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Influence of the Surtsey Eruption on the Nutrient Content of the Surrounding Seawater

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ABSTRACT

The influence of the recent Surtsey eruption on the nutrient content of the surrounding seawater was studied over a period of one year. During the first months, while the eruption was explosive and when seawater flooded the vents, a significant increase in reactive silicates was observed within 30 km of the eruption center, and the silicate concentration had increased by a factor of three near the island. After the eruption changed to an effusive phase, in early April 1964, the amounts dissolved were negligible, except close to the island where hot lava entered the sea. Phosphate enrichment due to the eruption was much less pronounced than the silicate enrichment, and no increase in nitrates was observed. Laboratory experiments on the rate of dissolution of nutrients from tephra relative to temperature, reaction time, and surface area showed agreement with the field data; the results of these experiments indicate that the dissolution was primarily caused by the action of seawater on hot erupted material. Estimates of the rate of dissolution of reactive silicate from Surtsey during the first weeks of the volcanic activity indicate that erupted materials may constitute an important source of silicate for seawater in areas where underwater eruptions occur.

Introduction. Early in the morning on 14 November 1963 a submarine eruption was observed at 63°18’N, 20°36.5’W, about 5–6 km WSW of Geirfuglasker, the southernmost island in the Westmann Islands group. The following night an island was born. Later it was officially named “Surtsey.” The main bathymetrical features around and west of Surtsey, July–August 1964, are shown in Fig. 1. The course of the eruption and the development of the new island have been described by Thorarinsson (1964, 1965) and Thorarinsson et al. (1964).

Precursory indications of the eruption were few. In the early morning on 13 November, a ship searching for herring recorded a distinct temperature maximum of 9.4°C about 3.7 km from the eruption center; the temperature in other parts of the shelf area at that time was about 7°C. This indicates that some volcanic activity had started at least as early as 12 November. Because

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the ocean depth at the eruption center was about 30 m before the eruption started, it may have been a few days before the volcano was built up to sea level.

On 16 November, two days after the eruption was first observed, the island above sea level had reached a height of 40 m and was about 500 m in length. At this time it had the form of a narrow ridge. About mid-December it had become nearly circular, with a diameter of 1100 m and a height of 145 m. Thus, in spite of marine erosion, it grew very rapidly during the first weeks of the eruption. One year after the eruption started, the area of the new island was about 2.0 km² and its maximum height 174 m.

During the first four and one-half months, the eruption was wholly explosive, the ejected material consisting of tephra, volcanic gases, and steam. During most of this period, seawater had easy access to the vents, either by direct flooding or by seeping through the porous crater walls. This type of activity continued until 3 April 1964, when enough tephra material had built up around the crater to prevent access of seawater to the vents. The eruption
now changed to an effusive phase, with outflow of lava that has continued until 17 May 1965.

The Surtsey eruption afforded an opportunity to study the effect of submarine volcanic activity on the components of seawater. The present paper deals with one aspect of this effect, viz., the dissolution of nutrients from the erupted materials.

**Material and Methods.** From 15 November 1963 to 17 November 1964 nine cruises were conducted to the sea area surrounding Surtsey. The number of stations as well as the type of data collected are listed in Table I. During all of these cruises except one, observations were made along one north-south section and one west-east section, with Surtsey in the center of each section. Along each section collections were made at ten stations, located between 0.4 and 22 km from the island. On four occasions, additional sections were worked across the shelf farther west in the Selvogsbanki region; on one occasion (June 1964) only nine stations could be worked due to adverse weather conditions.

Nutrient samples were collected in polyethylene bottles, frozen aboard the ships, and stored in the dark until thawed and analyzed ashore. Colorimetric determinations were made with a Unicam SP-500 Spectrophotometer according to the methods of Mullin and Riley (1955) for nitrates and reactive silicates and of Murphy and Riley (1962) for phosphates. Facilities for freezing samples were poor on some of the ships, and this limited the number of samples taken. Fluorides were determined according to the method of Thompson and Taylor (1933).

In addition to the observations made in the sea around Surtsey, a few water samples were procured by landing parties.

