GEOLOGY AND GEOPHYSICS

The Submarine Morphology of Surtsey Volcanic Group

By

JOHN O. NORRMAN AND ULF ERLINGSSON

Department of Physical Geography
Uppsala University
P.O.Box 554, S-751 22 Uppsala
Sweden

INTRODUCTION

The volcanic activity in the Surtsey area, Vestmannaeyjar, commenced in November 1963 and ended in June 1967, when the island attained its maximum size (Norrman, 1970). On Surtsey, two large craters produced most of the lava that covers the tephra slopes in the southern half of the island. The lava not only covered the supra-aquatic slopes, but also advanced into the sea, thereby considerably enlarging the island (Thorarinsson 1966, Norrman 1980). This lava plateau, with a height of 20 to 100 m a.s.l., rests on tephra and lava breccia below sea-level (cf. Norrman 1980, Fig. 3). The present degree of consolidation of these covered deposits is imperfectly known, but has been estimated by Jakobsson and Moore (1982, Fig. 9). Two more volcanoes, Surtla and Syrtlingur, were formed ENE of Surtsey, and another, Jólnir, to the WSW. Before the eruptions, the depth of the fairly level sea bed varied between 125–135 m.

At the site of Surtla a submarine eruption was noticed on December 28, 1963. A volcanic cone was built up, but did not reach the sea surface. Syrtlingur was seen above sea level on May 28, 1965, and had disappeared by abrasion on October 24 the same year. Jólnir reached sea level for the first time on December 28, 1965, and finally disappeared in October 1966. In these islands no lava was observed. The Surtsey events offer a unique opportunity to study the early stages of a submarine geomorphological cycle.

MARINE ABRASION

Abrasion in bedrock caused by wave action is generally thought to produce shallow, almost horizontal platforms. The gradient of the "bench" is normally very slight and from existing observations seems to be no more than 0.05% (Zenkovich 1967, p. 155). Summarizing her review of The Marine Cycle, King (1972, p. 558) states: "Waves cannot erode rocks below surf-base, which is about 10 m depth."

The depths at which unconsolidated sediments can be set in motion by waves are far larger as is easily demonstrated by wave dynamics formulae (Komar 1976), and also witnessed from field observations. "On the basis of all information available, it is permissible to assume that the base of the submarine beach slope in an open ocean may lie at a depth of more than 100 m" (Zenkovich 1967, p. 163).

In many treatments of the transport of unconsolidated sediments on open coasts, only one wave height and period is considered, the so-called significant wave characteristics. However, the full spectra of wave characteristics has to be considered, since different waves have different rates of damping with depth. The effect of this is illustrated in Norrman (1964, Fig. 56). It has been demonstrated by calculations that the "significant wave height", in a real environment where there are also currents to consider, varies with depth (Erlingsson 1990, Fig. 74).

Furthermore, the morphologically significant property to monitor is not the critical erosion velocity but the actual sediment transport. This varies with depth according to the wave spectra, the grain size, and the current spectra, as illustrated in Erlingsson (1990, Figs. 72 and 75). His calculations showed that with a specific wave and current spectrum, the transport of coarse sand and gravel will decrease rapidly with depth. The transport of medium and fine sand will decrease less rapidly with depth, actually crossing the former curve at a certain depth. Under certain conditions, there will be a mixture of two or even three grain sizes in the same bottom area.

In a situation where sediment is being transported down a slope with decreasing transport capacity, there will be a depth at which the rate of input is greater than the rate of output. Erlingsson (1990, p. 131) suggested the term *wave-base deposit* for the resulting sediment accumulation, thus abandoning the disputed and poorly defined term "wave built terrace" (as suggested also by Moore and Curray 1964). Thus, the depth of the "wave-base deposit" depends on the sediment input, as well as on the wave and current regime.

THE ABRASION OF THE SURTSEY VOLCANIC GROUP

There are no published wave records for Vestmannaeyjar. Wind and wave exposure at Surtsey have been calculated from meteorological statistics by Norrman (1970) and by Bruun and Viggósson (1972). Waves of morphological importance are mainly generated by cyclonic depressions moving from the WSW and the SW. Wind from the southern semicircle dominate within the moving fetches of the depressions. Bruun and Viggósson found 250 nautical miles (1 n.m.=1.852 km) to be a representative length of fetch for winds from the W and the SW, and 135 n.m. to be representative for winds from the S and the E. Within a sector from the NW to the ENE the fetch is limited by the Icelandic mainland, and most strongly so in the sector from the N to the NE where it is only 16–27 n.m. The northern tephra coast of Surtsey is thus far less exposed to wave attack than the southern lava coast.

From the southern coast of mainland Iceland, Viggósson and Tryggvason (1985) have recorded the largest significant waves at Dyrholaey (80 km east of Surtsey) to be H_0=8.1 m and T=13.0 s, and at Thorlákshöfn (60 km NW of Surtsey) to be H_0=10.1 m and T=15.5 s.

The shape of the coastline of Surtsey reflects extremely well the distribution of wave force: The strong erosion of the southern lava cliff coast – the north directed littoral transport along the eastern, and western coasts (where the steep tephra cliff has been consolidated into tuff) – and the deposition that forms the northern ness, which slightly shifts position with alternate storm attacks from the east and the west.

Because of the large depths close to the island, there is little wave refraction, with one possible exception: The greatest erosion of the lava cliff is observed on the side facing Jólnir. If the abrasional platform had protected the cliff by absorbing some of the energy, that part of the cliff would have been less eroded. Instead it appears as if the waves from the dominating SW direction are refracted over Jólnir so that the energy that reaches Surtsey from that direction is reinforced.

Through several expedition to Surtsey by various parties it has been possible to monitor the coastal and submarine development from the last stage of volcanic activity in 1966/67 to the present. Numerous "Surtsey Reports" were summarized by Norrman (1980). The use of photogrammetric surveys carried out by Landmaelingar Íslands, has meant that observations of coastal and inland changes are far more frequent than observations of submarine change.

At the end of July 1966 the submarine slopes of Surtsey were echosounded to produce a map with 5 m contour intervals (Rist 1967, Fig. 1). In this map the submarine morphology is characterized by a sloping platform around the island with a width of 100–200 m, a slope of 1:7 and a depth at its outer margin of 25–30 m. Off this platform the slope steepens sharply to about 1:2 to 1:3. The steep slope gradually flattens below a depth of 60 to 100 m. Lack of good positioning makes this map very difficult to compare with later soundings.

The first complete sounding of the area was made in 1967 (Norrman 1968). It was followed up by diving operations in 1968 in order to study active processes and morphology (Norrman 1970). The area was again sounded in 1973 (Norrman 1980), by Sjómaelingar Íslands in 1985, and in 1989 (see below).

The most spectacular phenomena on the map based on the soundings of 1967 are the table-like sea mounts produced by abrasion of the tephra cones of Surtla, Syrtlingur and Jól-

Fig. 1. The survey vessel in front of Surtla I. Surveys can be made at a speed of up to 12 knots; top speed in transit is 30 knots.

nir. From diving observations the plateaux of these shoals were found to be covered with rippled tephra and lava fragments, mainly of coarse sand and granule size. No trace of solid lava beds was found.

Diving and echosounding at the northern ness of Surtsey showed a sharp transition from the platform to the steep slope at a depth of 12 m. This slope was at the frictional angle of repose (30°–34°) down to about 70 m, and below that gradually levelled off. Boulders were deposited at the top of the slope, and others that had moved down the slope formed boulder streams. Touching the slope caused widespread avalanching (Norrman 1970, Fig. 7).

