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).

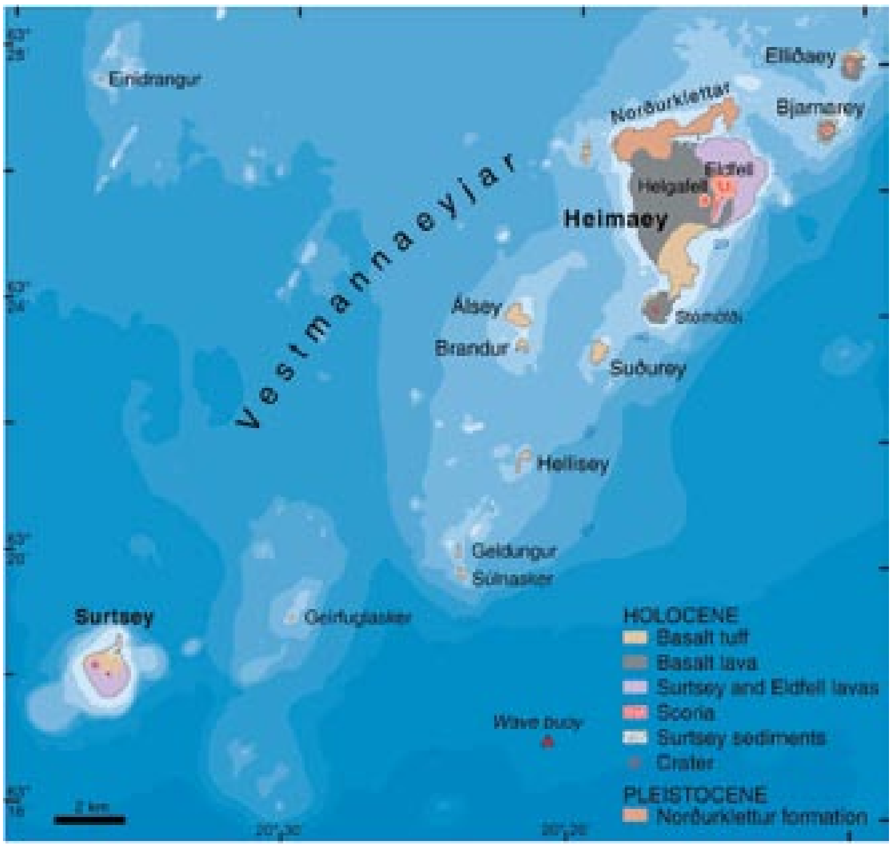


Figure 1. Simplified geological map of the Vestmannaeyjar archipelago. Depth contour lines are in meters. The Surtsey volcano is depicted as in 2007. The coastline of Surtsey island is based on aerial photographs from July 2007. The position of the wave buoy of the Icelandic Maritime Administration is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

