GEOLOGY AND GEOPHYSICS

Geological monitoring of Surtsey, Iceland, 1967-1998

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ABSTRACT

Aspects of the geological monitoring of the volcanic island of Surtsey 1967-1998, are described. A hydrothermal system was developed within the tephra craters in late 1966 to early 1967. Temperatures in a drill hole, situated at the eastern border of the hydrothermal area, indicate that the hydrothermal system at that site has been cooling at an average rate of ≤ 1°C per year since 1980.

The tephra was altered rapidly within the hydrothermal area, producing the first visible palagonite tuff in 1969. A substantial part of the tephra pile above sea level was probably converted to tuff by 1972. The visible area of tuff has gradually increased since then, primarily due to erosion of tephra at the surface. By 1998 52 % of the exposed tephra area had been converted to palagonite tuff. By volume, however, some 80-85% of the tephra pile above sea level had been converted to tuff in 1998.

The area of Surtsey has shrunk from its original 2.65 km^2 (1967) to 1.47 km^2 (1998) due to marine abrasion. The geological formations on Surtsey have, however, responded quite variably to erosion. The tephra pile was easily eroded, but marine abrasion has also caused rapid cliff recession of the lava field, and longshore currents have deposited a sand-gravel spit on the north shore. The palagonite tuff, however, is very resistant to marine abrasion. The central core of palagonite tuff is estimated to be ≤ 0.39 km^2.

Statistical estimation of models of the decrease of Surtsey indicate that it will last for a long time. The numerical experiments indicate that it will take over 100 years until only the palagonite tuff core is left. It is postulated that the final remnant of Surtsey before complete destruction will be a palagonite tuff crag, comparable to those of the other islands in the Vestmannaeyjar archipelago.

INTRODUCTION

The island of Surtsey was constructed from the sea floor by volcanic activity during 1963-1967, on the Vestmannaeyjar shelf off the south coast of Iceland. The sea water depth prior to the eruption was 130±2 m. The eruption history of Surtsey has been described in detail (Thórarinsson *et al.* 1964, Thórarinsson 1966, 1968), and summarised in numerous papers (e.g. Jakobsson & Moore 1982).

Several research groups have monitored the development of Surtsey within various fields of geology after the eruption ceased in 1967. Some of these projects were initiated during the eruption. Coastal erosion and geomorphological changes until 1993 have been followed by Thórarinsson (1968), Norrman (1980, 1985) and Jakobsson (1995), and the submarine morphology of the Surtsey volcanic group 1967-1989 by Norrman & Erlingsson (1992). The consolidation and palagonitization of the Surtsey tephra and the development of the hydrothermal area 1968-1979 has been reported by Jakobsson (1978), and Jakobsson & Moore (1986).