Off the lava cliff on the southern coast, the platform was found to be covered by large boulders. At the top of the steep submarine slope, 150 m from the shore and at a depth of 20 m, giant blocks, some with a diameter of 5 m, were loosely piled on top of each other. Further down, the blocks were smaller and coarse sand started to fill up the space between the boulders at a depth of 30–40 m. The sand below 40 m was deposited at its frictional angle of repose, which was less than the boulder slope.

When the depths of the abrasion surfaces at Surtla, Syrtlingur and Jólnir from 1967, 1968 and 1973 were plotted versus time since the islands disappeared below sea level (Norrman 1980, Fig. 7; see also Jakobsson 1982, Fig. 2), it was found that the shoals had been lowered rapidly down to about 20 m b.s.l. (ca. 1.5 yrs). Thereafter the abrasion slowed down most markedly at the rather sheltered Syrtlingur, far less at the freely exposed Surtla (down to 40 m), and intermediately at Jólnir (down to 30 m).

In a recent paper by T. Sunamura (1990), these data (excluding Syrtlingur) have been used to verify his model for describing submarine bedrock erosion, considering the wave-induced shear stress as the primary force causing abrasive bedrock lowering. The "design wave" is represented by a mean of the maximum wave records from Dyrholaey and Thorlákshöfn: $H_0=9$ m and $T=14$ s. Sunamura finds the wave base below which abrasion is insignificant to be 54 m, and 95% of this abrasion is reached within 10.7 yrs.

FIELD SURVEY

The 1989 expedition was focused on studying the submarine morphology and processes.

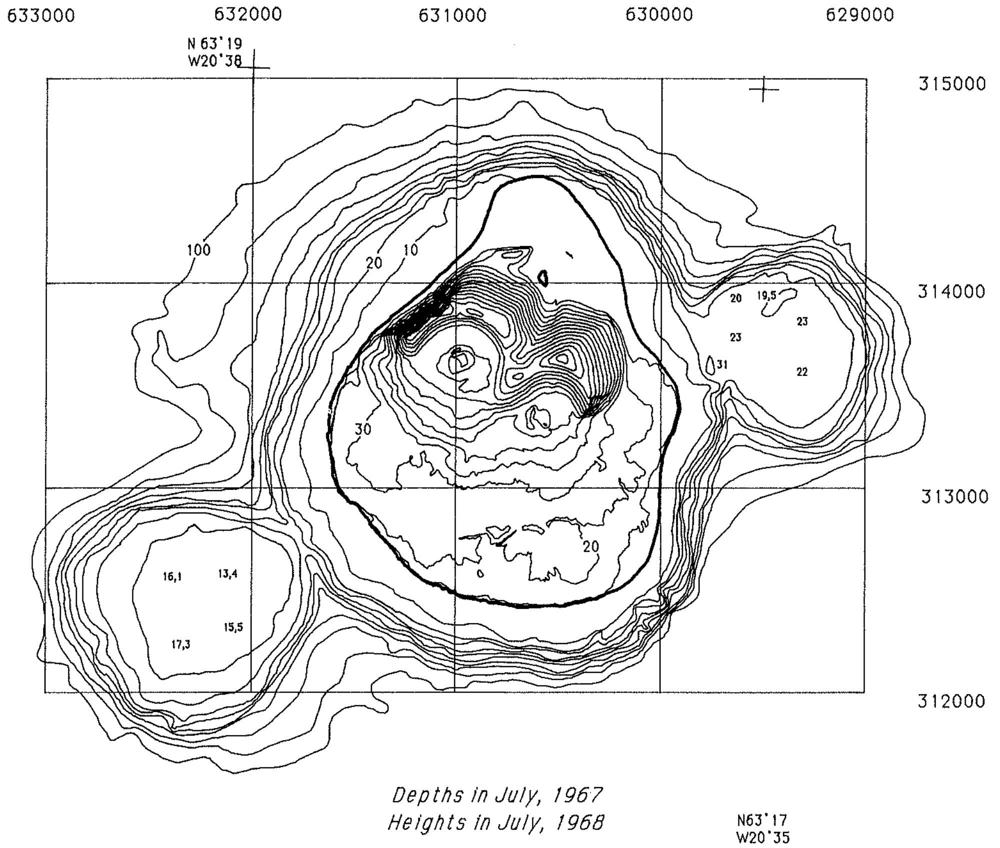


Fig. 2. Topographical map based on soundings from 1967 and air photos taken in 1968. The contour intervals is 10 m, with the coastline emphasised. Jólnir is the volcano to the west of Surtsey, and Syrtlingur on the east of it. Surtla is outside the map in the direction ENE (cf. Fig. 5).

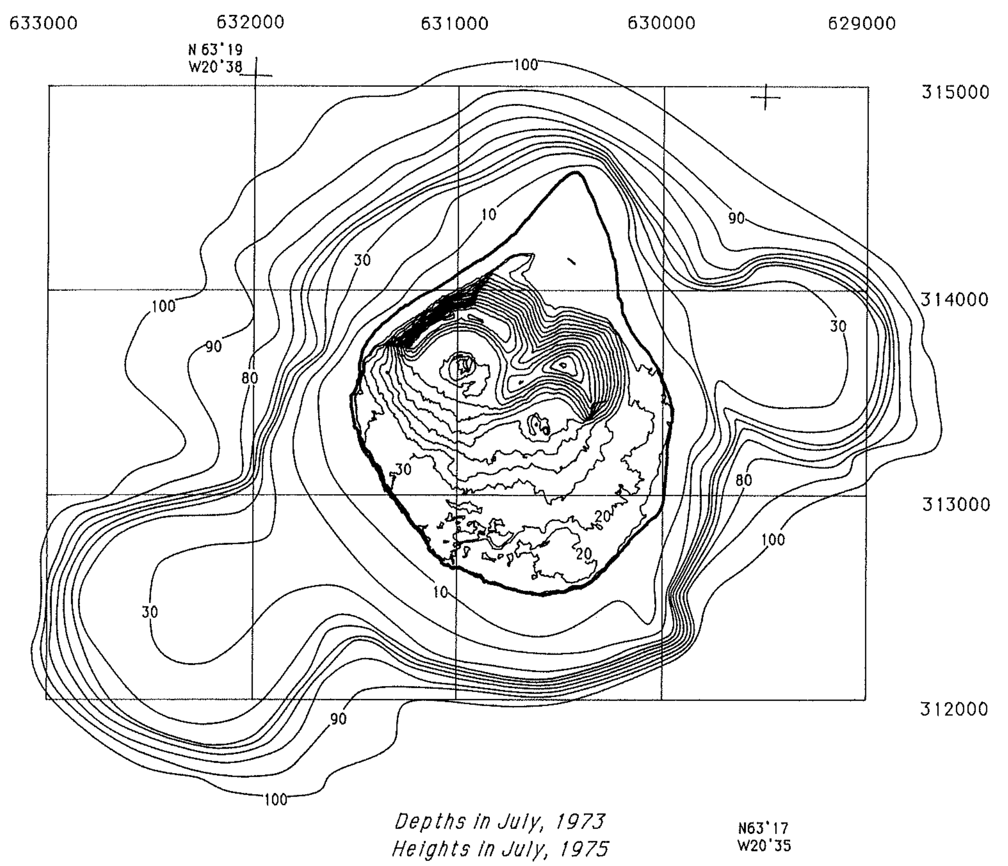


Fig. 3. Topographical map from 1973/1975 (cf. Fig. 2).