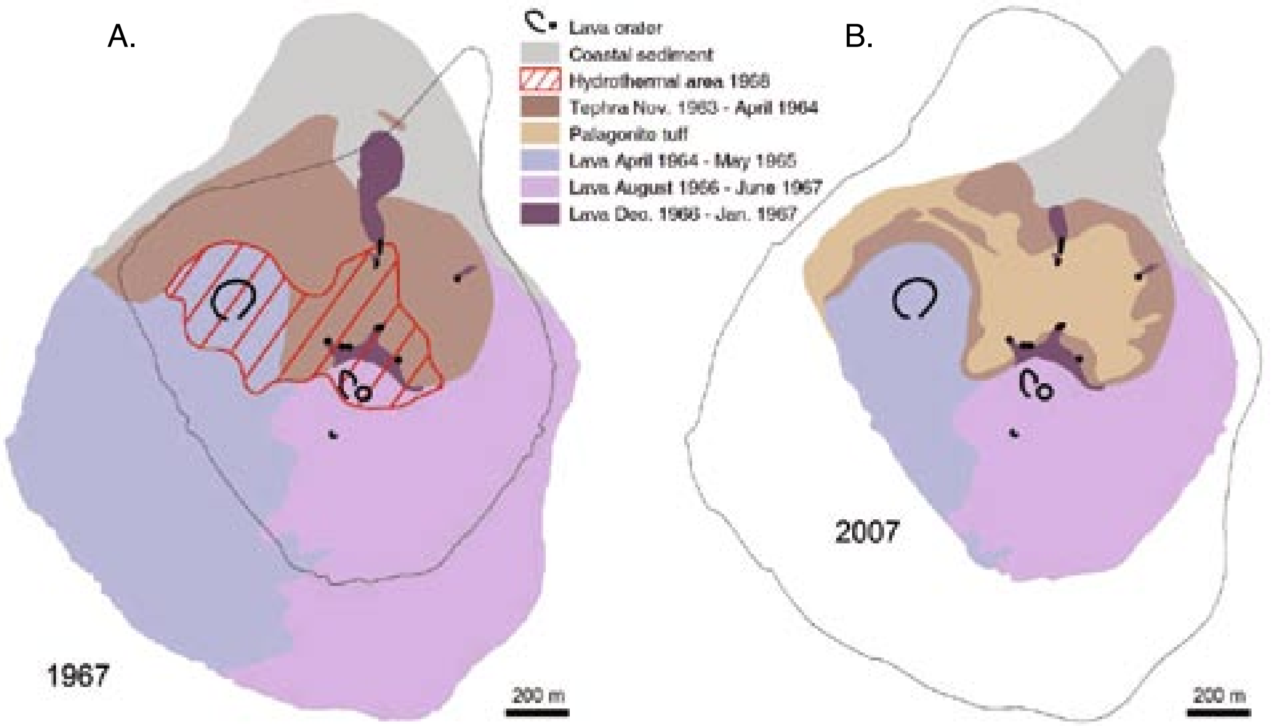


Figure 2. Geological map of Surtsey. A. As in 1967, with approximate extent of the hydrothermal area as in 1968; the outline of the island is based on aerial photographs from August 1967. B. As in 2007; the outline of the island is based on aerial photographs from August 2007. This diagram also illustrates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

