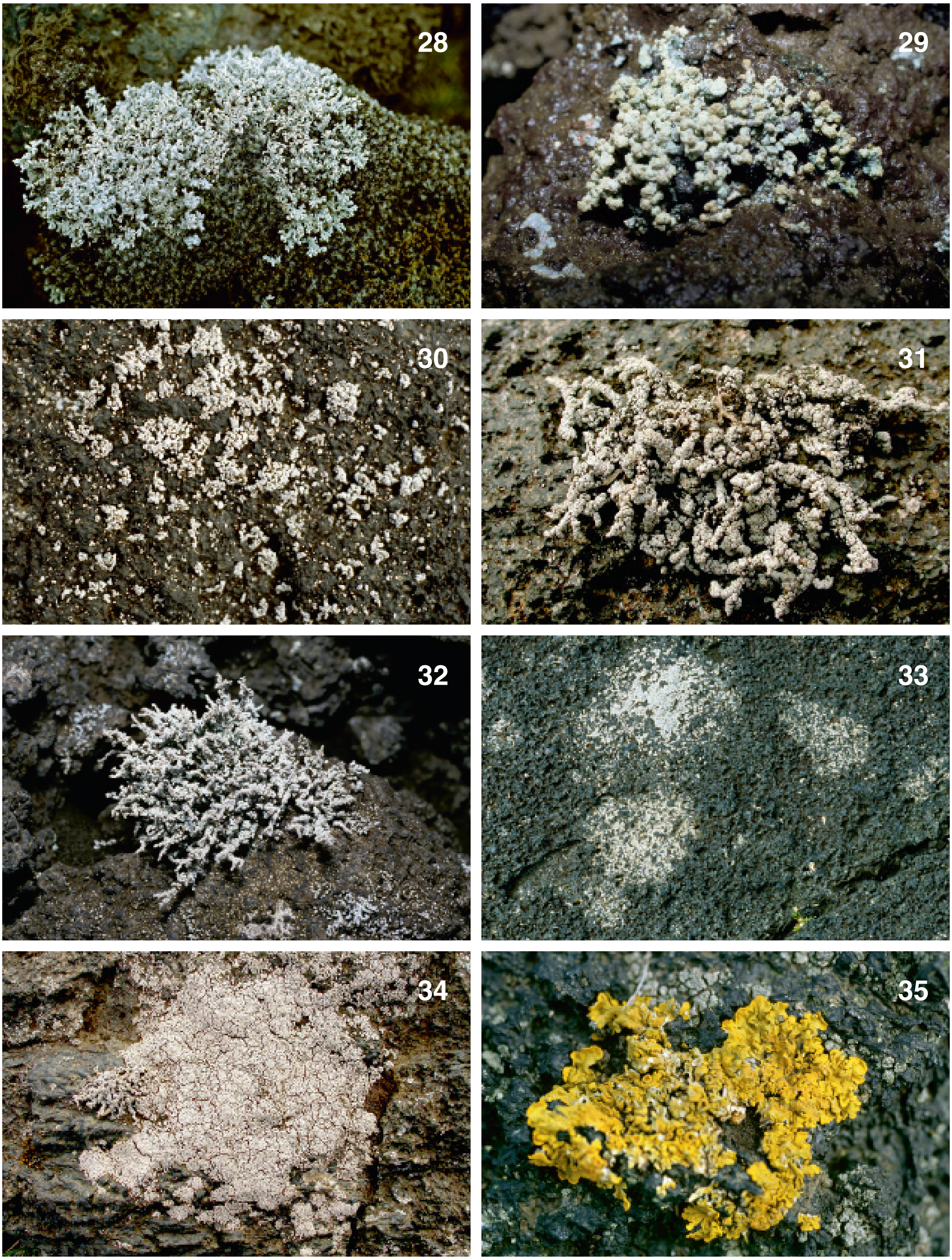
Typical, fertile specimens of *S. tomentosum*, characterized by many, small apothecia, were first collected in 1998, and again in 2002 and 2006. Some of the older samples from 1984 and 1990 might also possibly be young, infertile specimens of this species. It usually grows on mossy soil or in carpets of *Racomitrium lanuginosum.* Most sterile specimens with the appearance of *Stereocaulon alpinum* on Surtsey contain stictic and norstictic acids and should therefore rather be referred to *S. tomentosum*, which appears to be more common on Surtsey than *Stereocaulon alpinum.* These two species are morphologically similar and can hardly be distinguished from each other in sterile condition. *Stereocaulon tomentosum* differs mainly in having crowds of lateral, small apothecia, and reacting slowly orange by Pd because of its content of stictic acid.

Stereocaulon *cf.* ***tornense*** *(H.Magn.) P.James & Purvis*

Rare and scattered in different parts of Iceland, but locally common, especially in the southern part of the Central Highlands. In 1990 and again in 1994 a crustose lichen was collected in a crevice in the Surtungur crater. It had not fully developed apothecia and has therefore not been securely identified, but the phyllocladia resemble those of *Stereocaulon tornense* in habit and the chemical reaction fits that species. As in *S. tornense*, cephalodia with cyanobacteria are prominent between the phyllocladia.

Stereocaulon vanoyei *Duv.*

This species was originally described from Krýsuvík, Iceland by Duvigneaud (1941) in his account of an expedition which Prof. P. van Oye made to Iceland in 1938. It is now known from about eight localities in Southwest and South Iceland, all on rocks in recent lava flows. It is related to, but morphologically distinct from, *Stereocaulon vesuvianum*, differing by having large and inflated or bullate phyllocladia, usually without the dark, concave



Figures 28–35. Fig. 28. *Stereocaulon alpinum* in a carpet of *Racomitrium lanuginosum* in the Surtsey lava field in 1998. Fig. 29. *Stereocaulon capitellatum* with capitate soralia and pinkish brown cephalodia in the Surtungur crater in 1994. Fig. 30. Young stage of *Stereocaulon vanoyei* on lava rock in 1994. Fig. 31. *Stereocaulon vanoyei* with mature pseudopodetia in 2006. Fig. 32. *Stereocaulon vesuvianum* on the Surtsey lava. Fig. 33. *Stereocaulon* sp., rather young stage in the lava field east of Pálsbaer in 1994. Fig. 34. Mature *Stereocaulon* sp. forming flat, compact surface in the lava field east of Pálsbaer in 2006. On its left side is rather small specimen of *Stereocaulon vesuvianum* with elongated pseudopodetia. Fig. 35. *Xanthoria parietina* on lava rock near the gull colony in 1998.

central part characteristic for *S. vesuvianum* and *S. arcticum.*

It was first discovered on Surtsey in 1994. It has been found in two localities, in the lava fields on the eastern side of the island (Figs. 30, 31) and within the Surtungur crater. It grows directly on the lava rock.

Stereocaulon vesuvianum *Pers.*

This species was one of the first three species to be discovered on Surtsey in 1970. In that year it was only found on lava blocks kept wet by steam from nearby steam holes, close to the Surtungur crater. In the following years it was widely distributed in lava fields all over the island. Its wide and rapid distribution throughout the entire lava fields at the same time is support for effective wind dispersal from the mainland. The growth is on the other hand very slow, starting with a single, small, sphaerical phyllocladia growing out from every bubble hole in a colony of a few cm in diameter. A dark depression in the center of each phyllocladium confirms that this is *S. vesuvianum.* These dispersed, round phyllocladia develop slowly over a period of several years (Fig. 4) and finally unite to form a colony of short, elongate branches interspersed with black cephalodia (Fig. 32). This process is especially slow in the drier parts of the lava field, but faster in moist habitats protected against the drying effects of the wind, for instance within Surtungur crater or in depressions in the lava fields.

Stereocaulon sp.

In 1990 a new *Stereocaulon* was noticed in the lava fields in the eastern part of the island, differing clearly from *Stereocaulon vesuvianum.* It forms very compact, low cushions directly on the lava surface, with very small (0.1–0.2 mm) granular phyllocladia without the dark center characteristic for those of *S. vesuvianum* (Fig. 33). The pseudopodetia are richly branched in the upper part with dichotomous branching, resulting in the relatively smooth and compact surface of the colony (Fig. 34).

Morphologically it is similar to *Stereocaulon depressum* but differs by containing stictic and norstictic acids besides atranorin. This secondary chemistry leaves only a few possibilities apart from *S. vesuvianum*, which is morphologically different (Fig. 33). Two species treated in Lamb's Conspectus deserve special attention (Lamb 1977): *S. lavicola* H.Magn. and *S. vulcani* (Bory) Ach. The former is known only from Hawaii. The morphological description of the lectotype given by Lamb fits the *Stereocaulon* from Surtsey rather well. The latter, *S. vulcani*, is known from Hawaii, the Azores and the Canary Islands. It is morphologically variable, but forma *maunae-loae* (H.Magn.) Lamb, which Magnusson originally described as a separate species, *Stereocaulon maunae-loae*, represents a compact, pulvinate form very similar to the specimens from Surtsey. Further study is needed to find out whether the Surtsey specimens may belong to either of these species or represent a new undescribed species.

We have seen a few other specimens from the mainland of Iceland, which appear to belong to this species, containing either atranorin, stictic and norstictic acids, or atranorin alone. Also one specimen from Faroe Islands identified as *Stereocaulon evolutum* but containing atranorin, stictic and norstictic acids seems to belong to the same species.

Trapelia coarctata *(Sm.) M.Choisy*

This was the first species discovered on Surtsey in 1970. At that time it was limited to steep lava rocks on the outside of the Surtungur crater (Kristinsson 1972), in a site constantly kept wet by steam from nearby steam holes (Fig. 3). Already in 1970 it was very abundant in this habitat, covering wide areas with richly fruiting thalli. Judging from its appearance, it must already have been present in this locality in 1969 but lichens were not investigated that year. In the following years it was found in several other localities also influenced by steam holes, and later it was seen in other damp or relatively dry but sheltered localities, such as in the craters or other depressions in the lava fields. It is still present in many localities but not abundant.

Trapelia involuta *(Taylor) Hertel*

Very rare in Iceland, only two localities outside Surtsey known: Vidvík in the North (Branth 1903, as *Lecanora coarctata* var. *ornata*) and Thórsmörk in the South (collected by Svanhildur Svane 1972, kept in C).

On Surtsey it is apparently also rare, collected in 1994 and again in 2006. In both cases it was growing on rock near the activity of birds.

Verrucaria aquatilis *Mudd*

First collected on Surtsey 1998 and discovered on several locations on the island since then, although easily overlooked because of the small perithecia. *Verrucaria aquatilis* has only been found in a few localities in Iceland, but it is probably overlooked. On Surtsey it grows on the lava although it is an aquatic species that usually is found growing along rivers or creeks, even inundated in some places.

Verrucaria muralis *Ach.*

Discovered on Surtsey in 2006 growing on palagonite tuff on Austurbunki in a moist habitat close to steam holes. The species was first recorded in Iceland by Branth (1903), based on material collected by Ólafur Davídsson in northern Iceland

and determined as *Verrucaria rupestris.* Alan Orange collected the species on two localities in the North and East in 2007 with the specimens kept in Cardiff. Specimen from Surtsey was determined by Alan Orange in Cardiff, Wales. A specimen collected in 1998 also seems to belong to this species. It was collected close to the locality where it was found 2006.

Verrucaria *sp.*

There are three *Verrucaria* specimens collected in 2002 and 2006 which have not yet been identified. They might belong to more than one taxon. Two of them have brown thalli while the thallus of the third one is rather indistinct. The sporelength is ranging from 15 to 26 µm and an involucrellum is present. At least one of the specimens has a black prothallus. These specimens might belong to *Verrucaria aethiobola* and/or *V. nigrescens.*

Xanthoria candelaria *(L.) Th.Fr.*

Very common in Iceland growing on wood, trees and rocks frequently visited by birds. It was first detected on Surtsey in 1972, in connection with experiments carried out by hydrobiologists by placing fresh water tubs in the lava field in order to study colonization of fresh water life (Kristinsson 1974). One of these tubs attracted some gulls that used it for bathing. Within the splashing zone of the tub very small thalli of *Xanthoria candelaria* were seen in 1972 and 1973, but already deteriorating in 1975, and not seen in the years thereafter. Apparently the diaspores of the lichen had been transported by the gulls, washed out in the water and splashed around onto the lava rock. But since this is an extremely coprophilous lichen, it apparently did not get the necessary nourishment after the tub had been removed, and died off.

It was not found again until 1990 after the permanent colonization of the gulls had taken place. Then it colonized the lava rocks most frequently trampled by the gulls along with *Caloplaca verruculifera* and *Xanthoria parietina* and has been seen in each visit after that.

Xanthoria parietina *(L.) Th.Fr.*

Common in the more oceanic regions of Iceland, absent in the northeastern inland areas where it is replaced by *Xanthoria elegans.* Often gives the cliffs of the sea birds bright yellow colour.

On Surtsey the first small thalli of *X. parietina* were seen on lava rocks in the gull colonies in 1990. From 1998 it was found in several localities in the area affected by the gulls (Fig. 35). It is often accompanied by *Caloplaca verruculifera,* and has, like that species, probably been transported on feet of gulls to Surtsey.

DISCUSSION

Surtsey has given unique opportunity for the study of primary lichen colonization on a pristine island. Although several volcanic islands can be found throughout the world, Surtsey is the only one where lichen succession has been monitored since it appearance. The island Krakatau has some similarity to Surtsey but its location in the tropics makes all comparison difficult.

How were the lichens transported to the island?

For most of the 87 lichen species recorded on Surtsey the travel route to the island is unknown, especially those with very local or scattered distribution. However, the data obtained from the 40 years monitoring allows some speculations on the topic for a number of species. It is most likely that the most successful colonizers in the lava fields were transported by air currents. It is the only way that can explain the simultaneous appearance of their initial stages almost all over the lava fields where suitable conditions were present. This applies to *Placopsis gelida, Psilolechia leprosa, Stereocaulon capitellatum* and *S vesuvianum.* (see distribution maps in Kristinsson 1974). Local spread after their first appearance can be excluded for at least two of the species (*Placopsis gelida* and *Stereocaulon vesuvianum*) because they were sterile and without soralia for several of the first years eliminating that possibility.

Dispersal by air currents probably also applied to *Trapelia coarctata,* which early colonized rocks in close vicinity of the steam holes. The limited distribution seen on distribution maps from 1973 (Kristinsson 1974) reflected mainly the limited occurrence of steam condensating on bare rock, the most suitable habitat for that lichen. Another lichen that hypothetically could have been dispersed by air currents is *Acarospora smaragdula.* Its distribution throughout the island rather early supports this. However, the species preferred the elevated margin of the craters, and protruding lava peaks and that may suggest an alternative, i.e. the role of small birds that tend to rest on these tops in the lichen's dispersal.

Several species have most likely been dispersed to Surtsey by birds. The best evidence is provided by the colonization history of *Xanthoria candelaria,* the lichen which had its first colonization in the splashing zone of the experimental water tubs that the gulls used for bathing (see under that species, and also Kristinsson 1974). For most of the other species colonizing only the rocks in the gull colony, transport by gulls seems to be the most acceptable dispersal route. Certainly wind dispersal is also possible, but since few of these species have been seen in the isolated nesting places of fulmars found in small lava outlets in the slopes of the large crater cones, is seems to be less important than dispersal by gulls for these species. This could apply to *Lecania subfuscula*, *Lecanora* sp., *Xanthoria parietina* and probably also *Phaeophyscia orbicularis*, *Physcia caesia* and *Physcia tenella.* Three further species (*Caloplaca verruculifera*, *Lecanora poliophaea*, *Rinodina gennarii*) are in Iceland like elsewhere confined to coastal cliffs. This suggests two possible dispersal routes but it cannot be distinguished between them, e.g. by birds and by sea water that can be sprayed far up from the shore on Surtsey during winter storms.

Species considered rare in Iceland

It is remarkable that many of the lichen species known from Surtsey are considered extremely rare, or even not present in Iceland, but still have found their way to Surtsey. Examples of such species are *Arthonia lapidicola*, *Gyalidea fritzei*, *Gyalidea* sp., *Hymenelia arctica*, *Lecania subfuscula*, *Micarea* sp., *Pilophorus cereolus*, *P. dovrensis*, *Psilolechia clavulifera* and *Trapelia involuta.* Many of these species are, however, very small and inconspicuous, sometimes even just visible to the naked eye. They may therefore be more frequent in Iceland than the few records indicate for owing to the extensive monitoring of the lichen colonization on Surtsey.

Some of the species colonizing Surtsey appear to be ecological opportunists, they reproduce very quickly when managing to colonize empty niches, like on Surtsey, but retreat again as their habitat gets colonized by stronger competitors. Such species are likely to be rare on the mainland, except in very special habitats, or only at times when similar empty niches are created locally by volcanic eruptions. Such examples are *Trapelia coarctata*, which spread very rapidly in the beginning where steam escaped out from the lava, and *Stereocaulon capitellatum* which was very widely distributed throughout the lava fields in the beginning but has become rather rare during the last years. Still other examples are *Lecania subfuscula* and the presumably new species of *Lecanora*, both of which very rapidly colonized all rock faces in and around the gull colony, sites that were more or less constantly traversed by the gulls. All these species have relatively few records in the mainland of Iceland.

Common species that have not arrived on Surtsey

Many of the most common rock lichens in Iceland, species that one would expect on Surtsey sooner or later, have still not arrived there. Among those are species like *Aspicilia cinerea, Lecanora intricata*, *L. polytropa*, *Rhizocarpon geographicum* and *Tremolecia atrata*, which can be found on almost every piece of rock in Iceland. The rocks on Surtsey should provide them with plenty of suitable sites. Even though some initial time might be needed before they can colonize fresh volcanic rock, 45 years is a long time. All five species mentioned had already colonized the Hekla lava flows within 20 years of the 1947 eruption (Kristinsson unpublished data from 1967 and 1968). This fact suggests that the distance over the sea from the mainland of Iceland to Surtsey presents a barrier for their dispersal. The fungal or the algal part, or both, might have difficulties in getting to the island to establish the symbiosis.

Furthermore, not a single *Umbilicaria* species has been seen on Surtsey, whilst in the Hekla lava four *Umbilicaria* species had established within 20 years from the eruption in 1947. These were *Umbilicaria cylindrica*, *U. torrefacta*, *U. proboscidea* and *U. hyperborea*, each represented by very small thalli. The first three of these species are very common in the Icelandic lowlands and should be expected on Surtsey. Apart from these exceptions, the main colonizing species around Hekla were the same as on Surtsey, *Placopsis gelida*, *Stereocaulon capitellatum* and *S. vesuvianum* as well as the bryophytes *Racomitrium lanuginosum* and *R. ericoides*. As on Surtsey *Acarospora smaragdula* was equally frequent on top of lava peaks (Kristinsson, unpublished data).

CONCLUSIONS

High proportion of the primary lichen colonizers on Surtsey were cephaloid. The simultaneous lichenization in a group of adjacent cavities on the lava surface is characteristic for the three most successful colonists. With soil formation in the gull colony habitat for lichens dependent on soil as species of the genera *Cladonia* and *Peltigera* appeared in the island which partly explains the increased rate of lichen colonization after 1986. Sea erosion has prevented most common sea-shore species from establishing on Surtsey. The great success of the two genera, *Stereocaulon* and *Porpidia*, on Surtsey is apparent, as 75% of all *Stereocaulon* and 50% or more of all *Porpidias* in Iceland have already arrived there, while some other large genera are absent or represented only by one or two species.

ACKNOWLEDGEMENTS

We thank Ulf Arup, for help with the *Lecanora* sp., and Alan Orange, for the determination of *Verrucaria muralis.* Anders Nordin, Alan Orange and Kristín Svavarsdóttir gave many useful comments on the manuscript which are acknowledged.

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Investigation of the funga of Surtsey 2008

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ABSTRACT

In August 2008 eighteen specimens of at least ten species of agarics (mushrooms) were collected on Surtsey. *Entoloma sericeum* was well established in grassland in the oldest part of the gull colony and at least seven ectomycorrhizal species, *Hebeloma collariatum, H. marginatulum, H. mesophaeum, H. vaccinum var. vaccinum, Inocybe lacera var. lacera, Laccaria laccata* and an unidentified *Cortinarius* species, were collected near their *Salix* hosts. One *Psilocybe* species, *P. inquilinus,* and one unidentified *Entoloma* species grew in *Leymus* dunes. Three collections identified to the genus *Entoloma* and three to the genus *Hebeloma* could represent two additional species. The findings in 2008 increase the total number of agarics from two to nine and of species of fungi on Surtsey from 26 to 33, counting only those which have been identified to species.

INTRODUCTION

The first mushroom on Surtsey was photographed in 1971 and collected several times in August 1975 growing with *Racomitrium* moss on lava. It was identified as *Arrhenia rustica* (Fr.) Redhead, Lutzoni, Moncalvo & Vilgalys s.l., but recently a *Botrydina*-type thallus was discovered at the base of the stem making it a basidiolichen of the genus *Lichenomphalia* (Kristinsson & Heidmarsson 2009). *A. rustica* s.l. is probably also present as a specimen referred to that species was collected in 1990 growing on soil in the gull colony (Table 1).

In middle of July 2005 *Entoloma sericeum* Quél., which is common species in grassland in Iceland, was collected growing amongst *Poa pratensis* and *Leymus arenarius* grass in the oldest part of the gull colony. During the same expedition mushrooms were observed near a willow, *Salix phylicifolia,* in the Surtungur crater. Based on photographs, one fruiting body could belong to a species of the genus *Hebeloma* and two to the genus *Laccaria*, thus confirming the presence of ectomycorrhizal fungi of the willows on Surtsey. Based on records of vascular plants on Surtsey 1965–2008 (Magnússon *et al.* 2009) and Gardes & Dahlberg (1996) for information on ectomycorrhizal plants, the three willow species were the only plants on Surtsey known to form ectomycorrhizae. Greipsson & El-Mayas (2000) found endomycorrhizal fungi in roots of *L. arenarius* grass from a 22 year old dune, the only plant species on Surtsey they investigated. They subsequently classified the early colonizing plants on Surtsey based on their dependency on arbuscular mycorrhizal (AM) fungi as: AMF non-dependent species, AMF facultative species, or AMF dependent species, using a list of the type of mycorrhizae formed by British plant species (Harley & Harley 1987).

In 1995 the first willow was discovered on Surtsey, two *S. herbacea* plants estimated to be two years of age. At present it is the most important ectomycorrhizal host with a few older plants and many young plants growing in the lava in the younger part of the gull colony. In 1998 the second willow species,

Table 1. Fungi on Surtsey island recorded prior to 2006, including species that were isolated from soil and grown in culture in the research laboratory. Based on Appendix 5 in Baldursson & Ingadóttir (2007). Fungi of each phylum are listed with a reference for each species but AMNH for specimens in the herbarium of the Icelandic Institute of Natural History in Akureyri.

Fungi	References
Oomycota	
Aphanomycopsis bacillariacearum Scherff.	Johnson & Cavaliere 1968
Zygomycota	
Absidia corymbifera (Cohn) Sacc. & Trotter	Henriksson & Henriksson 1974
Mucor hiemalis Wehmer	Henriksson & Henriksson 1974
Glomeromycota	
Glomus hoi Berch & Trappe	Greipsson *et al.* 2002
Scutellospora dipurpurascens Morton & Koske	Greipsson *et al.* 2002
Ascomycota	
Ceriosporopsis halima Linder	Johnson & Cavaliere 1968
Kirschsteiniothelia maritima (Linder) D. Hawksw.	Johnson & Cavaliere 1968
Lamprospora crouanii (Cooke) Seaver	AMNH
Lulworthia medusa (Ellis & Everh.) Cribb & J.W. Cribb	Johnson & Cavaliere 1968
Octospora axillaris (Nees) M.M. Moser	AMNH
Onygena corvina Alb. & Schwein.	AMNH
Peziza varia (Hedw.) Fr.	AMNH
Anamorphic fungi	
Cadophora fastigiata Lagerb. & Melin	Henriksson & Henriksson 1974
Cadophora malorum (Kidd & Beaumont) W. Gams	Henriksson & Henriksson 1974
Cladosporium macrocarpum Preuss	Henriksson & Henriksson 1974
Dinemasporium marinum Sv. Nilsson	Johnson & Cavaliere 1968
Epicoccum nigrum Link	Henriksson & Henriksson 1974
Lecanicillium psalliotae (Treschew) Zare & W. Gams	Schwabe 1970
Penicillium citrinum Thom	Schwabe 1970
Penicillium palitans Westling	Henriksson & Henriksson 1974
Phoma putaminum Speg.	Schwabe 1970
Trichoderma harzianum Rifai	Henriksson & Henriksson 1974
Trichoderma viride Pers.: Fr.	Henriksson & Henriksson 1974
Ulocladium botrytis Preuss	Henriksson & Henriksson 1974
Basidiomycota	
Arrhenia rustica (Fr.) Redhead, Lutzoni, Moncalvo & Vilgalys	AMNH
Entoloma sericeum (Bull.) Quél.	AMNH
Lichenomphalia sp. (misapplied name *A. rustica*) (lichen)	AMNH

S. phylicifolia, was found and the third, *S. lanata,* in 1999. Each of the three plants of *S. phylicifolia* has formed a low bush of several stems while the four plants of *S. lanata* are smaller. As the willows form ectomycorrhizae with many different fungi (Nara, Nakaya & Hogetsu 2003, Mühlmann & Peintner 2008) some of which would produce their fruiting bodies in the vicinity of their host's roots, an effort was made to locate these plants in the search for fungi. However, willows also form arbuscular mycorrhizae (Allen *et al.* 2005, Trowbridge & Jumpponen 2004) and only some of their ectomycorrhizal fungi produce fruiting bodies around the plants as research using molecular methods on the ectomycorrhizal roots has shown, species of ascomycetes, anamorphic fungi and basidiomycetes which form inconspicuous, resupinate or fan-shaped fruiting bodies, were more common on the roots than were the agarics commonly associated with willows (Mühlmann & Peintner 2008, Nara *et al.* 2003).

Driftwood on the northern shore was another habitat where marine microfungi and some wood decay fungi could be present. The only dung of herbivores which is suitable substrate for coprophilic fungi is goose dung while keratinophilic fungi could grow on remains of dead birds and feathers such as in regurgitated bird pellets.

Over the years a few mushrooms belonging to five species have been found on Surtsey some of which were collected and kept as dried specimens in the herbarium of the Icelandic Institute of Natural History in Akureyri (AMNH). In 2006, in a document prepared for the nomination of Surtsey for the UNESCO World Heritage List (Baldursson & Ingadóttir 2007), a brief outline of the research on fungi prior to 2006 and a list of 24 species of fungi, two of which were agarics, was compiled based on articles (Johnson & Cavaliere 1968, Schwabe 1970; Henriksson & Henriksson 1974) and herbarium specimens. Specimens identified to the genus level were excluded from that list (Table 1). Since the identity of the *Lichenomphalia* species has not been confirmed it was not assigned to a species here but earlier it was included in the species *A. rustica* s.l. (misapplied name). Since it is a lichen it is counted with the other lichens (see Kristinsson & Heidmarsson 2009) but as it belongs in the order Agaricales of the phylum Basidiomycota with numerous other agarics it is also treated here. Missing from the list were two species of arbuscular mycorrhizal (AM) fungi *Glomus hoi* Berch & Trappe and *Scutellospora dipurpurascens* Morton & Koske of the phylum Glomeromycota isolated from a 22 year old *Leymus arenarius* sand dune using the trap culture method. Younger dunes, five or ten years old, yielded no AM fungi (Greipsson *et al.* 2002).

The funga of Surtsey was further studied in 2008, when a mycologist joined the biological expedition in early July and the geological expedition in middle of August. In July microfungi on overwintered plant material and some parasitic fungi on living plants were collected and in August more microfungi on various substrates were added. However, in August it was the search for and collection of mushrooms, the fruiting bodies of agarics, a major group of the basidiomycetes, that was the focus of the investigation.

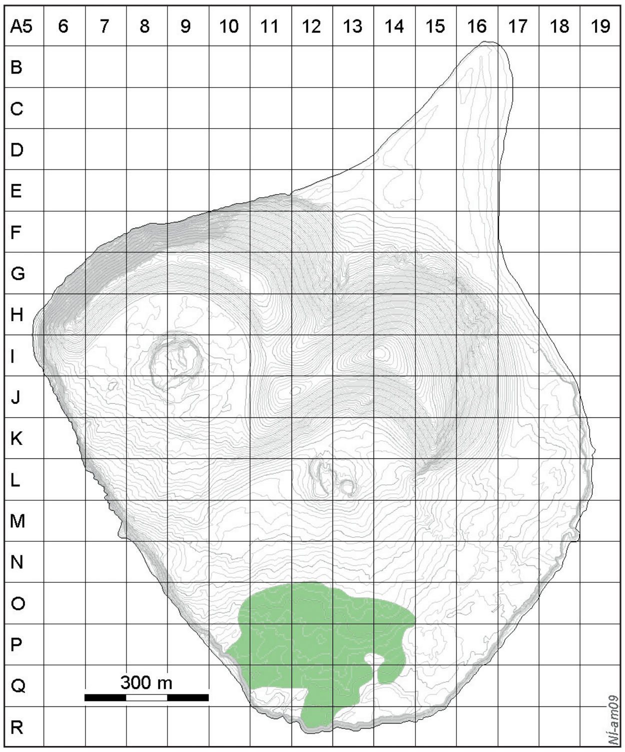

Fig. 1. Surtsey in 2007 with the area of dense vegetation shown in green and the 100 x 100 m grid system for mapping distribution of plants on Surtsey. The names of quadrats of the grid where agarics were collected were used as localities, e.g. plot I9 or plot L17.