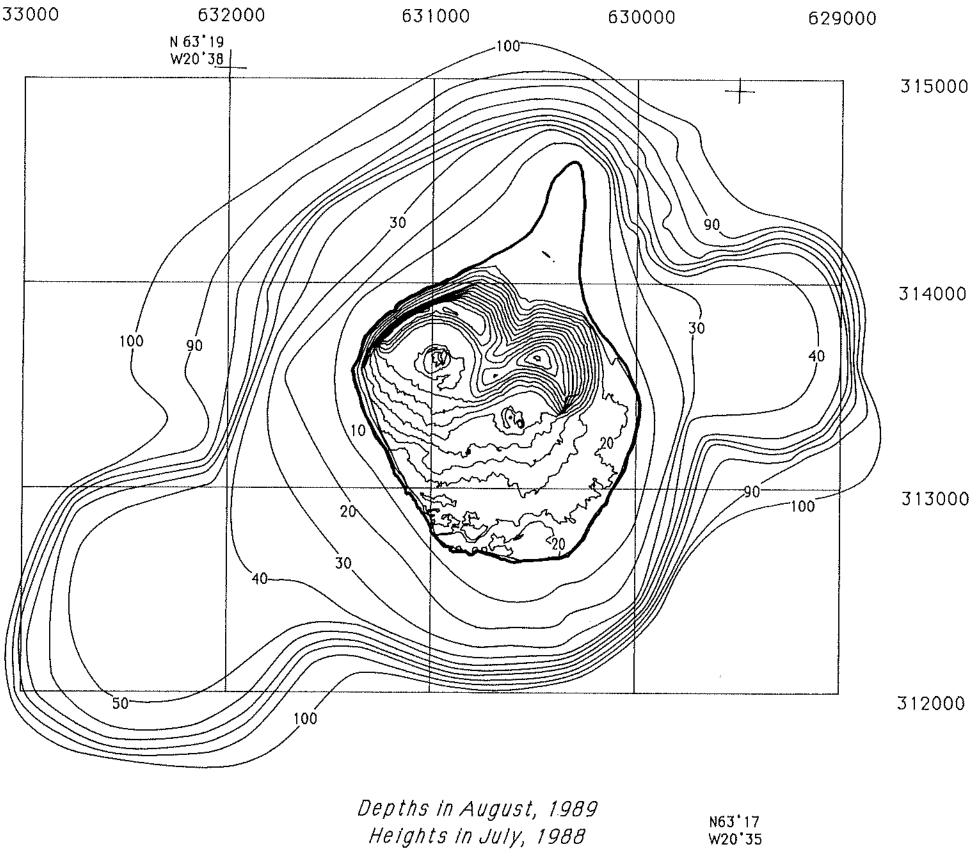
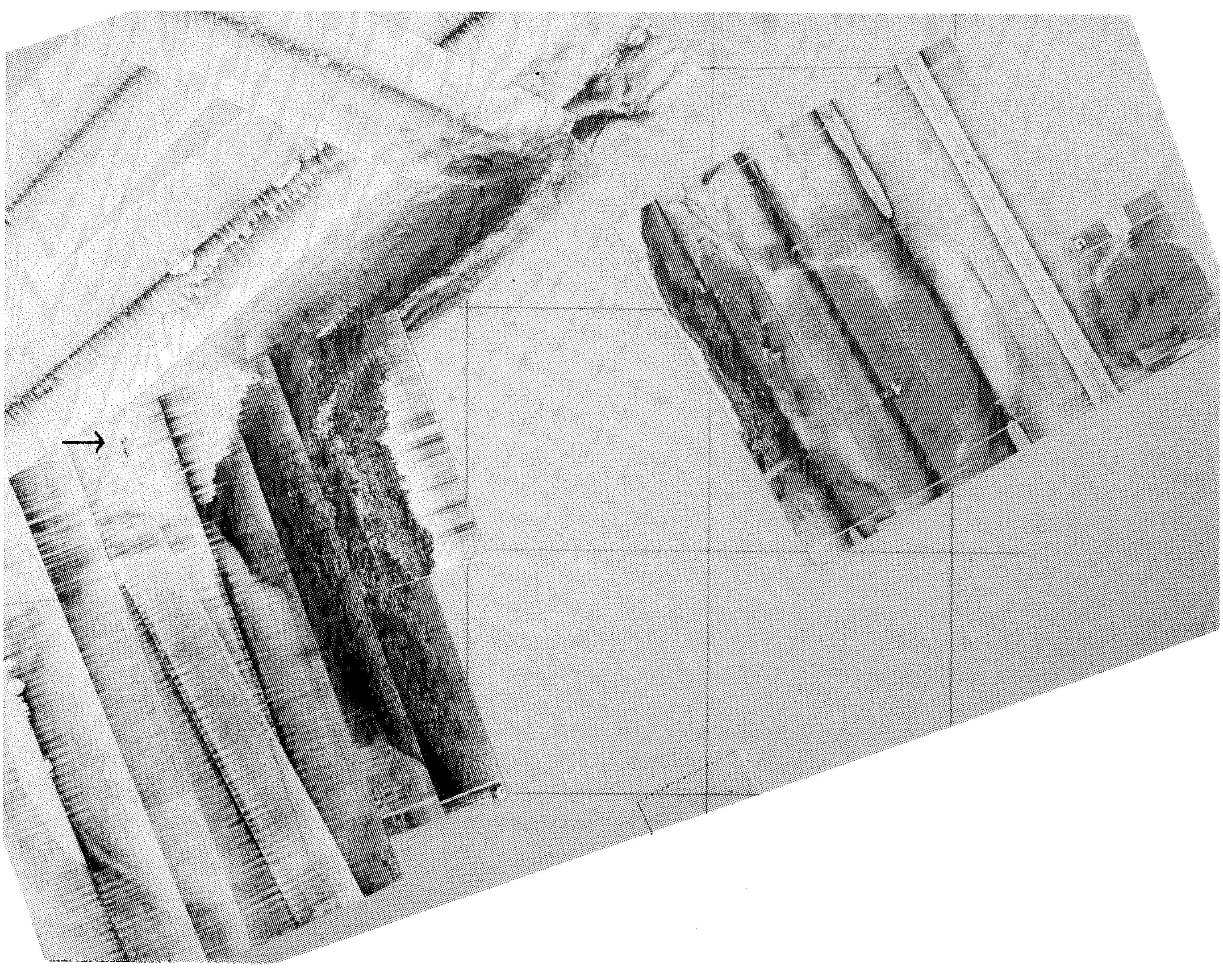


Fig. 4. Topographical map from 1988/1989 (cf. Fig. 2).

Fig. 5. Side-scan sonar mosaic of the bottom around Surtsey (the island occupies the empty space in the centre). Surtla can be seen to the far right. The background lines mark a 1 km^2 grid (cf. Figs. 2–4), and the arrow points to three volcanic plugs at 110 m depth (see text). The former position of the western coastline of Surtsey can be seen as the border between large blocks on the bottom (speckled area) and the lava breccia sand (uniform dark tone). See also Fig. 6.