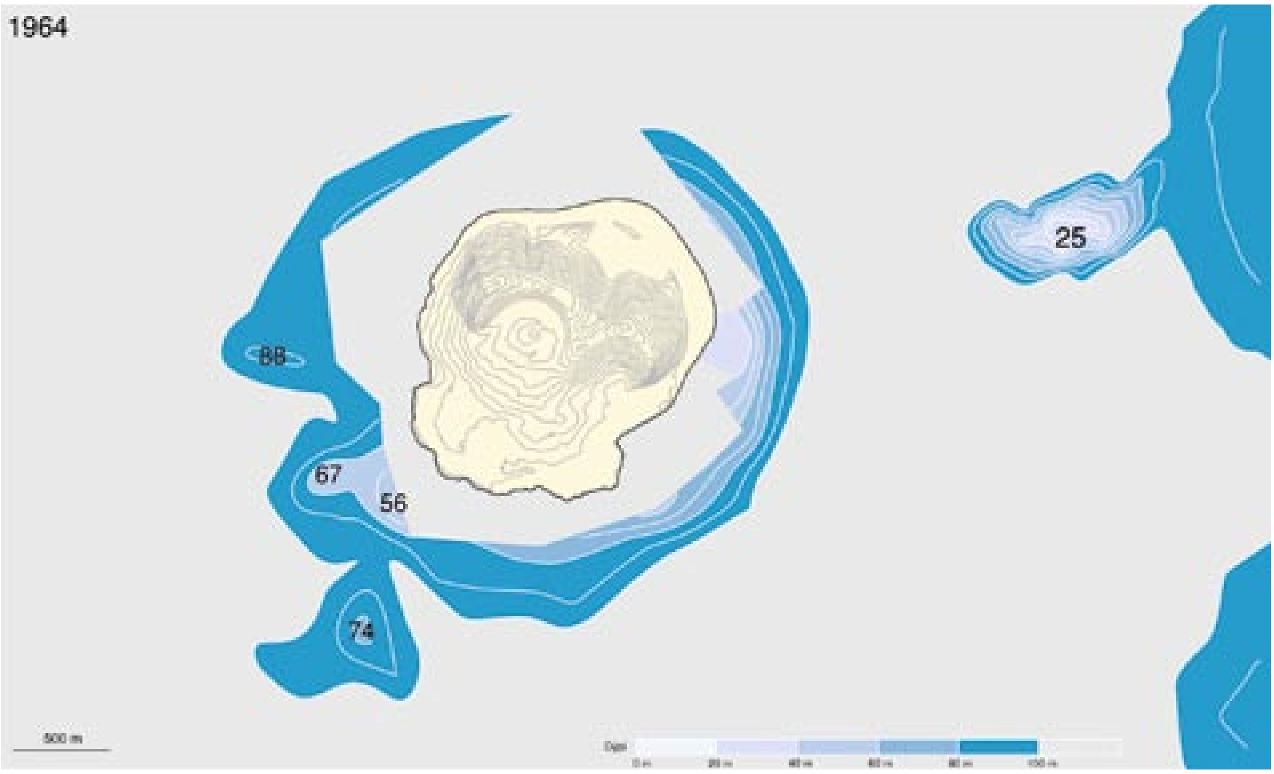
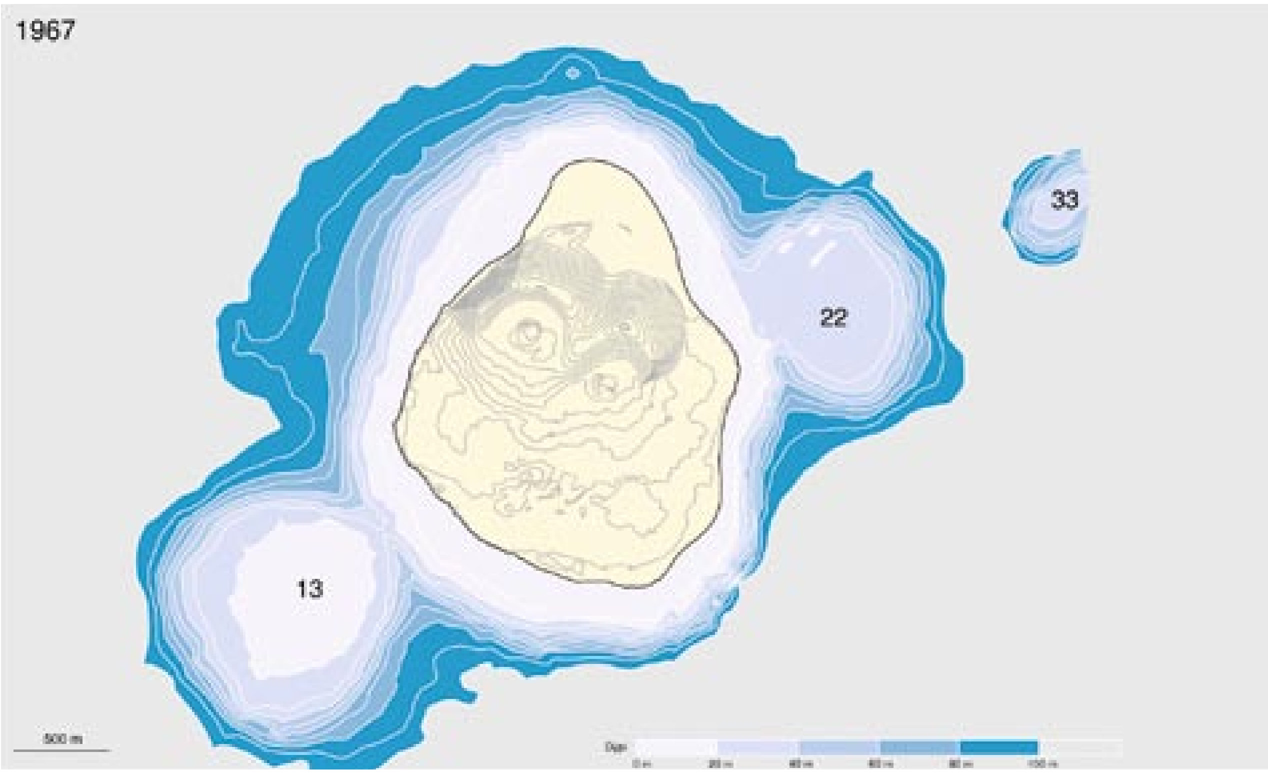
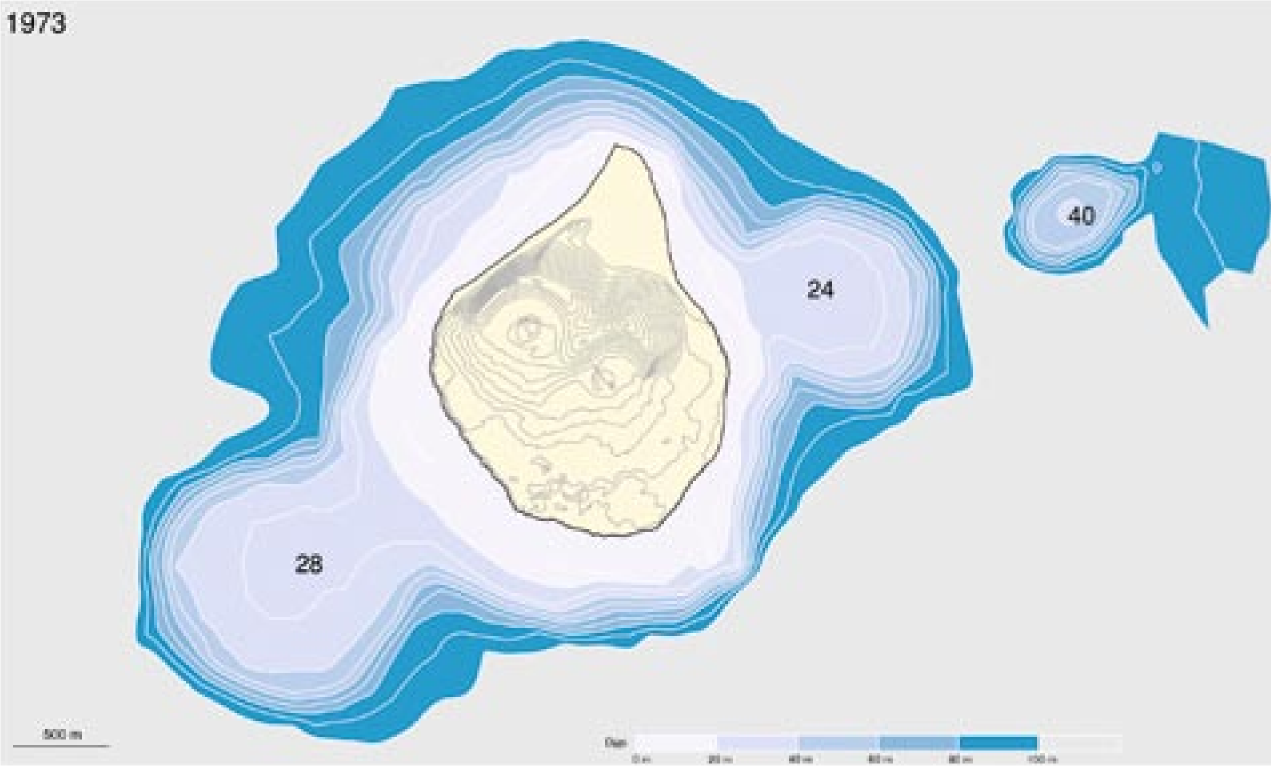