**Table I. Chemical observations around Surtsey and in the Selvogsbanki region.**

<table>
<thead>
<tr>
<th>Cruise no.</th>
<th>Ship</th>
<th>Date</th>
<th>No. of stations</th>
<th>Hydro*</th>
<th>SiO$_4$$^{-4}$</th>
<th>PO$_4$$^{-3}$</th>
<th>NO$_3$$^{-}$</th>
<th>F$^{-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ALBERT</td>
<td>15-16/XI/63</td>
<td>20</td>
<td>87</td>
<td>87</td>
<td>-</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>MARÍA JÚLIA</td>
<td>1-3/XII/63</td>
<td>21</td>
<td>98</td>
<td>46</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>ÆGIR</td>
<td>18-24/I/64</td>
<td>37</td>
<td>156</td>
<td>88</td>
<td>73</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>DORSTEINN</td>
<td>31/III-3/IV/64</td>
<td>43</td>
<td>198</td>
<td>113</td>
<td>97</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>DORSKAB.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>DORSTEINN</td>
<td>10/IV/64</td>
<td>20</td>
<td>87</td>
<td>42</td>
<td>41</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>DORSKAB.</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>FANNEY</td>
<td>29-30/V/64</td>
<td>21</td>
<td>112</td>
<td>95</td>
<td>95</td>
<td>93</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>ÆGIR</td>
<td>22-23/VI/64</td>
<td>9</td>
<td>48</td>
<td>33</td>
<td>33</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>ALBERT</td>
<td>5-7/IX/64</td>
<td>28</td>
<td>177</td>
<td>172</td>
<td>172</td>
<td>164</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>FLOÁKLETTUR</td>
<td>16-17/XI/64</td>
<td>21</td>
<td>83</td>
<td>81</td>
<td>75</td>
<td>75</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>220</td>
<td>1046</td>
<td>757</td>
<td>586</td>
<td>332</td>
</tr>
</tbody>
</table>

* With temperature and salinity at all stations, and dissolved-oxygen observations during the first cruise.
Vertical and Horizontal Distribution of Silicates. Field observations as well as laboratory experiments revealed that, of the nutrients studied, reactive silicates were the only ones that showed a clear relationship to the volcanic activity. The following discussion, therefore, refers mainly to the silicate distribution.

During the first months following the eruption, a significant increase in reactive silicates was observed in the water adjacent to the island. Generally, the maximum concentrations occurred within a few kilometers of the eruption center; beyond, the concentration decreased in all directions. However, wind, currents, and other factors played an important part in modifying the distribution pattern.

During the first survey, conducted on the second and third days of the visible eruption (15–16 November 1963), silicate concentrations as high as 20 µg-at/l were observed (Figs. 2, 3). At this time, the wind was from the north and east, establishing a wind current toward the west. The eruption column, which showered tephra into the sea, was bent toward the southeast and rose more than 1 km into the air. At the water surface, the highest concentrations of silicate were observed less than 1 km from the island on the west side. However, near the sea bottom the highest concentrations were found south of the island; this distributional pattern may have resulted from two factors: (i) flow of the erupted materials along the bottom, which slopes toward the south or southeast, and (ii) dissolution from the airborne tephra sinking through the water and accumulating at the bottom. A west-to-east section indicates that the vertical distribution of silicates was irregular during the first days after the visible eruption (Fig. 3). This is not surprising in view of the variable nature of the volcanic activity, which consisted of (i) intermittent and irregular explosions when seawater flooded the vents or (ii) an uprush of tephra and vapor when the access of water was blocked by a tephra reef (Thorarinsson et al. 1964).

During the second survey, on 1–2 December (Figs. 4, 5), the silicate concentrations at the surface were somewhat lower than they were during the first survey, and the area of maximum concentration was now located north of the island. Although the wind on 1 December was calm, on 30 November the wind was south-southwesterly, with gusts up to 32 knots. Thus, at this time also the distribution of silicates at the surface was consistent with the prevailing wind direction. Near the bottom, the distribution was somewhat more symmetrical with respect to the island than during the first survey. The vertical distribution (Fig. 5) also showed a more regular pattern than before, suggesting that conditions were approaching a steady state.