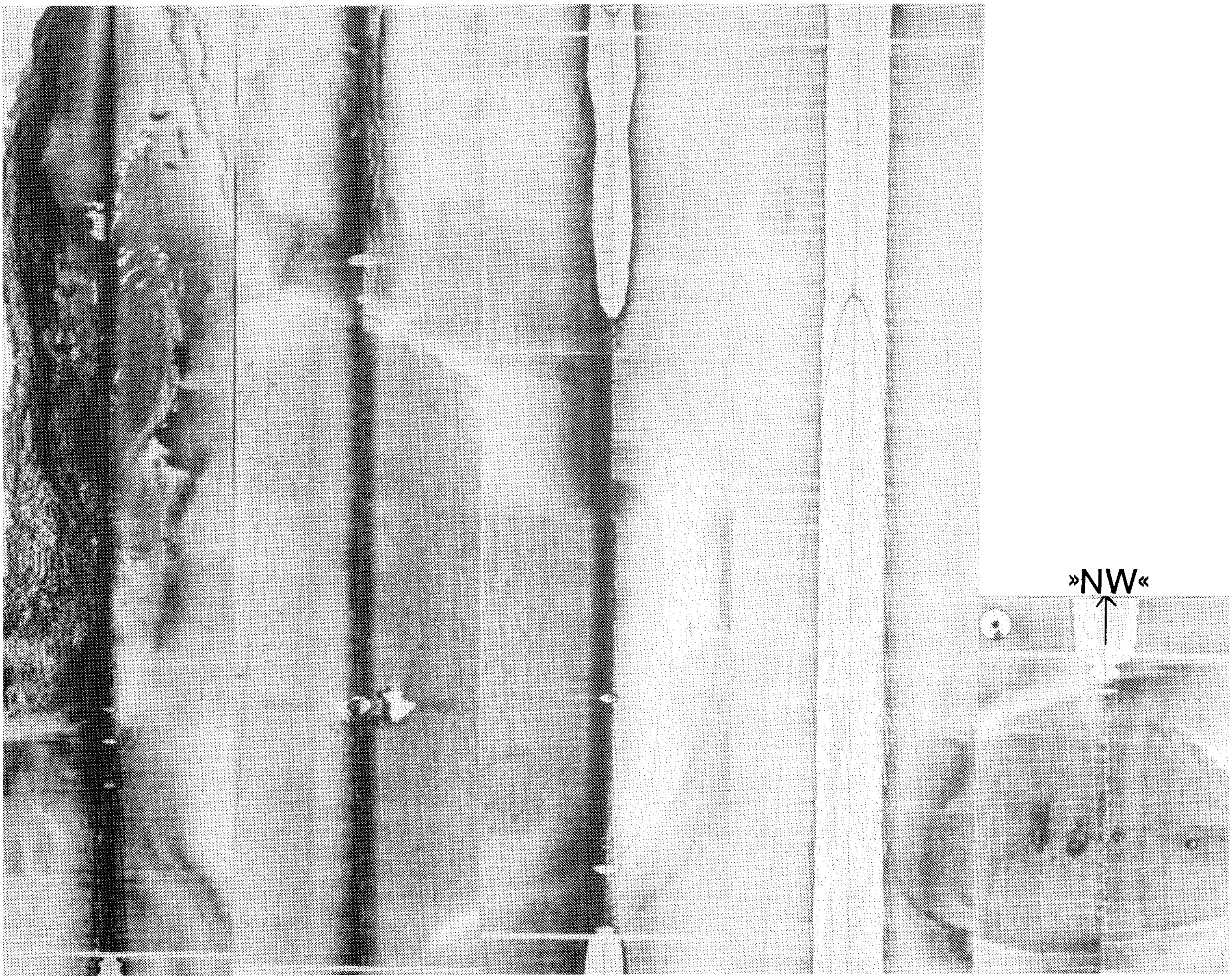


Fig. 6. Side-scan sonar mosaic over Syrtlingur (left) and Surtla (right). Scale 1:10,000. The white stripe between them, and N and SE of Syrtlingur, is caused by the water depth being too great for the instrument set-up. The two volcanic plugs on Syrtlingur, and the four on Surtla, are seen as dark objects – the former are so high that they also throw a considerable white shadow. The arrow at Surtla marks the direction of the survey line, from which the sub-bottom profile in Fig. 14 is taken. To the far left, Surtsey can be seen in white (no echoes are obtained from land).

A survey vessel, Akusta (Fig. 1), equipped with side-scan sonar (EG&G Mod 260 with 100/500 kHz towfish) and sub-bottom profiler (O.R.E. Geopulse Pinger with four 3.5 kHz hull-mounted transducers) were used for the surveys. Positioning was made with the use of a Geodimeter "total-station" from Surtsey. The equipment has been described by Erlingsson (1990, pp. 41–46).

Based on these surveys, and air photos from 1988, a topographical map with 10 m contour interval has been constructed (Fig. 4). Maps in the same style have also been made based on earlier maps from 1967/68 and 1973/75 (Figs. 2 and 3).

A side-scan sonar mosaic (Fig. 5) could be made over most of the bottom around Surtsey, the main uncovered part being the southern slope. Tephra areas have a light gray shade, as seen on Surtla, Syrtlingur and Jólnir. Samples taken on Syrtlingur in 1989 gave a mean size of ca. 1.2 mm, and a flume test showed the critical erosion velocity to be ca. 48 cm/s at 1 m above the bed (which is in line with the "Sundborg diagram" for this relatively light material; cf. Sundborg 1967). The west-

Fig. 7. The base on the northwest side of the western volcanic plug on Syrtlingur (depth 34 m). The bottom material is tephra in sand and granule size (mean≈1.3 mm), with some small boulders. There is an abundance of fish that blurs the sonographs, which makes it difficult to measure the exact size of these features.

ern slope off Surtsey is speckled with blocks from the lava cliff, whereas the NW slope has an even dark colour, suggesting lava breccia in sand or granule size. The lightest shade, indicative of medium or fine sand, is found on the bottom to the north and east of the northern ness of Surtsey (which is the area of maximum accumulation).

During a submarine volcanic eruption, the outflowing lava will be chilled rapidly and form pillow lava, unless the gas pressure in the lava is so great that it explodes to form tephra. At what depth this will occur has been discussed by Thórarinsson (1966) and Kjartansson (1966), on theoretical grounds, but no field data was available at the time. A later drilling project on Surtsey did not encounter any pillow lava (Jakobsson and Moore, 1982), but a dredge haul at 85–95 m depth at the base of Jólnir, did (Jakobsson, 1982; see also Thors and Jakobsson, 1982).

On the side-scan sonar mosaic in Figure 6, two "volcanic plugs" can be seen on Syrtlingur (top level ca. −25 m), and four on Surtla (top level ca. −45 m). On Jólnir no volcanic plug was found, but it may be present below the tephra. A group of volcanic plugs was also found at one location at ca. 110 m depth, north of Jólnir and west of Surtsey (Fig. 5). This group, situated on a low elevation of the old sea-bed, may possibly be a remnant of a tephra island formed by an earlier eruption.

The more western of the volcanic plugs on Syrtlingur was visited by diving. It protrudes ca. 10 m above the surrounding bottom (34 m), and it is narrower at the base than at the top (Fig. 7). The diameter at the top is ca. 25 m. The entire volcanic plug is cleaved by a ca. 0.2 m wide crevasse running in ENE-WSW (Fig. 8). A rock sample taken at the crevasse, at the top of the volcanic plug, was identified as tuff (pers. comm., Sveinn Jakobsson). The upper surface is fairly flat (Fig. 8), the relief being generally less than 1.5 m, but at several places up to 1 m high structures protrude. As can be seen on Figure 9 these may be cleaved by the crevasse (the rock sample mentioned was taken close to this point).