METHODS

In 2008 fungi were collected during the periods July 7 to 10 and August 11 to 14. In July microfungi parasitic on living plants or saprophytic on overwintered, dead plant material and on driftwood were collected but no agarics were found at that time. In August more microfungi on dead plant material and other substrates were collected and the search for agarics was successful as fruiting bodies of several species were found. For each site the coordinates were recorded using a GPS unit and later placed in the 100 x 100 m grid system for Surtsey (Fig. 1). Samples of greylag goose (*Anser anser*) dung were collected and sent to Scotland to a specialist in coprophilic fungi for incubation in moist chambers. Three small soil samples were also collected and sent to a mycologist in Canada who will attempt to isolate microfungi of the genus *Leohumicola* from the soil.

Fruiting bodies were photographed and their macroscopic characteristics recorded before each collection was dried in warm air. Microscopic characteristics of the larger basidiomycetes have been examined and each collection identified to a genus, assigned a collection number (FA-number), and recorded in the AMNH herbarium database. Specimens were identified using keys (Knudsen & Vesterholt 2008) and monographs, e.g. Vesterholt (2005) for *Hebeloma*, Noordeloos (1992, 2004) for *Entoloma*, and Brandrud *et al.* (1998) for the genus *Cortinarius*. Presently, the identification to the species level is tentative for many of the collections and the names assigned may change. In the coming years the current name for each collection can be accessed through the GBIF data portal www.gbif.net by its FA-number in the AMNH herbarium.

RESULTS AND DISCUSSION

Fungi on driftwood and microfungi collected on Surtsey have not been examined and those results will be reported later. Most of the driftwood on the northern shore was in good condition and relatively few boles showed signs of decay.

Fruiting bodies of several different agarics were found on Surtsey in August (Table 2). Since most of the time fungi are practically invisible as delicate mycelia in soil or other substrates, only those producing fruiting bodies at this particular time were investigated. The maritime climate, lack of water, sandy soil and the lack of ectomycorrhizal hosts other than the three *Salix* species, limit the funga of Surtsey to species adapted to such habitats. Fruiting bodies of one or more ectomycorrhizal species were found near six *Salix* plants, two *S. herbacea* plants, one *S. lanata* plant, and three *S. phylicifolia* plants.

At least four ectomycorrhizal species were found with the older *S. herbacea* plants, while no fruiting

Table 2. Agarics collected on Surtsey 2008, their lifestyle and location (grid plot) in the 100 x 100 m grid for Surtsey (Fig. 1). (Lifestyle: ectomycorrhizal (EM), and saprophytic (S). One unidentified species of a genus is indicated by an sp. after the genus name or spp. when there are more than one species. When (?) is in front of a grid plot name the identification of collections from that site needs confirmation.)

Species	New on Surtsey	Life-style	Host plant or substrate	Grid plots
Cortinarius sp. (subgen. *Telamonia*)	x	EM	*S. herbacea*	O12
Entoloma sericeum Quél.		S		O11, P11, P12
Entoloma spp. (at least two species)	x	S		O12, O13, O14, L17
Hebeloma collariatum Bruchet	x	EM	*S. herbacea*	O12
Hebeloma marginatulum (J. Favre) Bruchet	x	EM	*S. phylicifolia*	I9
Hebeloma mesophaeum (Pers.) Quél.	x	EM	*S. phylicifolia*	?I8, O13
Hebeloma vaccinum Romagn. var. *vaccinum*	x	EM	*S. phylicifolia*	O13
Hebeloma spp.	x	EM	*S. herbacea* *S. lanata*	I8, O14
Inocybe lacera (Fr.: Fr.) P. Kumm. var. *lacera*	x	EM	*S. phylicifolia*	O13
Laccaria laccata (Scop.: Fr.) Berk. & Broome	x	EM	*S. herbacea*	O12
Psilocybe inquilinus (Fr.: Fr.) Bres.	x	S	*L. arenarius*	M12, M13

bodies were found near the younger plants. The fifth species, an unidentified *Entoloma* sp. (Table 2), could either be mycorrhizal or saprophytic as some members of the genus form mycorrhizae with plants while many are saprophytic (Knudsen & Vesterholt 2008). When the young *S. herbacea* plants grow and form approximately 30 cm wide mats their mycorrhizal partners should be able to produce fruiting bodies if conditions are right. Nara, Nakaya & Hogetsu (2003) who investigated fungi associated with *Salix reinii* growing on tephra on Mount Fuji in Japan found that the biomass of fruiting bodies increased with host size as did species diversity of the associated fungi which produced fruiting bodies. Since numerous fungi are able to form ectomycorrhizae with *S. herbacea* it will be interesting to document the establishment of its funga as the plants grow older.

Agarics associated with willows

In the following section the specimens collected in 2008 at different localities are listed. Localities are named with a letter and a number, e.g. I8, which refers to the 100 x 100 m grid for Surtsey (Fig. 1). Most of the fruiting bodies found close to the willow plants were less than 2 m from the plants often at the base of lava ridges or inside small lava cavities and apart from one species (*Entoloma* sp.) are known to form ectomycorrhizae with *Salix* spp.

Plot I8. *Hebeloma* spp., seven fruiting bodies (Fig. 2), five brownish (FA-19519) and two which were greyish in color and could represent a different *Hebeloma* species (FA-19518). Both specimens appear to belong to species in the section *Hebeloma,* perhaps *H. mesophaeum* (Pers.) Quél. Both collected 12.8.2008 close to *S. herbacea* (plant 1) in the Surtungur crater in a sandy patch on lava partly covered by *Racomitrium* moss.

Fig. 2. Brown fruiting bodies (FA-19519) above, and grayish (FA-19518) below, of unidentified *Hebeloma* species mycorrhizal with *Salix herbacea* in the crater Surtungur (I8). Photo GGE.

Fig. 3. *Hebeloma collariatum* (FA-19523) mycorrhizal with *Salix herbacea* in the oldest part of the gull colony (O12). Photo GGE.

Plot O12. *Hebeloma collariatum* Bruchet, six fruiting bodies (FA-19523) (Fig. 3). This is the second record of the species in Iceland. One fruiting body of *Laccaria laccata* (Scop.: Fr.) Berk. & Broome (FA-19524) and a group of seven small, brown fruiting bodies of an unidentified *Cortinarius* sp. of the subgen. *Telamonia* (FA-19526) (Fig. 4). One fruiting body of an unidentified, small *Entoloma* sp. (FA-19525), a species which may or may not be mycorrhizal (Fig. 4). Collected 13.8.2008 close to *S. herbacea* (plant 2) in the oldest part of the gull colony growing in a depression between lava ridges with *Honckenya peploides* and *Poa pratensis.*

Plot O14. *Hebeloma* sp., three fruiting bodies (FA-19527), collected 13.8.2008. This collection appears to belong to one of the species in the section *Hebeloma,* its spores somewhat larger than is typical for *H. mesophaeum.* It was close to a *S. lanata* (plant 1) in the younger part of the gull colony in a deep depression in lava with *Honckenya peploides, Cerastium fontanum* and *Sagina procumbens.* This was the only agaric found near a *S. lanata* plant as no fruiting bodies were found near the other plant located in this survey (plant 2 in plot O12).

Plot O13. *Hebeloma mesophaeum* (Pers.) Quél., two fruiting bodies (FA-19517), collected 11.8.2008 (Fig. 5), and *Hebeloma vaccinum* Romagn. var. *vaccinum,* three fruiting bodies (FA-19521) (Fig. 6) and five fruiting bodies of the larger *Inocybe lacera* (Fr.: Fr.) P. Kumm. var. *lacera* (FA-19522) grew amongst the smaller *H. vaccinum* (Fig. 6). Collected 13.8.2008. If the identification of *H. vaccinum* is correct then this is the second record of the species in Iceland. *H. mesophaeum* grew with *S. phylicifolia* (plant 1) in the younger part of the gull colony, sheltered at the bottom of a lava channel, while the other two grew by *S. phylicifolia* (plant 3) also in the younger part of the gull colony amongst grasses in a slight depression between low lava ridges.

Plot I9. *Hebeloma marginatulum* (J. Favre) Bruchet, five fruiting bodies (FA-19520) (Fig. 7). Collected 12.8.2008 close to *S. phylicifolia* (plant 2) in the slope of Surtungur crater in gravelly patches on lava.

Each of the three *S. phylicifolia* plants currently growing on Surtsey was associated with one or more ectomycorrhizal fungi producing fruiting bodies.

Agarics in grassland, sand dunes, or sandy soil

With the exception of one species of the genus *Psilocybe* all the fungi saprophytic in grassland on sandy soil, in *Leymus arenarius* dunes, or sparse vegetation, belong to the genus *Entoloma.* The number of species is at least two, perhaps more, with *Entoloma sericeum* being common in grassland in the oldest part of the gull colony. Identification of *Entoloma* species is difficult and all the collections from

Fig. 4. A group of *Cortinarius* sp. subgen. *Telamonia* fruiting bodies (FA-19526) mycorrhizal with *Salix herbacea* in the oldest part of the gull colony (O12) and one small fruiting body of an *Entoloma* species (FA-19525) (bottom central). Photo GGE.

Fig. 5. *Hebeloma mesophaeum* (FA-19517) mycorrhizal with *Salix phylicifolia* in the younger part of the gull colony (O13). Photo GGE.

Fig. 6. *Hebeloma vaccinum* var. *vaccinum* (FA-19521) three smaller fruiting bodies below central and four larger *Inocybe lacera* var. *lacera* fruiting bodies (FA-19522) above, mycorrhizal with *Salix phylicifolia* in the younger part of the gull colony (O13). Photo GGE.

Fig. 7. *Hebeloma marginatulum* (FA-19520) mycorrhizal with *Salix phylicifolia* in the crater Surtungur (I9). Photo GGE.

Fig. 8. *Entoloma sericeum* (FA-19512) fruiting bodies picked from a 3 m long line in grassland in the oldest part of the gull colony (P12). Photo GGE.

Surtsey had isodiametric spores of approximately the same size range. Collections with cheilocystidia remain unidentified while those without were tentatively identified as *E. sericeum*.

Plots O11, P11, P12. *Entoloma sericeum* Quél. was relatively common in grassland on sandy soil in the oldest part of the gull colony. Ten fruiting bodies in a 3 m long line (P12) (FA-19512) (Fig. 8), in (O11) a small cluster (FA-19513), in (P11) (FA-19514). Three collections 11.8.2008. These and additional fruiting bodies (not collected) in clusters and forming short lines in the oldest part of the gull colony indicate that this species has become well established and must have been growing in this area for many years. Fruiting bodies usually form near the growing edge of a mycelium, in a young mycelium sometimes forming a circle but as the fungus grows and forms a wider circle, parts of which may die, thus producing fruiting bodies in short, nearly straight lines.

Plot O13. *Entoloma* sp., five fruiting bodies in a cluster (FA-19516). Collected 13.8.2008 in grass in the younger part of the gull colony in a slight depression between low lava ridges.

Plots L17, M16, M17. *Psilocybe inquilinus* (Fr.: Fr.) Bres. and *Entoloma* sp. The *P. inquilinus,* thirty fruiting bodies (FA-19528) (Fig. 9), was collected 12.8.2008 in a sheltered *Leymus arenarius* dune in lava east of the research hut Pálsbaer (M16–M17) at the entrance of a lava cave on dead stems and leaves of the plant. Most of the fruiting bodies were attached to decaying fragments of *L. arenarius* grass buried in sand in this relatively moist dune. This fungus had low conical cap which became plane as it matured with only slightly moist surface and very limited, if any, fragments of veil. *P. inquilinus* has viscid cap and is thinner than the largest fruiting bodies of this collection but they share the same habitat and produce spores which are 7–8 µm long with a distinct and large germ pore, are rather thick-walled, and ovoid to rhomboid in front view

Fig. 9. *Psilocybe inquilinus* (FA-19528) growing on fragments of *Leymus arenarius* in a dune at the opening of a lava cave (M16 – M17). Photo GGE.

(Knudsen & Vesterholt 2008). Thus although the collection deviates somewhat from the species concept of *P. inquilinus* it is tentatively identified as that species. The *Entoloma* sp. (FA-19511) was collected 12.8.2008 in an exposed *Leymus arenarius* dune in lava east of the research hut Pálsbaer (L17). It was found as three solitary fruiting bodies each in a different part of the dune. The fruiting bodies were smaller than those of *E. sericeum* from the oldest part of the gull colony and cheilocystidia were present.

Plot O14. *Entoloma* sp., a single fruiting body (FA-19515). Collected 13.8.2008 in sand within a *Honckenya peploides* plant in lava at the northern edge of the gull colony.

General conclusions

In total, at least ten species of agarics were collected in the 2008, eight of which have been identified to a species and seven were new for Surtsey (Table 2). The findings in 2008 increase the total number of fungi identified to a species on Surtsey to 33 thereof the number of agarics to nine (Tables 1 and 2).

The presence of fruiting bodies of several different agarics in middle of August 2008 shows that conditions have been right for reproduction of these fungi while other species, reproducing earlier or later in the year or not at all, may also be present. The willows are still young, the oldest plants have been growing on Surtsey for 15 years while most of the plants are less than ten years of age. Thus their ectomycorrhizal funga may change as the plants mature. The maritime climate, sandy soil, *L. arenarius* dunes, and *S. herbacea* as the primary ectomycorrhizal host species, are some of the parameters influencing the development of the funga of Surtsey.

ACKNOWLEDGEMENTS

I am most grateful to the Surtsey Research Society for the opportunity to study the funga of Surtsey and to the Icelandic Coast Guard and their helicopter crews for the transportation to and from Surtsey. Toyota Iceland supported the biological research on Surtsey.

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The land-invertebrate fauna on Surtsey during 2002–2006

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ABSTRACT

Formal studies on invertebrate colonizers and establishments on Surtsey started in 1965 and the island was visited regularly for longer and shorter periods till 1984. After a period of sporadic invertebrate studies, yearly visits to Surtsey started again in 2002. Here are presented the results from a five year study period, 2002–2006.

Surtsey is characterized by three kinds of substrates, viz. lava, sand and palagonite rock. The invertebrate collecting is mainly based on pitfall trapping in permanent plots on sand and lava substrates, also informing on the impact of a gull breeding colony that started in the lava field in 1985. Netting and direct picking takes place on all three kinds of substrates of the island. Also, three traps were set up close to the hut and helicopter platform to test for signs of human impact.

Hitherto, 354 species or taxa ranked as species have been found on Surtsey. Thereof 144 are regarded permanent settlers. In 2005 an invasion of flying insects by air mass was witnessed. Transport of invertebrates by birds was probably underestimated in the beginning, but the existence of a number of permanently settled species can hardly be explained differently.

The gull breeding colony was an advantage to the invertebrate diversity on Surtsey. Higher species diversity is found within the colony than outside it and a clear distinction in species composition between plots outside and within the gull colony. Also, a great faunal diversity is within the colony while the fauna is rather homogenous on the sand substrate.

Land-invertebrates have proved to play a very important role in the developing ecosystem on the island, also forming the basis for colonization of invertebrate feeding birds.

INTRODUCTION

Invertebrate colonization and community assembly of islands have been intriguing questions for ecologists. Questions commonly rise on where the invertebrates come from, how they get there and what the community assembly is like. It is a unique opportunity to be able to study young oceanic islands where sterile soil has become invaded by living organisms and formed different kinds of habitats. Colonization of invertebrates on young volcanic islands has been studied on Krakatau Island between Java and Sumatra in Indonesia (e.g. Thornton & New 1988), Long Island near Papua New Guinea (Edwards & Thornton 2001), Nishinoshima Island south of Japan (Abe 2006) and Surtsey Island, south of Iceland.

The first land-invertebrate, the midge *Diameza zernyi*, was found on Surtsey in 1964 (Fridriksson 1964, Oliver 1965). In 1965, while the volcano was still erupting, Surtsey was protected and reserved for scientific research. Organized studies on land-invertebrates started immediately and for gaining knowledge on the nearest invertebrate source, collections were also made on other nearby islands

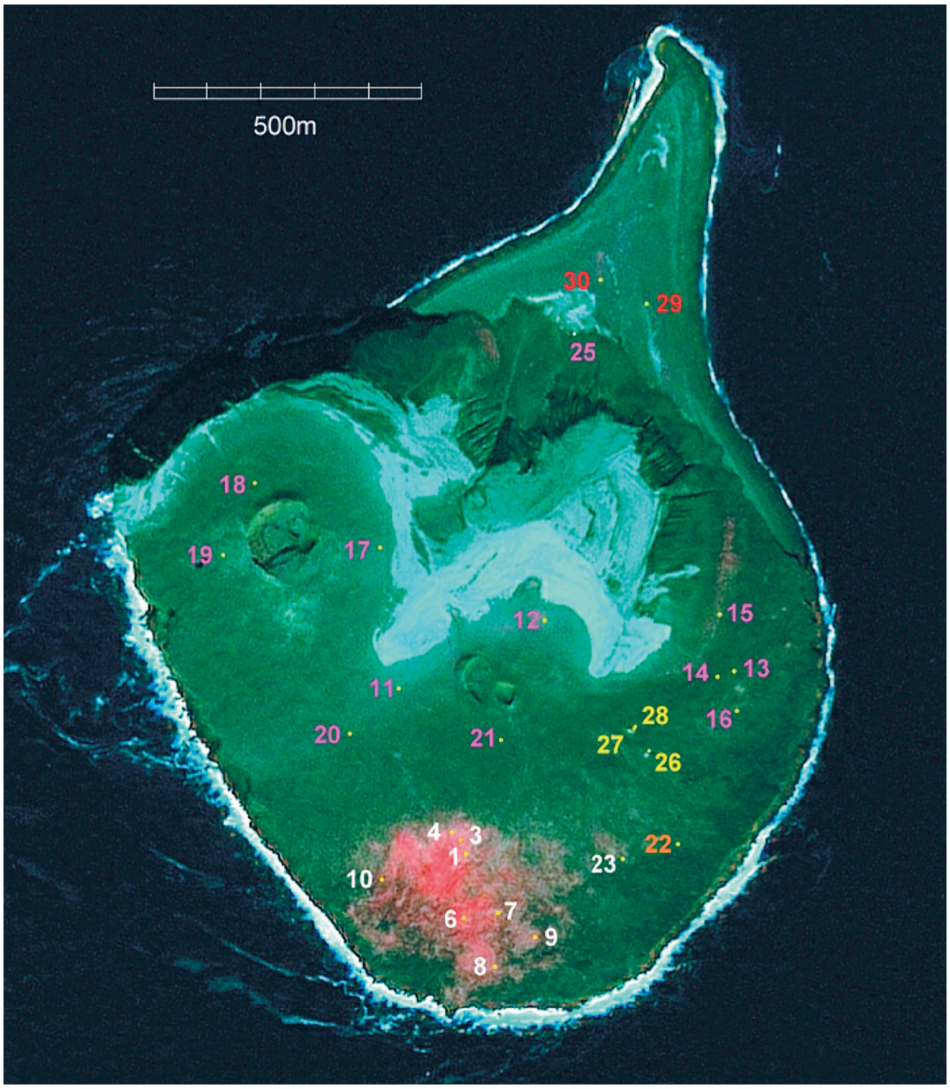

Fig 1. Plots for pitfall trapping invertebrates on Surtsey 2002–2006. Colours indicate different types of surface; white = lava with gull colony; purple = sand-filled lava; orange = bare lava; red = sandy spit; yellow = human effect study. Infra-red SPOT 5 image from July 16, 2003. Dense vegetation appears in red colour, educing the gull breeding colony.

(Vestmannaeyjar) as well as in the closest coastal region of mainland Iceland (Lindroth *et al.* 1973). During 1965–1974 invertebrates were collected every summer on Surtsey, followed by visits during the summers of 1976, 1978, 1981 (Lindroth *et al.* 1973, Ólafsson 1978, 1982, Bödvarsson 1982) and 1984. The research during these first two decades (1964–1984) resulted in a list of 193 species of land-invertebrates found on the island.

Several pairs of lesser black-backed gulls (*Larus fuscus*) and herring gulls (*L. argentatus*) started a breeding colony on Surtsey around 1985. The gull colony increased gradually during the following years. This resulted in a breakthrough in plant succession (Magnússon & Magnússon 2000). Unfortunately the process initiated by the breeding gulls was not followed up by entomological studies until 1995, when soil-invertebrates were explored (Gjelstrup 2000, Sigurdardóttir 2000).

In 2002, invertebrate studies started again on Surtsey. The aim was to follow up the status of invertebrate colonization and the development of invertebrate communities on different substrates in relation to other environmental factors.

METHODS

Study area

In 2004 the constantly eroding Surtsey Island (Fig. 1) covered 1.4 km^2 of land, what was left of a 2.7 km^2 island at the end of the eruption in 1967 (Jakobsson *et al.* 2007). Surtsey is located 32 km off the south coast of mainland Iceland and 4.8 km from the nearest small island, Geirfuglasker, in the Vestmannaeyjar archipelago.

The island is characterized by three kinds of surfaces, e.g. palagonite rock, lava and sand. There are two hills made of palagonite rock mostly devoid of vegetation. The lava makes the slopes and flats south and east of the hills. Part of the lava was colonized by gulls which influenced the plant colonization and succession process so now it has rich vegetation (Magnússon & Magnússon 2002, Magnússon & Ólafsson 2003, Magnússon *et* *al.* 2009). Windblown sand fills the lava adjacent to the hills. On the north side the sea currents have built up a spit from loose material, boulders and sand, originating from the constantly eroding lava and palagonite cliffs (Jakobsson *et al.* 2007). The sandy surfaces are characterized by a beach vegetation community dominated by *Honckenya peploides*, *Mertensia maritima* and *Leymus arenarius* (Magnússon & Magnússon 2002, Magnússon *et al.* 2009).

Data collecting

Each year invertebrates were sampled over a period of four days in July, starting the earliest on 15th and at the latest on 21st of July. The sampling was based on pitfall trapping, netting and direct picking.

Pitfall trapping was performed under the different conditions on the island. In 1990–1995 permanent plots (10x10 m) were set up for measuring vegetation succession. The sites for the plots were originally chosen to represent two of the main surface types considered, sand and lava (the palagonite surface was omitted), including the gull colony (Magnússon & Magnússon 2000). In 2002–2006, 21 of those plots were still in use and in 2005 two additional ones were set up on the spit. To have the opportunity to process results together with other environmental factors measured, each year a pitfall trap (6.3 cm in diameter, and depth of 6.5 cm) filled up to 1/3 with 4% formaldehyde, was placed in the centre of each plot, collecting for approximately 70 hours. The trap sampling has been limited to a single trap within each plot to have as little impact on the fauna as possible on the by law protected island.

For further invertebrate studies four additional plots were selected. One was located on the north side of the hills, i.e. at the base of the spit, where the sandy surface is unstable and vegetation has little chance to develop (a plot formerly used for measuring plants). Three traps were set up to look for signs of human impact; two of them close to the research hut, one under the terrace, the other behind the hut, and one at the helicopter platform near by. Thus a total of 27 pitfall traps have been utilized in this survey. Five categories of plot sites are defined: 1) lava with gull colony; 2) sand-filled lava, no gulls; 3) bare lava, no gulls; 4) sandy spit; 5) human effect study (Fig. 1).

Manual collecting (i.e. netting and direct picking) has also been performed each year to sample invertebrates that seldom are caught in pitfall traps. Netting takes place primarily in the gull colony as many species tend to fly around there but also on the sand and on the palagonite hills. However, netting is not performed within the plots to prevent effects on the vegetation to be monitored. Direct

Table 1. Land-invertebrates, orders and higher taxa, collected on Surtsey during the 2002–2006 surveys; number of specimens collected annually given.

Species groups	2002	2003	2004	2005	2006	Total
Entognatha						
Collembola	2.545	3,386	645	1,684	1,837	10,097
Insecta						
Coleoptera	222	250	361	344	342	1,519
Diptera	431	590	877	1,240	1,429	4,567
Hemiptera	128	72	132	194	143	669
Hymenoptera	42	211	122	131	81	587
Lepidoptera	8	17	11	15	26	77
Neuroptera					2	2
Thysanoptera	405	473	115	575	320	1,888
Arachnida						
Araneae	221	232	558	405	334	1,750
Neomolgus	19	26	10	119	30	204
Acari	1,617	1,762	4,480	1,997	3,481	13,337
Mollusca						
Gastropoda	6	18	16	6	11	57
Annelida						
Oligochaeta	11	3	4	6	11	35
Total	5,655	7,040	7,331	6,716	8,047	34,789

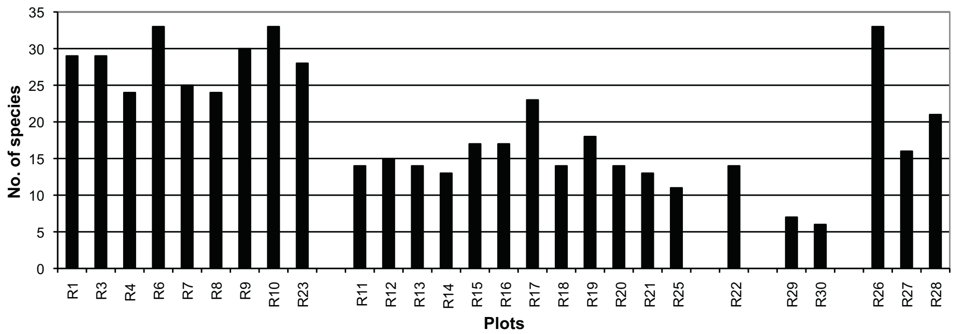

Fig. 2. Land-invertebrates caught by pitfall traps, total number of species (springtails and mites excluded). Plots arranged in five categories, from left: lava with gull colony (9 plots), sand-filled lava (12 plots), bare lava (1 plot), sandy spit (2 plots), human effect study (3 plots).

picking takes place mostly from under stones and under dead birds on the lava and from under driftwood on the spit. Collecting has also taken place around a steaming hot fumarole and in ruins of a lighthouse on top of the island (built in 1973 but no longer in use). The lighthouse has an uncovered door-opening facing north, thus serving as an excellent trap for just arrived flying insects.

Identification

All beetles (Coleoptera), moths (Lepidoptera), thrips (Thysanoptera), lacewings (Neuroptera), spiders (Araneae) and snails (Gastropoda) have been identified to the species level, except for juvenile stages of some. A great majority of flies and midges (Diptera) have been identified to species (Sciaridae and Cecidomyiidae excluded), hemipterans (Hemiptera) to species except for aphids (Aphididae) and hymenopterans (Hymenoptera) either to species or generic level, with several unsolved exceptions. Springtails (Collembola), mites (Acari) and the oligochaete worms of the family Enchytraeidae are still unrecognized.

Some of the older material collected, before 1984, was checked specially and revised in connection with the present work.

Data analysis

DECORANA-ordination (Hill 1979) was used to test the similarities between the pitfall trap samples. From each plot the five year sampling series (2002–2006) was combined to a single data set prior to analyses as samples from a single year are too small to be analysed as such. All species or taxa equivalent to species were considered in the analyses. Also the number of specimens caught, calculated to catch per day (24 hours). Rare species were downweighted.

RESULTS

Annually several thousand specimens have been sampled during the five year period considered. The total material counts 34,789 specimens (including Collembola and Acari), of which 84.5% were achieved by pitfall trapping and 15.5% by manual collecting (i.e. by netting and direct picking).

The species groups considered belong to the large taxa Entognatha, Insecta, Arachnida, Mollusca and Annelida (Table 1, Appendix I). A total of 168 species or species equivalent taxa have been named (Collembola and Acari excluded). The total number is a minimum as some named and not fully treated taxa may include more than a single species (for instance Sciaridae, Aphididae). In such cases the relevant taxon is counted as one species. Of those 168 species, 156 have been collected manually and 83 by pitfall traps, 85 only manually and 12 only by traps.

The invertebrate fauna of different habitats

The lava with gull colony is richest in invertebrate species. Nine plots give an average of 28.3 species and an average daily catch of 17.7 speci-

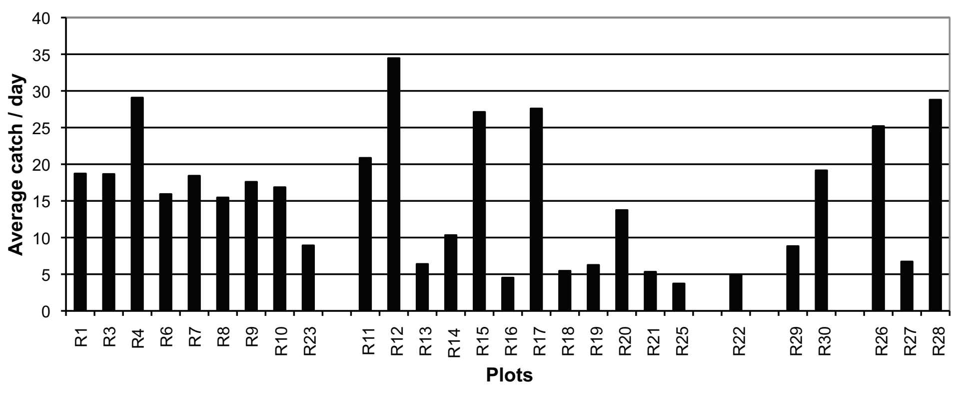

Fig. 3. Land-invertebrates caught by pitfall traps, the average daily catch of specimens (springtails and mites excluded). Plots arranged in five categories, from left: lava with gull colony (9 plots), sand-filled lava (12 plots), bare lava (1 plot), sandy spit (2 plots), human effect study (3 plots).