Geomagnetic field measurements were carried out repeatedly between 1968 and 1973

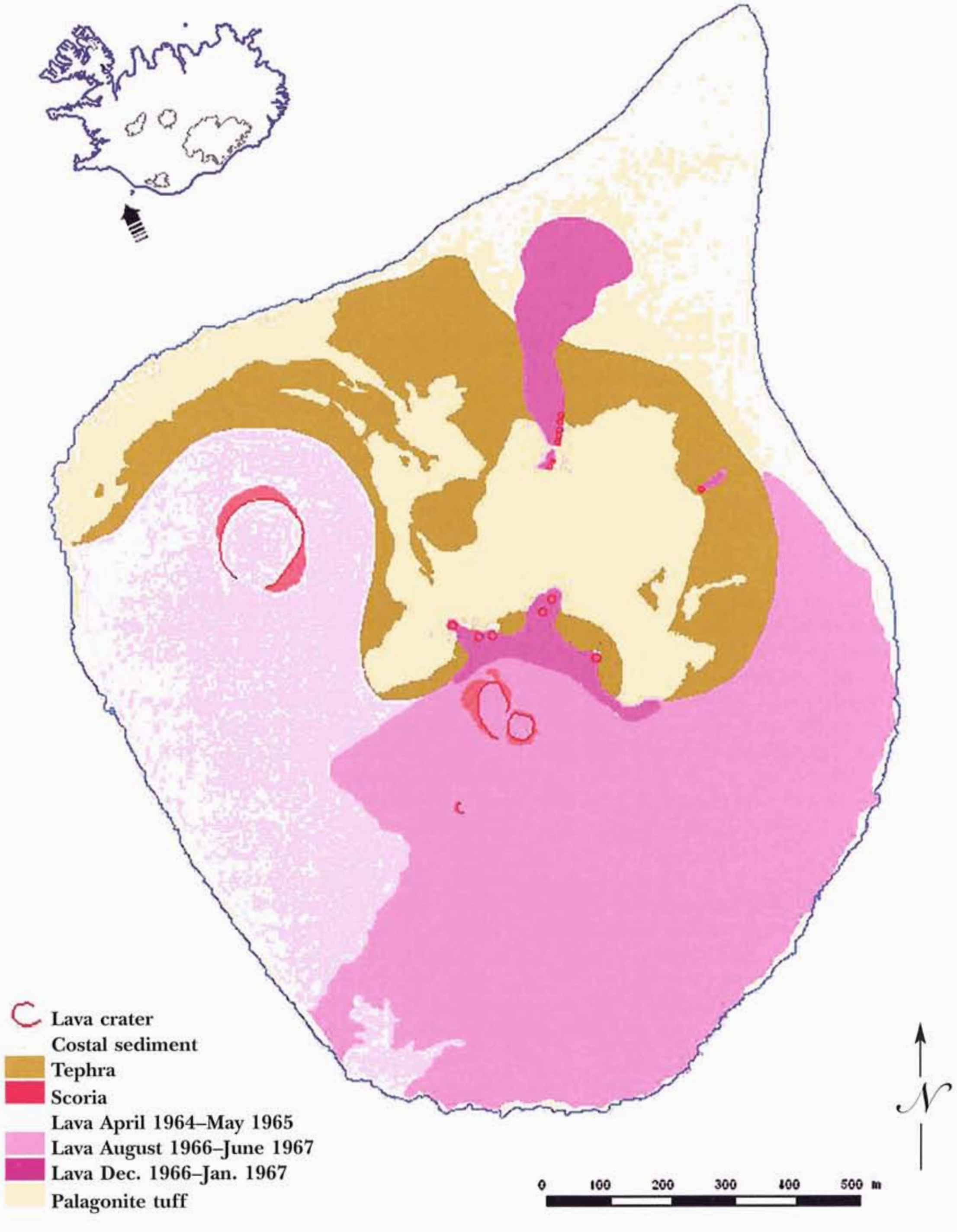

Figure 1. Geological map of Surtsey as in August 1998, modified after Jakobsson (2000).

(Sigurgeirsson 1974). The subsidence of Surtsey until 1991 has been measured by Tryggvason (1972) and Moore *et al.* (1992). Precise GPS measurements, first carried out in 1992 (Einarsson *et al.* 1994) and to be repeated in the summer of 2000, will make it possible to record accurately both vertical and horizontal movements in Surtsey. The area is also closely monitored seismologically, as the Vestmannaeyjar archipelago falls within the area covered by the seismographic net in Iceland (Einarsson & Björnsson 1987, Stefánsson *et al.* 1993).

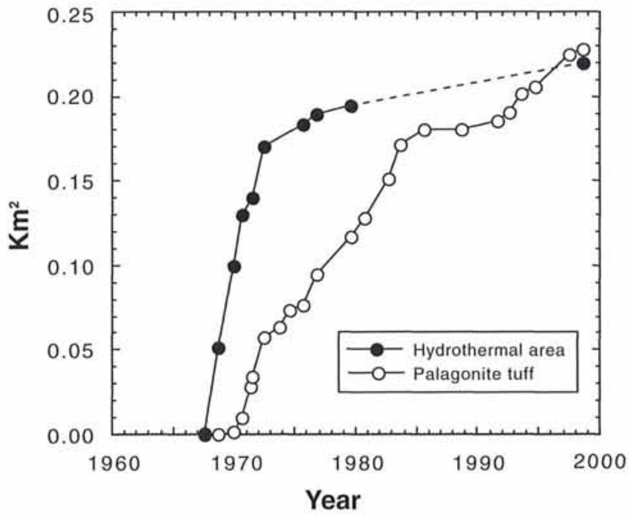

Figure 2. Mapped extent (km²) of the hydrothermal area in the tephra craters and the area of palagonite tuff, 1968-1998. Field observations indicate that after about 1972, the expansion of the hydrothermal area and palagonite tuff is primarily due to aeolian erosion.

During the period 1967-1998, 29 geologic expeditions were made to the island to follow the above mentioned changes and 24 air photo stereo sets were taken by Landmaelingar Islands, at the request of the Surtsey Research Society. The extent of the hydrothermal area and the palagonite tuff has been mapped with the aid of air photos on the scale of 1:5,000. Temperature measurements at the surface were carried out with conventional mercury thermometers until 1979 and after that with electronic thermometers. Temperature measurements in the drill hole were carried out with a thermocouple. Samples of tephra and tuff have been collected regularly to follow the process of palagonitization.