A dive was also made on the east side of the northern ness, where the sand on the slope below the knee at 25 m depth was found to lie at the angle of repose, and avalanches started

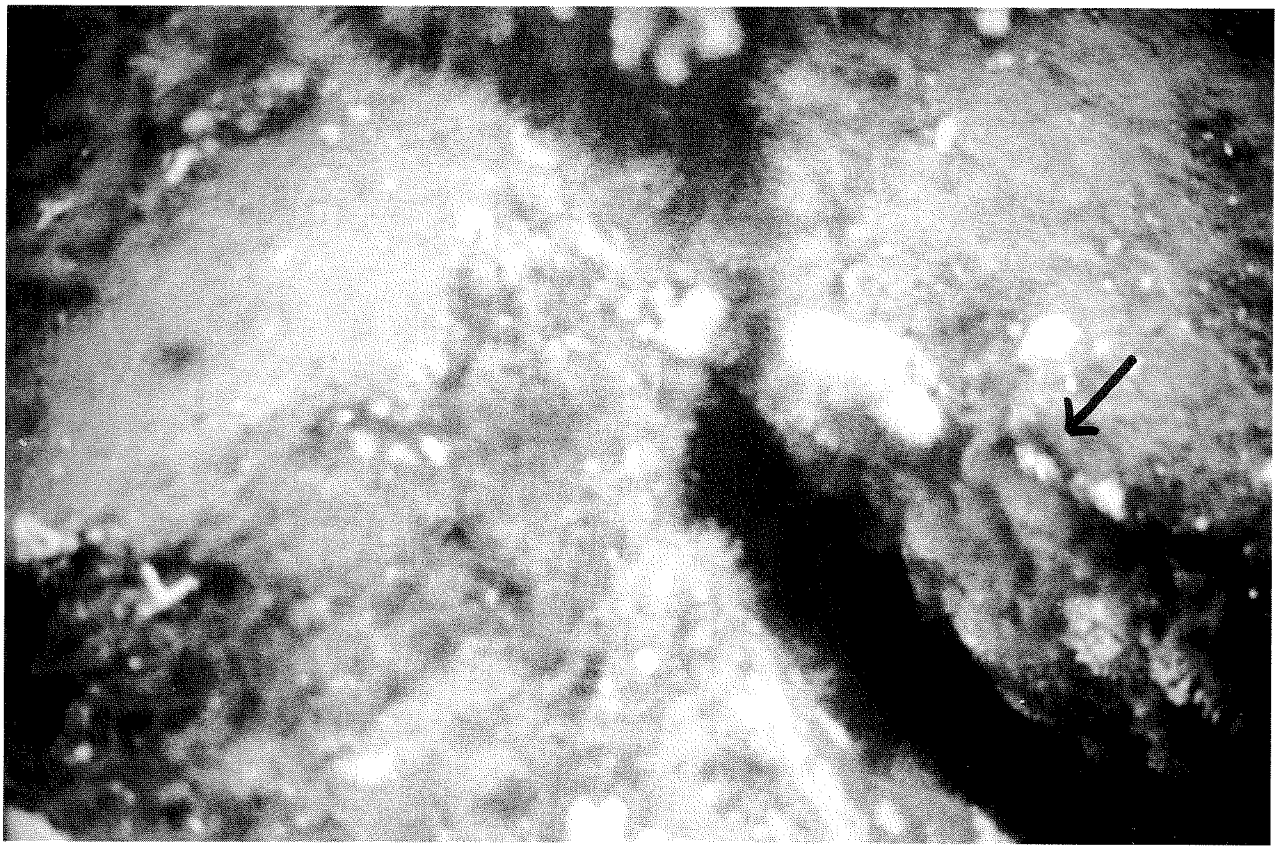


Fig. 8. The top surface of the volcanic plug in Figure 7, showing the crevasse where the sample was taken (depth 24 m).

if it was touched. On the southeastern slope, the bottom between 25 and 30 m depth was found to be covered by rippled coarse sand in patches, and boulders in the size range 0.3 to 0.8 m. Below the knee at 30 m, only boulders were found (in the same size range). These were sparsely overgrown, and it appeared that only some of the larger ones had been at rest since the previous summer, thus achieving a more flourishing vegetation. In contrast, the lava rock on Syrtlingur was densely covered by soft corals, etc. (Fig. 9).

MORPHOLOGICAL EVOLUTION OF THE VOLCANIC GROUP

The evolution of the Surtsey volcanic group, as shown by the hypsographic curves in Figure 10, is one of constructing a "shelf" by a combination of cliff erosion and the accumulation of a "wave-base deposit". As mentioned, the depth at which this accumulates depends on the sediment input rate, and since the

Fig. 9. Horizontal view through the crevasse at the top of the volcanic plug in Fig. 7 (depth 24 m). The width of the crevasse is ca. 0.2 m. Note the dense "vegetation" cover that indicates stable geomorphological conditions – a similar vegetation cover is not found on the blocks on the submarine slopes off Surtsey.

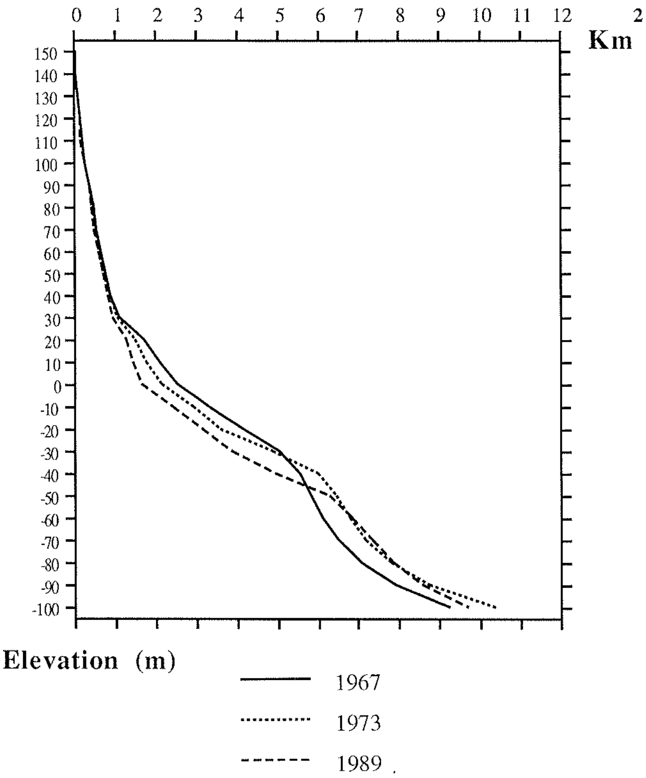


Fig. 10. Hypsographic curves based on the maps in Figs. 2–4.

eruption has ceased there is a steadily diminishing amount of material available for sediment transport. The effect can be seen on the hypsographic curves: The (local) "shelf break" moves down, from −30 m in 1967, to −40 m in 1973, and to −50 m in 1989. At the same time the coastline has moved back through cliff erosion – thus creating a situation very similar that envisaged in many early concepts for the evolution of a continental shelf, although on a smaller scale. The future for the tephra areas is that the "shelf break" will move down until it merges into the surrounding, insular (continental) shelf level at ca. 110 m depth. Surtla, Syrtlingur and Jólnir will be reduced to volcanic plugs on the shelf floor, similar to many other shoals in the area.