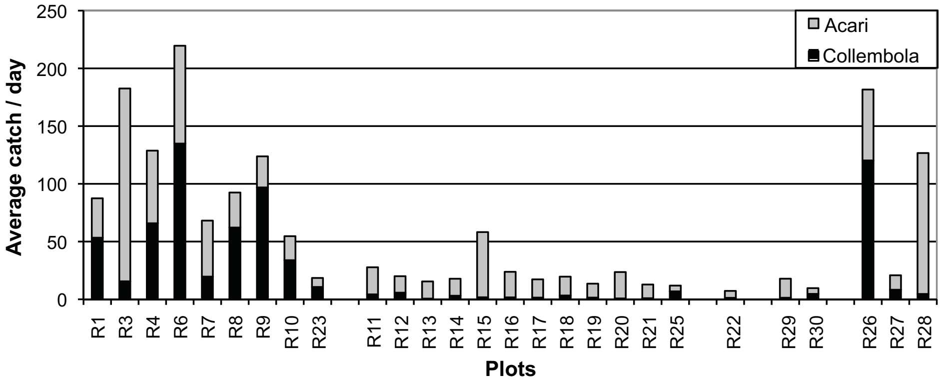

Fig. 4. Land-invertebrates caught by pitfall traps, the average daily catch of springtails (Collembola) and mites (Acari). Plots arranged in five categories, from left: lava with gull colony (9 plots), sand-filled lava (12 plots), bare lava (1 plot), sandy spit (2 plots), human effect study (3 plots).

mens (Figs 2 & 3). These plots show a relative stability in number of species and catch. The catch at plot 4 exceeds the average markedly, with an exceptional number of linyphiid spiders (*Erigone arctica*) caught. Plot 23 is, on the other hand, markedly lower in the same point, the plot being located at the margin of the colony (Fig. 1), thus being under minor influence of breeding gulls.

On the sand-filled lava outside the colony, twelve plots give the average of 15.3 species and the daily catch average of 13.8 specimens (Figs 2 & 3). The number of species is markedly lower than in the gull colony, only one plot approaches the lowest colony plots. Considering the number of species, the sandy plots are comparable mutually. On the other hand the daily specimen catch shows a wide range of results, ranging from 3.7–34.5 specimens. The high scorers are due to a great number of *Thrips vulgatissimus*, dominating in the catches. Plot 25 is the poorest plot on the island, located under extremely unfavourable conditions at the northern side of the hills where surface is so unstable that plants are unable to grow.

The bare lava which is neither affected by gulls nor moving surface sand has been surveyed on a single plot only (plot 22), resulting in 14 species and a poor catch of 4.9 specimens on daily average (Figs 2 & 3).

The sandy spit lies considerably lower over sea level than the sand-filled lava sites and is clearly affected by the vicinity of the beach. The plots are species poor, giving an average of 6.5 species, and 14.0 specimens in average daily catch (Figs 2 & 3). It must be kept in mind that the results are based on catches from two years only. In daily catch plot 30 slightly exceeds the average of plots within the colony on the lava, which is explained by a great catch of *Thrips vulgatissimus* dominating the catch as in some of the plots accounted for above on the sand-filled lava.

The human effect study by two plots at the hut and one at the helicopter platform give an average of 23.3 species and an average daily catch of 20.2 specimens (Figs 2 & 3). The plot at the helicopter platform (plot 26) gives a species number comparable with the lava with gull colony while the other two, by the hut, are more similar to the sand-filled lava plots. When considering the catch in traps, the plot under the terrace of the hut (plot 27) has the fewest specimens of the three.

As stated springtails and mites have not been identified to species or sorted to any higher taxonomic categories for this report. Still, individuals belonging to these two invertebrate groups have been counted. The results indicate low number in all sandy plots, both on sand-filled lava and on the spit (Fig. 4). Two of the plots for human impact studies show similar number as the plots in the lava with gull colony.

DCA-ordination

The results of the DCA-ordination show a clear distinction between plots outside and within the gull colony (Fig. 5). Also, a great faunal diversity is indicated within the colony and the invertebrate fauna is affected by the human activity around the hut.

The results show little variation when plots on sandy soils are considered separately, independent on location on the island. The two plots on the spit (29 and 30), that only were sampled for two years, are the extreme outsiders furthest to the left on ordination Axis 1.

The plots within the gull colony are separated on the right side of the graph from sandy plots. They are also more distributed than the sandy plots. This variation is best explained by the gradually developing vegetation. Plots 1–6 are located in the oldest part of the colony. The locations of plots 7–9 are near this oldest core, but plot 10 and plot 23 are at the margins, gradually being incorporated into the colony, plot 10 well ahead. Plot 22, the only bare lava plot outside colony, is placed close to plot 23 in the eastern part of the lava, still unaffected by the breeding gulls.

The human effect study plots 26, at the helicopter platform, and 27, under the terrace of the hut, take positions on level with the marginal plots in

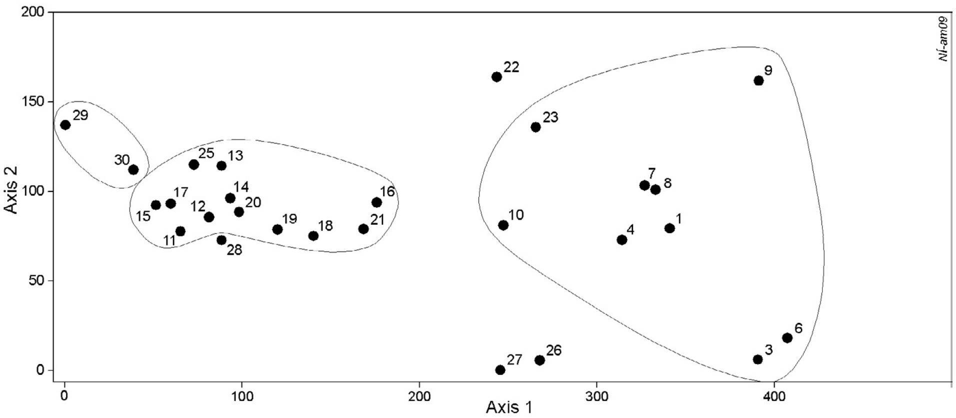

Fig. 5. DCA-ordination results from pitfall trap plots on Surtsey. Encircled from left: sandy spit (2 plots), sand-filled lava (12 plots), lava with gull colony (9 plots); outside circles: bare lava (plot 22), human effect study (plots 26–28). Axis 1 shows 73% of the sample variation and Axis 2 stands for 18%.

the colony, i.e. near the centre of Axis 1, while plot 28, behind the hut, is intermixed with other sandy plots.

DISCUSSION

Dispersal

Several means of transport of invertebrates over open sea to Surtsey have been confirmed and described; 1) by winds or air currents, 2) by sea currents, and 3) by birds (Lindroth *et al.* 1973, Ólafsson 1978).

Aerial dispersal is a favoured explanation for invertebrates (Drake & Farrow 1988, Bell *et al.* 2005, Nkem *et al.* 2006) and flying insects have been shown to be carried along with air masses (Coulson *et al.* 2002a). In 2005 such an invasion was witnessed to Surtsey following northern winds. Numerous individuals were found inside the ruins of the lighthouse and several species not previously

Table 2. Land-invertebrates, orders and higher taxa, collected on Surtsey during the 2002–2006 surveys; total number of species and their evaluated status in 2006.

	Species total no.	Species settled	Status uncertain	Species not settled	Dead in drift only*
Collembola	22	9	5	8	
Protura	1			1	
Diptera	155	45	8	102	
Hymenoptera	41	12	6	23	1
Lepidoptera	21	5	3	13	1
Coleoptera	18	12	4	2	6
Hemiptera	9	6		3	1
Thysanoptera	3	3			
Trichoptera	3			3	1
Neuroptera	2			2	
Mallophaga	1			1	
Siphonaptera	1			1	
Acari	59	41	1	17	
Araneae	14	7	2	5	
Oligochaeta	2	1	1		
Gastropoda	2	2			
Total	354	143	30	181	10*

* Not included in the total number

found on the island were flying around in the gull colony. Some of those species were typical wetland species, e.g. the dipterans *Platycheirus granditarsus*, *Tetanocera robusta*, *Dictya umbrarum* and *Rhamphomyia simplex,* some not capable of surviving on Surtsey due to lack of fresh water on the island.

Invertebrates, such as soil arthropods, can survive long time in sea water (Coulson *et al.* 2002b) and more invertebrate species have been brought to Nishino-shima island by sea than by air (Abe 2006). Invertebrates (springtails, shield bugs, a proturan and mites) have come to Surtsey either floating directly on the surface, hiking with floating objects or in turfs of vegetation and soil (Lindroth *et al.* 1973, Ólafsson 1978). Some species have been found dead in drift only (Table 2).

Invertebrate dispersal by getting a lift with birds has received speculations and some support (Lindroth *et al.* 1973, Smith & Djadjasasmita 1988, Thornton & New 1988, Ashmole & Ashmole 1997, Figuerola *et al.* 2005). When the gulls had established the breeding colony, the importance of birds as transport media became more obvious. The first gull settlers built their nests by plucking mosses around the nesting site, but so it seemed that some of them adopted the act of bringing nesting material from sites outside Surtsey, which led to colonization of new plant species (Magnússon & Magnússon 2000, Magnússon & Ólafsson 2003). Our conclusion is that birds, as transport method, have probably been underestimated by Lindroth *et al.* (1973) and that birds must have carried invertebrates with the nesting material, like aphids and thrips, and most likely also hidden in their feather coats, like springtails, mites, beetles and gastropods; some of which certainly could also have been carried with nesting material. However, dispersal of molluscs by birds to Krakatau has been considered unlikely (Smith & Djadjasasmita 1988) and aerial dispersal suggested for smaller invertebrates like thrips (Thornton & New 1988).

Import of organisms to Surtsey by humans is strictly controlled and it has not been detected that species have been able to colonize due to humans. Two species have been found there, accidentally brought to the island in food supplies, the beetle *Lathridius minutus* and the fly *Drosophila funebris*, neither of which can survive under conditions outside the hut (Jakobsson *et al.* 2007).

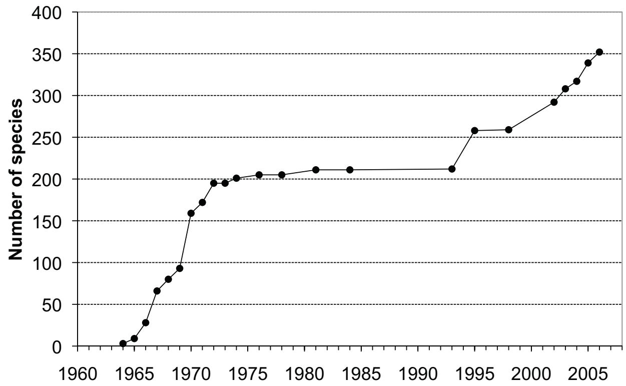

Fig. 6. Land-invertebrate species found on Surtsey, cumulative numbers from 1964–2006 (excluded are eleven species found dead on drift only).

Colonization

Since the first invertebrate was found on Surtsey in 1964 (Fridriksson, 1964, Oliver 1965), 354 species or taxa ranked as species have been listed as found on Surtsey (Appendix I) and as in the case of other young islands the major part of the species in question have a wide distribution (Edwards & Thornton 2001, Abe 2006).

The collecting activity during the first years led to a gradual increase in invertebrate species found (Fig. 6). The more sporadic visits of collectors that followed this active start added only a few species to the list. It should also be kept in mind that during these years the plant succession process was very slow. Species poor beach plant communities were developing in the sandy areas but few new plant species were successful in their colonization attempts (Magnússon & Magnússon 2000, Magnússon & Ólafsson 2003). The soil-invertebrate expedition in 1995 (Gjelstrup 2000, Sigurdardóttir 2000) added 46 species to the list and since the annual visits started again in 2002 gradual additions have been made to the species list (Fig. 6).

In connection with the present work the status of the 171 species obtained during the first 20

Table 3. Land-invertebrates found on Surtsey; number of species during three study periods, 1964–1984, 1995 (soil invertebrates only), and 2002–2006, and their evaluated status for the respective periods.

	1964–1984	1995	2002–2006	Total
Settled species	17	46	99	144
Status uncertain	16		22	29
Not settled	149		52	181
Dead in drift on beach	(11)			(11)

years of studies (1964–1984) has been evaluated, i.e. their status at the relevant survey period. The majority of the species was for the relevant period regarded "not settled" (Table 3). In 2006, 144 invertebrate species are regarded permanent settlers (Table 3, Appendix I). Permanent settlers are here defined as species that have been found under conditions required of the species in question, found annually from 2002 or a later year in increasing number either in traps or netted. Soil animals discovered during the survey in 1995 (Gjelstrup 2000, Sigurdardóttir 2000) are regarded settlers even if not confirmed by a similar survey in later years as most of them were obtained in a great or considerable number in soil. Some of the earlier recorded soil-animal species were not rediscovered during that survey, indicating failed colonization attempts (Gjelstrup 2000).

It can certainly take several years for a population of a settler to grow to a size that is discoverable. Additional 29 species are suspected to be permanent settlers as the conditions required for the species are present on the island, but awaiting further data to approve the actual status is recommended. The remaining 181 species on the list, mainly winged insects, are regarded accidental stragglers to the island, some showing up quite regularly while others are more sporadic. Some of those will have to wait till the ecosystems have developed further, while others, like species with aquatic live forms at some developmental stages or denoted wetland species, will hardly ever find the opportunity to become local citizens on Surtsey.

Invertebrate communities of different habitats

Habitat diversity gives rise to more diverse communities and more species richness than do uniform landscapes. With the gull colony the variety of habitats on Surtsey increased and both the invertebrate fauna and the flora are different within and outside the gull colony and vary more in species composition within and close to the gull colony than outside (Fig. 5; Magnússon *et al.* 2009).

Sand-filled lava and the sandy spit. Both the sand-filled lava and the spit are characterised by a differently scattered *Honckenya peploides*, sometimes accompanied by stands of *Leymus arenarius* (Fig. 7), and nutrient poor soil (Magnússon *et al.* 2009). They are all rather similar concerning invertebrate species composition (Fig. 5). Plots 29 and 30 on the spit are marginal, probably on account of the species poor fauna (Fig. 2), which partly might be affected by only two years of sampling.

Species characterizing the sandy surface are, as on other young and vegetation poor areas, mainly predators and scavengers (Edwards & Thornton 2001, Kaufmann 2001, Hodkinson *et al.* 2004), in this case consisting of beetles, spiders and dipterans. This is the proper habitat for the liniphiid spiders *Meioneta nigripes* and *Islandiana princeps*, also the carabid beetle *Amara quenseli*. The well developed batches of *Honckenya peploides* produce a great number of the thrips *Thrips vulgatissimus*, dominating in the catches. The number of thrips explains the great variety in catches between plots in this habitat, i.e. traps placed within or close to *Honckenya peploides* batches catch numerous thrips (Fig. 3). This similarly explains the high catch at plot 30 on the spit, which is located on a relatively stabilized flat on the inside of the spit with developed *Honckenya* batches (Fig. 8). Plot 29 is closer to the beach and still affected by over-flooding during winter time (Fig. 1).

Human effect study. Plots 26 and 27 are more similar to the plots from the gull colony than other

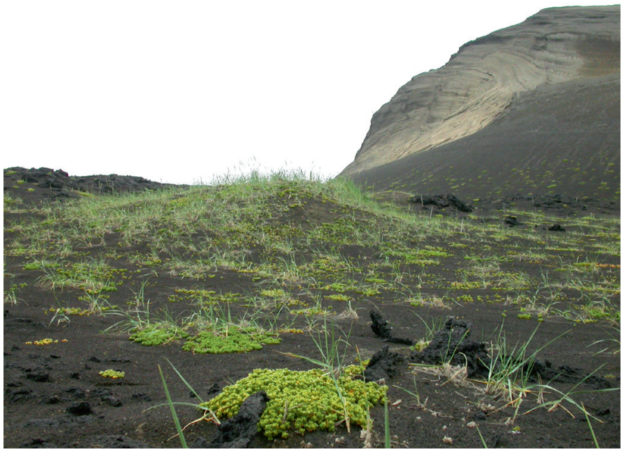

Fig. 7. Sand-filled lava on the eastern side of Surtsey; a beach plant community with *Honckenya peploides* and *Leymus arenarius*. Photo E. Ólafsson, July 11, 2007.

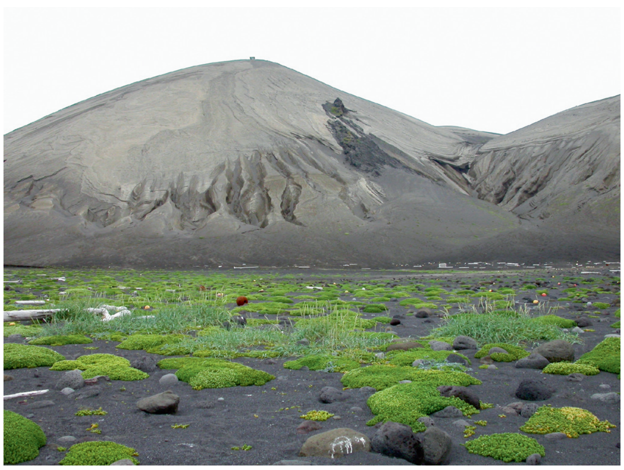

Fig. 8. The sandy flat of the northern spit of Surtsey; a beach plant community with *Honckenya peploides*, *Leymus arenarius* and *Mertensia maritima*. Austurbunki, a palagonite hill, in background. Photo E. Ólafsson, July 11, 2007.

Fig. 9. From the gull colony on Surtsey; *Tripleurospermum maritimum*, *Festuca richardssonii*, *Poa pratensis* and *Leymus arenarius* dominating in luxuriant vegetation. Photo M. Ingimarsdóttir, July 19, 2005.

Fig. 11. The slug *Deroceras agreste*, was discovered in the gull colony on Surtsey in 1998 and has been found regularly since. Photo E. Ólafsson, July 22, 2003.

plots regarding species composition (Fig. 5). The nutrients in soil have not been measured in these plots but we assume those plots are rather nutrient rich. Gulls use the helicopter platform as a roosting site, thus nourishing the soils around it and flourishing the vegetation. Considering plot 26 the species composition and number of species is comparable with plots within the gull colony (Figs 2 & 5). Plot 27 shows a similar tendency but much fewer specimens are caught there, showing more of a typical sandy plot character, also regarding vegetation (Figs 2–4). Still, there must be a reasonable explanation for the plot to be placed beside plot 26 on the ordination graph (Fig. 5). The soil might be richer than generally in this kind of substrate as it is watered by rainwater running from the huts roof and walls, washing off the dust, also from the terrace where gear and supplies are regularly left to stand for undefined hours. Also persons have been caught taking a leak on the spot! Plot 28, behind the hut, is not distinguished from other sandy plots regarding species composition (Fig. 5) but has a high catch of both soil and above ground invertebrates (Figs 3–4). This is probably due to the location of the trap in a well developed batch of *Honckenya peploides* rather than to effects of humans.

Bare lava. The weak information, based on a single plot only, does not allow much discussion. The results indicate that the species composition differs from the sandy substrate fauna even if it similarly has a low number of species and meager general

Fig. 10. The tortricid moth *Eana osseana*, the most common lepidopteran in the gull colony on Surtsey. Photo E. Ólafsson, July 20, 2004.

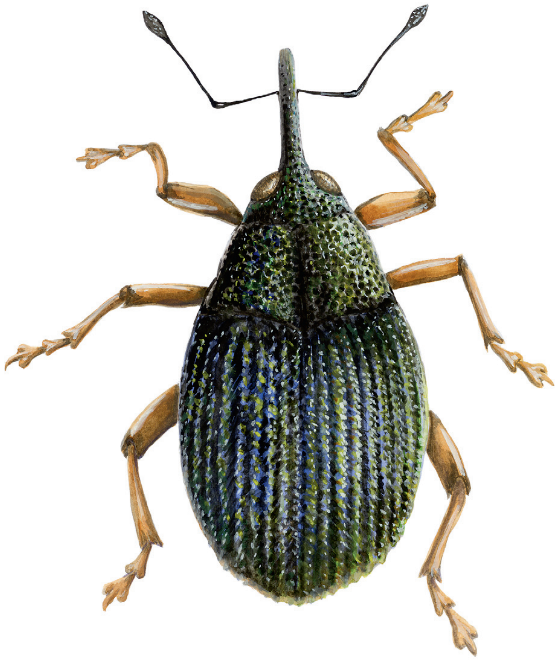

Fig. 12. The weevil *Ceutorhynchus insularis*, a world rarity described in 1971, common on *Cochlearia officinalis* in Surtsey. (The weevil is 2 mm in length). Drawing J.B. Hlídberg.

catch. The fauna seems to be composed of species that have accidentally and randomly drifted in from the nearby margin of the gull colony. Here are found the open surface beetle *Amara quenseli* and the generalist spider *Erigone arctica*, also several dipterans common in the gull colony, like *Dolichopus plumipes*, *Hydrellia griseola*, *Botanophila fugax*, *Delia platura* and *Cynomya mortuorum*. Thus, the bare lava shows a similarity with the nearby margin of the colony (Fig. 5).

Lava with gull colony. Most invertebrate species were found in the gull colony (Fig. 2.) and when compared with the sandy surfaces, the species composition is more diverse (Fig. 5). Soil invertebrates are abundant (Fig. 4) contributing to decomposition of plant remains and formation of organic soil. There are parasitic wasps, both primary and secondary, attacking insect larvae, aphids and spider eggs, and a good number of predators, like the aphid feeding syrphid *Platycheirus manicatus*, the spider *Erigone arctica* and several staphylinid beetles, for instance *Atheta graminicola* and *A. fungi*. Saprophagous dipterans like *Calliphora uralensis*, *Cynomya mortuorum*, *Hydrotaea dentipes*, *Heleomyza borealis* and *Meoneura lamellata* allure decaying bird carcasses.

Invertebrates dependent on this most luxuriously vegetated area of the island (Fig. 9) include the moths *Eana osseana* (Fig 10) and *Xanthorhoe decoloraria*, also anthomyiids and muscids of various species, like *Botanophila fugax*, *B. rubrigena*, *Delia echinata*, *D. radicum* and *Coenosia pumila*. Also commonly swarming around is the fanniid *Fannia glaucescens*, which previously in Iceland was known from a single locality near Reykjavik (unpubl.). The slug *Deroceras laeve* (Fig. 11) is seen in the vegetation after rainfalls, but the snail *Vitrina pellucida* hides under stones.

Active pollinators are present in the gull colony as well as plant eating representatives, both on leaves and roots. The latter include aphids and thrips and a tiny weevil *Ceutorrhynchus insularis* (Fig. 12) which feeds on *Cochlearia officinalis*. It was first found in 1968 on Sudurey, another small island in the Vestmannaeyjar archipelago and described as a new species for science (Dieckmann 1971, Lindroth *et al.* 1973). It was discovered on Surtsey in 2002 when it turned out to be quite numerous on a small spot in the gull colony. Since then it has widened its range and become one of the most common beetles on Surtsey. The validity of *C. insularis* as a species has not been confirmed.

The soils of the gull colony are nutrient rich compared with the sandy surfaces and changes are noted in the vegetation succession as well as in invertebrate communities (Fig. 5; Magnússon *et al.* 2009). A part of the oldest gull colony is approaching the most developed succession stage, comparable with the nearest islands, with dense and luxuriant grassland vegetation dominated by *Festuca richardsonii*. The plots at the margin of the gull colony, plots 10 and 23, were originally on sand-filled and bare lava, respectively, before they were affected by the gull colony and the invertebrate fauna of both plots shows similarities with their origin. Other plots in the gull colony have invertebrate species composition with similarities to both the margins and the most developed stage of the gull colony. The exception is plot 9 that is similar to other plots of the gull colony regarding nutrient and vegetation but has almost twice as many gull nests in its nearest surroundings than other plots of the gull colony (Magnússon *et al.* 2009).

Invertebrates promote bird diversity

Colonization of some of the bird species has certainly been dependent on the developing invertebrate fauna. The first passerine to start breeding on Surtsey was the snow bunting (*Plectrophenax nivalis*), which appeared in 1996. Even if the adults are foremost seed feeding the species is dependent on invertebrates for raising young. In 2002 there were indications of solely insect feeding passerines to be breeding on the island, i.e. the meadow pipit (*Anthus pratensis*) and the white wagtail (*Motacilla alba*); the former has since being a regular breeder on Surtsey (Magnússon & Ólafsson 2003, Jakobsson *et al.* 2007, Petersen 2009). This shows clearly the important role of invertebrates to keep the island's ecosystem functioning and how they accomplish further progresses.

ACKNOWLEDGEMENTS

The Surtsey Research Society has been a firm backstop for this project and previous expeditions from the very beginning, insured on site accommodation and supported the transports. The Icelandic Coast Guard has seen to the transport. The Environment Agency of Iceland has given permits to enter the island to perform the field-work. The Icelandic Institute of Natural History has financed the field-work and processing of material. Colleges and co-operators in the biological research team, guided by Borgthór Magnússon, are thanked, Borgthór also for assisting with the DCA-analysis. Sigurdur K. Gudjohnsen is thanked for preparing the map, Mr. Jón B. Hlídberg for the permit to use his drawing of *Ceutorhynchus insularis*, and Ms. Gudbjörg I. Aradóttir for her contribution during the field-work in 2002. Helene Bracht Jørgensen gets our gratitude for valuable comments on the manuscript.

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Appendix 1. Land-invertebrate species and species equivalent taxa of Enthognatna, Insecta, Arachnida, Gastropoda and Annelida found on Surtsey during surveys 1964–2006. Their evaluated status is given, i.e. permanently settled species, uncertain settlement, not settled, and found dead in drift only.

1	Settled	Uncertain	Not settled	Dead in drift	2	Settled	Uncertain	Not settled	Dead in drift
ARTHROPODA					**Drepanociphidae**				
ENTOGNATHA					*Euceraphis punctipennis* (Zetterstedt, 1828)			x	
COLLEMBOLA					**Aphididae**				
Hypogastruridae					*Acyrtociphon auctum* (Walker, 1849)	x			
Ceratophysella denticulata (Bagnall, 1941)			x		*Brachycaudus helichrysi* (Kaltenbach, 1843)			x	
Ceratophysella succinea Gisin, 1949	x				Aphididae indet. spp.	x			
Hypogastrura assimilis Krausbauer, 1898		x			**Orthezidae**				
Hypogastrura purpurescens (Lubbock, 1867)	x				*Arctorthezia cataphracta* (Shaw, 1794)			x	
Neanuridae					**THYSANOPTERA**				
Anurida granaria (Nicolet, 1847)			x		**Thripidae**				
Friesea mirabilis (Tullberg, 1871)			x		*Apterothrips secticornis* (Trybom, 1896)	x			
Onychiuridae					*Aptinothrips rufus* Haliday, 1836	x			
Mesaphorura krausbaueri Börner, 1901		x			*Thrips vulgatissimus* Haliday, 1836	x			
Mesaphorura macrochaeta Rusek, 1976	x				**NEUROPTERA**				
Protaphorura armata (Tullberg, 1869)		x			**Hemerobiidae**				
Thalassaphorura duplopunctata (Strenzke, 1954)	x				*Wesmaelius nervosus* (Fabricius, 1793)			x	
Isotomidae					**Chrysopidae**				
Archisotoma besselsi (Packard, 1877)	x				*Chrysoperla carnea* (Stephens, 1836)			x	
Desoria violacea (Tullberg, 1876)			x		**TRICHOPTERA**				
Folsomia fimetaria (Linnaeus, 1758)			x		**Limnephilidae**				
Folsomia quadrioculata (Tullberg, 1871)			x		*Limnephilus affinis* Curtis, 1834				x
Halisotoma maritima (Tullberg, 1871)		x			*Limnephilus elegans* Curtis, 1834			x	
Isotoma anglicana Lubbock, 1873	x				*Limnephilus fenestratus* (Zetterstedt, 1840)			x	
Isotomiella minor (Schaeffer, 1896)	x				*Limnephilus griseus* (Linnaeus, 1758)			x	
Parisotoma notabilis (Schaeffer, 1896)	x				**LEPIDOPTERA**				
Proisotoma minuta (Tullberg, 1871)			x		**Tineidae**				
Pseudisotoma sensibilis (Tullberg, 1876)	x				*Monopis laevigella* (Denis & Schiffermüller, 1775)			x	
Vertagopus arboreus (Linnaeus, 1758)			x		**Plutellidae**				
Neelidae					*Plutella xylostella* (Linnaeus, 1758)			x	
Megalothorax minimus (Willem, 1900)		x			*Rhigognostis senilella* (Zetterstedt, 1839)	x			
PROTURA					**Gelechiidae**				
Protentomidae					*Bryotropha similis* (Stainton, 1854)				x
Protentomon thienemanni Strenzke, 1942			x		**Tortricidae**				
INSECTA					*Eana osseana* (Scopoli, 1763)	x			
MALLOPHAGA					**Pyralidae**				
Menoponidae					*Matilella fusca* (Haworth, 1811)		x		
Eidmanniella pustulosa (Nitzsch, 1866)			x		**Crambidae**				
HEMIPTERA					*Crambus pascuella* (Linnaeus, 1758)			x	
Saldidae					*Nomophila noctuella* (Denis & Schiffermüller, 1775)			x	
Salda littoralis (Linnaeus, 1758)	x				**Nymphalidae**				
Corixidae					*Aglais cardui* (Linnaeus, 1758)			x	
Arctocorisa carinata (Sahlberg, 1819)				x	*Vanessa atalanta* (Linnaeus, 1758)			x	
Miridae					**Geometridae**				
Teratocoris saundersi Douglas & Scott, 1869	x				*Epirrhoe alternata* (Müller, 1764)			x	
Cicadellidae					*Xanthorhoe decoloraria* (Esper, 1806)	x			
Macroseles laevis (Ribaut, 1927)	x				*Xanthorhoe designata* (Hufnagel, 1767)			x	
Delphacidae					**Noctuidae**				
Javesella pellucida (Fabricius, 1794)	x				*Agrotis ipsilon* (Hufnagel, 1766)			x	

Appendix 1, continued.