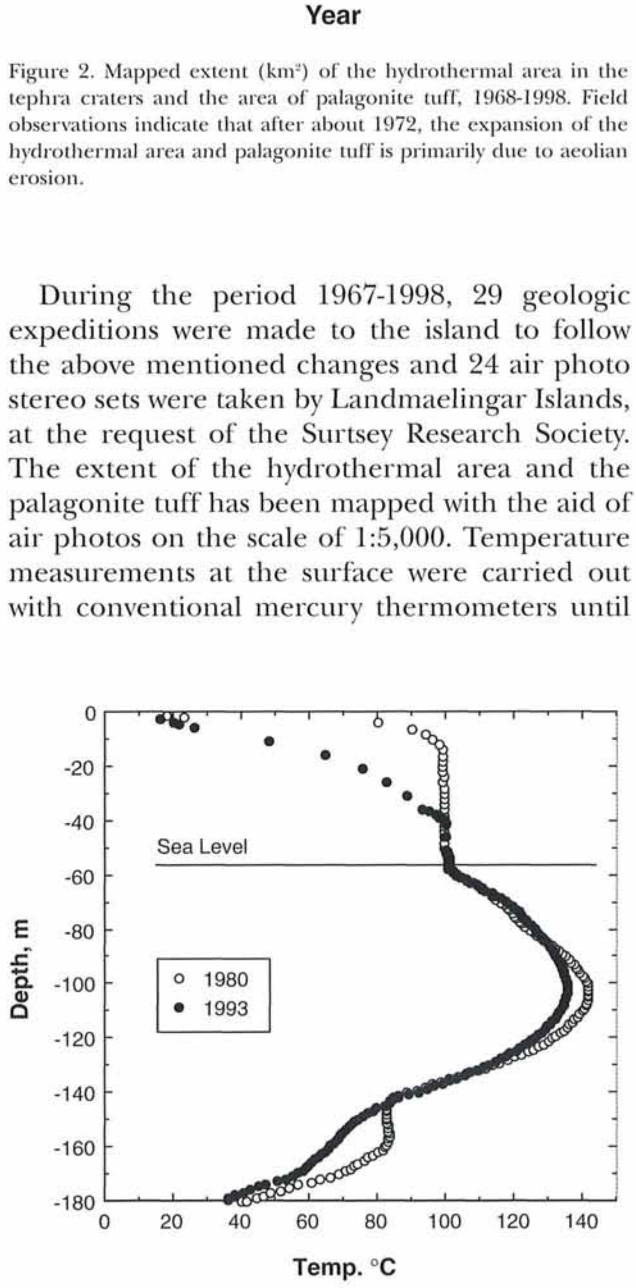

Figure 3. Temperature measurements within the drill hole, as of September 1980 and August 1993. Sea water level is at 58 m depth and the hole is cased down to 165 m depth.

The subject of this report is the monitoring of Surtsey from 1967 to 1998 as regards the development of the hydrothermal system of the volcano, the consolidation of the tephra to palagonite tuff and the marine abrasion of the island (Jakobsson *et al.* 1998). An attempt is also made to predict the future development of Surtsey by simple models, estimated from the observed area.

ERUPTION HISTORY

During the initial phreatic phase of the eruption, from November 1963 to April 1964, tephra (hyaloclastite) was deposited as air fall tephra and base surge flows, creating two horseshoe-formed craters (Fig. 1). The tephra is generally finely bedded and fine grained, with 60-70 % in the coarse ash (0.06 - 2 mm) fraction. Less than 0.5 % falls into the fraction blocks and bombs (> 64 mm). About 85-90 % of the tephra is basaltic glass, the remainder being olivine and plagioclase phenocrysts, and rock fragments. Initial total porosity of the tephra at surface is as high as 45-50 % (Oddsson 1982).

Lava started to flow from the western crater in April 1964 and continued to do so until May 1965. A lava shield, dipping towards the south and southeast, was gradually built up with foreset-bedded breccia forming at the same time below sea level. This lava shield has a thickness of 100 m at the western lava crater. Lava again erupted from August 1966 to June 1967, this time from a new fissure inside the eastern tephra crater, Surtur, forming an irregular lava shield towards the southeast (Fig. 1). In December 1966 and January 1967 small lava flows erupted from five different fissures in the eastern tephra crater (Thórarinsson 1968). The Surtsey lavas are generally thin and fractured. At the east coast individual lava units average a few meters in thickness, while at the southwest coast the lava flows are often less than 1 m thick. One lava flow at the south coast exceeds 20 m in thickness.

When the eruption ceased the volume of Surtsey itself was about 0.8 km³, of which 0.12 km³ was above sea-level. The island had then reached a maximum height of 174 m above sea level and an area of about 2.65 km². The material erupted is alkali olivine basalt. Morphologically, Surtsey is

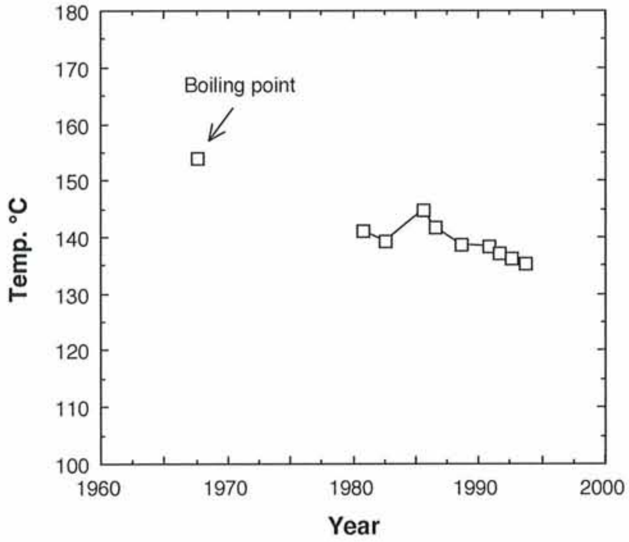

Figure 4. Maximum temperatures (at 101-104 m depth) in the drill hole 1980-1993. The boiling point for sea water at this depth is also indicated for mid 1967, when the hydrothermal system probably was established.