Using the 1989 soundings along with the older ones, the rates of abrasion of the former tephra islands were calculated. The data were fitted to an equation of the form

$$d=K+e^{(At^{q})} \qquad \text{Eq. 1}$$

where d=depth over the tephra plateaux, t=time in years since the plateaux disappeared from the surface, K=−1, a constant needed to obtain the depth 0 at time 0, and A and q are the variables. The first depth measurement on Jólnir is at t=0.9 yrs, for Syrtlingur at t=1.75 yrs. After such a short period the variations in the weather around the long-term average can be expected to give unreliable results in the calculations, so the same

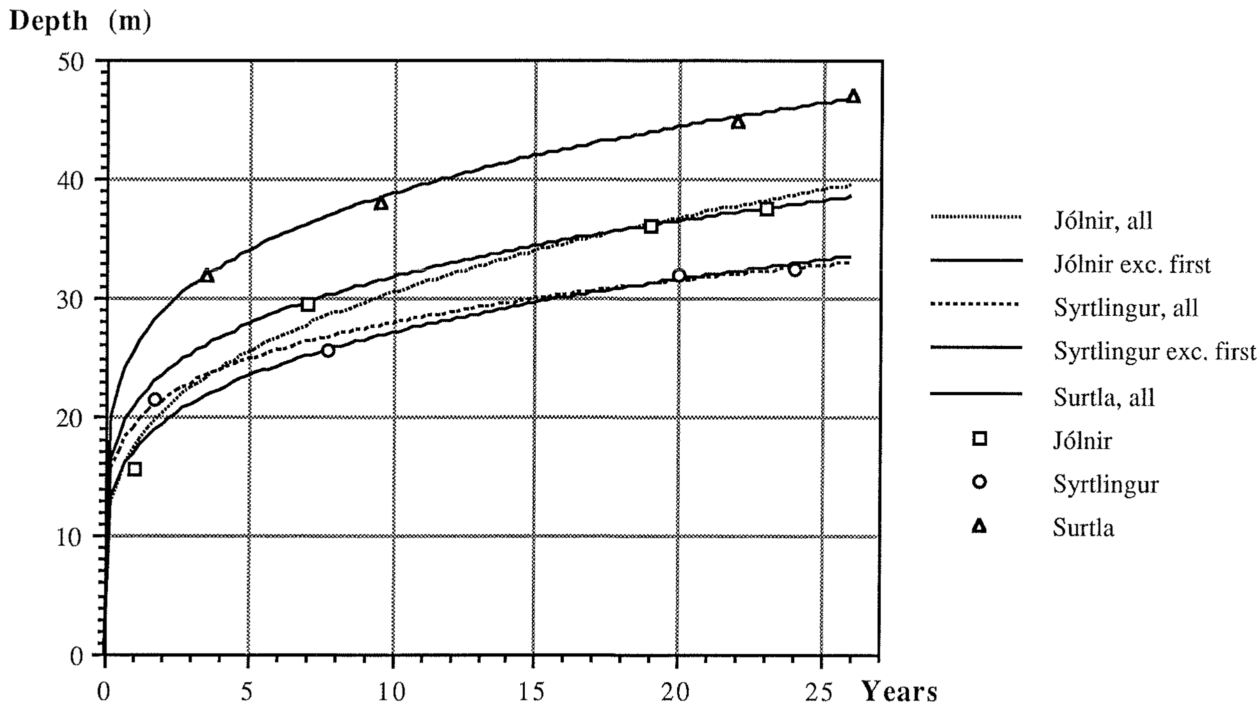


Fig. 11. Data points and fitted curves for the abrasion of the tephra plateaux of Surtla, Syrtlingur and Jólnir. The origin is when they disappeared from the sea surface. The dashed lines are the curves resulting when the first data point (after the origin) of Jólnir and Syrtlingur are included. That first point is not reliable, since it depends on whether a major storm appeared or not during the first winter.

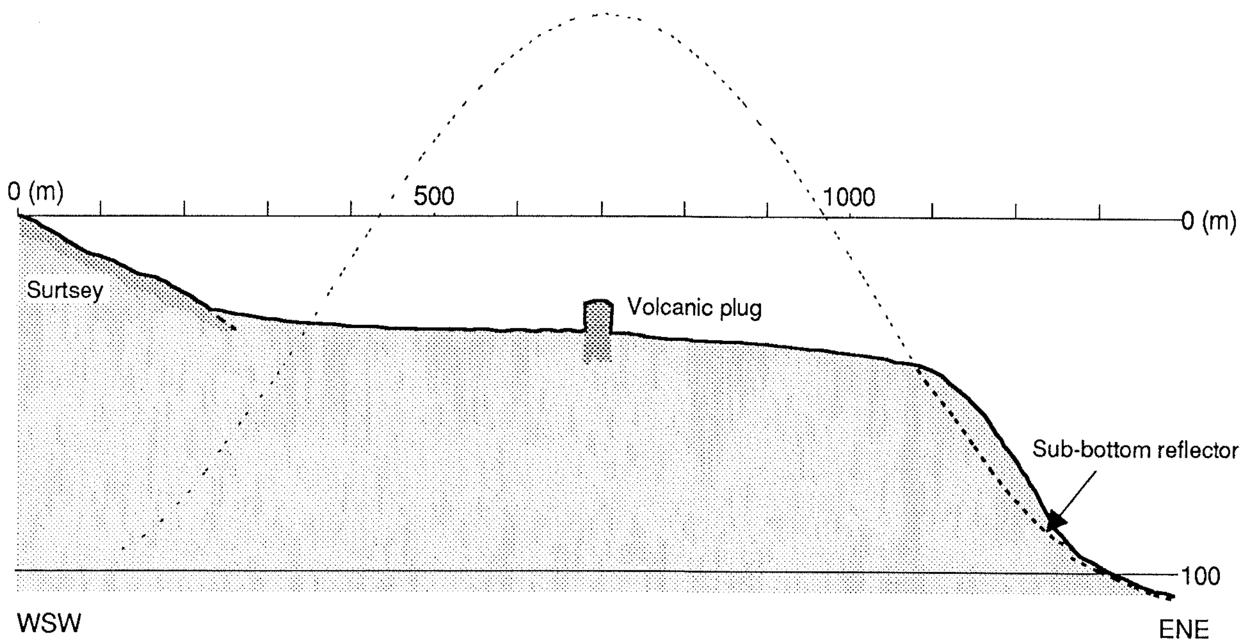


Fig. 13. Profile from WSW to ENE from Surtsey over Syrtlingur with one of its volcanic plugs. The dashed lines are internal reflectors, indicating the position of the sea-bed at an earlier time. The dotted line suggests a profile of the former island Syrtlingur, consistent with the dashed line on the plateau slope. (Interpreted from a 3.5 kHz sub-bottom profile).

curve fit was tried without these two data points. The result can be seen in Figure 11. The solid lines are fairly parallel and all agree well with the data points (with the exceptions mentioned). The dashed curves represent the fit with those two points. The values of A and q are listed in Table 1. Note that the predictions are only valid for the tephra – the volcanic plugs will last much longer.

The maps of Figures 2 to 4 were imported into a GIS-program (Map II) using 10 m spatial resolution and 10 m contour intervals, from +150 m to −100 m. All bottoms beyond that were given the value −110 m, which is a fair approximation, and relevant for the purpose. By subtracting an older map from a newer, pixel by pixel, a map is obtained showing the net mass balance. It turned out that the change from 1967/68 to 1973/75 was positive, instead of negative as one would expect. This and other indications, like the regional distribution of the areas of positive and negative mass balance, make it clear that the depth map from 1973 displays such major errors due to unsatisfactory positioning that it does not deserve a comprehensive treatment. The change from 1967/68 to 1988/89 is shown in Figure 12. (The 1985 map from Sjómaelingar Íslands was not digitized, since the differences to 1989 were within what can be expected to be the error margin.)