3	Settled	Uncertain	Not settled	Dead in drift
Autographa gamma (Linnaeus, 1758)			x	
Cerapteryx graminis (Linnaeus, 1758)		x		
Chortodes stigmatica (Eversmann, 1855)	x			
Diarsia mendica (Fabricius, 1775)	x			
Euxoa ochrogaster (Guenée, 1852)		x		
Noctua pronuba (Linnaeus, 1758)			x	
Peridroma saucia (Hübner, 1808)			x	
Phlogophora meticulosa (Linnaeus, 1758)			x	
COLEOPTERA				
Carabidae				
Amara quenseli (Schönherr, 1806)	x			
Bembidion bipunctatum (Linnaeus, 1761)				x
Nebria rufescens (Ström, 1768)				x
Notiophilus biguttatus (Fabricius, 1779)	x			
Patrobus septentrionis (Dejean, 1828)				x
Trichocellus cognatus (Gyllenhal, 1827)	x			
Dytiscidae				
Agabus bipustulatus (Linnaeus, 1767)				x
Staphylinidae				
Amischa analis (Gravenhorst, 1802)	x			
Atheta amicula (Stephens, 1832)	x			
Atheta atramentaria (Gyllenhal, 1810)			x	
Atheta excellens (Kraatz, 1856)	x			
Atheta fungi (Gravenhorst, 1806)	x			
Atheta graminicola (Gravenhorst 1806)	x			
Atheta vestita (Gravenhorst 1806)		x		
Omalium excavatum Stephens 1834	x			
Omalium rivulare (Paykull, 1789)		x		
Oxypoda haemorrhoa Mannerheim, 1830	x			
Oxypoda islandica Kraatz, 1857		x		
Parocyusa rubicunda (Erichson, 1837)		x		
Lathridiidae				
Lathridius minutus (Linnaeus, 1767)			x	
Coccinellidae				
Coccinella undecimpunctata Linnaeus, 1758				x
Curculionidae				
Barynotus squamosus *Germar, 1824*				x
Ceutorhynchus insularis Dieckmann, 1971	x			
Otiorhynchus arcticus (O. Fabricius, 1780)	x			
HYMENOPTERA				
Ichneumonidae				
Aclastus gracilis (Thomson, 1884)	x			
Atractodes ambiguus Ruthe, 1859	x			
Atractodes bicolor Gravenhorst, 1829			x	
Campoletis sp.			x	
Cratichneumon rufifrons (Gravenhorts, 1829)			x	
Ctenopelmatinae indet.			x	
Diadegma boreale Horstmann, 1980		x		
Enizemum ornatum (Gravenhorst, 1829)			x	
Homotherus locutor (Thunberg, 1822)			x	

4	Settled	Uncertain	Not settled	Dead in drift
Homotherus magus (Wesmael, 1855)			x	
Nepiera collector (Thunberg, 1822)		x		
Ophion nigricans (Ruthe, 1859)				x
Phygadeuontinae indet.			x	
Pimpla arctica Zetterstedt, 1838			x	
Pimpla flavicoxis Thompson, 1877			x	
Pimpla sodalis Ruthe, 1859			x	
Plectiscidea collaris (Gravenhorst, 1829)			x	
Plectiscidea peregrinus (Ruthe, 1859)			x	
Polytribax picticornis (Ruthe, 1859)			x	
Saotis sp.?			x	
Stilpnus tenebricosus (Gravenhorst, 1829)	x			
Sussaba pulchella (Holmgren, 1858)			x	
Braconidae				
Alysia manducator (Panzer, 1799)		x		
Alysiinae indet.			x	
Aphidiinae indet. spp.	x			
Chorebus cf. cytherea (Nixon, 1837)			x	
Chorebus sp(p).	x			
Dacnusa sp(p).		x		
Meteorus rubens (Nees, 1811)			x	
Monoctonus caricis (Haliday, 1833)	x			
Fitigidae				
Alloxysta sp(p).	x			
Trybliographa sp(p).	x			
Pteromalidae				
Cyrtogaster vulgaris Walker, 1833		x		
Trichomalopsis fucicola (Walker, 1835)			x	
Pteromalidae indet. spp.	x			
Eulopiidae				
Chrysocharis pallipes (Nees, 1834)	x			
Diapriidae				
Pantoclis trisulcata Kieffer, 1907			x	
Polypeza ciliata (Thomson, 1859)		x		
Psilius frontalis (Thompson, 1859)			x	
Scelionidae				
Trimorus sp.	x			
Platygastridae				
Platygaster splendidula Ruthe, 1859			x	
Megaspilidae				
Dendrocerus bifoveatus (Kieffer, 1907)	x			
DIPTERA				
Tipulidae				
Prionocera turcica (Fabricius, 1787)			x	
Tipula confusa van der Wulp, 1883			x	
Tipula rufina Meigen, 1818			x	
Limoniidae				
Dicranomyia autumnalis (Staeger, 1840)			x	
Symplecta hybrida (Meigen, 1804)			x	
Anisopodidae				

Appendix 1, continued.

5	Settled	Uncertain	Not settled	Dead in drift
Sylvicola fenestralis (Scopoli, 1763)			x	
Trichoceridae				
Trichocera maculipennis Meigen, 1818			x	
Bibionidae				
Bibio nigriventris Haliday, 1833			x	
Dilophus femoratus Meigen, 1804			x	
Cecidomyiidae				
Cecidomyiidae indet. spp.	x			
Scatopsidae				
Scatopse notata (Linnaeus, 1758)			x	
Sciaridae				
Bradysia cf. *nitidicollis* (Meigen, 1818)			x	
Lycoriella conspicua (Winnertz, 1867)			x	
Lycoriella sp.			x	
Sciaridae indet. spp.	x			
Mycetophilidae				
Allodiopsis domestica (Meigen, 1830)		x		
Brevicornu griseicolle (Staeger, 1840)		x		
Brevicornu sp. (female)				
Exechia borealis Lundström, 1912			x	
Exechia frigida (Boheman, 1865)			x	
Exechia micans Lastovka & Matile, 1974			x	
Exechia nigra (Edwards, 1925)			x	
Exechia pectinivalva Stackelberg, 1948			x	
Leia fascipennis Meigen, 1818			x	
Keroplatidae				
Macrocera parva			x	
Chironomidae				
Chironomus spp.			x	
Cricotopus sp.			x	
Diamesa aberrata Lundbeck, 1898			x	
Diamesa bertrami Edwards, 1935			x	
Diamesa bohemani Goetghebuer, 1932			x	
Diamesa incallida (Walker, 1856)			x	
Diamesa zernii Edwards, 1933			x	
Eukiefferiella minor (Edwards, 1929)			x	
Halocladius variabilis (Staeger, 1839)	x			
Metriocnemus eurynotus (Holmgren, 1883)			x	
Micropsectra atrofasciata Kieffer, 1911			x	
Micropsectra lindrothi Goetghebuer in Lindroth, 1931			x	
Oliverida tricornis (Oliver, 1976)			x	
Paracladopelma laminata (Kieffer, 1921)			x	
Procladius islandicus (Goetghebuer in Lindroth, 1931)			x	
Psectrocladius limbatellus (Holmgren, 1869)			x	
Smitthia sp.	x			
Tanytarsus gracilentus (Holmgren, 1883)			x	
Telmatogeton japonicus Tokunaga, 1933	x			
Ceratopogonidae				
Ceratopogonidae indet. sp.			x	
Simuliidae				

6	Settled	Uncertain	Not settled	Dead in drift
Simulium aureum (Fries, 1824)			x	
Simulium vittatum Zetterstedt, 1838			x	
Empididae				
Clinocera stagnalis (Haliday, 1833)			x	
Rhamphomyia simplex Zetterstedt, 1849			x	
Dolichopodidae				
Dolichopus plumipes (Scopoli, 1763)	x			
Hydrophorus viridis (Meigen, 1824)			x	
Syntormon pallipes (Fabricius, 1794)			x	
Lonchopteridae				
Lonchoptera bifurcata (Fallén, 1810)	x			
Syrphidae				
Eupeodes corollae (Fabricius, 1794)			x	
Eupeodes lundbecki (Soot-Ryen, 1946)			x	
Eupeodes punctifer (Frey, 1934)			x	
Helophilus pendulus (Linnaeus, 1758)			x	
Melangyna lasiophthalma (Zetterstedt, 1843)			x	
Melanostoma mellinum (Linnaeus, 1758)	x			
Parasyrphus tarsatus (Zetterstedt, 1838)			x	
Platycheirus albimanus (Fabricius, 1781)		x		
Platycheirus clypeatus (Meigen, 1822)			x	
Platycheirus granditarsus (Förster, 1771)			x	
Platycheirus manicatus (Meigen, 1822)	x			
Platycheirus peltatus (Meigen, 1822)			x	
Sphaerophoria scripta (Linnaeus, 1758)			x	
Syrphus ribesii (Linnaeus, 1758)			x	
Syrphus torvus Osten-Sacken, 1875			x	
Phoridae				
Megaselia giraudii (Egger, 1862)			x	
Megaselia pumila (Meigen, 1830)			x	
Megaselia sordida (Zetterstedt, 1838)	x			
Piophilidae				
Parapiophila vulgaris Fallén, 1820	x			
Agromyzidae				
Phytomyza farfarella (Hendel, 1935)	x			
Sciomyzidae				
Dictya umbrarum (Linnaeus, 1758)			x	
Pherbellia ventralis (Fallén, 1820)			x	
Tetanocera robusta Loew, 1847			x	
Helcomyzidae				
Heterocheila buccata (Fallén, 1820)			x	
Sepsidae				
Themira arctica (Becker, 1915)	x			
Themira pusilla (Zetterstedt, 1847)		x		
Coelopidae				
Coelopa frigida (Fabricius, 1805)			x	
Anthomyzidae				
Anthomyza socculata (Zetterstedt, 1847)	x			
Chamaemyiidae				
Chamaemyia geniculata (Zetterstedt, 1838)			x	

Appendix 1, continued.

7	Settled	Uncertain	Not settled	Dead in drift	8	Settled	Uncertain	Not settled	Dead in drift
Carniidae					*Fucellia maritima* (Haliday, 1838)			x	
Meoneura lamellata Collin, 1930	x				*Lasiomma picipes* (Meigen, 1826)	x			
Heleomyzidae					*Pegomya bicolor* (Wiedemann, 1817)			x	
Heleomyza borealis (Boheman, 1866)	x				*Pegoplata infirma* (Meigen, 1826)	x			
Heleomyza serrata (Linnaeus, 1758)			x		*Zaphne brunneifrons* (Zetterstedt, 1838)			x	
Neoleria prominens (Becker, 1897)	x				*Zaphne divisa* (Meigen, 1826)			x	
Tephrochlaena oraria Collin, 1943			x		*Zaphne frontata* (Zetterstedt, 1838)			x	
Drosophilidae					**Muscidae**				
Drosophila funebris (Fabricius, 1787)			x		*Coenosia pumila* (Fallén, 1825)	x			
Scaptomyza graminum (Fallén, 1823)	x				*Graphomya maculata* (Scopoli, 1763)			x	
Scaptomyza pallida (Zetterstedt, 1847)	x				*Helina annosa* (Zetterstedt, 1838)			x	
Sphaeroceridae					*Hydrotaea armipes* (Fallén, 1825)		x		
Copromyza equina Fallén, 1820			x		*Hydrotaea dentipes* (Fabricius, 1805)	x			
Copromyza nigrina (Gimmerthal, 1847)		x			*Limnophora pandellei* Séguy, 1923			x	
Crumomyia nigra (Meigen, 1830)			x		*Limnophora sinuata* Collin, 1930			x	
Ischiolepta pusilla (Fallén, 1820)			x		*Musca domestica* Linnaeus, 1758			x	
Minilimosina fungicola (Haliday, 1836)	x				*Mydaea palpalis* Stein, 1916			x	
Minilimosina vitripennis (Zetterstedt, 1847)			x		*Myospila meditabunda* (Fabricius, 1781)	x			
Phthitia empirica (Hutton, 1901)			x		*Spilogona baltica* (Ringdahl, 1918)	x			
Rachispoda lutosa (Stenhammar, 1855)			x		*Spilogona contractifrons* (Zetterstedt, 1838)			x	
Spelobia clunipes (Meigen, 1830)			x		*Spilogona micans* (Ringdahl, 1918)			x	
Spelobia luteilabris (Rondani, 1880)			x		*Spilogona pacifica* (Meigen, 1826)	x			
Spelobia pseudosetaria (Duda, 1918)			x		*Thricops rostratus* (Meade, 1882)	x			
Spelobia rufilabris (Stenhammar, 1855)		x			*Trichops cunctans* (Meigen, 1826)			x	
Thoracochaeta zosterae (Haliday, 1833)			x		**Fanniidae**				
Ephydridae					*Fannia canicularis* (Linnaeus, 1761)	x			
Gymnoclasiopa bohemanni (Becker, 1896)			x		*Fannia lucidula* (Zetterstedt, 1860)	x			
Hydrellia griseola (Fallén, 1813)	x				**Calliphoridae**				
Parydra pusilla (Meigen, 1830)			x		*Calliphora uralensis* Villeneuve, 1922	x			
Philygria vittipennis (Zetterstedt, 1838)	x				*Calliphora vicina* Robineau-Desvoidy, 1830			x	
Scatella stagnalis (Fallén, 1813)			x		*Cynomya mortuorum* (Linnaeus, 1761)	x			
Scatella tenuicosta Collin, 1930			x		*Protophormia terraenovae* (Robineau-Desvoidy, 1830)			x	
Scathophagidae					**Hippoboscidae**				
Chaetosa punctipes (Meigen, 1826)			x		*Ornithomya avicularia* (Linnaeus, 1758)			x	
Scathophaga calida Haliday in Curtis, 1832			x		*Ornithomya chloropus* Bergroth, 1901			x	
Scathophaga furcata (Say, 1823)	x				**SIPHONATERA**				
Scathophaga litorea Fallén, 1819	x				**Ceratophyllidae**				
Scathophaga stercoraria (Linnaeus, 1758)	x				*Dasypsyllus gallinulae* (Dale, 1878)			x	
Anthomyiidae					**ARACHNIDA**				
Botanophila betarum (Lintner, 1883)		x			**ARANEAE**				
Botanophila fugax (Meigen, 1826)	x				**Lycosidae**				
Botanophila profuga (Stein, 1816)			x		*Pardosa palustris* (Linnaeus, 1758)			x	
Botanophila rubrigena (Schnabl, 1915)	x				**Linyphiidae**				
Delia angustifrons (Meigen, 1826)	x				*Allomengea scopigera* (Grube, 1859)	x			
Delia echinata (Séguy, 1923)	x				*Erigone arctica* (White, 1852)	x			
Delia fabricii (Holmgren, 1872)	x				*Erigone atra* Blackwall, 1833			x	
Delia platura (Meigen, 1826)	x				*Erigone tirolensis* L.Koch, 1872			x	
Delia radicum (Linnaeus, 1758)	x				*Improphantes complicatus* (Emerton, 1882)		x		
Delia setigera (Stein, 1920)	x				*Islandiana princeps* Brændegaard, 1932	x			
Fucellia fucorum (Fallén, 1819)			x		*Leptothrix hardyi* (Blackwall, 1850)			x	

Appendix 1, continued.

9	Settled	Uncertain	Not settled	Dead in drift
Meioneta nigripes (Simon, 1884)	x			
Savignya frontata (Blackwall, 1833)	x			
Tenuiphantes mengei Kulczynski, 1887			x	
Tenuiphantes zimmermanni Bertkau, 1890		x		
Walckenaeria clavicornis (Emerton, 1882)	x			
Walckenaeria nudipalpis (Westring, 1851)	x			
ACARI				
Gammasina				
Arctoseius cetratus (Sellnick, 1940)	x			
Dendrolaelaps oudemansi Halbert, 1915			x	
Eugamasus kraepelina (nomen dubium)	x			
Eviphis ostrinus (C.L. Koch, 1836)	x			
Haemogamasus nidi Michael, 1892			x	
Halolaelaps sp.	x			
Halolaelaps suecicus Sellnick, 1957			x	
Macrocheles matrius Hull, 1925			x	
Parasitus halophilus (Selnick, 1957)	x			
Rhodacarus roseus Oudemans, 1902			x	
Thinoseius spinosus Willmann, 1930		x		
Zercon triangularis C.L. Koch, 1836	x			
Ixodida				
Ceratixodes uriae (White, 1852)			x	
Ixodes ricinus (Linnaeus, 1758)			x	
Actinedida				
Anystis sp.	x			
Bakerdalia sp.	x			
Bdella sp.	x			
Cocceupodes clavifrons (Canestrini, 1886)			x	
Ereynetes agilis (Berlese, 1923)			x	
Nanorchestes arboriger (Berlese, 1904)	x			
Neomolgus littoralis (Linnaeus)	x			
Pedeculaster mesembrinae (Canestrini, 1881)			x	
Penthalodes ovalis (Dugès, 1834)	x			
Petrobia apicalis (Banks, 1917)	x			
Rhagidia mordax Oudemans, 1906	x			
Rhagidia sp.			x	
Tarsonemus fusarii Cooreman, 1941	x			
Acaridida				
Caloglyphus regleri (E. Türk & F. Türk, 1957)			x	
Histiostoma feroniarum (Dufour, 1839)	x			
Histiostoma (*hypopus*) - same as above?	x			
Myianoetus digiferus			x	

10	Settled	Uncertain	Not settled	Dead in drift
Myianoetus vesparum			x	
Schwiebia cavernicola Vitzthum, 1932	x			
Tyrophagus dimidiatus (Hermann, 1804)			x	
Tyrophagus similis Volgin, 1948	x			
Oribatida				
Achipteria coleoptrata (Linnaeus, 1758)	x			
Ameronothrus lineatus (Thorell, 1871)	x			
Ameronothrus nigrofemoratus (C.L. Koch, 1879)	x			
Autogneta longilamellata (Michael, 1885)	x			
Chamobates cuspidatus (Michael, 1884)	x			
Eniochthonius minutissimus (Berlese, 1903)	x			
Hermannia sp.	x			
Hypochthonius rufulus C.L. Koch, 1836	x			
Lauroppia falcata (Paoli, 1908)			x	
Liochthonius lapponicus (Trägardh, 1910)	x			
Liochthonius muscorum Forsslund, 1964	x			
Liochthonius propinquus Niedbala, 1972	x			
Medioppia subpectinata (Oudemans, 1900)	x			
Ophidiotrichus connexus (Berlese, 1904)	x			
Oppiella nova (Oudemans, 1902)	x			
Oppiella splendens (C.L. Koch, 1841)	x			
Oribotritia faeroensis (Sellnick, 1923)			x	
Quadroppia quadricarinata (Michael, 1885)	x			
Quadroppia sp.	x			
Suctobelbella acutidens (Forsslund, 1941)	x			
Suctobelbella sarekensis (Forsslund, 1941)	x			
Suctobelbella subcornigera (Forsslund, 1941)	x			
Tectocepheus velatus (Michael, 1880)	x			
Zygoribatula exilis (Nicolet, 1855)	x			
ANNELIDA				
OLIGOCHAETA				
Lumbricidae				
Lumbricus castaneus (Savigny, 1826)		x		
Enchytraeidae				
Enchytraeidae indet. spp.	x			
MOLLUSCA				
GASTROPODA				
Agriolimacidae				
Deroceras agreste (Linnaeus, 1758)	x			
Vitrinidae				
Vitrina pellucida (O.F. Müller, 1774)	x			

Chortodes stigmatica (Eversmann, 1855) (Lepidoptera, Noctuidae) – a moth new to Surtsey, 1995

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ABSTRACT
In the dusk the of July 19, 1995 two specimens of the rare moth *Chortodes stigmatica* (Eversmann, 1855) were collected above an old stand of *Leymus arenarius* on the eastern part of Surtsey. At least 19 other similarly looking moth specimens were seen at the same time and place. They were considered to be of the same species suggesting that this rare moth was one of the first Lepidoptera species to establish a resident population on Surtsey.

INTRODUCTION

Since the eruption of Surtsey in 1963–1967 a total of about 19 moth species and 2 butterfly species have been observed in the island (Lindroth et al. 1966, 1967, 1972, 1973, Ólafsson 1978, 1982). The more common species of Lepidoptera found on Surtsey are well-known migratory species, but others may have spread from other eruptive islands or the mainland of Iceland (Lindroth, 1973), where 89 naturally existing wild species of Lepidoptera have been found (Ólafsson, pers. comm.). On a visit to Surtsey during July 17–20, 1995, I decided to investigate if the rare moth *Chortodes stigmatica* (Eversmann, 1855) could be found on the island since *Leymus arenarius* one of the probable food plants for the species, had established on the island.

Synonyms: Leucania stigmatica Eversmann, 1855, Hypocoena dispersa (Wolff, 1970), Photedes stigmatica ssp. dispersa in Wolff, 1971, Chortodes stigmatica (in Nowacki & Fibiger, 1996).

FIELD SAMPLING

During an entomological investigation of the Faroe Islands in 1991 Dr. Svend Kaaber and I recognized, that the little known moth species *Chortodes stigmatica* could be found in numbers in and above the dense *Ammophila arenaria* and *Elymus (=Leymus) arenarius* vegetation during late nights on the island of Sandoy (S. Kaaber unpublished). I therefore decided to study if it was possible also to find *Chortodes stigmatica* on Surtsey as old and

Fig 1. *Leymus arenarius* vegetation on eastern part of Surtsey where *Chortodes stigmatica* was found, July 19, 1995. Other small volcanic islands north of Surtsey in the background.

Fig 2. Chortodes stigmatica dark morph from Surtsey, forewings normally cover most of the animal at rest.

younger stands of *Leymus* had established on the island.

On a calm evening of July 19, 1995 I visited some of the dense and oldest *Leymus* vegetation located about 250 m NE of the research hut on eastern part of Surtsey. The *Leymus* was about 80 cm high and surrounded by *Honckenya peploides* (Fig. 1). Almost lying on the ground very close to the *Leymus*-vegetation I could see the grass vegetation as a silhouette on the light northerly sky and waited, hoping that some moth would come up from the base of the *Leymus* vegetation or just pass the site by accident. In my hand I had a butterfly net. In the dusk a moth suddenly was seen flying very fast around the *Leymus* vegetation. I tried to catch it, but without success. Soon other moths were seen, and some of them even coming up from the base of the *Leymus* vegetation. During the following hour I saw in all at least 21 dark similarly looking moths circling around the *Leymus* vegetation, and incidentally I succeeded in catching two of them (Fig. 2). In the field it was not possible to identify them. When I left Surtsey to Reykjavik the next day, I went to some of the impressive stands of *Leymus* vegetation in the sand dunes close to Vik, South Iceland, to see if it was possible to find some dark moth specimens, but without success. Back in Denmark it soon was recognized that both of the moth specimens from Surtsey actually belonged to the rare species *Chortodes stigmatica*, a very dark form.

DISCUSSION

Chortodes stigmatica was for the first time found in the North Atlantic area, in Medalland Skardsmyri, Iceland, in 1929 by C. H. Lindroth (Eliasson, 1992) and later in northern Iceland (Kopasker) by A. Nørrevang in 1937, as a dark morph (Wolff, 1971). Later the species was found in hundreds of specimens at Skeidarársandur, SE Iceland (Ólafsson & Björnsson, 1976), and then in other places along the southern coast line of Iceland (Eliasson, 1992).

In the Faroes the first observation of *Chortodes stigmatica* was a male found in a pit-fall trap in the island of Sandoy, 1978 (Bengtson, 1982). The species was rediscovered in the same area in the years 1991 to 1997 (Kaaber 1997).

However, the specimens from Surtsey were not the well known light form from the Faroes. It was on the other hand a dark-brown morph of nearly the same colour as the dark tephra volcanic material in which the *Leymus* grows on Surtsey (Fig.1). In Iceland both light and dark specimens have been found, and the rather dark specimen from Kopasker, 1937, was described as a new subspecies *dispersa* by Wolff (1970, 1971). The dark morph *dispersa* seems to be common in Iceland. The sand dunes in southern Iceland are all made of almost black sand, and dark specimens of *Chortodes stigmatica* seem to be well adapted to hide in the dark sand dunes as well as in the dark tephra material in Surtsey and thus avoid bird predators. The moths at the southern coastline could be found on the roots of *Leymus* vegetation (Eliasson, 1992). In Iceland *Chortodes stigmatica* is characteristic by having light wing venation on the forewings.

Apart from Iceland and the Faroes *Chortodes stigmatica* is known from easterly Siberia, Mongolia, Baikal, Amur and Ural. It is unknown how the species may have arrived to the north Atlantic islands, but following Eliasson (1992) the species may have arrived from Siberia by ice-rafting just after the last Ice-age. Eliasson also discusses the possibility that populations of *Chortodes stigmatica* may be found in *Leymus*-stands in Finnmark, Norway, but this has not been verified.

The biology of the species seems not to have been clarified, but the observations of numbers of specimens in or above *Ammophila arenaria* and *Leymus* vegetation in Sandoy, the Faroe Islands, indicate that the species is closely associated with *Ammophila* (not found in Iceland) or *Leymus* vegetation, as it is the case on Surtsey. It is also striking that tufts of *Leymus* were found at or very near most of the localities, where *Chortodes stigmatica* have been found in Iceland. As larvae most European species of the genus Chortodes live endophagous in the stems of their host grasses. However, one species, *Chortodes brevilinea* (Fenn) lives in its last larval instar freely on the leaves of its host plant, the Reed (*Phragmites communis*) (South, 1948).

Thus *Chortodes stigmatica* seems to be one of the first moth species having established a resident population on Surtsey. It may even have been there for several years since *Leymus arenarius* was among the first plant species to colonize Surtsey in 1966 (Fridriksson, 1967, 2000).

The only other moth species found on Surtsey besides *Chortodes stigmatica* was a single specimen of *Plutella xylostella* observed at the crater Surtur on July 17, 1995.

In July 2005 a biological expedition on Surtsey rediscovered *Chortodes stigmatica*. A single moth was caught flying near a *Leymus* dune in the tephra covered lava in the easternmost part of the island (Ólafsson, pers. comm.).

ACKNOWLEDGEMENTS

Dr. Svend Kaaber is thanked for identifying the dark form of the species *Chortodes stigmatica* and for comments to the text. I am also very grateful to the Surtsey Research Society, Iceland, which made it possible for me to visit Surtsey in 1995, to the Icelandic Coast Guard handling the helicopter, and to the Carlsberg Foundation, Copenhagen, supporting the journey financially.

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Formation of a bird community on a new island, Surtsey, Iceland

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ABSTRACT

The present paper summarizes bird observations from Surtsey, Iceland since the formation of the island in 1963 until 2008. Continuous observations were maintained in the early years of the island; in spring and autumn 1967–1971 and summers 1970–1973. Since then much of the bird observations are incidental by various scientists and bird watchers visiting the island for a limited period.

Different aspects of the bird fauna are examined, the at-sea bird community, vagrants, migrant species, and winter birds, while emphasis is placed on the formation of the breeding bird community. With increasing numbers of breeding species and size of breeding populations as the years passed more structured census of the breeders was needed. Hence whole island censuses were organized in 1990 and 2003. Ringing has been carried out on five occasions. In total 91 bird species have been recorded on or offshore from the island.