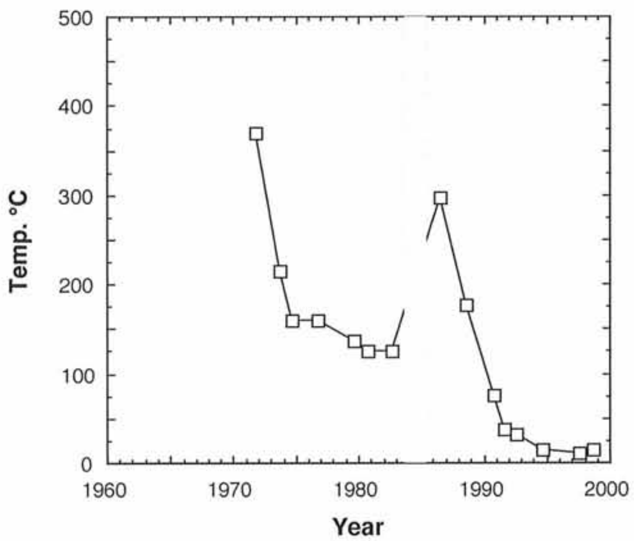

Figure 5. Temperature measurements at surface at a locality on the southern rim of the Surtungur (western) lava crater, 1971-1998. Only maximum temperatures measured each time are registered (cf. Jakobsson 1978, his Fig. 2, curve 1). The vertical shaded area indicates the time period when the fissures at the western lava crater opened up.

a marine tuya (table mountain, stapi), built up in the same manner as the Pleistocene sub- and intraglacial tuyas (Kjartansson 1966).

THE HYDROTHERMAL SYSTEM

Anomalous temperatures were first detected at the surface in the tephra pile in April 1968 (Jakobsson 1978). A thermal anomaly is clearly visible on the surface of the eastern tephra crater on an infrared image taken on August 22, 1968 (Friedman & Williams 1970). It has been suggested that the hydrothermal system was developed as a consequence of intrusive activity in the eastern tephra crater during December 1966 - January 1967 (Jakobsson & Moore 1986). The hydrothermal system is vapour-dominated above sea level and temperatures around 100° C will therefore prevail in the porous tephra pile, except close to the surface where temperatures were lower because of precipitation and circulation of air.

Since the hydrothermal area was detected in 1968, it has, as measured at the surface, continued to expand within the tephra craters (see Fig. 2). It is tentatively suggested that the birth and development of the hydrothermal system is recorded in the increase in the surface exposure of the hydrothermal area from 1967 to 1970. In 1970 the conversion of tephra to tuff may have started to affect the heat flux, resulting in a slowing down of the expansion of the hydrothermal area. It takes about 1-3 years for the Surtsey tephra to convert to compact tuff at 80-100° C (Jakobsson 1978). The decline in surface temperatures after 1971 is probably also due to the sealing effect of the newly formed palagonite tuff. The surface extent of the hydrothermal area continued to expand in 1972-1979, partly because the vapour was forced to the sides of the almost impermeable core of palagonite tuff, but probably more importantly due to removal of loose tephra from surface by wind and water. After 1979 it was difficult to get accurate estimates on the extent of the hydrothermal area, and in 1998 its extent was estimated to be less than the area of palagonite tuff (Fig. 2).

Temperature measurements in a 181 m deep hole, which was drilled in 1979 at the eastern border of the hydrothermal area (Jakobsson & Moore 1982), show that the hydrothermal system in that area has cooled down in a regular fashion with the greatest cooling occurring near the surface, at the bottom, and at middle depth where the hole is hottest (Fig. 3). The cooling varies with depth in the well. The region of maximum temperatures at 101-104 m depth apparently caused by heat from nearby dykes (Jakobsson & Moore 1986) declined from 154° C in 1967 to 133° C in 1993, or at a general rate of ≤1° C per year (Fig. 4).

Fairly continuous surface temperature measurements are available from a 40x30 m area at the southern rim of the western lava crater (Fig.