During the third survey, on 18–24 January (Figs. 6, 7), the silicate distribution revealed an especially interesting pattern. At the surface, high concentrations were found (i) near the coast just off the mouth of the big glacial river Ölfusá, (ii) just north of Surtsey, and (iii) west of Surtsey. The concentrations
Figure 2. Horizontal distribution of salinity at 0 m, and of silicate at 0 m and near bottom. 15–16 November 1963.

Figure 3. Vertical distribution of silicate on a west-east section, with Surtsey in the center. 15–16 November 1963.
Figure 4. Horizontal distribution of salinity at 0 m, and of silicate at 0 m and near bottom. 1-2 December 1963.

Figure 5. Vertical distribution of silicate on a west-east section, with Surtsey in the center. 1-2 December 1963.
near the coast, 12–22 µg-at/l, coincided with low salinities and therefore resulted from admixture of river water, which is high in reactive silicates. The area north of Surtsey was small, with concentrations between 10 and 13 µg-at/l. The area west of Surtsey, which extended at least 90 km west of the island and was therefore much larger than the second area, also had concentrations of 10–13 µg-at/l; the shape of this area was consistent with the direction of the prevailing current and of the strong south-southeasterly winds on the day prior to the observations. The salinity distribution west of Surtsey indicates that the silicate concentrations in this area did not result from admixture of high-silicate fresh water and therefore must have been related to the volcanic activity—possibly a powerful explosion at some previous time. Near the bottom, high silicate concentrations were found in two areas: north and west of the island; the concentrations north of Surtsey probably resulted from outflow through a new fissure in the ENE portion that developed at the end of December. The profiles of vertical distribution (Fig. 7) suggest that, at this time, the silicate concentrations were much more pronounced in the bottom water layers than in the upper layers.

At the end of March and in early April (Figs. 8, 9), the effect of the eruption on the silicate concentration in the surrounding water had decreased markedly from the effect in January. At the surface, only slightly higher concentrations were found near Surtsey than in the adjacent water farther away. Near the bottom the silicate concentrations close to the submerged part of the island were, with one exception, only about 1 µg-at/l higher than elsewhere in the Selvogsbanki region; the exception was a station east of the island, where the concentration was as high as 10 µg-at/l (about 3 µg-at/l higher than in other parts of the area). Similarly, the vertical distribution (Fig. 9) indicates only a slight addition of silicates due to the eruption, except near the island on the east side. During this survey and just before it the weather had been relatively calm, with light westerly or northwesterly winds; this may explain the southward extension of the tongue of slightly higher silicate concentration.

On 10 April, about seven days after the eruption changed to an effusive phase, the Surtsey area was reinvestigated. The results (Figs. 10, 11) indicate that the silicate concentrations near the island had not increased significantly in the surface layers and had increased little if any in the bottom layers. The vertical profile (Fig. 11) shows a silicate maximum about 12 km west of the island; this maximum is clearly related to low-salinity water, which at this time extended southward to the section (cf. Fig. 10); but the maximum cannot be ascribed to volcanic activity.

The nutrient data collected during the three succeeding cruises, i.e., May, June, and September, showed reduced concentrations due to biological uptake. However, a silicate maximum in the surface layers around Surtsey (Figs. 12, 13, 16, 17, 18, 19) is clearly indicated. Although these data might reflect dissolution from lava flowing into the sea, a closer analysis indicates that these
Figure 6. Horizontal distribution of salinity at 0 m, and of silicate at 0 m and near bottom. 18–24 January 1964.
higher values around the island were not appreciably affected by the volcanic activity. In late May, the distribution pattern of the phosphates and nitrates (Figs. 14, 15) resembled closely that of the silicates; since laboratory experiments (see p. 251) have shown that significant amounts of nitrates do not dissolve from erupted materials, it follows that the increased nitrate concentrations around Surtsey in late May must have been related to variations in the biological activity. The same must be true of the increased phosphate and silicate concentrations. Substantial evidence for this is furnished in Fig. 20, which shows the correlation between nitrates and phosphates and nitrates and silicates. The slopes of the envelopes enclosing the points indicate a ratio of change in nitrate and phosphate of about 16:1 and a ratio of change in nitrate and silicate of about 16:23. These values are in agreement with normal values previously reported (e.g., by Redfield et al. 1963, Stefánsson and Richards 1963, Grill and Richards 1964) for simultaneous changes in nutrients due to biological processes. If the increased concentrations were due to dissolution from erupted material, these ratios would not be expected.