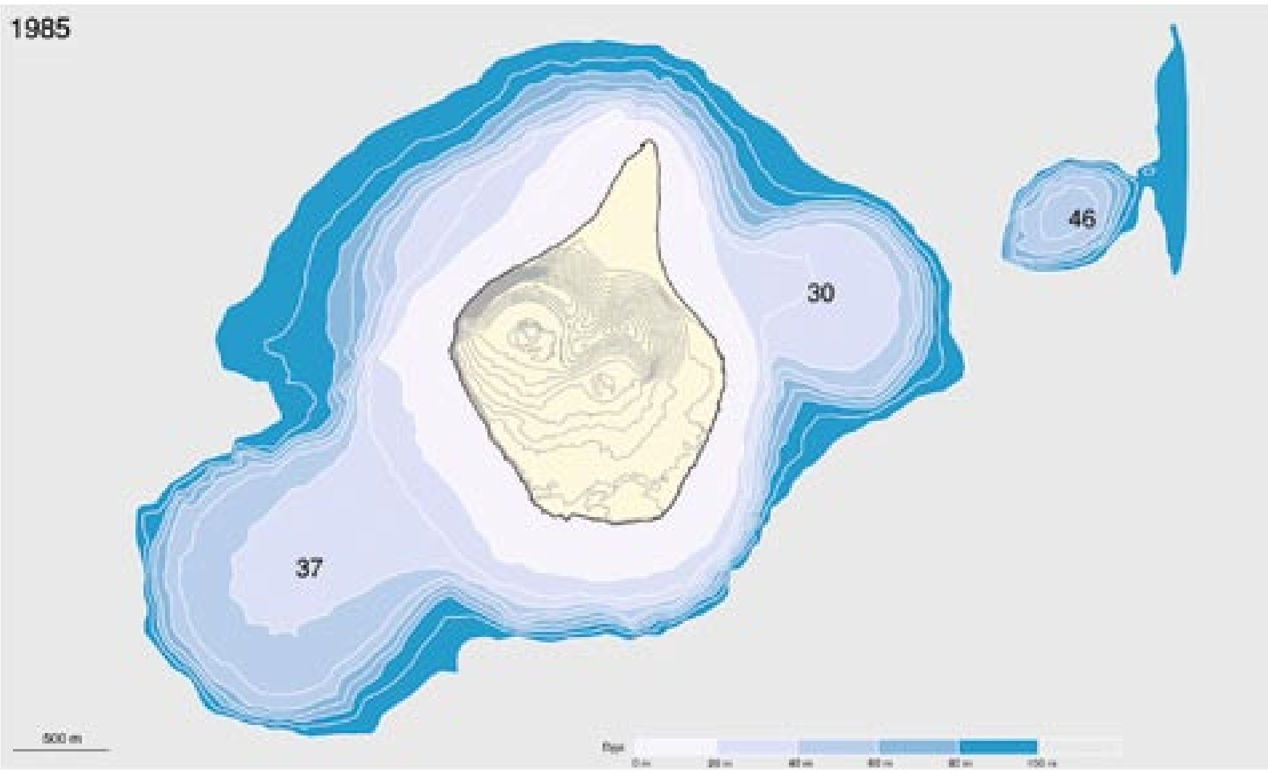
Figure 4. The development of the sea floor topography around Surtsey, 1966–2007. Depth contours at 10 m intervals. See main text for discussion.
A: depth soundings of July–August 1964 (Kjartansson 1966). The topography of Surtsey is based on aerial photographs from August 1964. The irregular shape of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