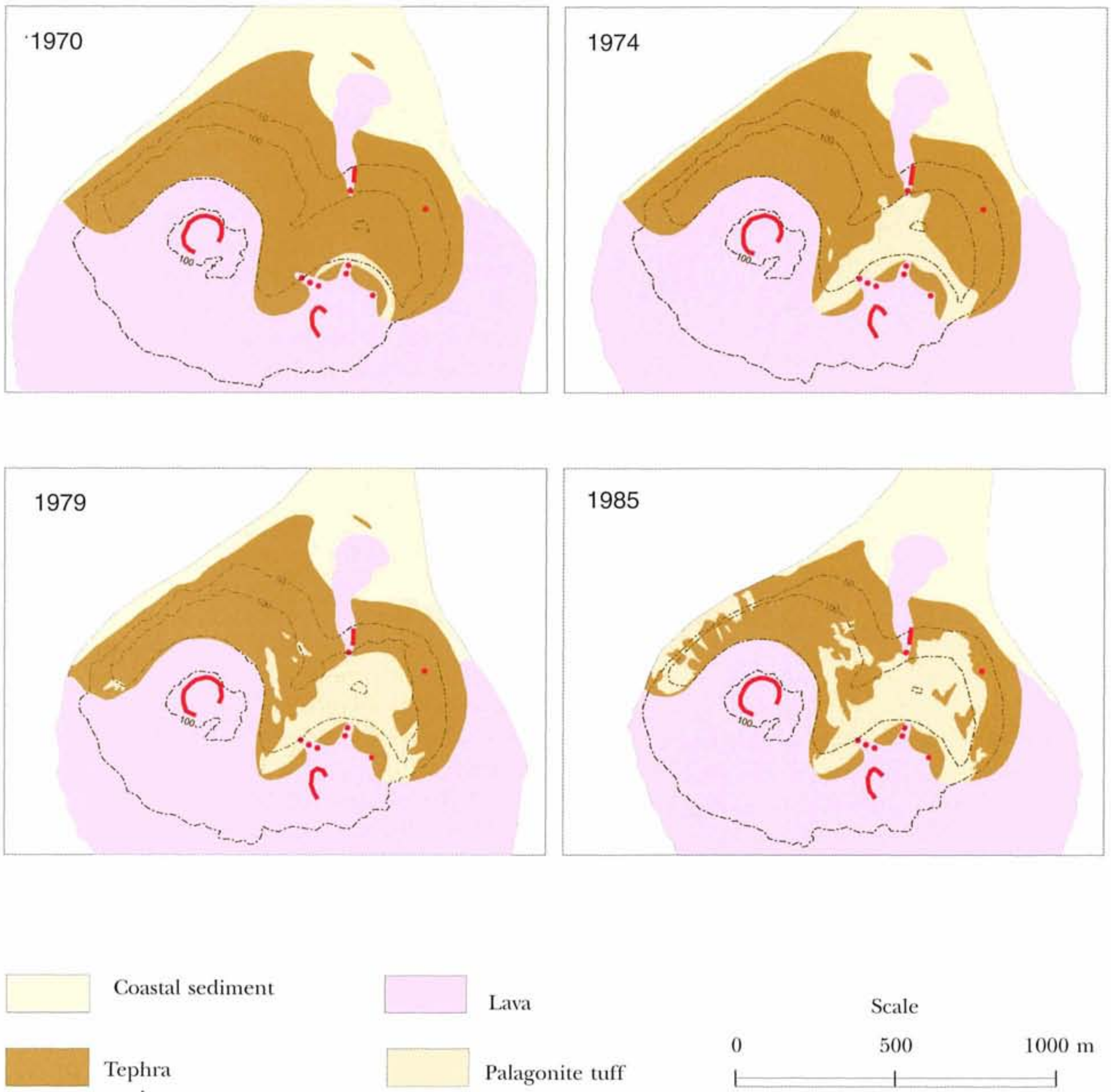

Figure 6. Four simplified geological maps of the central part of Surtsey showing the expansion of the mapped area of palagonite tuff, from 1970 to 1985. Aeolian sand and talus is omitted. Different outlines of the island are traced after air photographs (Landmaelingar Íslands) from respective years. Different height contours are from maps after Norrman (1970), Landmaelingar Íslands (pers. comm. 1977), Norrman (1978) and Norrman & Erlingsson (1992).

5). A series of E-W fissures in the surface lava widened about 10-20 cm between September 1983 and August 1985. An unexpected rise in temperature was observed at this site in 1985 and was apparently caused by subsidence of the southern part of the 100 m thick lava pile, opening of these fissures, and conduction of hot gases from below. A small rise in 1985 of the maximum temperature at 101-104 m depth in the drill hole (Fig. 4) was evidently produced by this event.

CONSOLIDATION OF THE TEPHRA

The hydrothermal activity caused rapid alteration of tephra, producing the first visible palagonite tuff in 1969, in the southeastern corner of the eastern tephra crater (Jakobsson 1978). Fig. 6 shows how the surface exposure of the palag-

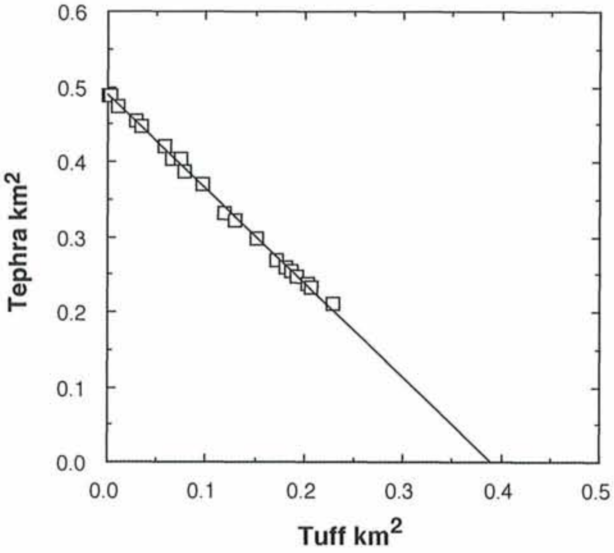

Figure 7. Variations (km^2) in the exposed area of palagonite tuff related to the area of unaltered tephra, 1967-1998. It is inferred that the area of palagonite tuff is ≤ 0.39 km^2 when all tephra has been altered to tuff or eroded away.

onite tuff has gradually increased from 1969 to 1998, when 52 % of the exposed area of tephra in Surtsey had converted to palagonite tuff. However, the unaltered tephra is a relatively thin blanket encircling the tuff area, and it is estimated that by volume some 80-85 % of the remaining tephra pile above sea level had been altered to palagonite tuff in 1998.

The expansion of the area of palagonite tuff is further elucidated and compared to that of the hydrothermal area in Fig. 2. The expansion of the surface exposure of palagonite tuff is probably directly linked to the expansion of the hydrothermal area in 1969-1972. After that field observations indicate that the mapped expansion of the tuff area is primarily due to removal of loose tephra from the surface by wind and water. The rather irregular curve of the area of palagonite tuff after 1972 (Fig. 2) is probably primarily reflecting the frequency of heavy winter storms. By comparing the variations in the mapped areas of tephra and palagonite tuff from 1967 to 1998 (Fig. 7), it is inferred that the area of palagonite tuff is ≤ 0.39 km^2 when all tephra has been altered to tuff or eroded away.