It is well known that turbulence is generally greater near oceanic islands than in the open sea. In agreement with this, the density distribution around Surtsey in May and June 1964 revealed that the stability near the island was minimal and increased outward. The assumption that replenishment of sur-
Figure 8. Horizontal distribution of salinity at 0 m, and of silicate at 0 m and near bottom. 31 March–3 April 1964.
face nutrients from below is greater near an island is consistent with the observed variations in nutrients. This greater turbulence near the island may have led to reduced biological uptake. There was evidence of this in late June. According to Mrs. Thorunn Thordardóttir (personal communication), the mean primary production in the uppermost 30 m as measured by the C\textsuperscript{14} technique was 5.35 mgC/m\textsuperscript{3}/hour at St. 1, about 22 km east of Surtsey, but only 2.74 mgC/m\textsuperscript{3}/hour at St. 4, less than 1 km east of the island (see Fig. 17). The corresponding differences in density ($\sigma_t$) between 0 and 50 m were +0.27 $\sigma_t$-units at St. 1, but -0.02 $\sigma_t$-units at St. 4. The reduced plant production near Surtsey at this time can thus be ascribed to intense turbulence.

In November 1964 the silicate distribution appeared to be quite normal, and the effect of the eruption obviously was negligible (Figs. 21, 22). The great contrast between the distribution in November 1963 and that almost exactly one year later is clearly demonstrated in a comparison of the vertical profiles (Figs. 3 and 22).

**Laboratory Experiments on Dissolution of Nutrients from Erupted Material.** Samples for experiments to study the dissolution of nutrients from the tephra were collected from the deck of patrol ships sailing under the ash cloud during the first days after the eruption started. According to Sigvaldason (in Thora-
Figure 10. Horizontal distribution of salinity at 0 m, and of silicate at 0 m and near bottom. 10 April 1964.

Figure 11. Vertical distribution of silicate on a west-east section, with Surtsey in the center. 10 April 1964.
Table II. Amounts of silicate dissolved from different size fractions.

<table>
<thead>
<tr>
<th>Grain size (µm)</th>
<th>Amounts of silica dissolved (µg-at/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>23°C</td>
</tr>
<tr>
<td></td>
<td>Run 1</td>
</tr>
<tr>
<td>&gt;590</td>
<td>2.4</td>
</tr>
<tr>
<td>250–590</td>
<td>2.6</td>
</tr>
<tr>
<td>149–250</td>
<td>2.7</td>
</tr>
<tr>
<td>74–149</td>
<td>3.2</td>
</tr>
<tr>
<td>&lt;74</td>
<td>4.9</td>
</tr>
<tr>
<td>Unsieved</td>
<td>-</td>
</tr>
</tbody>
</table>

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rinsson et al. 1964), the major part of the tephra material from Surtsey is dark-brown, translucent sideromelan glass.

Portions of tephra were weighed and added to polyethylene bottles containing 200 ml synthetic seawater. Following a suitable time for reaction, when the bottles were occasionally shaken, the samples were filtered and the filtrate was analyzed for nutrients.

In one set of experiments the amounts of silica dissolved relative to particle size were investigated. The sample used was obtained on the first day of the visible eruption, i.e., 14 November 1963. Four grams of dried tephra per 200 ml of synthetic seawater were used for each run and allowed to react for two hours. The results are shown in Table II. As was expected, the dissolved amounts increased with decreasing particle size, i.e., with increased surface area of tephra exposed to the solvent. However, the difference in this respect between size groups is not very marked.

To study the rate of dissolution of nutrients at various temperatures, four-gram portions of unsieved tephra were used. The bottles were kept for two hours at temperatures varying from 10°C to 100°C. The following results were obtained: below 50°C, 3–6 µg-at/l of silicate were dissolved; at 80°C, about 15 µg-at/l; and at 100°C, 27–28 µg-at/l (Fig. 23).