The first birds started breeding in 1970, Black Guillemot *Cepphus grylle* and Fulmar *Fulmarus glacialis*. A total of fourteen species have since bred on the island. Four species of large gulls breed (mostly in one colony); Great Black-backed Gull *Larus marinus* (bred first in 1974), Herring Gull *Larus argentatus* (1981), Lesser Black-backed Gull *Larus fuscus* (~1985), and Glaucous Gull *Larus hyperboreus* (1993). The colony, starting to form in 1984, has been particularly important for furthering the development of plant and invertebrate communities. Through the fertilizing agency complete vegetation cover is now found in the oldest part of the gull colony. This development has paved the way for terrestrial birds to start breeding; Snow Bunting *Plectrophenax nivalis* (1996), Greylag Goose *Anser anser* (~2001) and Meadow Pipit *Anthus pratensis* (~2003). Other breeding species are Kittiwake *Rissa tridactyla* (1975) and White Wagtail *Motacilla alba* (~2003), but Arctic Tern *Sterna paradisaea* (1975) has not bred since 1978. In 1990 the island had 316 breeding pairs of six species. In 2003 eleven species bred on the island with a total of about 850 breeding pairs. After 2003 two more species have started breeding, Common Puffin *Fratercula arctica* (2004) and Raven *Corvus corax* (2008).

Surtsey Island was entered on the UNESCO World Heritage list in 2008, not the least for the long history of research and monitoring of various aspects of the island's natural history. As the breeding bird fauna develops a structured bird monitoring program becomes the more important. Recommendations on how this should be carried out are presented in the paper.

INTRODUCTION

Surtsey Island had just risen above the ocean surface when the first birds made their landfall. On 1st December 1963 only two weeks after the eruption began gulls were seen touching down on the island in between eruption bursts (Fridriksson 1964, Gudmundsson 1966). A number of bird species have since been recorded on or near the island. Some are on feeding trips from breeding colonies on neighbouring islands in the Westman

Islands group. Others are transient migrants *en route* between breeding areas elsewhere in Iceland or the Arctic and wintering areas in Europe or Africa. Some are immature birds or non-breeders on feeding excursions from other parts of Iceland. Still others are incidental vagrants from either side of the North Atlantic. Some of these species have successively colonized the island and now form the developing breeding bird community.

Gudmundsson (1966) predicted that birds would quickly start breeding on the new island. Proven right he further noted birds would be of considerable ecological importance. Over the years an increasing number of species has colonized Surtsey, contributing increasingly to the young developing ecosystem. Some of the species, gulls in particular, have demonstrated their importance to the ecosystem development, by contributing nutrients to plant and invertebrate communities (Magnússon & Magnússon 2000, Magnússon & Ólafsson 2003).

Through the years bird studies on Surtsey have concentrated on six aspects; (1) recording the bird species seen, (2) observing migration, (3) collecting scientific specimens to augment various research, (4) studying the role of birds in the development of plant and invertebrate communities, (5) registering the breeding species, numbers and distribution, and (6) bird ringing. In the beginning significant importance was attached to birds carrying seeds of pioneering plants to the island, reported in many publications. A detailed overview of the development of the Surtsey bird community has however not been reported in recent years, or since the breeding birds became more than just a few pairs. Censuses were carried out of the entire breeding bird fauna in 1990 and 2003. A structured monitoring program is becoming more and more needed as the bird fauna develops, with increasing numbers of species and breeding pairs. The purpose of the present study is among others to suggest the structure of such a program.

In 2008 Surtsey was entered on the UNESCO World Heritage list (Baldursson & Ingadóttir (eds) 2007). One of the main arguments for its acceptance was the history of various research and monitoring since the island was formed. The nomination makes further demands on keeping the island as free of human influences as possible, while continuing to collect scientific information on the natural environment. The present paper brings together the information that has been collected on birds since the creation of Surtsey. Emphasis is placed on the breeding bird fauna. For general texts on Surtsey, including the bird life, see e.g., Fridriksson (1968, 1975, 1989, 1994), Petersen (1993, 2004), Magnússon & Ólafsson (2003), and Baldursson & Ingadóttir (eds) (2007).

MATERIALS AND METHODS

Materials

Regular bird observations were maintained on Surtsey from 1966 to 1971 during spring and autumn. Observations were primarily directed at staging migrants, recording vagrant species, looking for indications of breeding, and collecting specimens for the scientific collection of the Icelandic Museum of Natural History (now the Icelandic Institute of Natural History). During 1970–1973 wardens were also stationed on the island during the summer months and one of the aims was to record any breeding attempts. Frequent coverage was made of the island and all birds observed on land carefully recorded. Unfortunately regular sustained bird observations could not be maintained after the very early years of the island.

Ever since people first stepped on the island it has been visited annually by scientists, biologists and other natural history scientists alike, as well as students and amateur bird-observers for various studies. These visitors have provided irregular records of new or other bird species, and partial counts of breeders. Together these records document reasonably well new breeding species and to some extent the development of the breeding bird community. These materials were compiled and form part the datasets available here. Much of the bird observations are found in diaries of previous wardens and other visitors, unpublished reports, newspaper reports from expeditions, websites, emails, and records in the log book at the Pálsbaer research hut. This unpublished material is too much for individual inclusion in the bibliography and not referred to in the text.

Some population estimates are available at irregular intervals through the years but more concentrated and systematic efforts were clearly necessary as the breeding populations increased and complete coverage became more challenging and time-consuming. Therefore, in 1990 the island was visited on 5–7 June to map the distribution of the breeding birds and census their numbers. To follow the changes an entire island census was repeated on 27–30 June 2003. It is important to monitor and map all the breeding populations carefully at regular intervals. Besides its own value such observations will assist scientists, who examine the importance of birds in the formation of vegetation and invertebrate communities on Surtsey, and helps to fulfil the requirements placed upon Icelandic authorities by the UNESCO listing.

Census methods in 1990 and 2003

Different methods have to be employed to estimate breeding population size of the various bird species. The passerine species, Snow Bunting *Plec-*

Table 1. Counts and calculations of correction factors in the Surtsey gull colony on 29 June 2003.

	Pairs	Single adults	Correction factors	
			Birds	Pairs
Great Black-backed Gull	48	38	1.28	0.64
Lesser Black-backed Gull	117	58	1.20	0.60
Herring Gull	29	8	1.12	0.56

trophenax nivalis, Meadow Pipit *Anthus pratensis*, and White Wagtail *Motacilla alba*, were mapped using „the territory" as the census unit, mostly based on locating singing males and nests. Repeated visits were needed to separate territory holders and obtain an idea of the rough size of the territories. Kittiwakes *Rissa tridactyla* and Fulmars *Fulmarus glacialis* were counted using the „Apparently Occupied Nest-site", as the counting unit (cf. Nettleship 1976). Kittiwakes are confined to the sea-cliffs and the counting unit was a nest considered able to hold eggs or young. Fulmars do not build nests, hence sitting birds that looked like incubating or brooding a chick, was the counting unit. The numbers of gulls, which nest on level ground mostly in one large colony, were counted with a telescope at a distance from the higher grounds at the middle of the island (the Surtur crater). Black Guillemots *Cepphus grylle* were counted on the water, in the early evening period when the largest numbers of birds are present at colonies (cf. Petersen 1981). Greylag Geese *Anser anser* had already hatched their young at the time of fieldwork. Therefore the number of families i.e. pairs with young, were used to estimate the number of breeding pairs.

Certain problems are encountered on Surtsey when estimating the populations of various species, resulting in different accuracies to the estimates. Fulmars and Kittiwakes breed dispersed on the sea-cliffs, and in some situations their nests cannot easily be viewed from land. For Kittiwakes this related primarily to the highest cliffs on the west side (Vesturbúnki), and also to some extent to Fulmars. There the cliff is made of tuff, the cliff surface smooth but does not offer the same possibilities for the birds to nest compared to the lava cliffs so nests are few and dispersed. The sea-cliffs from Vesturbúnki in the southwest, around the southern parts towards the cliffs and southeast from the research hut, cannot be fully viewed from land but offers much greater possibilities for birds to breed. These cliff areas were scanned from a helicopter and a rough estimate made of the birds not seen during land censuses. Some Fulmars nest on level ground on the lava fields inland. They are sometimes difficult to spot due to roughness of the terrain, such as one bird which was found nesting in a closed lava trench in 2003.

Correction factors for gull counts

The large gulls – Great Black-backed Gull *L. marinus*, Lesser Black-backed Gull *L. fuscus*, Herring Gull *L. argentatus*, Glaucous Gull *L. hyperboreus* – present a special challenge in estimating their populations. Sometimes a pair was obviously standing guard by their nest while also many birds were seen standing singly in the colony. A few birds were in flight during the census period while an unknown proportion of the breeders are away from the colony at any one time. The value of counting from a distance is that the colony birds are mostly tranquil and the counts not influenced by the observers. Since the lava field in the colony area is rough in many places many incubating birds could not be seen. The partner however was perching on guard, if not away from the colony on a feeding trip. This applies above all to the Lesser Black-backed Gulls, which tend to conceal their nest rather than place it clearly visible like do the Great Black-backed Gulls. Problems of estimating the size of large gull colonies are discussed in Barbraud & Gélinaud (2005). The best counting unit for comparing figures between censuses is „Numbers of birds". Methodological baseline studies from elsewhere could potentially be used to estimate of the proportion of birds away from the colony at any one time and to achieve corrections from numbers of birds to numbers of pairs. However, such studies do not seem to be available, although dividing bird numbers by two for converting to breeding pairs has been applied (Lloyd *et al.* 1991). That method clearly underestimates the numbers of pairs since often only one of the pairs is present during counts.

The proportion of single adults present against a pair was estimated in 2003 and correction factors worked out. The gull colony was counted on 29 June 2003 (at 2045–2115) and figures for pairs and single adults kept separate. The details are given in Table 1 for three the most common gull species. All correction factors were similar, i.e. around 60% of the adult breeding birds were present in the colony during counts. These results are similar as previously obtained elsewhere in Iceland for Black-headed Gulls *Larus ridibundus* (0.61; Petersen & Thorstensen 1993). Further counts, at different times of summer and day, are needed to substantiate these results, but for the time being they are used here to calculate the numbers of breeding pairs in the Surtsey gull colony.

RESULTS

General composition of the bird fauna

Altogether 91 bird species have been recorded on or near Surtsey since the island was formed (Appendix 1). Half (47) of these species are waterbirds while the other half (44) are terrestrial birds. Six different categories can be recognized; (a) regular breeders elsewhere in Iceland make up over half of the species (58); (b) regular transient migrants which breed in Greenland-Canada and overwinter in Europe (5), (c) regular winter visitors (6), (d) vagrants (12), (e) primarily vagrants but also rare or incidental breeders in Iceland (9), and (f) escapes (1). Of the 21 vagrant species most (19) are of European origin, the others Holarctic (1) and North-American (1).

The breeding species

Fourteen species of birds had been confirmed breeding on the island by 2008. Twelve of them are now annual breeders. One has not been found nesting since 1978, while one first bred in 2008 so it remains to be seen if that species will continue to nest every year. Already in 1966 certain species, particularly Kittiwake and Black Guillemot started prospecting for nest sites. They were probably prevented from nesting by the volcanic activity of the nearby temporary crater islands, Syrtlingur and Jólnir, which discharged ash over Surtsey (Gudmundsson 1967). In 1968, Fulmars began attending ledges (Gudmundsson 1970).

The first birds were discovered breeding in 1970, three years after the cessation of volcanic activity. The first nests were those of Black Guillemot (two) and Fulmar (one) (Ólafsson 1971). Another 12 species have since then been confirmed breeding on the island; Great Black-backed Gull (Fig. 1) were recorded first in 1974; Kittiwake and Arctic Tern *Sterna paradisaea* in 1975; Herring Gull in 1981; Lesser Black-backed Gull ~1985; Glaucous Gull in 1993; Snow Bunting in 1996; Greylag Goose in ~2001; White Wagtail and Meadow Pipit in ~2003; Puffin *Fratercula arctica* in 2004. The latest addition is Raven *Corvus corax* that nested in 2008.

The year of first breeding is not accurately known for some species. In other cases the first nesting attempt had a long prologue. Greylag Goose probably nested in 1999 but was first confirmed in 2001. Similarly White Wagtail probably bred in 2001 and Meadow Pipit in 2002 but both first confirmed in 2003. The Puffin was first suspected to breed in 2001 when apparently produced scrapes, although first landfall was observed as early as 1978 (Fridriksson 1979). In 2003 behaviour indicated nesting, although this could not be confirmed, while in 2004 food-carrying adults were seen entering nesting burrows on the sea-cliff face on three occasions. Several more birds were seen attending that part of the island. Several birds were seen in the same area every year since 2005. In 2006 burrowing attempts suspected due to Puffins were noticed in the grassy inner parts of the island. Lastly, Ravens have built nest (or attempted to do so) intermittently since 1986 without laying eggs until 2008 when three young were raised.

Development of breeding populations

In the 1990 census six breeding species were encountered on the island. Fulmar and the Lesser Black-backed Gull were the most common breeders, each with over 120 pairs. Other species were

Fig. 1. An adult Great Black-backed Gull on Surtsey. Photo: Erling Ólafsson, July 9, 2007.

Table 2. Population sizes of breeding birds on Surtsey during whole island censuses in 1990 and 2003. The estimates for the gulls have been recalculated from previous publications (Petersen 1993, 2004) using the correction factors in Table 1.

	1990	2003
Black Guillemot	15	35–40
Fulmar	120	350–400
Kittiwake	4	130
Great Black-backed Gull	31	86
Lesser Black-backed Gull	126	175
Herring Gull	20	37
Glaucous Gull		3
Snow Bunting		11
Greylag Goose		2
Meadow Pipit		2
White Wagtail		1
Total	316	832–887

Table 3. Population figures for the breeding species on Surtsey Island from first colonization in 1970 to 2008. The information is compiled from various sources published and unpublished. Shading indicates first year of confirmed breeding. In many cases breeding was confirmed (+) but no estimate was available for the island population. Parentheses indicate possible breeding.

	Black Guillemot	Northern Fulmar	Great Black-b. Gull	Kittiwake	Arctic Tern	Herring Gull	Lesser Black-b. Gull	Glaucous Gull	Snow Bunting	White Wagtail	Greylag Goose	Meadow Pipit	Common Puffin	Raven
1970	2	1												
1971	7	11												
1972	6-8	13												
1973	2+	8												
1974	4	7+	1											
1975	4	17	1	8	1									
1976	6	13	3	0	4									
1977	10+	13-15	3	7	0									
1978	11-12	26	7	2	1									
1979		+	4	+	0									
1980		3	4	+	0									
1981	15-16	6	5	0	0	1								
1982														
1983														
1984		20-30	7	+	0	1								
1985			6											
1986		+				+	+							
1987		13+	15		0	11	+							
1988														
1989														
1990	15	120	31	4	0	20	126							
1991														
1992							+							
1993	+	+	+	+	0	+	+	1						
1994														
1995	+	+	+	+	0	+	+	+						
1996	+	+	+	+	0	+	+	+	1					
1997	+	140+	50	20	0	45	95-100	5	1					
1998									+					
1999	+	+	+	+	0	+	+	+	1		(1)			
2000		+	+	+	0	+	+	+	+		(1)			
2001		+	+	+	0	+	+	+	1	1	1			
2002	25	140+	35	30+	0	35	65+	1	2+	1	1	(2)		
2003	35-40	350-400	86	130	0	37	175	3	11	1	2	2		
2004	+	+	+	+	0	+	+	+	+	+	+	+		
2005	+	+	+	+	0	+	+	+	+	0	+	+	2	
2006	+	+	+	+	0	+	+		+	1		+	+	
2007	+	+	+	+	0	+	+		+				+	
2008	+	+	+	+	0	+	+		+	0	0	+	+	1

less common, in declining order, Great Black-backed Gull, Herring Gull, Black Guillemot, and Kittiwake (Table 2).

At the 2003 census five new species had started breeding since 1990 and all of the previous ones were still present (Table 2). The total numbers of breeding pairs had increased from 316 to around 850. In both years Fulmar was the most common species, with 350–400 nests in 2003 and Lesser Black-backed Gull second with 175 pairs. Kittiwake had increased considerably, as had Great Black-backed Gull, Herring Gull, and Black Guillemot. The Snow Bunting, which started breeding in 1996, had reached 11 pairs by 2003. Glaucous Gull had three pairs, and there were two pairs each of Greylag Goose and Meadow Pipit. White Wagtail was represented by only a single pair. One mixed pair of Glaucous Gull and Herring Gull was found in 2003, but these species commonly hybridize (Ingólfsson 1970, Vigfúsdóttir, Pálsson & Ingólfsson 2008).

Available population estimates for the breeders since birds started breeding in 1970 are presented in Table 3. On the whole the populations have increased slowly since starting to breed. The main exception is the Arctic Tern that was found breeding in 1975, 1976 and 1978 but never thereafter. Arctic Tern colonies are often unstable, especially small ones (Petersen 1998). The Glaucous Gull has maintained its number of breeding pairs, with 5 pairs in 1997 to 4–5 in 2003. One White Wagtail pair was present in at least 2001–2003 and 2006. The Great Black-backed Gull has more or less held its breeding population from 1990 and the Herring Gull since 1997. The Kittiwake and Snow Bunting have increased in numbers. The Fulmar and Lesser Black-backed Gull greatly increased until 2003, in line with the general population development elsewhere in Iceland (Petersen 1998). The rarest species did not seem to be fully annual; White Wagtails were at least not present in 2004 and 2008, nor were Greylag Geese in 2008 but data are not complete for every year.

Breeding distribution

Distribution of the breeding species in 2003 is shown in Fig. 2. Notable changes had taken place since 1990. In 2003 Fulmars had started nesting on level ground in the gull colony, but were earlier confined to the sea cliffs and several inland slopes on the craters. The gull colony had expanded in all directions, except north. The reason is probably unsuitable habitat of unstable sand dunes in the centre of the island. In 2003 the Great Black-backed Gulls nested primarily where the colony was formed in 1986 and which is now densely vegetated. The Lesser Black-backed Gulls showed the widest distribution, flanking the Great Black-backed Gulls towards southwest, south and east, extending eastwards all the way to the seaward side of the research hut. Herring Gulls showed much the same distribution as the Lesser Black-backed Gull but were much less common. The Glaucous Gulls nested where they started in 1993, at the eastern limit of the gull colony. Distribution of the different gull species did not have clear-cut boundaries but mixed within the colony. Four species of large gulls nesting together is rather uncommon in Iceland but can e.g. be found on the island of Grímsey in Steingrímsfjördur, NW-Iceland (cf. Jóhannsson & Gudjónsdóttir 1995).

Since first breeding in 2003 the Meadow Pipits have nested within the most densely vegetated part of the gull colony (Fig. 3). Individual birds were seen on occasions in 2003 at the centre of the island, near the research hut and the large craters but they were believed to be the breeding birds

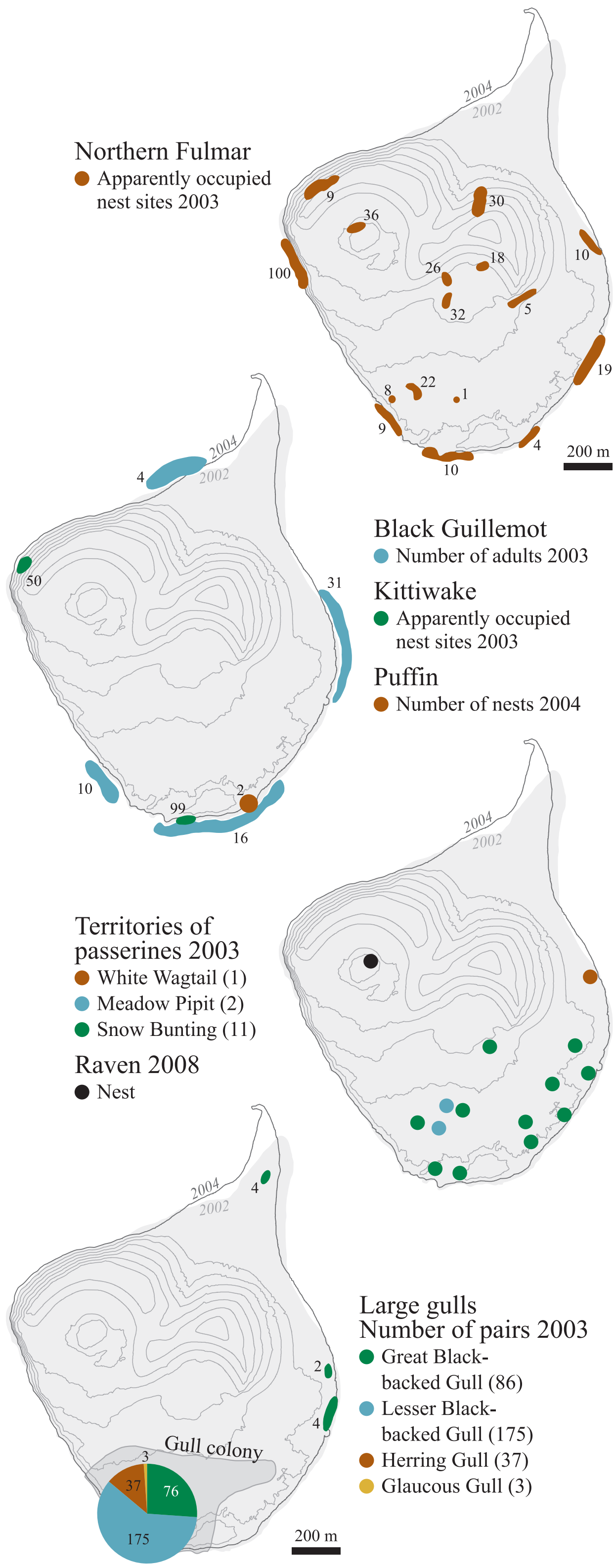

Fig. 2. Breeding distribution of the eleven bird species nesting on Surtsey in 2003 and two species nesting thereafter until 2008. The two years shown indicate the shore line in 2002 and 2004.

from the gull colony on feeding excursions. Similarly in 2003 White Wagtails, which were only found nesting at one place on the eastern sea-cliffs, were

Fig. 3. Meadow Pipit chicks in nest on Surtsey. Photo: Erling Ólafsson, July 9, 2008.

seen on occasions in the centre of island. Snow Buntings were found on their territories mainly towards east from the gull colony in the direction of the research hut. The lava fields are roughest in this southeast part of the island. Three nests were discovered and also adults with fledglings.

One of the two areas frequented by Puffins in 2003 is the same place where they were breeding in 2004. The Ravens nested in 2008 and produced three chicks in the large westernmost carter (Surtungur), where nest-building had been attempted on and off in many years from as early as 1986.

The gull colony

The growth of the gull colony on the southern part of Surtsey has had significant effects on the development of plant and invertebrate communities (Magnússon & Magnússon 2000, Magnússon & Ólafsson 2003). Effects of gulls and other seabirds on the vegetation of their breeding sites are well known (Fridriksson 1979, Sobey & Kenworthy 1979, Stempiewicz 1990, Ellis 2005). Various aspects of gull behaviour contribute to this; the delivery of food ashore, defecation, regurgitation, and nest-building. Soil analyses on Surtsey have showed much higher nutrient values (P, K, NH_3) in gull nests than away from them (Fridriksson 1977a, Magnússon & Magnússon 2000).

Gulls are omnivores; they feed on natural foods (fish, eggs), scavenge, take offal and discards from fishing vessels while predating on other birds, even kleptoparasize other birds. Most of their foods are of marine origin and some carried on land, some eaten by chicks, later regurgitating the indigestible remains as pellets. Some foods get partially eaten and others left untouched to decay, becoming food for micro organisms and invertebrates. The adult gulls as well as the chicks defecate all over the colony area. Food remains and pellets found at gulls' nests on Surtsey have included a leg of gull and unidentified bones, adult Razorbill *Alca torda* head, and legs of alcid young (possibly Razorbill) taken at sea or nearby colonies. In 2003 food remains found included several Puffin and guillemot *Uria* eggs (originating from neighbouring islands), predated gull chick, and fish remains, e.g. small Redfish *Sebastes* and relatively large (10–20 cm) unidentified fish lying around in the colony. In 2003 a fish tag (Isl. Hafr. 62014) was found in the gull colony, the fish was most likely carried on land as food for gull chicks. The Marine Research Institute confirmed that it came from a Pollock *Pollachius virens* fry tagged ca 20 km away a year before then 40 mm long. Herring Gulls on Surtsey were in 1990 seen prospecting Fulmar eggs, which are particularly vulnerable if the birds are off duty, being snow white against the black lava and sand. Eaten Fulmar eggs were found near predated nests in the gull colony on human disturbance. Gulls also predate on land birds. Snipe *Gallinago gallinago*, unidentified wader leg, and a female Crossbill *Loxia curvirostra* have been found by gulls' nests. Bones and wings of Golden Plover *Pluvialis apricaria* were found in a nest (Fridriksson 1977b).

In the early years of the island concern was expressed that the gulls were having negative influence on the vegetation development. They tore colonizing plants, at that time mainly Sea Sandwort *Honckenya peploides*, for use as nest material, possibly setting back their expansion but also dispersing seeds. Plant growth took rapid steps forward after the gulls formed a colony in 1984 but previously they had only nested dispersed. In 1990 an analysis was made of the nest material in gulls' nests (Table 4). There was a clear difference in nest material selection between the gull species. Great Black-backed Gulls choose primarily Sea Sandwort, while Lesser Black-backed and Herring Gulls selected mosses. The timing of breeding differed between the gull species, as shown in 1990 (Table 5). Great

Table 4. Nest material in gulls' nests on Surtsey 1990. Numbers of nests are given. The gull species are Great Black-backed Gull (GBBG), Lesser Black-backed Gull (LBBG) and Herring Gull (HG).

	GBBG	LBBG	HG
Lymegrass	1		
Grasses	1		
Sea Sandwort	14	2	
Mosses	1	25	5
Mosses and grasses		6	3
Mosses and Sea Sandwort		6	3

Table 5. Difference in the timing of breeding of three gull species nesting on Surtsey in 1990. No. of nests with % in parentheses is shown.

	Eggs	Chicks
Great Black-backed Gull	4 (23)	12 (77)
Herring Gull	10 (91)	1 (9)
Lesser Black-backed Gull	39 (100)	0 (0)

Black-backed Gulls nest earliest then Herring Gull and Lesser Black-backed Gull was the latest.

Sea watches

In order to obtain an idea of the use of the sea areas around Surtsey, sea watches were conducted in three sessions on 6–7 June 1990 using a fixed telescope at a preset location. Each session consisted of three 10-minute observation stints but all the data were combined on analysis. The results are summarized in Table 6. Altogether 466 birds were seen, of which 118 (25%) were unidentified. The great majority of the birds were in flight (448; 96%), the rest on the water. Fulmar was the most common species, then Puffin and Kittiwake, but all others with less than 10% frequency.

On the whole these frequencies reflect the commonness of the species in this general region but not quite. Fulmar (Fig. 4), Puffin and Common Guillemot *Uria aalge* are the most common breeding species on the Westman Islands. The last species should have been in greater frequency except it usually feeds further offshore. Arctic Tern and Arctic Skua *Stercorarius parasiticus* do not breed on the island but are commonly found feeding in the region. Oystercatchers *Haematopus ostralegus* nest on nearby Heimaey Island, while the three gull species nest on Surtsey, Black Guillemots and Fulmars. They most likely feed in the sea areas in the vicinity of the island.

Table 6. Birds seen offshore from Surtsey and their numbers during three observation sessions on 6–7 June 1990.

	Total	%
Fulmar	144	41
Puffin	62	18
Gannet	44	13
Kittiwake	34	10
Common Guillemot	33	9
Arctic Tern	18	5
Oystercatcher	5	1
Great Black-backed Gull	4	1
Lesser Black-backed Gull	2	1
Black Guillemot	1	<1
Arctic Skua	1	<
Unidentified*	118	

* Mainly birds, which were flying too near and rapidly across the telescope field of view, while some were too far away.

Fig. 4. Fulmars are common breeders on the Westmann Islands, including Surtsey. They were the first bird species to start breeding on Surtsey (in 1970) together with Black Guillemots. Photo: Erling Ólafsson, July 10, 2007.

Vagrants

The numbers of straggling species (vagrants) recorded depend heavily on the length of period and time of year studies are carried out. Regular observations were only maintained during the migration periods (spring, autumn) in the early years of the island. Therefore most of the vagrant records are from those years. In the last three decades greater emphasis has been placed on recording new species for the island and following the development of the breeding bird fauna, with visits mainly concentrated in the summer (June–July). Food availability, e.g. the type of plants and extent of vegetation, availability of insects and beached food, etc., also governs the length of stay of many of these vagrants.