Palagonitization of fine grained air fall and base surge tephra such as found in Surtsey and subsequent deposition of secondary minerals, produces a compact mass of rock, which has turned out to be extremely resistant to marine abrasion. Layering is hardly conspiceous in the tuff and fractures are relatively few.

EROSION

Heavy storms, mainly during winters, produce high wave activity at the southwest coast of Iceland (Viggósson *et al.* 1994). Marine abrasion has therefore caused rapid sea cliff recession in Surtsey (Thórarinsson 1968, Norrman 1978, Jakobsson 1995). The loose unconsolidated tephra was easily eroded, even during the phreatic phase of the eruption. Since the lava units are generally rather thin and fractured they have also been heavily abraded, particularly the thin pahoehoe sheets. The palagonite tuff, however, is much more resistant to marine erosion. This agrees with observations on the other islands in the Vestmannaeyjar archipelago, where marine erosion of cliffs made of palagonite tuff appear extremely slow, although no reliable records exist on the rate of marine erosion in Vestmannaeyjar.

Longshore currents have deposited a sand-gravel spit on the north side, see Figs 1 and 6. The material is primarily derived from the west and east lava cliffs, carried by heavy surfs towards the north. When marine abrasion reached compact palagonitized tuff at the west coast in 1981 and water depth increased at that site, less and less material was transported to the northern spit. The result was that after 1981 the northern spit has slowly been moved towards the east (Figs 6 and 9).

The unconsolidated tephra is also easily eroded by wind and running water. Exact figures on aeolian erosion in Surtsey do not exist, however, it is estimated that several meters have been eroded from the crest of the tephra craters. In the center of the western bowl of the eastern tephra crater (Surtur), it is estimated that some 10-15 m (vertical thickness) of tephra have been eroded by aeolian action. Much of the eroded tephra has been carried into the sea, the rest being deposited along the sides of the tephra craters and on the lava (Jakobsson 2000). The palagonite tuff is also somewhat sensitive to wind erosion and at places in the eastern tephra crater a few meters of the surface have evidently been eroded after the tephra was consolidated to tuff.

AREAL CHANGES

The three principal geological formations of Surtsey react quite differently to marine abrasion. Fig. 8 shows the cumulate areal change of Surtsey and separately the changes of its three

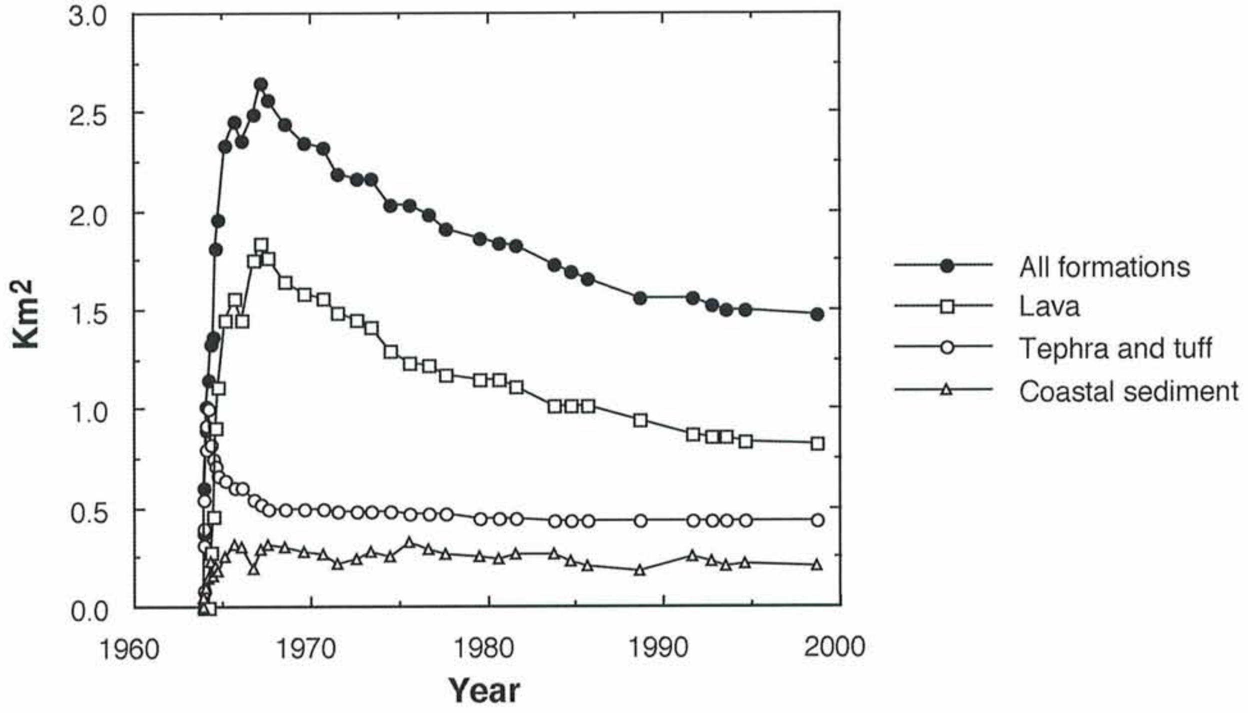

Fig. 8. Aerial changes (km²) of Surtsey and its three principal geologic formations, 1963-1998. The measurements are done on air photographs taken by Landmaelingar Íslands, at the scale 1:5,000. Aerial measurements during the eruption 1963-1967 are mainly from Thórarinsson (1966, 1968).

geological formations during the period of construction in 1963 to 1967 and subsequent destruction after the eruptions ceased in 1967. The diagram demonstrates that the erosion of lava dominates the reduction in size of the island. The total area of tephra plus palagonite tuff has only changed to a minor degree from 1967 to 1998, but the area of lava has been halved in this period. The area of the coastal sediment of the northern spit shows perceptible variations, probably primarily due to variations in intensity of winter storms, and was generally seen to diminish slightly during the period.