The tephra sample for this and the remaining experiments was collected on 21 November 1963. This sample was not dried and therefore contained a small percentage of water and probably sea salts; the results obtained are therefore not strictly comparable to those for the amounts of silica dissolved relative to particle size. This may explain why the 14 November sample yielded, at 100°C, somewhat greater amounts of dissolved silicates than the second sample.

Determinations of the amounts of inorganic phosphates dissolved at different temperatures gave the following results: at 22°C, 0.35 µg-at/l of PO₄³⁻-P; at 40°C, 0.34; at 60°C, 0.50; and at 100°C, 0.64.

No detectable amounts of nitrates were found dissolved in any of these samples.

The amounts of silicates dissolved at 100°C with different reaction times are shown graphically in Fig. 24. Since, in water solutions at 100°C, the
Figure 12. Horizontal distribution of salinity at 0 m, and of silicate at 0 m and near bottom. 29-30 May 1964.

Figure 13. Vertical distribution of silicate on a west-east section, with Surtsey in the center. 29-30 May 1964.
Figure 14. Vertical distribution of phosphate on a west-east section, with Surtsey in the center. 29-30 May 1964.

Figure 15. Vertical distribution of nitrate on a west-east section, with Surtsey in the center. 29-30 May 1964.
Figure 16. Horizontal distribution of salinity at 0 m, and of silicate at 0 m and near bottom. 22–23 June 1964.

Figure 17. Vertical distribution of silicate on a west-east section, with Surtsey in the center. 22–23 June 1964.
equilibrium concentrations of silica derived from rock glasses lie between the concentrations for saturation with respect to quartz—about 50 ppm—and to amorphous silica—about 400 ppm—(Ellis and Mahon 1964), the results show clearly that the solution at the end of the 21st hour was greatly undersaturated with respect to silica. This is not surprising in view of the fact that, with most forms of silica, equilibrium solubility is not reached for several days (Krauskopf 1956). However, the graph in Fig. 24 shows that even as short a reaction time as 15 minutes may be sufficient to dissolve significant quantities of silicate from hot erupted materials.

The amounts of silicates dissolved at room temperature (23°C) from 4 g of tephra in 200 ml of synthetic seawater with three different reaction times were as follows: 0.5 hour, 3.7 µg-at/l of SiO$_4^{4-}$; 4 hours, 4.6; 21 hours, 4.7.

Thus, as might be expected, the rate of dissolution is very slow at ordinary temperatures. The relatively great amounts (3.7 µg-at/l) dissolved during the first half hour might be due to a small amount of silica already present in the moisture contained in the tephra sample. Similarly, the amounts from the dried ash that were found to dissolve at room temperature (Table II) might have resulted largely from a small fraction of silica in a relatively soluble form remaining after the sample had been dried.

As expected, experiments on variations in the quantity of tephra per unit volume of solvent (Fig. 25) demonstrated that, during a period of a few hours, relatively greater amounts of silica are dissolved from a small quantity than from a large quantity. Thus, a 5-g portion of tephra in one liter at 100°C yielded a total of 17 µg-at, or 3.4 µg-at Si/g; a 50-g portion yielded about 70 µg-at, or only 1.4 µg-at Si/g.

Field Experiments. During a trip to Surtsey on 12 September 1964, young physicists from the University of Iceland measured temperature and collected water samples from a coastal indentation that had been formed by the lava on the southwest shore. The results of analysis, given in Table III, show clearly that concentrations of dissolved silicate in the water ran very high where seawater was in close contact with hot erupted material at the shore,

Table III. Analysis of samples collected from a lagoon on the southwestern shore of Surtsey, 12 September 1964.

<table>
<thead>
<tr>
<th>Distance from sea-lava interface (m)</th>
<th>Depth (m)</th>
<th>Sea temp. (°C)</th>
<th>Salinity (‰)</th>
<th>SiO$_4^{4-}$Si (µg-at/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-3</td>
<td>0</td>
<td>38.0</td>
<td>38.70</td>
<td>122.5</td>
</tr>
<tr>
<td>30-50</td>
<td>0</td>
<td>33.2</td>
<td>38.13</td>
<td>117.4</td>
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<tr>
<td>30-50</td>
<td>0</td>
<td>27.2</td>
<td>36.77</td>
<td>94.2</td>
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<tr>
<td>30-50</td>
<td>0</td>
<td>25.6</td>
<td>36.51</td>
<td>70.1</td>
</tr>
<tr>
<td>2-50</td>
<td>0.3-0.5</td>
<td>&lt;20</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 18. Horizontal distribution of salinity at 0 m, and of silicate at 0 m and near bottom. 5-7 September 1964.
but not very high at 500–700 m from the island. The high salinity indicates that intense evaporation must have been taking place. Also, the high temperatures were limited to a thin surface layer, less than 30 cm in thickness.