The depth of the conceptual "wave-base deposit", i.e., where there is a change from erosion to accumulation, can be seen to vary from 50 m on the southwestern slope of Jólnir, to sea-level at the northern ness. This image reflects a long-term average, meaning that there is probably erosion today at many places where the map shows a net accumulation.

TABLE 1

The values of the variables A and q were derived by fitting the data points in Fig. 11 to Equation 1 (the corresponding curves are plotted in the same figure). t_{100} is the time (in years) required to abrade the plateaux to a depth of 100 m, under the unrealistic assumption that they consist of nothing but unconsolidated tephra. The first two columns (Jólnir and Syrtlingur) give the values that resulted when the first data point (after depth=0 at time=0) was not included in the calculations. These values are more realistic than those in the last two columns, where all points were considered.

	Jólnir	Syrtlingur	Surtla all	Jólnir all	Syrtlingur all
A:	3.08	2.88	3.27	2.90	3.00
q:	0.0546	0.0629	0.0510	0.0746	0.0493
t_{100}	1685	1761	841	500	6128

Mass balance from 1967/68 to 1988/89

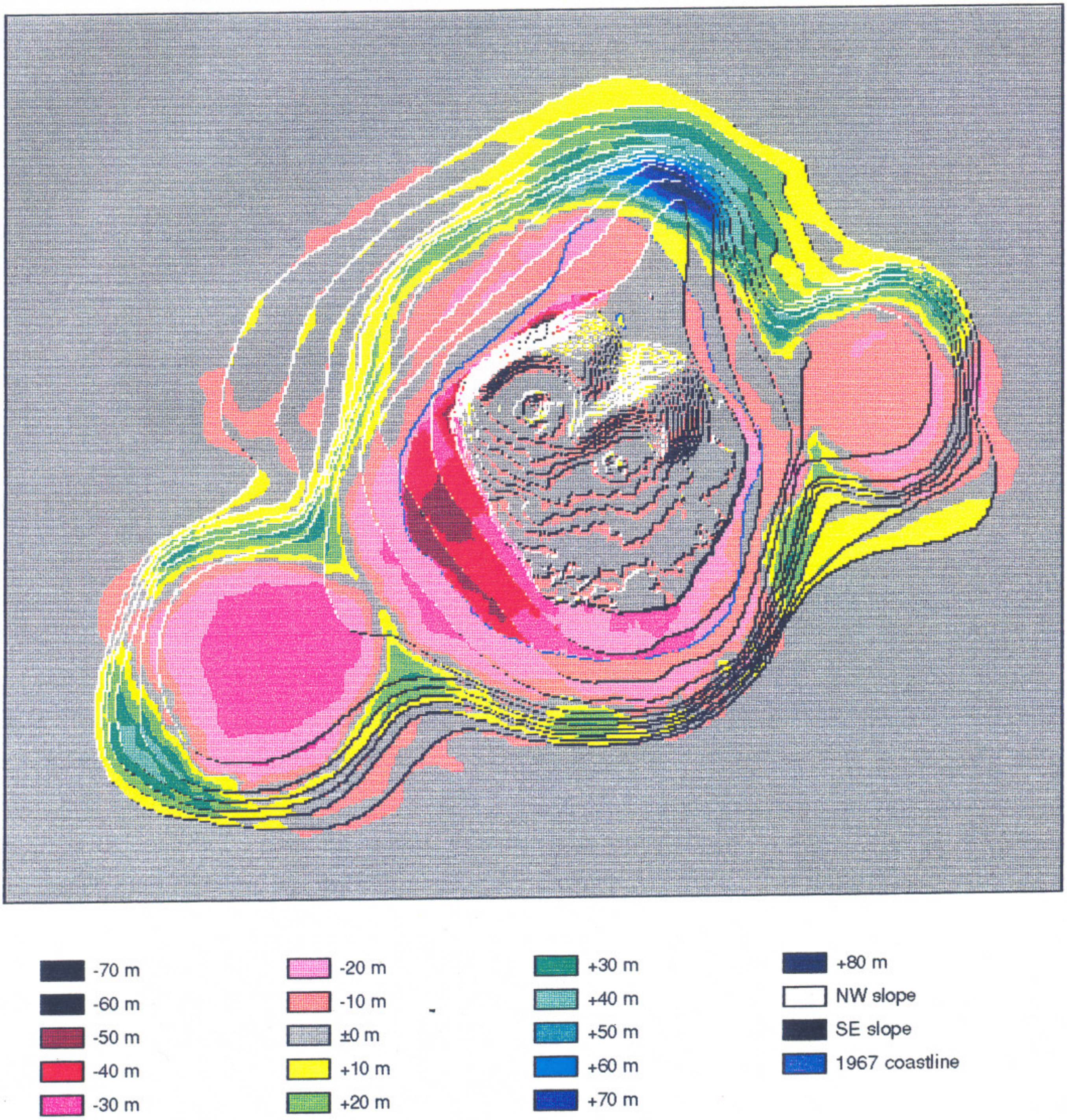


Fig. 12. Mass balance of the Surtsey volcanic group (except Surtla), obtained by subtracting the map in Fig. 2 from the map in Fig. 4. The values of the zones show the height difference thus obtained in each 10×10 m pixel. The contour lines from 1988/89 have been added, as has the 1967 coastline.