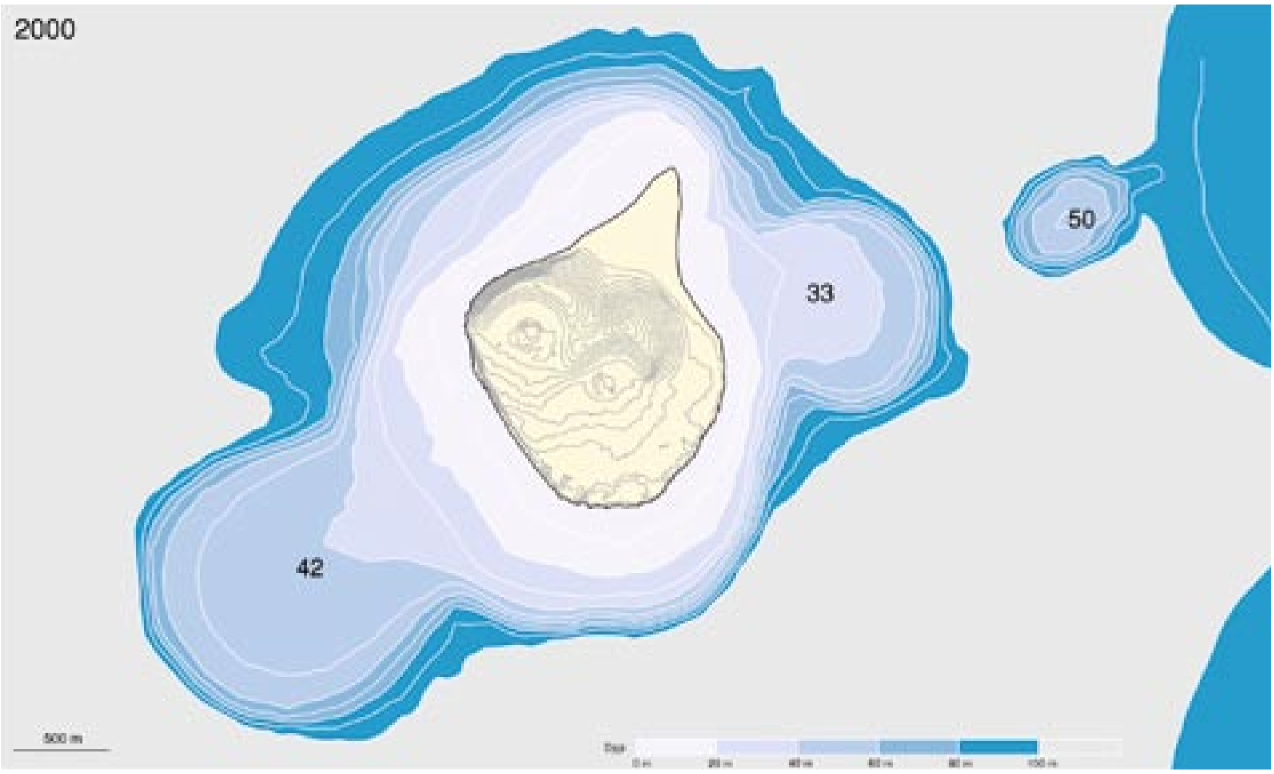
B: depth soundings of July 1967 (Sigurdsson 1968). The topography of Surtsey is based on aerial photographs from August 1967.