Two vagrant species very rare to Iceland have been recorded on Surtsey, the European Squacco Heron *Ardeola ralloides* (1969) and the North-American Northern Oriole *Icterus galbula* (1971). The former is the only record for Iceland while the last was the third. The other vagrant species mostly include the commonest and most regular vagrants in Iceland, such as Little Gull *Larus minutus,* Turtle Dove *Streptopelia turtur,* Long-eared Owl *Asio otus,* Swallow *Hirundo rustica,* European Robin *Erithacus rubecula,* Song Thrush *Turdus philomelos,* Garden Warbler *Sylvia borin,* Chiffchaff *Phylloscopus collybita,* Willow Warbler *P. trochilus,* Jackdaw *Corvus monedula,* Chaffinch *Fringilla coelebs,* Brambling *F. montifringilla,* Crossbill *Loxia curvirostra,* and Lapland Bunting *Calcarius lapponicus.* Several additional, but are generally not as common, vagrants in Iceland have been recorded, e.g. Corncrake *Crex crex,* Sky Lark *Alauda arvensis,* Rock Pipit *Anthus spinoletta,* Redstart *Phoenicurus phoenicurus*, and Ring Ouzel *Turdus torquatus*.

Several bird species do not breed but are regular and common visitors in Iceland, mostly as winter visitors. Some of those have been seen on or near Surtsey, such as Grey Heron *Ardea cinerea,* King Eider *Somateria spectabilis,* Iceland Gull *Larus glaucoides,* Little Auk *Alle alle,* and Fieldfare *Turdus pilaris*.

In addition to vagrants that have been seen on land, some have only been observed at sea in the vicinity of the island. This includes Sooty Shearwater *Puffinus griseus*, Common Tern *Sterna hirundo*, and Blackcap *Sylvia atricapilla*. Much greater numbers of vagrant species have been observed on Heimaey Island 20 km from Surtsey. This results from a permanent year-round human settlement, more feeding possibilities due to more diverse habitats, and considerable bird interest.

Migrants

Surtsey is ideally situated for the study of migration. It is the southernmost land in Iceland, and right on the migratory flyway between the High Arctic of Greenland – Canada and wintering areas in Europe – Africa. Migrating land-birds and waders are therefore likely to stop over on the island, although their length of stay depends on the food availability. The spring return of some Icelandic migrant breeders, which mostly travel southeast for winter, is more concentrated at the south-east parts of Iceland. Surtsey may hence not seem suited for studies of these migrants, depending on the species in question.

During 1966 to 1971 bird observers were stationed on the island to monitor various activities, including the bird migration, mainly during spring but also in the autumn (Gudmundsson 1966, 1967, 1968, 1970, 1972). From these studies a reasonably good overview is available of the migratory landbirds in the early years of the island, summarized here. The migration observations from Surtsey are interesting to compare to results elsewhere in Iceland, but a detailed analysis is outside the scope of this text.

The insect-feeding species, such as Wheatear *Oenanthe oenanthe*, Meadow Pipit, and White Wagtail were among the most common migrants. Insects were over the whole island, although patches of vegetation and the coastline are best suited (Ólafsson & Ingimarsdóttir 2009). These are passerines and common breeders in Iceland. The last two are undoubtedly of Icelandic origin but birds of the first belonged also to the population breeding in Greenland.

Other High-Arctic migrants included Turnstone *Arenaria interpres* and Snow Bunting. In these early years of the island these two species did not have opportunities for foraging except along the tideline, the first feeding on drifted small crustaceans (euphausids) and Goose Barnacles *Lepas* spp. The Snow Bunting is mainly a seed-eater and its food on the island is likely to have consisted mainly of drifted seeds when vegetation was still sparse. With ever increasing vegetation their feeding possibilities have dramatically changed, finally leading to the species starting to breed. Migratory Snow Buntings were also found to have grit (mineral stones) in the stomachs of such origin that they must have migrated from the British Isles (Fridriksson 1964, 1970, Fridriksson & Sigurdsson 1968, 1969).

The most frequent staging wader species was Oystercatcher, while others showed up e.g. Ringed Plover *Charadrius hiaticula*, Redshank *Tringa totanus*, and Dunlin *Calidris alpina*. These are all common Icelandic breeders, while the last could also be birds continuing to High-Arctic breeding grounds. These birds were mostly seen feeding on the coast, hence the length of their stay was dependent on what brought in by the tide. Other High-Arctic wader breeders, the Knot *Calidris canutus* and the Sanderling *C. alba*, have been observed on the island but only in small numbers. They regularly stage in Iceland in large numbers, especially the south-west and west. The habitat and food situations for these birds were most likely unfavourable on Surtsey. Same for three other waders, which are common breeders in Iceland, Golden Plover *Pluvialis apricaria*, Snipe *Gallinago gallinago*, and Whimbrel *Numenius phaeopus*. They did not find the right habitat or feeding conditions on Surtsey, not even nowadays. They have been recorded occasionally on land but not in the relative large numbers that are likely to pass the island during migration.

During the observation years around 1970 geese were often seen in flight on migration off the island. As they are vegetative feeders the island did not offer proper feeding conditions, although they were seen stopping in small numbers for short periods of time. Three species of geese have been recorded, Greylag Goose, Pink-footed Goose *Anser brachyrhynchus*, and Barnacle Goose *Branta leucopsis*. They all breed in Iceland, and the last two also in the High-Arctic. With increased vegetation staging by geese may have become more frequent, finally leading to Greylag Geese starting to breed, probably as early as 1999.

The most detailed studies on the migratory birds were made on the Meadow Pipit and the Wheatear. Information was gathered on the timing of arrival in spring (late April into May) and the body condition of the birds. Comparison of the two species

Table 7. Species and numbers of birds ringed on Surtsey in 1975, 1990, 1993, 1997 and 2003.

	Adults on nests					Unfledged chicks					
	1975	1990	1993	1997	2003	1975	1990	1993	1997	2003	Total
Fulmar					118		1				119
Lesser Black-backed Gull				5				14	10	25	54
Great Black-backed Gull						1	3	38	40	164	246
Glaucous Gull								1		6	7
Herring Gull								18	10		28
Meadow Pipit										1	1
Snow Bunting										3	3
				5	118	1	4	71	60	199	458

showed an interesting dichotomy in these related passerines in spring. Meadow Pipits were generally emaciated, as if they had used up most of their fat reserves during the flight from Europe. Recoveries of the Meadow Pipits have shown Icelandic birds overwinter in SW-Europe, while the Wheatear travel further, to W-Africa (Petersen 1998). Contrary to the pipits the Wheatears were in excellent body condition upon arrival on Surtsey. They needed this for travelling to the High-Arctic, while the pipits do not migrate further than Iceland.

As is apparent from above the combination of species stopping over on Surtsey, and their frequency in numbers, are likely to have changed since the early years of the island, when hardly any vegetation had colonized it. Therefore it would be of interest to repeat the earlier migration observations from around 35 years ago.

Winter visitors

The wintering birds are less well known than the situation in summer, or during the migration periods in spring and autumn. Only fragmentary observations exist but of the terrestrial birds Purple Sandpipers *Calidris maritima* and Ravens have been recorded in mid winter (31 January). European Redwings *Turdus iliacus* have been seen as late as 25 November, probably late migrants. Gulls of various species have also made landfall on Surtsey, for resting or scavenging for tide-line food. However, as expected seabirds dominate such as Kittiwake, Fulmar, gulls, and auks, mainly on the seas around the island.

The winter bird fauna is presumably similar to that registered on the nearby Heimaey during the annual Icelandic Christmas Bird Counts (Petersen 1983, Petersen & Hjartarson 1989, 1991, 1993). Besides the birds mentioned above, other common species include Great Cormorant *Phalacrocorax carbo*, Common Eider *Somateria mollissima*, and Snow Bunting.

Ringing

Bird ringing, by attaching a metal ring to a leg, is the traditional method of studying the travels of migratory birds. During the period of migration studies on Surtsey emphasis was placed on collecting museum specimens. Ringing has not been used much as a tool to study birds on Surtsey, but could add considerable knowledge to the birds' migratory habits, on the location of their wintering grounds, body condition, origin of their breeding place, etc.

Only on five occasions have ringing been undertaken on Surtsey, in 1975, 1990, 1993, 1997 and 2003, in all 458 birds of six species (Table 7). Recoveries of Surtsey-ringed birds have been few away from the island. By the end of 2008 these were nine; Lesser Black-backed Gull (3), Great Black-backed Gull (5), and Herring Gull (1). One Lesser Black-backed Gull was recovered nearly five years later in the Faeroes in spring, presumably on its way back to Iceland from the wintering grounds. One was sighted on the wintering grounds in Spain during height of winter half a year old. The third bird was sighted twice soon after fledging on fishing boats off the Westman Islands. Two Great Black-backed Gulls were recovered in the Faeroes in their first autumn, presumably southbound. A third bird of similar age over-wintered in Iceland and was shot near Reykjavik. The fourth bird was also shot near Reykjavik three years after ringing. The fifth bird was found dead three years old in the Heimaey harbour, the only inhabited island in the Westman Islands group. The only recovered Herring Gull was found dead at Breidamerkursandur, SE-Iceland two months after ringing on Surtsey. Then one bird, ringed outside Surtsey has been recovered there. A Redshank *Tringa totanus* was ringed in England as a full-grown bird and recovered on Surtsey two years later during the migration period in spring. Undoubtedly this was an Icelandic bird returning from the wintering grounds for the summer.

Fig. 5. Great Black-backed Gull chicks on Surtsey. When big enough the chicks wander from the colony area towards the sea cliffs on disturbance. Photo: Erling Ólafsson, July 8, 2008.

All the recoveries are in accordance with the general migratory behaviour of gulls from elsewhere in Iceland, also the appearance of the Redshank (cf. Petersen 1998). Despite relatively many Fulmars having been ringed on Surtsey none has been recovered to date. This species is among the largest bird populations in Iceland and adults not harvested, which normally increases the chances of recovery. On the other hand the ringed adults can be expected to show up on the nesting sites on Surtsey in many years to come as they are one of the most long-lived bird species.

The gull colony on Surtsey is in some ways ideal for ringing studies, as it contains four species of large gulls (Fig. 5), three of which are in relatively large numbers, and is relatively undisturbed from humans contrary to elsewhere in Iceland. But there are also drawbacks to such a dense colony, as discovered in 2003. Gulls are omnivorous and also predatory if opportunities arise, both interspecifically and cannibalistic. If the parents are flushed away on human approach and the chicks wander off their parents' territory, they are likely to get killed by other gulls. In July 2003, about a month after ringing, eight (of 195) gull chicks (and a number of unringed chicks) were found dead. Chick deaths were in general higher than in 2002 (E. Ólafsson, pers. comm.). Although poor feeding conditions in 2003 cannot be ruled out, it seems likely that disturbance in the colony resulted in unusually heavy chick mortality. Surtsey is a proclaimed nature reserve which is closed to visitors and where nature should take its own course and human influences be kept at a minimum. Bearing this is mind caution is therefore needed when approaching the gull colony and rules are clearly needed for visits.

DISCUSSION

Ecological relationships – development of a bird community

The development of a new breeding bird community is dependent upon many factors, both physical and biological. Different sectors of such a community depend upon different scenarios, which govern the rate at which the community develops. The birds, firstly, need to reach the island, and this in turn is dependent upon a host of factors such as population size, feeding habits, travelling capabilities, the distance to breeding sources, etc. On reaching the island another suite of factors influence the rate at which individual species colonize the island, e.g. time of year, feeding conditions, breeding habits, available habitats, etc. The sea has important influences, in that organic matter is brought on land in different forms by birds. Sea spray also brings minerals onto land and the terrestrial communities develop through interaction between the developing vegetation and its associated invertebrate fauna, which are food resources for the birds.

Bird communities are usually made up of species with different life styles; the complexity depends on the environmental conditions available at each location. In the beginning, all the breeding species on Surtsey relied on the ocean for their food. Such was the situation in the summer of 1990, but a decade later the island had become much more vegetated with increased insect life, making it possible for terrestrial birds to maintain themselves and breed. Currently Snow Buntings, which are seed and insect eaters, Greylag Geese which are grazers, and the insect-feeding White Wagtails and Meadow Pipits have successfully colonised the island. Ravens, which subsist on eggs, birds or by scavenging, have long been able to sustain themselves on the island, but the general feeding conditions were presumably still too poor for breeding and raising young until 2008. The large gull colony of around 300 pairs in 2003 could presumably supply enough energy for a breeding pair of Ravens. However, the gulls that breed on Surtsey are large, hardy birds, which by their sheer numbers are likely to keep the Ravens away. On the other hand Fulmars are vulnerable with its large and very visible white egg, although they spit stomach oil and partially digested food if provoked to keep predators at a distance.

The gull situation on Surtsey makes an interesting study, both the development of this multi-species community and the interactions with vegetation and the terrestrial invertebrate fauna. This is a colony which is largely unaffected by man, but gulls are generally harassed in Iceland if not killed, as they are looked upon as pests. Therefore many gull colonies are rather unstable and often difficult to separate natural influences from human-induced ones. Although the gulls on Surtsey have not been left fully undisturbed this colony provides excellent study opportunities, comparing species and comparing with different situations elsewhere.

The breeding birds so far have been largely seabirds although one could question why Arctic Terns, which still commonly feed offshore, have not bred for so long. Until rather recently feeding conditions have not been available for terrestrial birds. Greylag Geese and Meadow Pipits did not start breeding until the vegetation cover in the gull colony had become sufficient. Snow Buntings started earlier since they feed on seeds, which both drift ashore or stem from the developing plant community, complete vegetation cover was not needed since they nest in holes in the lava, unlike Meadow Pipits which usually place their nest in the side of grassy knolls.

The breeding birds are obviously very important in the formation of soil on the island, as well as in the development of the plant and insect communities. This is especially true for the seabirds, which actively transport nutrients from the ocean onto land. This is particularly noticeable in the gull colony in the southern part of the island, where full vegetation cover has developed on the oldest colony area from 1984 as a result of their breeding and nutrient-transfer activities.

The extensive organic matter carried by seabirds onto land in the form of excreta, food and nest material can lead to a species-few plant community as found in dense seabird colonies elsewhere. Nutrient enrichment has positive effects on various other organisms, such as fungi, algae, bacteria and the invertebrate community that feeds on these. The compilation of nest materials, dead bodies, pellets, food remains, excreta, etc. have positive effects on both flora and small fauna development (cf. Ólafsson 1982, Gjelstrup 2000). For instance, nests can serve as sites for seed colonization, and dead tissue as food for small animals (Ólafsson 1982). Grass-pulling for nest-building, in itself a destructive exercise can in the end be positive for the development of the ecosystem by dispersing plant seeds. On the negative side trampling and nest-scraping of birds can slow down vegetation development, but undoubtedly these factors are minor compared to the positive aspects of gull behaviour.

Since the geese and the Meadow Pipits nest within the gull colony predation can easily slow down the rate of their population development. On the other hand the gulls are likely to act as protectors against marauding Ravens. The delicate balance between predation and protection will decide if these terrestrial birds continue to breed in the long run. Ravens, as top predators, did not seem to be able to breed and successfully raise chicks until the seabird population had reached a certain size. Yet they are also able to seek food (eggs and dead birds) on nearby islands, or scavenge on bird corpses or marine biota washed up on the Surtsey beach.

Surtsey is subject to much erosion from ocean wave action and the island becomes constantly smaller (Jakobsson & Gudmundsson 2003). This creates instability for cliff-nesting birds, which are primarily Fulmars, Kittiwakes and Black Guillemots. The last two species breed exclusively on sea-cliff faces, while Fulmars are able to go inland for breeding, thus avoiding the effects of habitat destruction. Through the years Kittiwakes have changed breeding sites on the cliffs presumably as a result of the physical changes in the cliff faces that have taken place from one breeding season to another, unlike in more stable situations elsewhere. Black Guillemots are more likely to find appropriate fissures to breed on the same island section although the cliff has changed by erosion since the year before. But in the end it is likely that most of the flat lava fields on Surtsey will erode away but the more resilient tuff mountains will persist. Similar processes have taken place in the past to most of the twenty stacks which now form the Westman Islands group. Species like Greylag Goose and Meadow Pipits, and most of the gull colony, will likely disappear with time, after decades or a few centuries.

Candidate breeders

While the bird fauna is still developing, several species can be mentioned as likely breeding candidates in years to come. A Rock Pipit *Anthus petrosus* was seen in mid summer of 2002. The Oystercatcher and the Ringed Plover are also possible colonizers, while the Arctic Tern may well begin to breed again. Two petrel species, which nest on the other Westman Islands, the Storm Petrel *Hydrobates pelagicus* and Leach's Petrel *Oceanodroma leucorrhoa*, have been considered potentials for breeding but have so far evaded discovery. In 2007 Razorbill *Alca torda* was seen on the sea near the cliffs showing behaviour which pointed to breeding but this was not confirmed. No freshwater is found on the island and this will greatly influence the species likely to colonize Surtsey in years to come. Species that are attracted to freshwater, such as many waders and ducks are not likely to start breeding.

Potential human influence

Researchers and visitors alike can affect the development of the breeding bird community on the island albeit indirectly or unwittingly. The Fulmar and the gulls are particularly vulnerable in this respect. When scared Fulmars often throw their egg from the nest bowl which means breeding is over for them that season. Gulls are scavengers as well as predators and unguarded eggs and young are liable to predation by conspecifics or other species. So if humans stay unduly long in or very near the colony, this can result in heavy predation. Fulmars have also started nesting within the boundaries of the gull colony. If they are flushed off their eggs considerable time can last until they return and their large white egg, so visible against the black lava or sand on the island, is an easy catch for gulls, or perhaps Ravens. This became clear in 2003 when ringing of gull chicks was carried out and 21 Fulmar eggs were present in the epicentre of the gull colony in the beginning. The day after only 13 were left but 4 were found broken and the gulls probably removed the rest. In light of these facts, it is important to establish some code of conduct in the colonies of these birds, especially during the egg stage and when chicks are small from May to early July.

More alarming than unintended effects, are the actions by man which wittingly are affecting the breeding bird fauna. On one occasion at least gulls were found dead in numbers on land in the main breeding colony, also freshly fired patrons. Although any use of firearms is by regulation illegal they had obviously been shot by people who had landed on the island without permit. Surtsey has been sat aside for nature to develop on its own principles and direct influence of man prohibited. It is therefore sad that someone is prepared to jeopardize this unique opportunity for studying the development of a new ecosystem.

RECOMMENDATIONS FOR FUTURE MONITORING

It is important to maintain regular observations on the birdlife on Surtsey to obtain reliable data on the changes in the bird fauna. The following bird monitoring aspects are recommended for Surtsey: (a) breeding bird surveys, (b) registration of visitors and other incidental observations, (c) recording seabirds at sea, and (d) bird ringing. Detailed descriptions of methods used for each of these aspects are outside the scope of this paper. Some can be found in the general monitoring literature, such as Walsh & Harris (1995) and Gilbert, Gibbons & Evans (1998).

Breeding birds surveys

It is recommended that complete coverage of the breeding birds takes place at least every 3rd year. This involves censuses of the numbers breeding of each species and their breeding distribution. Mapping on aerial photographs is recommended. Different census techniques are needed depending on species. From land the gull colony is best surveyed by telescope from the slopes of the nearby crater (Surtur). The colony should also be surveyed by vertical aerial photography for comparison with ground truth. Ground transects for nests are also possible since many nests are invisible from air although the partners to incubating birds may show up on photographs. Disturbance may however be too severe. Only partial counts can be made on the sea cliffs from land. Hence counts from a boat or helicopter (Fulmar, Kittiwake, Black Guillemot), are desirable for complete coverage.

Registration of visitors and other incidental observations

New or rare bird species can be expected to show up on Surtsey virtually any time, and it is important that such records be noted and made available. Compilation of such records is one form of monitoring, giving an indication of the origin and frequency of potential settlers. A number of scientists visit Surtsey every year and many of them have a good knowledge of birds and can therefore contribute with their, albeit incidental, observations. Till now these observations are scattered in diaries and even not recorded. It is recommended that these observations be compiled in a common database so that they will become available for future consideration as part of the monitoring program for the island.

Recording seabirds at sea

The seabird community at-sea in the vicinity of Surtsey can be studied by three principal methods, sea-watching from land, transects from boats, and transects from aeroplanes. Such studies give the species composition, frequency of individual species, and how they use the sea areas around the island. It is recommended that such a distribution-at-sea aspect is added to the overall monitoring program for the island. Each of the three methods has their shortcomings, hence a combination of methods is recommended.

Bird ringing

It is suggested that bird ringing be a part of the bird monitoring effort on the island. Emphasis should be given to the breeding birds and the regular staging visitors in spring and autumn. Such studies broaden the knowledge of the birds visiting Surtsey and their travels, towards breeding regions elsewhere in Iceland or in the Arctic and the wintering areas, elsewhere in Iceland or at more southerly latitudes. New technologies, such as geolocators, can also be employed for this purpose.

ACKNOWLEDGEMENTS

This overview has benefited from the observations of numerous people, who have visited Surtsey since the island was formed. Thanks to all these individuals. In the early years of the island, a number of observers were stationed on the island for longer or shorter periods, such as Hálfdán Björnsson and Erling Ólafsson before and after 1970. Borgthór Magnússon and Sigurdur H. Magnússon have visited the island for decades and contributed many bird observations, as well as important papers on bird-vegetation interactions. In 1990 the island was visited by Jóhann Ó. Hilmarsson, who produced a short report on his visit, as did Hallgrímur Gunnarsson in 1997. Thanks to all these individuals, as well as the Surtsey research pioneers, to name but Sturla Fridriksson and Finnur Gudmundsson from the biological side. Thanks to my fellow travellers on recent Surtsey visits for their help and support, Gudmundur A. Gudmundsson (1993), Sverrir Thorstensen, Thórey Ketilsdóttir, and Magnús Magnússon (2003). Erling Ólafsson contributed the bird photographs from Surtsey, for which I am grateful. Lastly, Borgthór Magnússon and Tom Barry read a draft of the paper and their comments are greatly appreciated.

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Appendix 1. Bird species seen on or around Surtsey 1963 – 2008. Species that have bred are marked with *.

Red-throated Diver	*Gavia stellata*
Great Northern Diver	*Gavia immer*
Northern Fulmar*	*Fulmarus glacialis*
Manx Shearwater	*Puffinus puffinus*
Storm Petrel	*Hydrobates pelagicus*
Leach's Petrel	*Oceanodroma leucorhoa*
Gannet	*Sula bassana*
Great Cormorant	*Phalacrocorax carbo*
European Shag	*Phalacrocorax aristotelis*
Squacco Heron	*Ardeola ralloides*
Grey Heron	*Ardea cinerea*
Whooper Swan	*Cygnus cygnus*
Pink-footed Goose	*Anser brachyrhynchus*
Greylag Goose*	*Anser anser*
Barnacle Goose	*Branta leucopsis*
Brent Goose	*Branta bernicla*
European Widgeon	*Anas penelope*
European Teal	*Anas crecca*
Mallard	*Anas platyrhynchos*
Tufted Duck	*Aythya fuligula*
Common Eider	*Somateria mollissima*
King Eider	*Somateria spectabilis*
Harlequin Duck	*Histrionicus histrionicus*
Long-tailed Duck	*Clangula hyemalis*
Common Scoter	*Melanitta nigra*
Red-breasted Merganser	*Mergus serrator*
Merlin	*Falco columbarius*
Gyrfalcon	*Falco rusticolus*
Corncrake	*Crex crex*
Eurasian Oystercatcher	*Haematopus ostralegus*
Ringed Plover	*Charadrius hiaticula*
Golden Plover	*Pluvialis apricaria*
Knot	*Calidris canutus*
Sanderling	*Calidris alba*
Purple Sandpiper	*Calidris maritima*
Dunlin	*Calidris alpina*
Common Snipe	*Gallinago gallinago*
Whimbrel	*Numenius phaeopus*
Redshank	*Tringa totanus*
Turnstone	*Arenaria interpres*
Red-necked Phalarope	*Phalaropus lobatus*
Grey Phalarope	*Phalaropus fulicarius*
Arctic Skua	*Stercorarius parasiticus*
Great Skua	*Stercorarius skua*
Little Gull	*Larus minutus*
Black-headed Gull	*Larus ridibundus*
Common Gull	*Larus canus*
Lesser Black-backed Gull*	*Larus fuscus*
Herring Gull*	*Larus argentatus*
Iceland Gull	*Larus glaucoides*
Glaucous Gull*	*Larus hyperboreus*
Great Black-backed Gull*	*Larus marinus*
Kittiwake*	*Rissa tridactyla*
Arctic Tern*	*Sterna paradisaea*
Common Tern	*Sterna hirundo*
Common Guillemot	*Uria aalge*
Brünnich´s Guillemot	*Uria lomvia*
Razorbill	*Alca torda*
Black Guillemot*	*Cepphus grylle*
Little Auk	*Alle alle*
Common Puffin*	*Fratercula arctica*
Turtle Dove	*Streptopelia turtur*
Domestic (Razing?) Pigeon	*Columba livia domestica*
Long-eared Owl	*Asio otus*
Short-eared Owl	*Asio flammeus*
Sky Lark	*Alauda arvensis*
Swallow	*Hirundo rustica*
Meadow Pipit*	*Anthus pratensis*
Rock Pipit	*Anthus spinoletta*
White Wagtail*	*Motacilla alba*
European Robin	*Erithacus rubecula*
Redstart	*Phoenicurus phoenicurus*
Wheatear	*Oenanthe oenanthe*
Ring Ouzel	*Turdus torquatus*
European Blackbird	*Turdus merula*
Fieldfare	*Turdus pilaris*
Song Thrush	*Turdus philomelos*
European Redwing	*Turdus iliacus*
Garden Warbler	*Sylvia borin*
Chiffchaff	*Phylloscopus collybita*
Willow Warbler	*Phylloscopus trochilus*
Jackdaw	*Corvus monedula*
Raven*	*Corvus corax*
Starling	*Sturnus vulgaris*
Chaffinch	*Fringilla coelebs*
Brambling	*Fringilla montifringilla*
Redpoll	*Carduelis flammea*
Crossbill	*Loxia curvirostra*
Lapland Bunting	*Calcarius lapponicus*
Snow Bunting*	*Plectrophenax nivalis*
Northern Oriole	*Icterus galbula*

The value of Surtsey for ecological research

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ABSTRACT

Ecological research on Surtsey spans over 40 years of measurements, including monitoring of individual plants early on and later establishment of permanent plots with estimates of vegetation cover. In this paper we discuss the value of these studies for primary succession and the importance of strict control of access to the island. The long-term data set from Surtsey contains detailed demographic data, and they provide the opportunity to address aspects of species interactions, island biogeography, and nutrient dynamics. We conclude that Surtsey is unique for primary succession because the study provides a thorough census of an entire island since it was created, combined with minimal human influence because of the restricted access to the island.

INTRODUCTION

Ecological research on Surtsey has provided an unusual record of plant and animal colonization. Vascular plants, bryophytes, lichens, fungi, birds and invertebrates have been monitored on the island (Baldursson & Ingadóttir 2006). These data are unusual because they span over 40 years of measurements, they include several decades of monitoring individual plants, they allow one to distinguish between arrival and establishment of a species, they highlight how the interactions of birds, nutrients and plants impact primary succession and they provide a thorough census of an entire island. These are all very important aspects of this data set. However, what truly makes Surtsey unique is the minimal human influence. Set aside as a Nature Reserve in 1965 (category Ia according to the IUCN classification), Surtsey is accessible only by a limited number of people, mostly biologists and geologists and a crew that maintains the hut. Each of these teams limits its stay so people are on the island less than two weeks each year. The Surtsey Research Society manages the island on behalf of the Environment Agency of Iceland. Surtsey was added to the World Heritage List of UNESCO in July 2008. Natural remoteness of some studies of succession make human visits to study areas unlikely (e.g., landslides in the mountains of western New Zealand, glacial moraines in Alaska and Canada, uninhabitable volcanic islands in the Pacific) but we know of no other study of primary succession in the world where human visitation is so restricted. Such restricted access is extremely valuable to the study of primary succession.

We were both privileged to be guests of the biological research team that visited Surtsey for five days in July 2003. Our comments that follow come from our impression during that visit and lifelong interests in primary succession in general, research on Surtsey in particular and the interactions of science and society. The aim of this paper is to address the value of on-going research on primary succession in Surtsey.

RESEARCH VALUE

Long-term data

Primary succession involves the development of plant and animal communities and soil formation following such severe disturbance that little or no biological legacy remains. Typically this process takes decades or centuries before well-developed soils appear, so long-term studies are essential. Surtsey is one of only several studies of primary succession with such long-term data. Others include volcanic surfaces on Krakatau, Indonesia (since 1908), glacial moraines at Glacier Bay, Alaska, USA (since 1923) and dunes in Cooloola, Australia (since 1962). See Walker and del Moral (2003) for details. On Surtsey, we expect stable communities to take several hundred to several thousand years to develop, based on similar histories on the nearby Westman Islands. Minimal human interference allows us to examine this process of succession in its natural state.

Detailed demographic data

Marking individual plants as they colonize Surtsey has provided a remarkable record of natural invasion processes and species dynamics (Fridriksson 1978, 1982, 1992). Although data collection has now logically gone to plot-based sampling as the number of individuals has grown, such demographic data could be explored further. A potential use of the mapped plants around the entire island is to explore secondary dispersal from species already on the island. How individual species impact primary succession is best examined in such a field laboratory where details exist on the populations of individuals and individual species.