On 25 November 1964, the following experiment was undertaken: A pyrex beaker was partially filled with seawater taken at the island near the Bowing lava. With a pair of stainless steel tongs, pieces of red-hot lava were introduced into the beaker until it was almost full; the water temperature in the beaker rose to 80–90°C. When the content of the beaker had cooled for about 10 minutes, the water was drained into a polyethylene bottle. Thus 4.3 kg of lava were extracted with about 10 l of seawater. For comparison, a sample of seawater was collected at the shore about 500 m away from the flowing lava. Both samples were analyzed for nutrients and the results are given in Table IV.

Table IV. Experiment on extracting hot lava with seawater. Values in µg-at/l.

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO\textsubscript{4}^-4-Si</th>
<th>PO\textsubscript{4}^{3-}-P</th>
<th>NO\textsubscript{3}^-\textsubscript{-N}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treated</td>
<td>80.0*</td>
<td>3.18</td>
<td>9.1</td>
</tr>
<tr>
<td>Untreated</td>
<td>13.5</td>
<td>1.25</td>
<td>8.0</td>
</tr>
</tbody>
</table>

* Corrected for silicate dissolved from glass on the basis of a blank experiment.
Figure 20. Correlation between nitrates and phosphates (top) and nitrates and silicates (bottom) of observations around Surtsey, 29–30 May 1964. The broken lines have the slopes \( \Delta N: \Delta P = 16:1 \) (top) and \( \Delta N: \Delta Si = 16:23 \) (bottom).
Figure 21. Horizontal distribution of salinity at 0 m, and of silicate at 0 m and near bottom. 16-17 November 1964.

Figure 22. Vertical distribution of silicate on a west-east section, with Surtsey in the center. 16-17 November 1964.
This experiment also demonstrates that significant amounts of silicates and phosphates are dissolved where hot lava enters the sea. However, the apparent slight increase in nitrates is hardly significant and could very well be due to contamination.

Discussion. In agreement with results from previous studies on the solubility of various forms of silica at low temperatures (Krauskopf 1956), these laboratory experiments indicate that dissolution from erupted materials must indeed be a slow process at ordinary sea temperatures and probably does not contribute much to the observed increase in silicate concentration around Surtsey. However, the tephra that rained down from the erupted column and clouds and the tephra that eroded from the island may have contained significant amounts of silica that already were in water solution or in a comparatively soluble form. This may explain the relatively high concentration often found near the bottom of the adjacent sea after the island was formed. At high temperatures, on the other hand, the erupted materials, whether formed during the explosive or the effusive phase, must have been an important source of silicate. This has been clearly demonstrated with field data as well as laboratory experiments.

Results have shown that the heating effect on the surrounding seawater due to the volcanic activity of Surtsey was generally very small, even as close to the island as a few hundred meters (Malmberg 1965). However, there is evidence, as previously mentioned, that the heating effect was greater during the initial stages of the eruption, before the island was born. Seawater in direct contact with the erupted material must have been heated locally, but as a result of intense mixing with the vast quantities of surrounding seawater, this
effect could be traced only very short distances away from the island. Besides, a large part of the heat energy from the volcano must have been used in evaporating seawater.

The main dissolution process therefore must have taken place at the crater itself, where seawater flushed the eruption vents and percolated through the

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**Figure 24.** Dissolution of silicate at different reaction times (quantity: 4 g tephra/200 ml of solvent; temperature: 100°C).