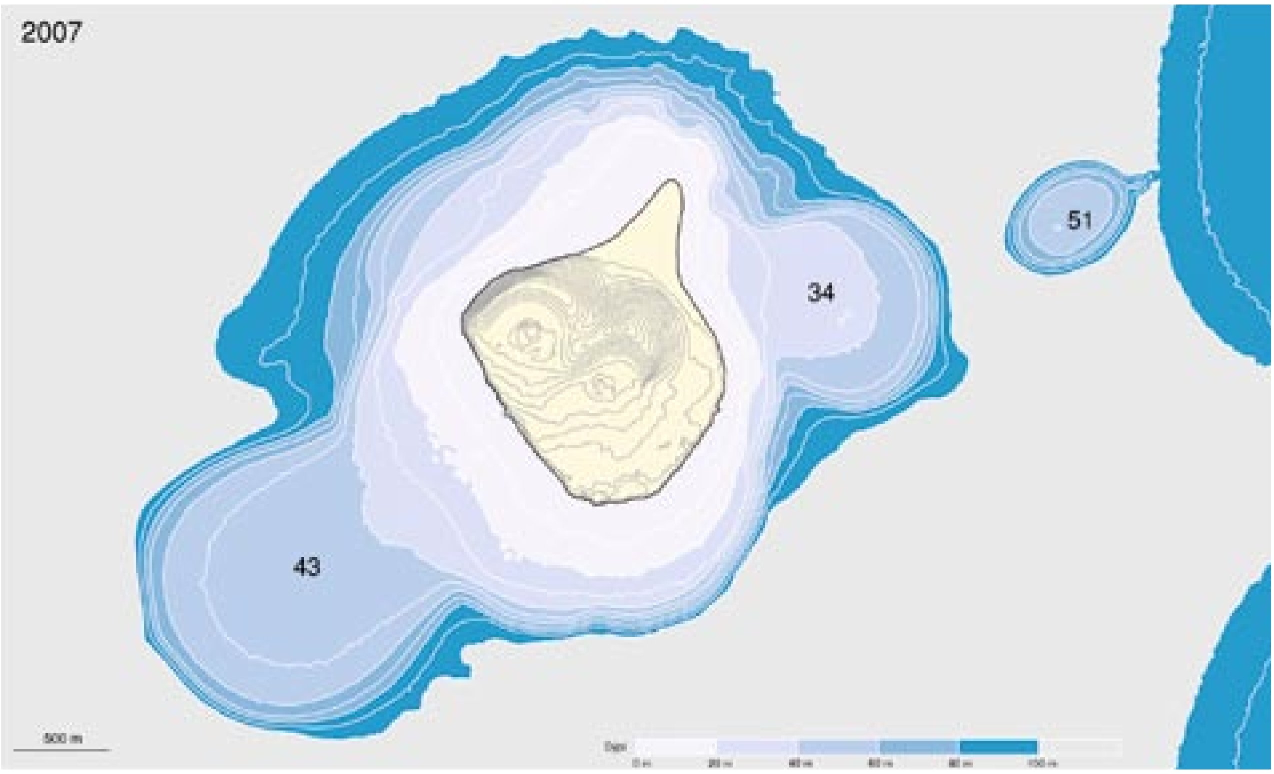
C: depth soundings of July 1973 (Icel. Hydrogr. Service). The topography of Surtsey is based on aerial photographs from July 1975.



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.