Species interactions

Surtsey is also an excellent setting in which to explore how species interact. One of the most important lessons from Surtsey is that gull colonies introduce nutrients and plants, and locally change successional change in dramatic ways (Magnússon & Magnússon 2000). This study has highlighted the importance of annual data collection in determining the pattern and rate of such changes. The sharp contrast between the lush, species-rich plant communities at the bird-impacted sites and the nearly barren sites outside that influence (Fig. 1 and 2) has been better documented on Surtsey than at any other primary succession site in the world. Insect diversity has also increased due to the fertilization effect of the birds (Erling Ólafsson, *pers. comm*). There is an urgent need to understand how fertilization (whether from birds or anthropogenic sources of pollution) impacts biological communities – particularly in the context of rehabilitating damaged lands. One suggestion

Fig. 1 The bird nesting area in Surtsey is clearly seen from a distance due to the impact of the birds on the vegetation.

(Walker & del Moral 2003) is that fertilization inhibits successional development and rehabilitation by favoring dense swards of vegetation. Surtsey is an ideal place to pursue such studies that will have important practical applications.

Island biogeography

Rarely are the flora and fauna of an entire, intact and undisturbed island recorded as they accumulate. Surtsey provides an excellent opportunity to understand colonization, extinction and carrying capacity of one island ecosystem. Additionally, as the island erodes in size, species numbers may decline. Such direct tests of the classic island biogeography concept (MacArthur & Wilson 1967) are invaluable and rare.

Additional opportunities

There are many other, non-destructive measurements that could be made on Surtsey that would

Fig. 2 The vegetation within the nesting area in Surtsey is lush and species rich compared with the area outside seen in the background.

further our understanding of primary succession. These include studying nutrient dynamics (particularly of nitrogen and phosphorus) and how these cycle through the increasingly complex yet still relatively simple ecosystems; linking nutrient fluxes to changes in both vascular plant and belowground invertebrate populations; measurements of carbon accumulation by species and location (above and below ground); the roles of herbivory and mycorrhizae in succession and consequences of escape from mainland herbivores; closer examination of microhabitats where plants colonize and how these are partitioned among functional groups; and the role of spatial aggregation of plants in succession. Finally, we want to emphasize that understanding scientific principles about primary succession has direct value to society, particularly in terms of improving our ability to restore severely damaged ecosystems.

VULNERABILITY AND HUMAN VISITATION

The new biota on Surtsey is vulnerable and at risk to disturbances, both natural and anthropogenic. The main natural disturbance on the island is the erosion of its coast that has occurred since it was created (Jakobsson *et al.* 2000, Jakobsson & Gudmundsson 2003). Any visit to Surtsey causes some disturbances to the island, including trampling and possible introduction of species. However, with the current strict control of access to the island that risk should be kept minimal.

There has been some debate, mainly amongst the local people from the Westman Islands, about releasing the strict closure of Surtsey and allowing some controlled tourism on the island. This has been seen as a possible way to promote the tourist industry in the area and counteract some of the decrease in employment and economic deprivation on the islands. In spring 2005, a local representative to Parliament formally asked the Minister of Environment whether there were any plans to allow tourists to enter Surtsey. On that occasion and again at a workshop held in Heimaey, Westman Islands in September 2005 on Surtsey and its management, the Minister said that there were no plans to change the management and strict control of access to Surtsey. We welcome this statement and emphasize the importance of it for future studies on primary succession on the island. Apart from the risk of increased anthropogenic disturbance with tourism on Surtsey, more frequent visits would jeopardize the continuing study of primary succession. In harsh climates such as exist on Surtsey, human impacts can have large and long-lasting impacts on the environment (Komárková & Wiegolaski 1999).

CONCLUSION

Ecological research on Surtsey is unusual and valuable to science for many reasons enumerated above but it is unique in its restricted access. We strongly urge the Environment Agency of Iceland to continue its current policy of limited access. Such a policy best advances our understanding of the development of biotic communities and leads to better land management and restoration practices.

ACKNOWLEDGEMENTS

We thank Borgthór Magnusson for inviting these comments and the biological research group for sharing their knowledge and enthusiasm with us during our visit to Surtsey. We also thank the Surtsey Research Society for ensuring the long-term value of Surtsey as a research laboratory for primary succession and Dr. Sturla Fridriksson, who initiated the successional studies, for his invaluable foresight at the time.

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Primary succession on Mount St. Helens, with reference to Surtsey

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ABSTRACT
Vegetation development on Surtsey and Mount St. Helens has been influenced by remarkably similar processes. Both are isolated, so colonizers are filtered. In each case, species accumulation and vegetation development were initiated by a few species, with a lag phase before biomass accumulated rapidly. On both, establishment was first concentrated in favorable microsites and facilitated by nutrient inputs. Established plants often fostered other species in both cases. That such contrasting systems exhibit similar mechanisms of community assembly offers important restoration lessons.

INTRODUCTION

Surtsey is a unique, new volcanic island. Mount St. Helens volcano (Washington State) erupted violently in 1980. Each provides a matchless opportunity to explore how ecosystems develop (Walker & del Moral 2003). Here I summarize plant primary succession mechanisms found on Mount St. Helens and compare them to those determining succession on Surtsey.

STUDY AREA

The 18 May 1980 eruptions of Mount St. Helens formed a complex pattern of new and denuded land (Dale *et al.* 2005). This extraordinary landscape beckoned irresistibly to ecologists to study reassembly (Fig. 1). This report draws on studies conducted by myself and colleagues since 1980. Methods are in the references. Vegetation structure was monitored in transects of permanent plots: 12 on Pumice (from 1989), 10 on a lower Ridge (from 1984) and 10 from upper sites on this ridge (from 1989; del Moral 2007).

RESULTS

Species richness and cover

Species assembly was slow. Pumice richness stabilized by 1998, and after 2003 it declined due to an

Fig. 1. Dense lupines along Pumice transect, Mount St. Helens (2007).

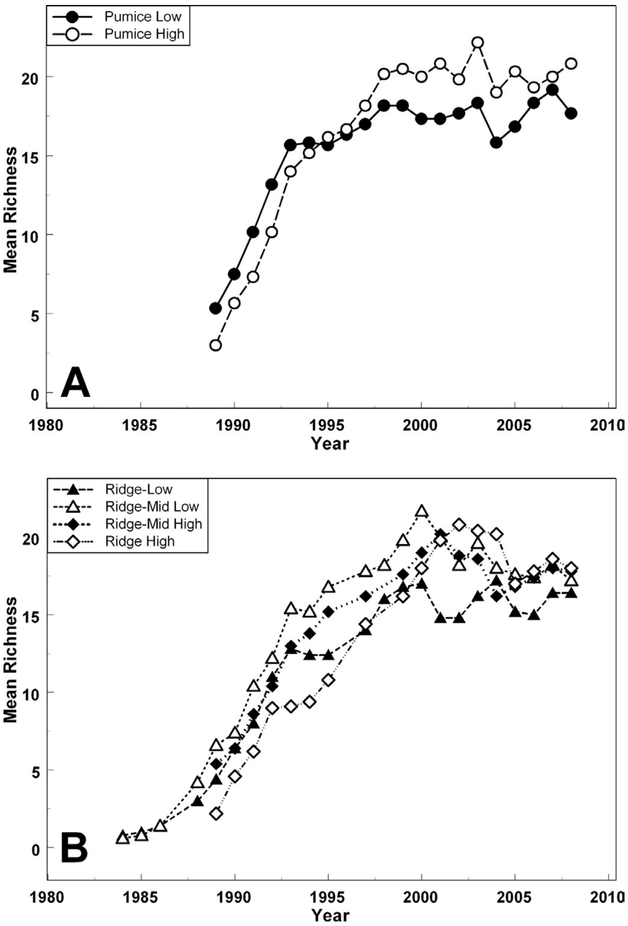

Fig. 2. Species richness in permanent plots on Mount St. Helens. A. Pumice; B. Ridge.

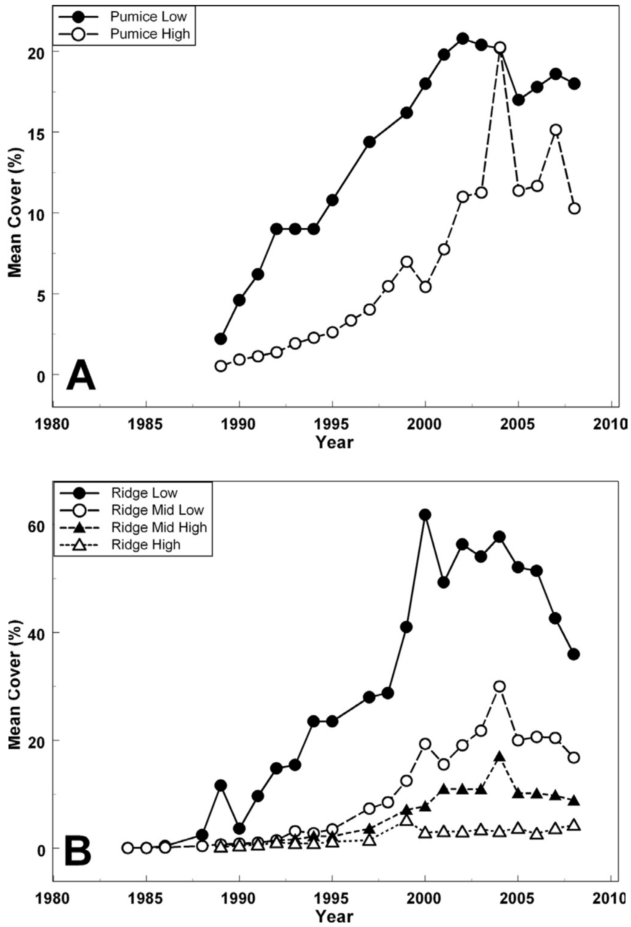

Fig. 3. Vegetation cover in permanent plots on Mount St. Helens. A. Pumice; B. Ridge.

explosion of *Lupinus lepidus* (del Moral & Rozzell 2005). Ridge richness declined after 1998 (Fig. 2). In each case, there was a core of species (stable) and several species with sporadic occurrences. Sporadic species absent for at least the last three years are deemed "extinct" (Table 1). More species persisted at higher elevations where cover was lower.

After a lag, cover on Pumice began to accrue (Fig. 3). Cover in lower plots peaked in 2000, then declined. Cover developed slowly in upper plots. Despite pulses of *L. lepidus* (1999, 2004, 2007), cover was 50% of the lower plots. The rate of development on the Ridge was related to elevation (del Moral 2007). *Lupinus* cover exploded in the lowest plots (1989, 1994, 1999), then declined. By 2008, there was a steady decline of cover with elevation.

Dispersal

Primary succession requires colonization, establishment, development and biotic interactions. In terrestrial systems, colonization is significantly less of a problem than on islands, but dispersal remains a significant constraint (del Moral & Eckert 2005). Seeds dispersed by animals are poorly adapted for

Table 1. Total number of species, stable species, sporadic species and species not found for at least three years after last occurrence in each data set from Mount St. Helens. (Plots were 250 m^2 circles, all species recorded).

Site	Total	Stable	Sporadic	"Extinct"
Pumice—Low	32	21	11	3
Pumice—High	37	25	12	2
Ridge—Low	41	21	20	9
Ridge—Mid Low	34	20	14	9
Ridge—Mid High	37	26	11	8
Ridge—High	34	25	9	6

Note: Pumice plots consist of six plots each, Ridge plots consist of six plots each

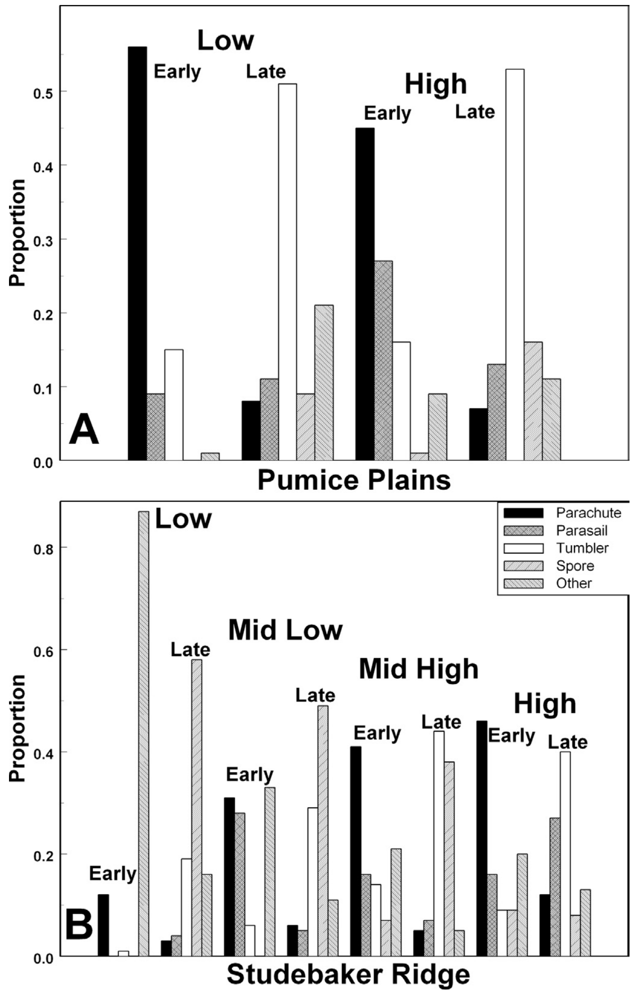

Fig. 4. Dispersal spectra on Mount St. Helens early (first four years) and late (last four years). A. Pumice; B. Ridge.

establishment in stressful sites (Wood & del Moral 1987). Wind dispersed species continue to dominate the flora, but shifts in the dispersal spectrum occurred. Wind dispersed species include Parachute (e.g. *Hieracium*, *Chamerion*), Parasail (e.g. *Abies*, *Carex*), Tumbler (e.g. several grasses, *Eriogonum*, *Polygonum*) or spore bearing (ferns, mosses). The Other category consists primarily of *Lupinus* (explosive dehiscence and ants) but includes a few animal-dispersed species (e.g. *Arctostaphylos*, *Fragaria*).

I summarized the transect data by the first and last four years to characterize the changing species spectra. Species were grouped by dispersal types and the spectra compared (Fig. 4). Pioneers were dominated by parachute species, but mosses and ferns were sparse; these species need facilitation to establish. Over time, dominance by less nimble species increased as they invaded, persisted and expanded. The temporal pattern is also revealed in spatial patterns. The dispersal spectrum changed over short distances. Isolated sites were initially dominated by parachutists, while sites near donors were dominated by other types (del Moral & Ellis 2004).

Safe sites

Initial establishment was facilitated by safe sites (del Moral & Wood 1993). Seedling survival was strongly favored by surface cracks, large rocks and erosion features. As conditions generally improved, seedling establishment became dispersed, and establishment of most species was no longer confined to special habitats.

Facilitation

Facilitation, processes that improve establishment, occurred in two ways. Nutrient inputs in the form of pollen, seeds and spores, insects, spiders, feces from birds (and later elk) and rainfall produced physical amelioration. Once plants established, they produce more organic matter. Thus, development was initially slow, but accelerated with the establishment of nurse plants, notably *Lupinus*. Young *Lupinus* colonies promoted grasses compared to adjacent sites with sparse lupines (del Moral & Rozzell 2005) while old *Lupinus* colonies promoted mosses.

Inhibition

A grid of 100-m^2 plots was sampled in 2008. Dense conifer (*Pinus* and *Abies*) plots (> 35% cover) were compared to sparse conifer plots (< 20% cover). Dense conifer plots had fewer species, lower ground layer cover and were less diverse (Table 2) than plots with sparse conifers. Conifers changed the understory composition and reduced the ground layer vegetation.

Table 2. Structural differences between plots dominated by conifers (cover > 30%) and sparse conifer plots (cover < 20%) on Mount St. Helens. (Dense, n=14; Sparse, n=22; comparisons significant, Wilcoxon rank sum test , P << 0.05).

	Conifers Included		Conifers Excluded	
Parameter	*Conifers Dense*	*Conifers Sparse*	*Conifers Dense*	*Conifers Sparse*
Richness	13.8	17.5	11.8	15.5
Cover (index)	51.3	21.5	5.7	9.9
H’	1.059	1.845	1.813	2.186

Fig. 5. Cracks provide safe sites on Surtsey that permit early establishment (*Cochlearia officinalis*).

Fig. 6. Gull colony on Surtsey demonstrates the importance of facilitation.

COMPARISONS WITH SURTSEY

Dispersal

Both volcanoes illustrate that isolation alone can structure vegetation. On Mount St. Helens, nearly all pioneers were wind dispersed, in contrast to the surroundings. On Surtsey, the sea provided the first few colonists, which still dominate beaches. Once seabird colonies became established, species common to Iceland's shores were introduced. Later, wind dispersed species became established in several habitats. The vegetation on Surtsey and on Mount St. Helens remains impoverished relative to their sources.

Species accumulation

The colonization patterns on Surtsey and Mount St. Helens were similar despite the context differences. Isolation and stress combined to constrain establishment for several years. On Mount St. Helens it took about 10 years to reach 50% of the current richness, and on Surtsey it took about 25 years to reach this point. Clearly, isolation and the late colonization by sea-birds retarded the plant colonization of Surtsey. Arrival does not guarantee persistence. On Surtsey, only 72% of species found in 2008 have viable populations. On Mount St. Helens, about 1/3 of the species are sporadic. These examples emphasize the importance of isolation in driving succession. They suggest that restoration projects cannot depend on spontaneous establishment to provide desirable vegetation and that reintroduction of desirable species is often required.

Safe sites

Safe sites were crucial to early development on Mount St. Helens. On old lava sites, plants established in crevices, while on new surfaces, erosion created favorable microsites and larger rocks offered protection. On Surtsey, upland colonization also appears to have been in cracks in the lava (Fig. 5), while the coarse surfaces on the beach offered refuge to seeds washed ashore. That such different volcanoes offer similar conclusions about establishment emphasizes that restoration plans should pay heed to seedling establishment conditions.

Facilitation

Without facilitation, both Surtsey and Mount St. Helens would have scarcely developed. Seabirds deposit nutrients in and around their colonies (Fig. 6). Wind carries in organic matter to Mount St. Helens and now birds and large mammals contribute nutrients. However, winds reaching Surtsey carry much lower nutrient loads and Surtsey also lacks vascular plants that can fix nitrogen. On Mount St. Helens, two *Lupinus* species and *Alnus* contribute to improving fertility. Both volcanoes demonstrate the importance of soil fertility to the rate of succession. However, where nitrogen is concentrated, as in the gull colonies, dominance by a few nitrophilous species is promoted (Magnússon *et al.*, 2009). Nitrogen levels remain generally low on Mount St. Helens, so that intense competition has not occurred. Restoration scientists who wish

Fig. 7 *Honckenya peploides* acts as nurse plant for *Cakile arctica* on Surtsey.

to develop diverse communities must control fertility.

Plants on both volcanoes can act as "nurse plants", sheltering seedlings until they can become established (Fig. 7). Erosion acts to facilitate succession on both volcanoes. On Mount St. Helens, tephra and mud were removed to reveal old surfaces, pumice rocks were fractured by frost and water channels were formed to support seedling establishment. On Surtsey, wind has moved sand over lava, allowing the invasion of *Leymus* and other species.

Permanent plots

Long-term studies of succession are few (Svavarsdóttir & Walker 2009). Permanent plot studies of succession avoid most problems associated with "chronosequence" studies. They allow us to track internal dynamics (e.g. expansion of species, local extinction, etc.) and climate effects. Studies on Surtsey, where human disturbances are regulated, promise to provide a clear record of succession under several stressful conditions, including how birds influence the pattern and whether succession on lava will result in significant species turnover. Because of its isolation and legal protection, Surtsey will offer ecologists important lessons for decades.

ACKNOWLEDGEMENTS

I thank Borgthór Magnússon and Sigurdur H. Magnússon (of Náttúrufraedistofnun Íslands) for kindly introducing me to Iceland's many natural wonders and for making my 2007 visit to Surtsey both possible and memorable. The U.S.N.S.F. has funded my work on Mount St. Helens since 1980, most recently under DEB-05-41972.

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Succession and benthic community development in the sublittoral zone at the recent volcanic island, Surtsey, southern Iceland

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ABSTRACT

The island Surtsey was formed south of Iceland during an eruption that lasted form 1963 to 1967. The settlement of marine benthic organisms has been monitored at the island from the beginning. First with visits every year but after 1971 with some years between each visit. Since 1984 standard photographs have been shot of the hard substrate in the sublittoral to monitor species composition, cover and density. Data collected 1997 are presented here. In the shallower part of the sublittoral, algae are dominant. Below 15 m depth the cover and density of animals increases and at 30 m algae have disapeared. At the eastern coast the substrate seems more stable than elsewhere along the coast. Multivariate analysis shows two separate communities. A community with a mixture of *Mytilus edulis*, hydrozoans, *Alaria esculenta* and *Polysiphonia stricta,* primarily found where the substrate is unstable, and a community with *Laminaria hyperborea*, deep water red algae, sponges and *Alcyonium digitatum* on the more stable substrate.

INTRODUCTION

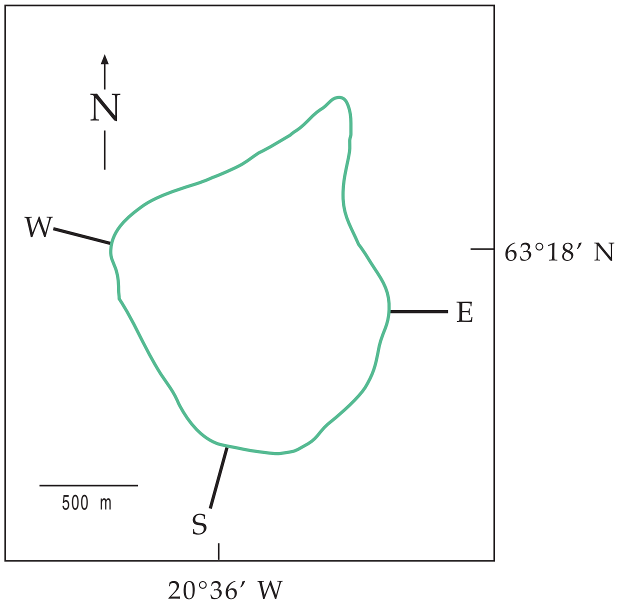
The island Surtsey (63° 18'N, 20° 36'W) was born from seabed at 120 m depth, in a series of eruptions that started in November 1963 and lasted until 1967. It is situated in the Vestmannaeyjar archipelago, about 30 km south of Iceland and 20 km from Heimaey the largest island in the archipelago. Most of the coastline is covered by basaltic rock, except the northern part which is of sand (Calles et al. 1982). Since its formation the island has diminished considerably due to intensive erosion by heavy waves. The break down of the shore is most severe at the south western part of the island. The part of the shoreline where the erosion has been the least is the eastern part (Jakobsson et al. 2000). The seawater around Surtsey is part of the North Atlantic current with salinity at 35.1. The surface temperatures reaches 12 to 13 °C during late summer and falls to 6 °C in the winter. Visibility of the waters in the area is reduces by the outflow of several large glacial rivers at the south coast of Iceland.

Monitoring the colonisation of benthos started as soon as rocky shores were formed in Sutrsey and the first colonizers of the island were found in the littoral zone on a newly formed lava in August 1964 (Jónsson 1966). Soon after the eruption stopped i.e. in 1967 direct sampling of the hard substrate was initiated in the sublittoral zone by diving (Jónsson 1968, Sigurdsson 1968). In the beginning rapidly colonizing species such as mussels, hydroids, filamentous diatoms and the phaeophyte *Alaria esculenta* dominated the substrate. The number of species found at Surtsey increased rapidly the first 10 years but levelled off after 1975 (Jónsson & Gunnarsson 1982, Hauksson 1992). Relatively stable substrate could then be found off the east coast of the island

Two pioneers in the study of the colonisation of marine life at Surtsey, Adalsteinn Sigurdsson and Sigurdur Jónsson recently passed away. They introduced the authors to the studies at Surtsey. This contribution is a tribute to them.

with perennial species growing on top of the biggest rocks and boulders (Jónsson et al. 1987). Due to difficult working conditions, in this extremely wave exposed area, direct studies of community development were difficult. Since 1980 photographs of defined areas of the bottom have been used to monitor the benthic community development.

Already in the beginning of the 80's Jónsson et al. (1987), distinguished two separate seaweed communities in the sublittoral zone at Surtsey, a shallow water community with nearly 100% cover of seaweeds and dominated by *Alaria esculenta* and *Porphyra miniata* growing at 5 to 15 m and a community at 20 to 30 m with much less seaweed cover and dominated by deep water red algae. But significant elements of the marine benthic biota found in neighbouring islands as e.g. crustose corallines, were still missing in Surtsey (Gunnarsson 2000). In this paper we describe the results of a sublittoral benthic community study in Surtsey in 1997.



Figures 1. Surtsey is situated about 20 nautical miles off the south coast of Iceland. Lines shown to the east, south and west of the island represent trancects examined in the present study.

METHODS

In the 1997 marine expedition to Surtsey three transect were studied to the east, south and west of the island (Fig. 1). Studies were made at 5, 10, 15, 20, 25 and 30 m depths. Pairs of divers visited each station took photographs and collected specimens to assist with the identifications of organisms on the photographs. Samples were hand collected into 1 mm mesh size sampling nets. At each depth station 10 photographs were shot covering an area of 40 x 60 cm of the bottom. Only hard substrate was studied. Due to heavy swell some stations on the south and the west transects could not be visited. The species were determined from fresh samples in the ships laboratory with microscopic examination as necessary. Species that could not be determined onboard were fixed in 5% formalin (algae) or 70% isopropanol (animals) for later identification.

Underwater photographs were projected on a 10 by 10 grid and cover of each species was assessed by counting the number of intercepts hitting the species. Individuals of errant species were counted on the images. As species may overlap the added cover of all sessile species can be much higher than 100%. This is not acounted for by our method which gives maximum cover of 100% for the photographed area. MDS plots of the data were created with MATLAB software, using Jaccard metrics. The metrics were one minus the Jaccard coefficient and percentage of nonzero coordinates that differed between images.

RESULTS

Depth distribution

The substrate in the sublittoral zone at Surtsey consists of rocks and boulders with sand in between. Hard substrate could be found at all depths but sand was observed to increase with depth. More sand cover was observed at the southern and western transects than the eastern one. In the shallower part of the sublittoral, algae were dominating on the hard substrate. Below 15 m depth the cover and density of animals increased and at 30 m algae had practically disappeared. On the eastern transect the most abundant algae confined to the shallow water were *Alaria esculenta* and *Porphyra miniata* covering each about 25% of the hard substrate at 5 m and *Polysiphonia stricta* and *Halosiphon tomentosum* covered 13% and 6% of the substrate respectively (Table 1). At 10 m *A. esculenta* and *P. miniata* had reduced their cover by half and similarly *Laminaria hyperborea* and *Desmarestia aculeata* each covered about 12% of the bottom at that depth. At 10 m hydrozoans had the highest cover 17%. At 15 m *A. esculenta* was still prominent with 35% cover and the filamentous brown algae *Ectocarpus siliculosus* had a cover of almost 40%. Below 15 m sessile animals started to dominate the substrate with *Tubularia larynx* and other hydrozoans most common at 20 and 25 m depth. *T. larynx* and *Alcyonium digitatum* dominated at 30 m (Fig. 2). In the deeper part of the sublittoral at 20 to 30 m the only seaweed found were deep water red algal species such as *Phycodrys rubens* and *Lomentaria orchadensis*. The total algal cover at 25 to 30 m was less than 10%.

At the southern and western transects the species number was much lower and algal cover was less. There, hydrozoans were the dominating element with filamentous brown algae, *A. esculenta, P. stricta*

Table 1. Mean cover by depth and transect of benthic species with more than 1% cover in the sublittorlal zone at Surtsey.