**Figure 25.** Dissolution of silicate with varying quantity of tephra per unit of solvent (temperature: 100°C; time: 4 hours).
hot tephra. So long as the sea had free access to the vents and each new uprush of tephra was brought into direct contact with the sea, the dissolution must have been very effective. However, as the island grew and the access of seawater became less frequent, temporarily, large amounts of erupted material that were not flooded while hot were built up. Thus the dissolving action must have been reduced after the first few weeks of the eruption. The new vent at sea level, which started to erupt in early February (Thorarinsson 1965), must have given new impetus to the production of dissolved silicates in the surrounding area. There are no seawater data available to confirm this.

Finally, after the eruption had changed to an effusive phase, in early April, seawater no longer flooded the vents, and the only contact of the water with the hot erupted material was where the lava stream entered the sea. Although it has been demonstrated that high silicate concentrations may be found at the lava-sea interface, dissolution from lava must be less effective than dissolution from an equal weight of tephra, presumably because of the smaller area of contact. The laboratory experiments support this.

The results obtained from laboratory and field experiments indicate that inorganic phosphates are dissolved from erupted materials—both tephra and lava—in quantities that amount to approximately 0.02–0.03 µg-at/µg-at of silicate brought into solution. Assume that initial winter concentrations of these elements in the waters south of Iceland were 6–7 µg-at/l of dissolved silicates and about 1 µg-at/l of phosphates. A phosphate enrichment of 1 µg-at/l would then correspond to an increase of about 40 µg-at/l of silicates, which implies that, while the silicates would be increased by a factor of 7, phosphates would be increased by a factor of only 2. Thus the phosphate enrichment due to the eruption is much less pronounced than the silicate enrichment. This agrees with actual findings in January and April 1964, which did not reveal a significant increase in the phosphate concentrations at stations worked near Surtsey.

In addition to material dissolved in seawater from tephra and lava, volatile material might conceivably have dissolved from the emanating gases, especially during the initial stage of the eruption. Thus volcanic fumaroles commonly contain appreciable quantities of hydrogen chloride, hydrogen fluoride and ammonia, traces of nitrate and phosphate, besides compounds of low volatility, such as silica (White and Waring 1963).

Results of chemical analyses on six gas samples from Surtsey have been reported by Sigvaldason and Elisson (1965). These samples were all heavily contaminated with air except one, collected on 15 October 1964; the results, expressed in volume per cent, were: H₂O, 80.00; H₂, 4.56; CO₂, 9.18; SO₂, 5.40; CO, 0.68, and N₂ + A, 0.18. The temperature measured at the sampling site was 1100°C. A search was not made for HN₃, but in view of the equilibrium between N₂ and NH₃ at this high temperature (Ellis 1957), it must have been practically absent. Analyses of water samples indicate that additions of nitrite or nitrate from the volcanic gases must have been insignificant.
Analyses of samples high in reactive silicates, collected during the first survey, showed no fluoride enrichment. This indicates that SiF₄, the most probable volatile compound of silicon, was absent, although it does not exclude the presence of other silica compounds. However, as pointed out by White and Waring (1963), the presence of components of low volatility, such as SiO₂, in volcanic emanations is probably due to their transport in droplets of water in wet steam, where these compounds may be present as aerosols, or in true solutions as result of the action of water on tephra or lava. The same is assumed to apply to phosphorous compounds. Hence, it is concluded that the addition of dissolved nutrients to the seawater surrounding Surtsey was primarily caused by solution of tephra and lava rather than by direct addition from the volatiles. However, it should be emphasized that, besides dissolved nutrients, considerable amounts—particularly of silicon—must have been present in suspended matter introduced from the erupted material. No investigations were made on suspended matter.

An estimate of the total amount of silica brought into solution in unit time due to the eruption would be of great interest. However, this would be very difficult to obtain with the available data.

From the actual concentrations found during the first survey—the day after the visible eruption—we can compute the approximate increase in total dissolved silicates within the area investigated. This computation gives a value of roughly $1.50 \times 10^4$ tons of silicon. Considering the losses from this area through processes of diffusion and advection, the actual quantities of dissolved silicates introduced must have been considerably greater; this figure, then, must be a minimum value.

It is not known with certainty when the underwater eruption started. According to Thorarinsson (1964), it must have taken some days for the ridge to build up to the sea surface. The Reykjavík seismographs recorded weak tremors a week before the visual eruption. Thorarinsson has pointed out that these tremors may have originated in the eruption area. Assuming that the eruption started eight days before the first survey was made, we arrive at a production rate of about $22$ kg/sec of dissolved silicon.