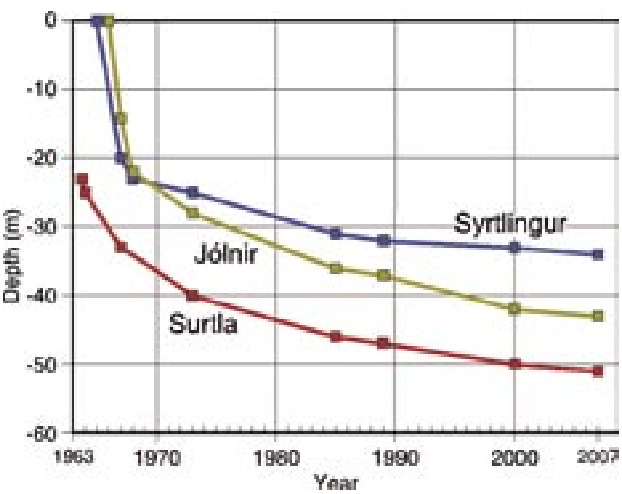


Figure 5. The erosion of the submarine hills of Surtla, Syrtlingur and Jólnir, with reference to mean depth of the top platform, cf. Table 1.

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

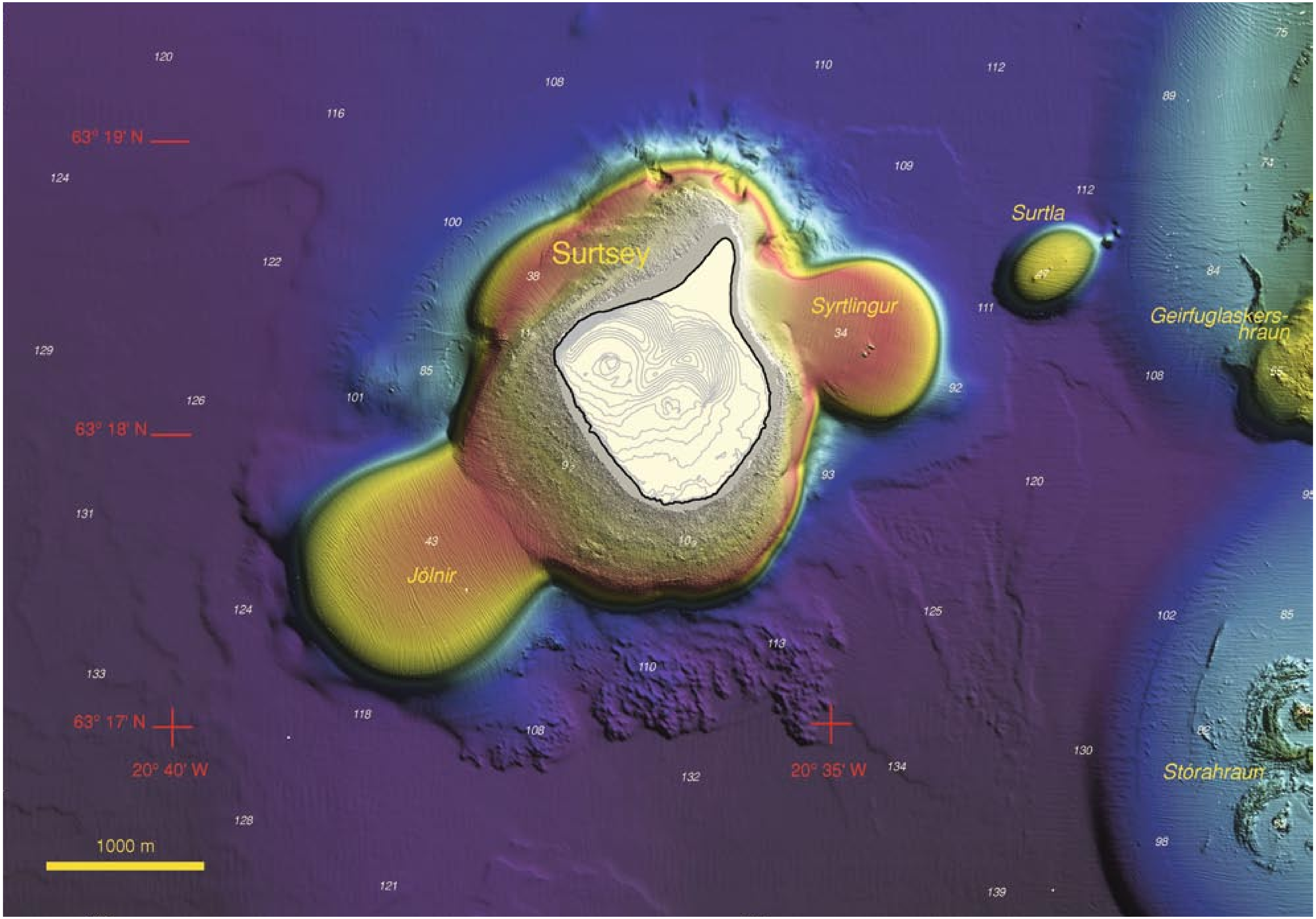


Figure 3. The 2007 bathymetry map of Surtsey volcano and surroundings.