Transect			East						West					South		
Depth (m)	5	10	15	20	25	30	**mean**	5	10	15	20	25	**mean**	15	20	25	**mean**
Hydrozoa (excl. *Tubularia*)	2,7	17,5	1,9	23,3	34,5	17,0	**16,1**	1,9	18,6	38,9	51,6	65,9	**35,4**	7,8	64,9	58,4	**43,7**
Alaria esculenta	25,1	12,4	35,7	0,7	0,1	0,0	**12,3**	0,0	2,4	9,7	0,0	0,0	**2,4**	22,5	0,0	0,9	**7,8**
Tubularia larynx	0,0	0,0	0,0	2,0	20,1	36,7	**9,8**	0,0	0,3	1,4	21,3	12,9	**7,2**	0,0	0,0	0,0	**0,0**
Filamentous brown algae	6,4	1,5	38,3	2,1	7,8	1,0	**9,5**	34,3	39,5	43,4	0,0	0,1	**23,4**	17,2	0,5	1,0	**6,2**
Porphyra miniata	26,0	12,0	0,2	3,0	0,0	0,0	**6,9**	0,2	0,1	0,1	0,0	0,0	**0,1**	0,0	0,0	0,0	**0,0**
Alcyonium digitatum	0,0	0,0	0,0	0,1	0,0	28,0	**4,7**	0,0	0,0	0,1	0,0	0,3	**0,1**	0,0	0,0	0,6	**0,2**
Desmarestia aculeata	0,0	11,3	0,0	8,1	8,4	0,0	**4,6**	0,0	0,0	0,0	0,0	0,0	**0,0**	0,4	0,0	0,0	**0,1**
Laminaria hyperborea	0,0	12,0	0,0	9,2	0,0	0,0	**3,5**	0,0	0,0	0,4	0,0	0,0	**0,1**	0,0	0,9	0,1	**0,3**
Polysiphonia stricta	13,0	3,4	1,4	0,9	0,2	0,2	**3,2**	0,0	24,6	1,1	0,0	0,0	**5,1**	2,2	0,0	0,0	**0,7**
Delesseria sanguinea	0,0	0,6	0,0	4,1	6,3	0,0	**1,8**	0,0	0,0	0,9	0,0	1,5	**0,5**	0,3	0,0	0,3	**0,2**
Phycodrys rubens	0,0	2,2	0,1	7,3	0,5	0,7	**1,8**	0,0	0,0	0,5	0,8	0,2	**0,3**	0,4	0,4	1,0	**0,6**
Halosiphon tomentosum	6,1	0,3	0,1	0,0	0,0	0,0	**1,1**	0,0	0,0	0,0	0,0	0,0	**0,0**	12,1	0,0	0,0	**4,0**
Ulvaria fusca	2,8	2,5	0,0	0,0	0,0	0,0	**0,9**	0,0	0,0	0,0	0,0	0,0	**0,0**	0,0	0,0	0,0	**0,0**
crustose Bryozoa on stones	0,1	1,0	0,0	3,4	0,2	0,2	**0,8**	0,0	0,1	0,2	0,2	0,3	**0,2**	0,2	0,6	0,3	**0,4**
Mytilus edulis	0,0	0,0	4,1	0,1	0,0	0,0	**0,7**	0,0	0,9	18,1	0,0	0,0	**3,8**	7,5	0,1	0,0	**2,5**
Bryozoa on algae	0,0	0,0	0,0	0,4	3,1	0,0	**0,6**	0,0	0,0	0,0	0,0	0,0	**0,0**	0,1	0,0	0,1	**0,1**
Desmarestia viridis	0,0	0,0	0,0	3,2	0,1	0,0	**0,6**	0,0	1,2	0,0	0,0	0,0	**0,2**	0,2	0,0	0,0	**0,1**
Grantia compressa	0,5	0,2	0,0	0,7	1,8	0,0	**0,5**	0,0	0,4	0,3	1,0	0,8	**0,5**	0,0	0,2	0,6	**0,3**
Lomentaria clavellosa	0,0	2,7	0,0	0,1	0,0	0,0	**0,5**	0,0	0,0	0,0	0,0	0,0	**0,0**	0,5	0,2	0,0	**0,2**
Chorda filum	1,9	0,0	0,2	0,1	0,0	0,0	**0,4**	0,0	0,0	0,0	0,0	0,0	**0,0**	3,8	0,0	0,0	**1,3**
Cirripedia	0,2	0,1	0,3	0,1	0,1	1,0	**0,3**	0,0	0,0	0,4	0,6	0,7	**0,3**	0,4	0,5	0,3	**0,4**
Lomentaria orchadensis	0,0	0,8	0,0	0,5	0,2	0,0	**0,2**	0,0	0,0	0,6	0,7	1,1	**0,5**	0,0	0,0	0,0	**0,0**
Ophiopholis aculeata	0,0	0,1	0,0	0,1	0,0	0,0	**0,0**	0,0	0,0	2,7	0,0	0,0	**0,6**	0,0	0,2	0,0	**0,1**
Alaria esculenta juv.	0,0	0,0	0,0	0,0	0,0	0,0	**0,0**	0,3	0,0	0,0	0,0	0,0	**0,1**	0,0	8,6	0,0	**2,9**

and *Halosiphon tomentosum* abundant at 5 to 15 m and at 15 m *Mytilus edulis* covered nearly 20% of the bottom. Deeper, *T. larynx* and other hydroids, were dominating.

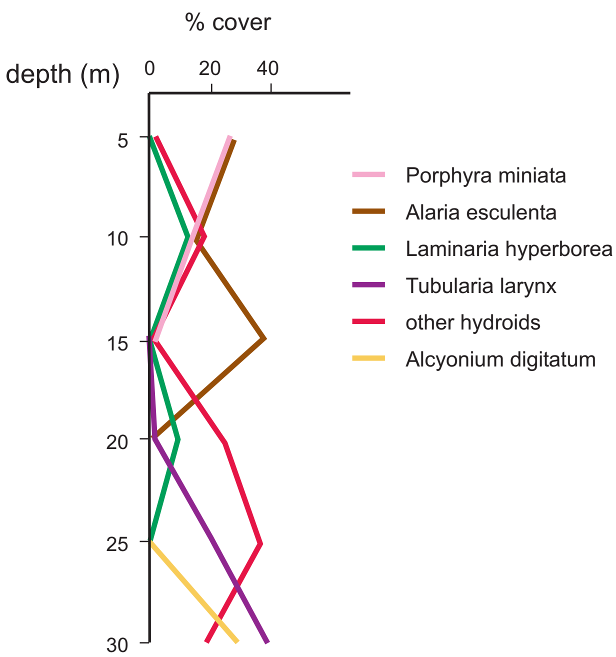


Figure 2. Cover of the most common sessile organisms in the sublittoral zone in relation to depth on the east transect.

Community structure

Multivariate analysis indicate the presence of two separate communities. A community in shallow water with a mixture of brown and green algae and shallow water red algae and a community in deeper water with deep water red algae, barnacles, gastropods, sponges (Fig. 3). Species occurring mainly in the shallow water community include hydrozoans and the algae *Alaria esculenta*, *Porphyra miniata*, *Polysiphonia stricta* and *Halosiphon tomentosum* (Fig. 4). In the deeper community *Laminaria hyperborea*, *Phycodrys rubens*, *Alcyonium digitatum* and *Tubularia larynx* dominate (Fig. 5 and 6).

Multivariate analyses of picture data showed a rather clear separation of pictures from the south and west coast from pictures taken in the east. Also most of the pictures taken at the deeper stations clustered together and the pictures from the shallower stations on the east coast grouped into another less distinct cluster (Fig. 7).

DISSCUSSION

The sublittoral zone at Surtsey is extremely exposed to wave action especially at the south and the western part as prevailing winds are south-westerly. The heavy waves, that can reach significant wave hights of about 17 m, have caused rapid breakdown of the island which has been reduced to about half of its original surface area (Viggósson et al. 1994, Jakobsson et al. 2000). Jakobsson et al

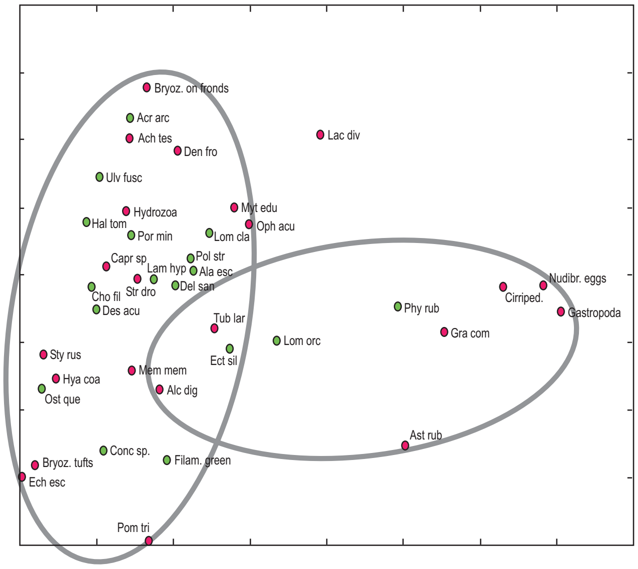


Figure 3. Multidimentional scaling (MDS) plot of the most abundant species in the shallow water (on the left) and deep water community (on the right) encircled by two ellipses. Red dots: animals; green dots: seaweeds.

Key to symbols on the plot: Ach tes, *Achmaea tessulata*; Acr arc, *Acrosiphonia arcta*; Ala esc, *Alaria esculenta;* Alc dig, *Acyonium digitatum*; Ast rub, *Asterias rubens*; Bryoz on fronds, bryozoans forming crusts on algae other than *Membranacea membranacea;* Byoz. tufts, tuftlike bryozoans; Capr sp, *Caprella* sp; Cho fil, *Chorda filum*; Cirriped., includes primarily *Balanus balanus* but also *Balanus hammeri* and *Verruca stroemia*; Conc sp., *Conchocelis* sp; Del sang, *Delesseria sanguinea*; Den fro, *Dendronotus frondosus*; Des acu, *Desmarestia aculeata*; Ech esc, *Echinus esculentus*; Ect sil, *Ectocarpus siliculosus*; Filam. green *Urospora* sp.; Gastropoda includes *Gibbula tumida, Margarites groenlandicus, Margarites helicinus, Nassa incrassata;* Gra com, *Grantia compressa*; Hal tom, *Halosiphon tomentosum*; Hya coa, *Hyas coarctatus*; Hydrozoa; several species of hydrozoans; Lac vin, *Lacuna vincta*; Lam hyp, *Laminaria hyperborea*; Lom cla, *Lomentaria clavellosa*; Lom orc, *Lomentaria orcadensis*; Mem mem, *Membranipora membranacea*; Myt edu, *Mytilus edulis*; Nudibr. Eggs, nudibranch eggs; Oph acu, *Ophiopholis aculeata*; Ost que, *Ostreobium queckettii*; Phy rub *Phycodrys rubens*; Pol str, *Polysiphonia stricta*; Pom tri, *Pomatoceros triqueter;* Por min, *Porphyra miniata*; Str dro, *Strogylocentrodus droebachiensis*; Sty rus, *Styela rustica*; Tub lar, *Tubularia larynx*; Ulv fusc, *Ulvaria fusca.*

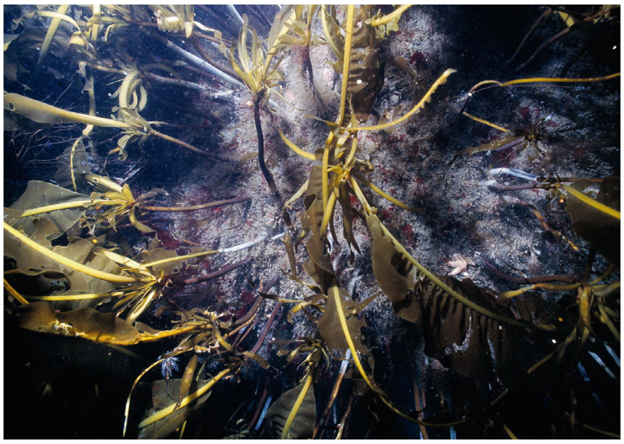


Figure 4. Shallow water benthic community at Surtsey is dominated by rapid colonising species as e.g. in this case hydroids and *Alaria esculenta. Lacuna vincta* snails can be seen on the fronds of *A. esculenta* that has grazing marks from the snail.

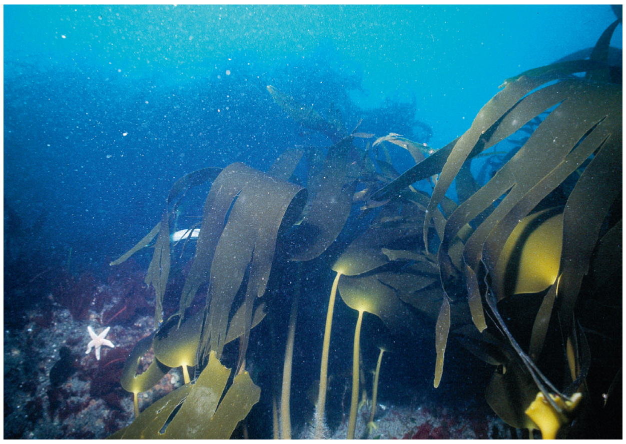


Figure 5. Patches of perennial *Laminaria hyperborea* forest have developed on upper surfaces of large rocks sheltered from moving sand and gravel at the east coast of Surtsey.

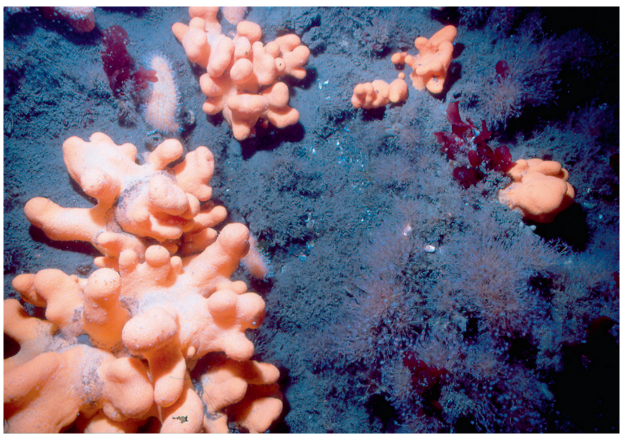


Figure 6. At depths below 20 meters the community is dominated by hydroids, especially *Tubularia larynx* and the octocoral *Alcyonium digitatum.*

(2000) predict that the islands recession will continue at a relatively fast albeit diminishing rate for more than a century to come. Gradually the lava covering the southern half of Surtsey will dissapear and the island will take on the same form as many of the other, older islands, of the Vestmannaeyjar archipelago that are mainly made of palagonite tuff with steep cliffs all-around. In light of the likely geological development, the biota of the littoral and sublittoral zone in Surtsey is probably still far from any final or climax stage in its development.

In the MDS-plots it can be seen that in the shallow sublittoral zone there was little difference between transects. The substrate was dominated by small *Mytilus edulis*, hydroids, *Alaria esculenta, Ectocarpus siliculosus,* and *Polysiphonia stricta.* These were represented by young individuals and the substratum seems to have been recolonized every year by the same group of species since the eruption stopped (Sigurdsson 1968, Jónsson 1968, Jónsson et al. 1987, Hauksson 1992, 2000). The shallow community is considered to represent an early successional stage. The abration caused by sand and gravel put into motion by the waves, especially during winter, is preventing the organisms to become permanently established in the shallow sublittoral zone all around the island. Due to continuous breakdown of the shoreline at the southwestern part of the island, gravel and stones roll down the submarine slopes killing the biota in their path and provide new substrate for colonisation. Here the sucession is also at an early stage. The eastern transect differed from the other transects. At middle depths it was characterised by the large perennial *Laminaria hyperborea* growing on the largest rocks and with *Alcyonium digitatum* dominating at the greater depths. This is in accordance with the fact that the substrate at the east coast of Surtsey is more stable than at other parts of the coast. At this transect the species diversity was also highest. These communities are considered to represent later successional stages.

No previous studies on the benthic colonisation of a whole island, isolated from other communities are available. A few studies have been undertaken on colonisation of lava flows that have partly covered areas with established benthic communities. Gulliksen et al. (1980) studied benthic colonisation of a lava flow in the sublittoral zone at Jan Mayen, eight years after its formation. In the shallow part of the sublittoral the fauna found on the new lava was similar to the fauna of the area not affected by the lava but at deeper stations the animal diversity was still significantly lower than on the old ground. Studies of a new lava flow at Heimaey, that was formed 10 years after Surtsey, indicated that the proximity of the established biota greatly affects the colonisation rate (Gunnarsson 2000).

Connell & Slatyer (1977) proposed three models to explain how early successional species could affect their replacement by late successional species. The early successional species could (1) facilitate, (2) tolerate or (3) inhibit the establishment of the late successional species. It is likely that, at Surtsey, space limitation caused by rapid colonisation of mussels and hydrozoans and the shading provided by *Alaria esculenta* might have retarded the settlement and growth of perennial species such as *Laminaria hyperborea* and *Alcyonium digitatum*. Similarily experimental studies on rocky shores indicate that early successional species most often delay the establishment of late successional species (Dean & Hurd 1980, Sousa 1984).

Further influence on the successional process is likely to come from several species of consumers that have increased their abundance in the sublittoral zone in Surtsey. Those are particularly *Asterias rubens* feeding on mussels, nudibranch species feeding on hydrozoans and *Lacuna vincta* feeding on algae, in particular *Laminaria hyperborea* and *Alaria esculenta* (Hauksson 1992). By selectively feeding on early successional species we expect that these consumers will have accelerated the establishment of late successional species. Similar results have been obtained elsewhere for the littoral and the sublittoral zone (Lubchenco 1983, Kennelly 1983, Kim 1997). The results from Surtsey therefore seem to indicate that the inhibition model of Connell & Slatyer (1977) best describes the successional processes in operation in the sublittoral zone, but that complex interactions between different trophic levels may affect the rate of succession.

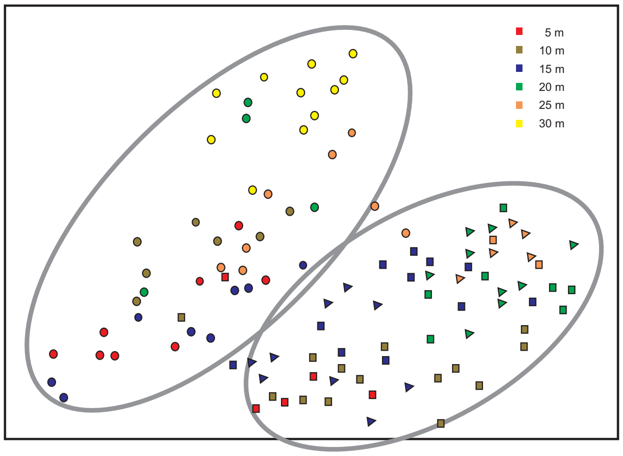


Figure 7. Multidimentional scaling (MDS) plot of pictures from the sublittoral zone at Surtsey in 1997. Circles: east transect; triangles: south transect; squares: west transect.

ACKNOWLEDGEMENT

We thank Kristinn Gudmundsson, Anton Galan and Erlendur Bogason for assistance in collecting samples in diving. We also thank the crew of rv Bjarni Saemundsson for their help during the expedition to the island of Surtsey in 1997.

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Seals in Surtsey, the period 1980–2005

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ABSTRACT

The author has been surveying common and grey seals on the coast of Iceland since 1980 and here are taken together all aerial sightings on Surtsey. The grey seal (*Halichoerus grypus* Fabricius) has established a considerable breeding site on the northern spit of the Surtsey island, which is now one of the biggest rookeries on the southern shores of Iceland, with estimated 63 (95% CI 62 – 66) pups born there in the autumn of year 2005. On the other hand, the common seal (*Phoca vitulina* L.) has not been numerous in Surtsey during its breeding time in the summer. Breeding sites of common seals on the South-Coast of Iceland closest to Surtsey are Ölfusá, Thjórsá, Markarfljót and Kúdafljót. They, however, haul-out in great numbers on the northern shores on Surtsey during the winter, presumably using the island as a resting place after making feeding trips to the adjacent waters.

INTRODUCTION

The author has been participating in research on sub-tidal marine invertebrates at Surtsey since 1972 (Hauksson 1974 & 1993), and has been surveying common and grey seal numbers on the coast of Iceland since 1980. He published a paper on seals on Surtsey in year 1992 and presented data on seals there until year 1989 (Hauksson 1992). Most of this data is presented here again for comparison with the newer data, from 1990 to 2005. Fridriksson (1994) made notice on that grey seal breed

Table 1. Observations on seals in Surtsey and vicinity from aerial surveys during the summer, aimed for common seals.

Day	Time of counting	Common seals	Grey seals	Time of midday	Weather	Tide	Time of low tide
11-Aug-1980	14:01	20	1	13:33	Wind force 1–2, cloudy	Spring tide	12:09
22-Jul-1985	14:57	4	3	13:34	NW-breeze, lightly cloudy	Spring tide	15:30
11-Jul-1988	12:18	0	6	13:33	N-4, lightly cloudy	Spring tide	16:11
09-May-1989	17:30	9	0	13:24	S-4, lightly cloudy	-	14:00
12-Aug-1990	16:40	18	0	13:33	S-breeze	Spring tide	15:27
12-Aug-1992	12:53	0	27	13:26	No wind cloudy	Increasing tide	11:17
23-Aug-1995	11:15	6	0	13:30	SV-4, cloudy	Neap tide	11:00
06-Aug-2003	20:57	2	1	13:26	NV-4, lightly cloudy	Neap tide	18:23

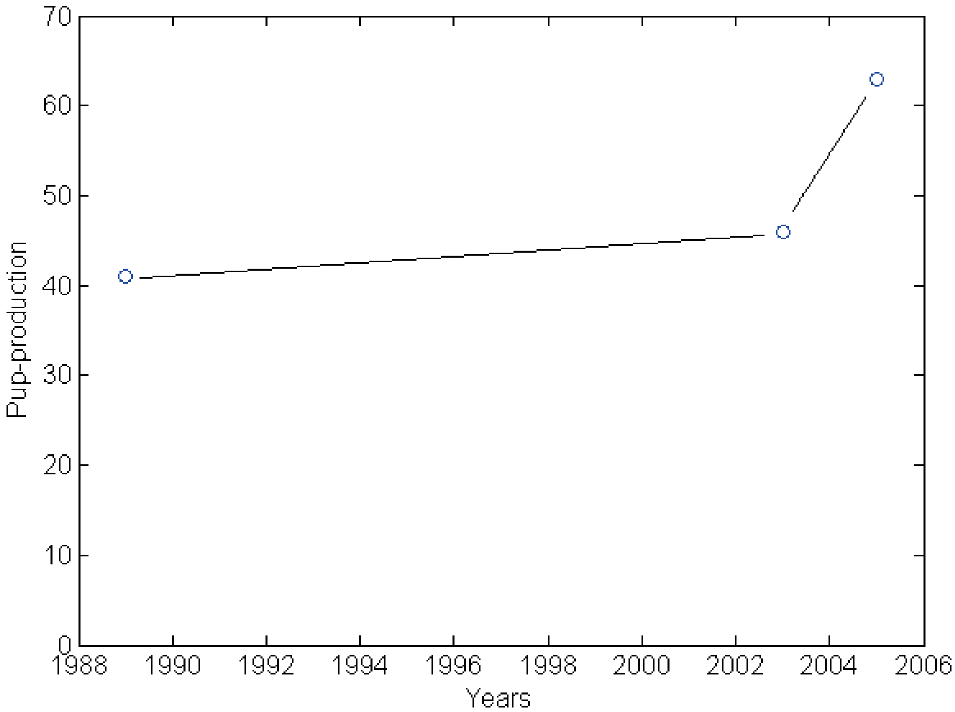

Fig. 1. Total estimated pup-production of the grey seal herd breeding on Surtsey, in years 1989, 2003 and 2005.

regularly on the island but common seals only sporadically.

MATERIAL AND METHODS

Here are combined the seal sightings on Surtsey and neighbouring waters from year 1980 to 2005. Further information about the grey seal pups surveys are published in (Hauksson 2007) and the common seal aerial census is described in (Hauksson 2009). Analyses of data and estimation of the grey seal breeding O-give for years 1989 and 2003 is described in (Hauksson 2007), and for year 2005 in (Hauksson unpublished).

Table 2. Observations on grey seals in Surtsey and vicinity from aerial surveys during the autumn, aimed for grey seal pups.

Day	Time	Pups	Adults	Notes
8-okt-1982	15:45	0	0	
19-okt-1986	13:14	34	16	
9-okt-1988	10:30	1	1	
21-nóv-1988	11:30	15	11	
25-okt-1989	11:05	3	1	
21-nóv-1989	10:55	35	0	
13-des-1989	12:00	73	0	Three white pups, 70 weaned pups
3-nóv-1990	11:00	23	0	
2-nóv-1992	10:30	35	-	
19-okt-1995	16:10	39	-	
15-okt-1998	-	30	-	Karl Gunnarsson counted on foot (personal comm.)
16-okt-2002	11:36	22	-	
6-nóv-2002	12:55	35	-	
10-sep-2003	14:10	3	-	
8-okt-2003	10:12	23	-	
30-okt-2003	11:11	37	-	
21-nóv-2003	9:40	8	-	
9-des-2003	16:02	5	-	
24-sep-2005	10:45	10	-	
20-okt-2005	13:00	34	-	
11-nóv-2005	10:30	29	-	
25-nóv-2005	12:50	66	-	Six white pups, 60 weaned pups

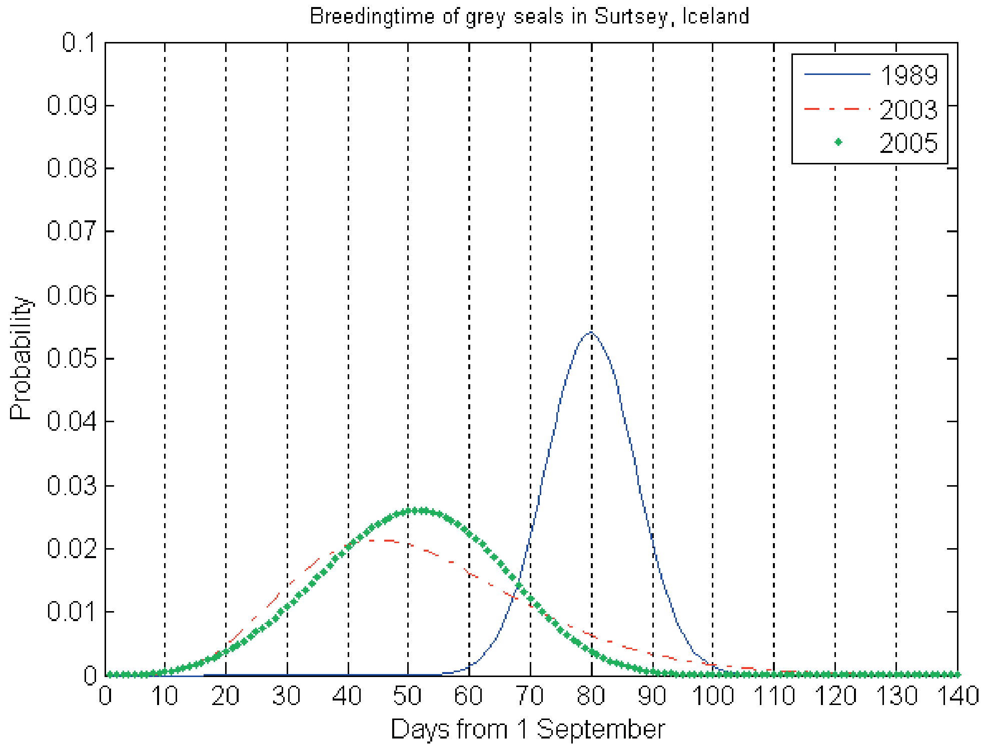

Fig. 2. Grey seal pup birth O-give for the breeding site in Surtsey, the autumn of the years of 1989, 2003 and 2005.

RESULTS

Only few common seals have ever been observed in Surtsey during August, and hardly any during the autumn months (Table 1).

The first time the author observed grey seals in Surtsey from the air, was in August 1980, and grey seals has been regularly seen there since (Table 1). In 1989 estimated pup-production on the breeding site there was at least 41 pups, in 2003 a total of 46 and in 2005 a total of 63 (95% CI 62–66) pups were born (Fig. 1). The maximum breeding date was the 19 of November, the 15 of October and 24 of October, in year 1989, 2003 and 2005 respectively. A normal, a gamma and a weibull probability distribution curve described the pup data best, in 1989, 2003 and 2005 respectively (Fig. 2).

DISCUSSION

It is not known why the peek birthing date of grey seals in Surtsey was about month earlier in year 2003 and 2005, compared with year 1989. However, the birthing O-give in 1989 was only based on three non-zero counts, which is the absolute minimum for fitting a normal distribution, so it was not as sound as the O-give in 2003 and 2005, which was based on five and four non-zero counts respectively. But there is evidence for different peek birthing dates in the same rookery in different years in Breidafiord, W-Iceland, but the reason for it is only speculative (Hauksson 2007).

The grey seal has established a sizeable breeding site on the northern spit of Surtsey, which is now one of the biggest rookeries on the southern shores of Iceland. It is of similar size in 1989 and 2003, but there is an increase in 2005, which implies a 2% annual increase in the study period of 1989–2005. This is in spite of considerable decrease in the Icelandic grey seal population (Hauksson 2007). All hunting is prohibited in Surtsey and only researchers are allowed to visit and stay on the island, so it can truly be said that the grey seal rookery in Surtsey is protected. That may be the reason for the observed increase in pups. In the unprotected rookeries on the South- and West-Coast of Iceland, the grey seals have decreased the most (Hauksson 2007).

The common seals are not numerous in Surtsey during breeding in the summer. Their main breeding sites on the South-Coast of Iceland closest to Surtsey are Ölfusá, Thjórsá, Markarfljót and Kúdafljót (Hauksson 2009). They however haul-out in great numbers there during the wintertime, when feeding. So it seems that Surtsey is not as important for breeding of common seals as it is for the breeding of grey seals. There is also evidence for grey seals driving common seals a way from places they have colonized (Hauksson & Ólafsdóttir 2004; Hauksson et al. 2004).

ACKNOWLEDGEMENT

The Research Committee for Biological Seafood Quality has funded all the aerial surveys of its own accord, except the surveys in 2003 which was a cooperation between the Committee and the Marine Research Institute. This is highly appreciated.

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ISSN 1608-0998

ISSN 1608-0998

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