Fig. 9 shows changes in the outline of Surtsey from 1967 to 1998. During this period the area of Surtsey shrunk from a maximum of about 2.65 km² in 1967 to 1.47 km² in 1998. It appears that the marine abrasion will proceed at a considerable speed until the core of palagonite tuff, volcanic necks and lava resting on palagonite tuff, have been reached. When the core is reached the erosion will slow considerably.

FUTURE DEVELOPMENT OF SURTSEY

In order to predict the future development of the size of Surtsey with some certainty we would need a credible theoretical model with satisfactory fit to the observed values according to statistical criteria. The shape of the island cannot be closely approximated by any simple geometrical model and the main geological formations, i.e. lava, tephra, tuff and sediment, have different properties with regard to erosion. But the data are not sufficiently accurate or numerous to estimate complicated models with many parameters. Our models are therefore gross simplifications of the actual circumstances and we can only hope to obtain some idea of the order of magnitude of the rate of erosion in the future.

Our observations are measurements of the area of Surtsey at given points in time. The total area at a particular time is

$$Y = Z + B$$

where B is the area of the palagonite tuff, which constitutes the permanent part of the island, and Z is the area of formations subject to erosion.

The rate of erosion at any time depends upon the weather, tides and currents and is highly variable. But our investigation is only concerned with long term changes so we ignore

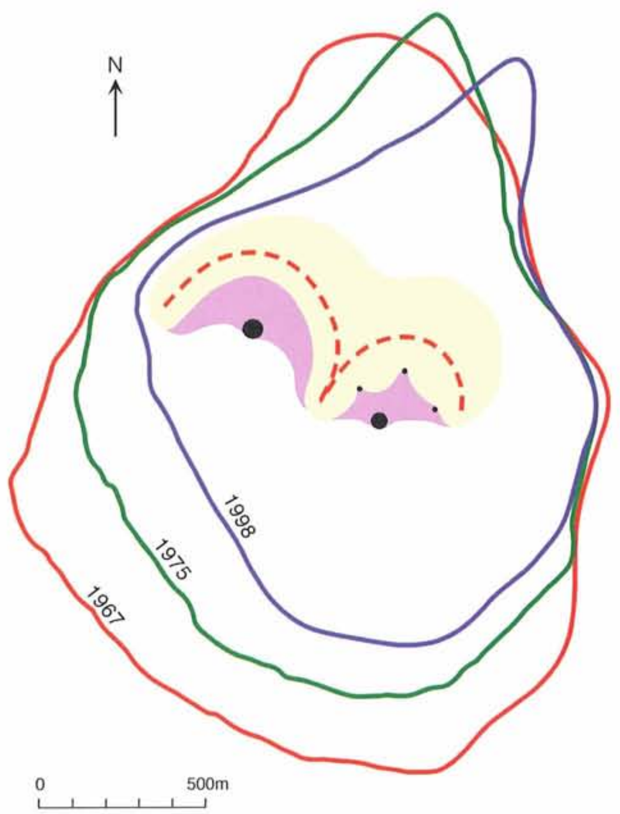

Figure. 9. Changes in the outline of Surtsey from 1967 to 1998, traced after air photographs taken by Landmaelingar Íslands. The estimated extent of the central core of palagonite tuff (brown), volcanic necks (black) and lava resting on tuff (violet), is indicated.

these variations. Let us first consider a rather naïve model and assume that the rate of reduction of the area at any time is proportional to the area of geological formations subject to erosion, i.e.

$$dZ = -\alpha Z dt. \qquad (1)$$

Solution of this equation gives the model

$$Y_i = A^{-\alpha t_i} + B + \varepsilon_i$$

for the observed area at time t_i with t_1=0 and Z=A at the first observation. The rate of erosion is determined by α. Measurement errors and irregularities in the process of erosion are represented by the residuals e_i. Estimation of parameters by least squares gives

$$Y_i = \underset{(0.030)}{1.223}\ e^{\underset{(0.0045)}{-0.0676} t_i} + \underset{(0.035)}{1.309}.$$

(0.030) (0.0045) (0.035)

Standard deviation of estimated parameters are presented in parentheses below respective value.

R^2 = 0.994 (adjusted for degrees of freedom),
s = 0.026 km^2 (estimated standard error of the residuals)
logL = 54.72 (L = likelihood function).

Estimation by least squares is maximum likelihood estimation when the residuals are serially uncorrelated, normally distributed with zero mean, constant variance and independent of t_i. The model passes statistical tests based on these premises and also tests whether the parameters are constant in time. (The assumption of constant residual variance is not realistic for this equation but an estimation, taking into account decreasing variance as the area approaches B, produces similar parameter values).