Another way of determining the total amount produced per unit time is to estimate, from field observations, the flux of silicates in a horizontal direction away from the eruption center. Assuming steady-state conditions, the dissolved silicates lost through a vertical cylindrical surface at the distance $r$ from the eruption center would be balanced by horizontal diffusion toward the cylindrical surface. The total flux is given by

$$F = -2\pi r \int_{z_0}^{z} A \left( \frac{\delta Si}{\delta r} \right) m \, dz,$$

where $F$ is the flux per second, $r$ the distance from the source to the boundary chosen, $A$ the horizontal eddy-diffusion coefficient, $z$ the depth, and $(\delta Si/\delta r)_m$...
the mean horizontal gradient in silicate concentration. This gradient can be estimated from the observational data. Since the concentration decreases away from the eruption center, the gradient will have a negative value. A rough calculation based on the data collected during the second survey, 1–2 December 1963, assuming \( A \) to be constant, leads to a value of \( \frac{F}{A} = 3.5 \times 10^{-3} \text{g} \times \text{cm}^{-2} \).

Unfortunately, the value of the horizontal mixing coefficient for this area is unknown. According to Sverdrup et al. (1946), values ranging from about \( 10^7 \) to \( 10^8 \text{cm}^2/\text{sec} \) have been determined for the Atlantic Ocean, and about \( 2 \times 10^6 \text{cm}^2/\text{sec} \) for the California coastal region. For the Irish Sea, Bowden (1950) found coefficients that range from \( 0.36 \) to \( 9.0 \times 10^6 \text{cm}^2/\text{sec} \). From the lateral spreading of Mediterranean water, Defant (1955) obtained a value of \( 5.5 \times 10^7 \text{cm}^2/\text{sec} \). Based on the spreading of pumice produced by volcanic eruption in the Pacific, Hansawa (1953) obtained a value of \( 4.3 \times 10^7 \text{cm}^2/\text{sec} \). If we use an assumed value of \( 10^7 \text{cm}^2/\text{sec} \) for southern Icelandic coastal water, we obtain a production rate of about 35 kg/sec, which is not far from the estimated minimum value of the mean production rate during the first days of the eruption.

Because of the several uncertainties involved, these estimates must be considered as tentative. At best, they may indicate the right order of magnitude. However, it is of interest to examine how these values compare with the amounts of silica introduced into the sea south of Iceland by freshwater runoff from land. According to Sigvaldason (1963) the silica content of three glacial rivers in southern Iceland ranges from 6 to 22 ppm, with a mean value of about 14 ppm. Analyses by the author on water samples from the big glacial rivers Ólfsúsa and Thjórsá in June 1964 and in February 1965 gave values of 12 to 14 ppm of \( \text{SiO}_2 \). From data on drainage areas and mean runoff given by Rist (1956), the mean total runoff for the whole area between Reykjavik and Vestrahorn is approximately \( 2500 \text{m}^3/\text{sec} \). If we assume an average value of 13 ppm of dissolved \( \text{SiO}_2 \) in the river water, the total amounts of dissolved silicon introduced into the sea by the southern Icelandic rivers will be approximately 15 kg/sec, or less than the estimated production from the Surtsey eruption during the first weeks.

Thorarinsson et al. (1964) have estimated an average production of 50 m³/sec of erupted materials during the first three months of the eruption. They believe that at least one fourth was produced during the first ten days of the visible eruption. Assuming the mean density of the tephra to be roughly 1.5 g/cm³, this would indicate a mean production of roughly 150 tons/sec during the first ten days. With a production of about 35 kg/sec of dissolved silicon, the dissolution per gram of tephra would be about 8.3 µg-at of silicon. In view of the values obtained under laboratory conditions, this would indicate a very efficient dissolution.

From the preceding discussion it is concluded that, during the first weeks of eruption, when seawater had free access to the erupted material and flooded
the vents, the erupted material from Surtsey constituted an important source of silica for the adjacent sea area. It is suggested that volcanic sources may contribute significantly to increased silicate concentrations in other areas where submarine eruptions occur.

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