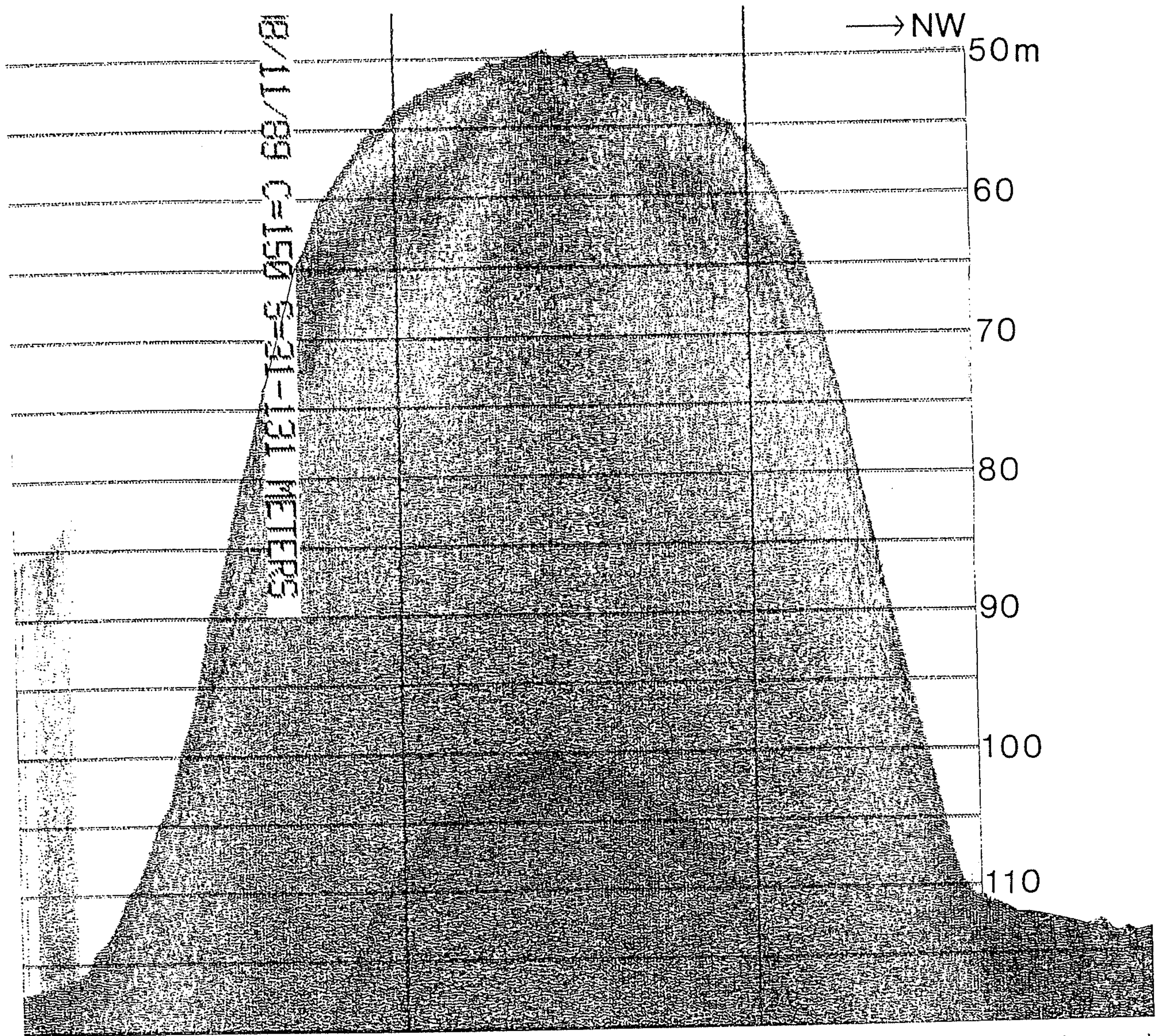


Fig. 14. Sub-bottom profile from Surtla (for position cf. Fig. 6). Some internal reflectors can be seen on the slopes of the plateau and on the bottom of the NW of it, indicative of post-volcanic deposition of tephra. The most prominent reflector on Surtla, however, is the prolonged echo at 5 to 10 m below the plateau surface. In the very centre of Surtla, where the profile passes the volcanic plugs, this reflector disappears. Instead, a long dark echo appears, obviously related to the volcanic plugs.

Nevertheless, the geographical distribution of the wave energy is clearly reflected by the net mass balance as shown by Figure 12.

The sub-bottom profiles were compared to this map, and it is obvious that the net accumulation on the slopes is a real feature. The dashed lines in Figure 13 reveal that there is a small accumulation on the NE slope of Syrtlingur, and an accumulation between Syrtlingur and Surtsey. It also shows one of the volcanic plugs. Profiles from around the northern ness reveal the presence of mass movement down the slopes, and profiles from the south slope of Surtsey and from the western and northern part of Jólnir also show the accumulation of material on the slopes.

In the central parts of the tephra plateaux of Surtla and Jólnir, a reflector (with a prolonged echo) is generally seen at 5 to 10 m below the surface. The best example is from Surtla (Fig. 14), where one also can see the stronger echoes obtained when passing over the volcanic plugs. The subsurface reflector bears a resemblance to reflections caused by gas in the sediments. But if there was gas (notably steam), the high temperatures would palagonitize the tephra and furthermore, there is no impermeable surface that prevents the gas from rising to the sea bottom. Instead, one may hypothesize that the reflection is caused by a steep temperature gradient, from the temperature of the ambient sea water, to 50–

100° (cf. the temperature log from Surtsey; Jakobsson and Moore, 1982, Fig. 7). When the tephra was deposited during the eruption it was chilled by the sea water, so the heat must be a secondary feature. The abrasion that lowers the platforms every year could explain why such high temperatures may be present so close to the cold surface.

CONCLUSION

In the future the lava cliff of Surtsey will probably become entirely eroded, unless it is resting on palagonitized tephra. Because of the decreasing transport of material towards the north, the northern ness will gradually become eroded while shifting position during storm events. The part of the island that will remain for probably thousands of years is the core of palagonite around the craters, very much like the other small islands and skerries in the Vestmannaeyjar archipelago.

The tephra plateaux of Surtla, Syrtlingur and Jólnir are still being abraded at a slowly decreasing rate. If they are not consolidated into palagonite, they will be abraded to the level of the surrounding bottom within 2000 yrs or less. The sub-bottom profiles of Surtla and Jólnir could indicate the presence of heat at a depth of less than 10 m below the tephra surface. If this heat causes the formation of palagonite, the plateaux will remain as sea mounts, with steep sides and a flat surface.

References:

Bruun, R., and Viggósson, G., 1972: Use of volcanoes for determination of littoral drift. Surtsey Res. Progr. Rep. 6, 117–120.

Erlingsson, U., 1990. Geomorphological development of the bottoms off Österlen, southernmost Sweden. UNGI Report 76, 136 p.

Jakobsson, S.P., 1982: Dredge hauls from Vestmannaeyjagrunn, Iceland. Surtsey Res. Progr. Rep. 9, 142–148.

Jakobsson, S.P., and Moore, J.G., 1982: The Surtsey Research Drilling Project of 1979. Surtsey Res. Progr. Rep. 9, 76–93.

King, C.A.M., 1972: Beaches and Coasts. 2nd ed. Edward Arnold.

Kjartansson, G., 1966: A contribution to the morphology of Surtsey. Surtsey Res. Progr. Rep. 2, 125–128.

Komar, P.D., 1976: Beach processes and sedimentation. Prentice Hall.

Moore, D.G., and Curray, J.R., 1964: Wave-base, marine profile of equilibrium, and wave-built terraces: Discussion. Geological Society of America Bulletin 75, 1267–1273. (Reprinted in: D.J.R. Swift and H.D. Palmer, Eds., Coastal Sedimentation. Dowden, Hutchinson & Ross).

Norrman, J.O., 1964: Lake Vättern. Investigations on Shore and Bottom Morphology. Geografiska Annaler, No. 1–2, 238 p.

Norrman, J.O., 1968: Shore and offshore morphology of Surtsey. Report on preliminary studies in 1967. Surtsey Res. Progr. Rep. 4.

Norrman, J.O., 1970: Trends in postvolcanic development of Surtsey Island. Surtsey Res. Progr. Rep. 5.

Norrman, J.O., 1980: Coastal erosion and slope development in Surtsey Island, Iceland. Z. Geomorph. N.F., Suppl. Bd. 34.

Rist, S., 1967: Echographic soundings around Surtsey. Surtsey Res. Progr. Rep. 3, 82–83.

Sunamura, T., 1990: A dynamical approach to wave-base problems. Trans. Jap. Geomorph. Union II (1), 41–48.

Sundborg, Å., 1967: Some aspects on fluvial sediments and fluvial morphology I. General views and graphic methods. Geografiska Annaler 49A (2–4), 333–343.

Thórarinsson, S., 1966: The Surtsey eruption. Course of events and the development of Surtsey and other new islands. Surtsey Res. Progr. Rep. 2, 117–123.

Thors, K., and Jakobsson, S.P., 1982: Two seismic reflection profiles from the vicinity of Surtsey, Iceland. Surtsey Res. Progr. Rep. 9, 149–151.

Viggósson, G., and Tryggvason, G.S., 1985: Wave measurements in Iceland. Proc. Iceland Coastal and River Symp., Reykjavik, 145–164.

Zenkovich, V.P., 1967: Processes of Coastal Development. (J.A. Steers, Ed.). Oliver and Boyd, Edinburgh.