This statistically satisfactory model predicts that the erosion ceases long before the area has reached the estimated size of the palagonite tuff, which contradicts the geological evidence about the future development of the size of Surtsey. The mathematical model of equation (1) is widely applied to describe the decline of mass or populations where each element of Z is equally liable to elimination at any moment of time. But the assumption that the rate of eroded area is proportional to the total area is implausible. The sea is the main erosive force and it is only active along the coastline.

Let us now try and derive a formulation based only on consideration of erosion by the sea. We ignore the actual shape of the island and different properties of the eroded geological formations and consider the erosion of a regular cone of initial height H and radius R. We assume uniform erosion along the coastline so that the circumference remains a circle. When the erosion proceeds the height at the coastline becomes h and the radius r. Let us now assume that the rate of erosion by the sea is proportional with the perimeter so that the change of volume in time interval dt is

$$dV = -2\pi rkdt, \qquad (2)$$

where the constant k is a property of the eroded material and erosive forces. The change in volume when r changes by dr is

$$dV = 2\pi rhdr$$

where h is the height at the perimeter. From the geometry we have H/R = h/(R-r) so that

$$dV = 2\pi rH(1 - r/R)dr. \qquad (3)$$

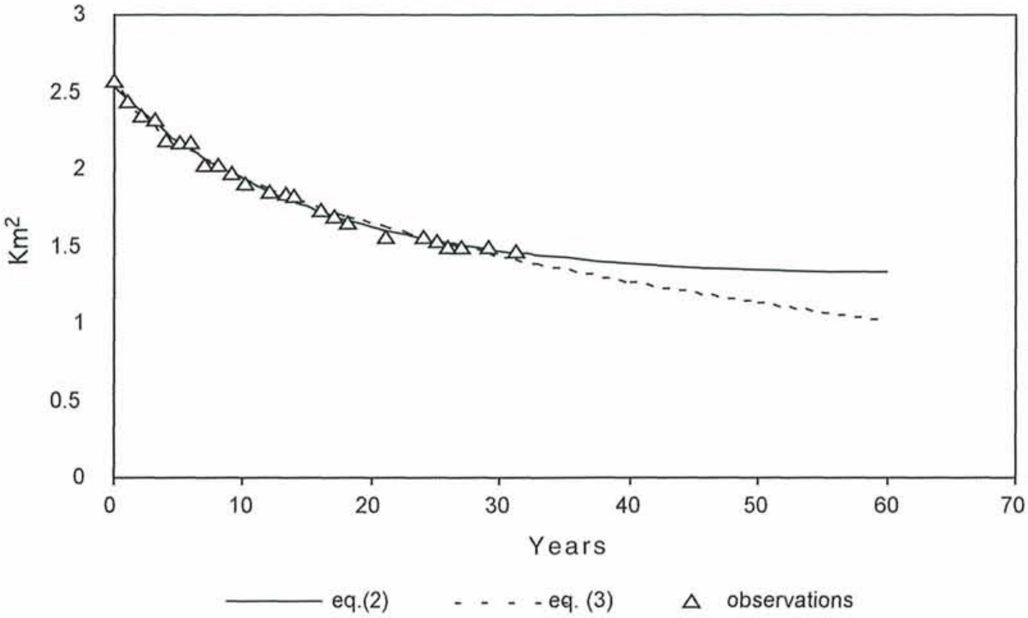

Figure 10. Observed area, fitted models and extrapolation, 3 decades ahead.

Equations (2) and (3) provide a differential equation for the change of r and with the initial value r=R at t=0 the solution is

$$(R-r)^2 = 2kRt/H.$$

In this equation t=0 must be when r=R and this may not coincide exactly with the first observation so we add a constant to t. By inserting the area for r we obtain the model

$$Y_i = (Y_0^{0.5} - (\beta(t_i - t_0))^{0.5})^2 + \varepsilon_i$$

for the observed area. Y_0 is the initial area, t_0 the time between r=R and the first value and

$$\beta = 2\pi kR/H.$$

Estimation by least squares gives

$$Y_i = (1.673 - (0.00738(t_i+0.62))^{0.5})^2$$
$$(0.016) \quad (0.00052) \quad (0.37)$$

$R^2 = 0.992$,
$s = 0.030\ km^2$,
$\log L = 51.39$.

The fit of this model is slightly worse than the exponential decay and it fails the test of constant parameters. According to this model the time when the area reaches 0.39 km^2 is 148 years after the first observation, i.e. about year 2115. But as the model fails the test of constant parameters this is not a reliable forecast. In view of the impeccable fit of the model with exponential decay a much longer time until only the palagonite formation is left is hardly inconsistent with the data.

Both models are based on the assumption of a homogeneous material with respect to erosion. Obviously the actual geological formations have different physical properties, geometry and exposure to the erosive forces. Fig. 8 shows that the rate of erosion has in fact differed considerably between the formations. However, the fits obtained when the models above (or simple polynomials) are estimated with the area of each formation were worse than we obtained for the total area. One reason for this is probably that the geometry of each formation is less regular than the whole island. We have not attempted any interpretation of these results.

Fig. 10 shows the observed values of the total area, fitted models and extrapolation, 3 decades ahead. The two curves are hardly distinguishable until the end of the interval of observations, but the predicted courses diverge rapidly. Future observations will therefore soon provide valuable additional information for this kind of model building.

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