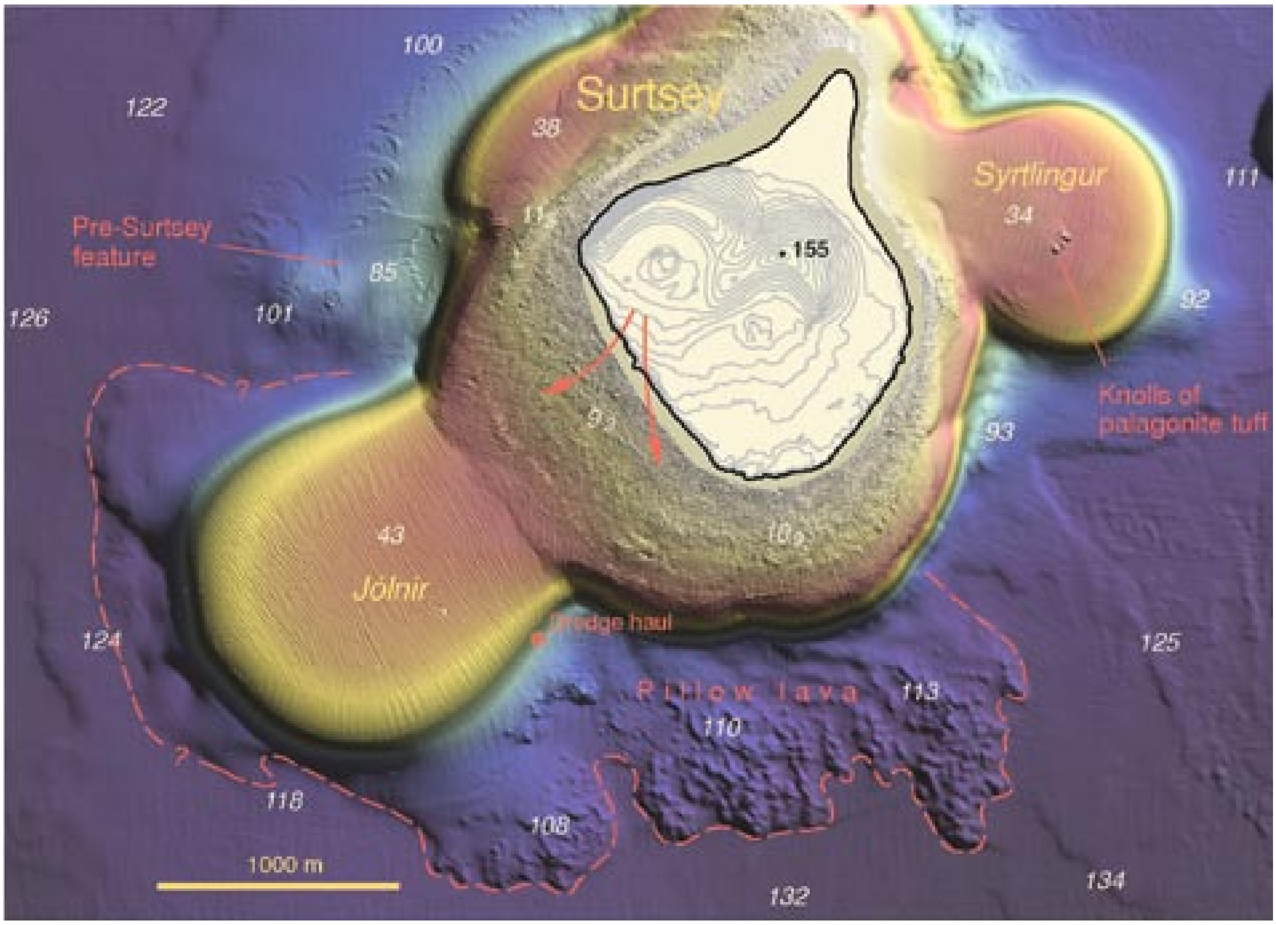


Figure 6. The submarine pillow lava field according to the new map. A cut-out from Figure 3. The estimated extent of the pillow lave is indicated along with flow directions of the lava from the western lava crater Surtungur. The site of the dredge haul of 1982 is shown, taken before the Jólnir mound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

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