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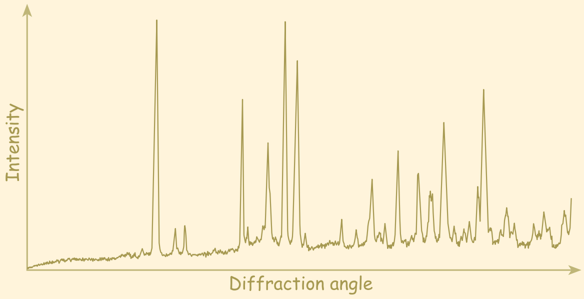

ENCRUSTATIONS FROM THREE RECENT VOLCANIC ERUPTIONS IN ICELAND:
The 1963–1967 Surtsey, the 1973 Eldfell and the 1991 Hekla eruptions

Sveinn P. Jakobsson, Erik S. Leonardsen,
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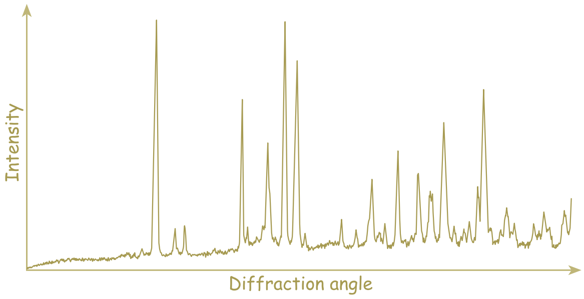

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ABSTRACT

A survey of 131 volcanogenic encrustation samples from the 1963–1967 Surtsey, the 1973 Eldfell and the 1991 Hekla eruptions in Iceland was undertaken, using the X-ray powder diffraction method. In addition, nine encrustation samples from the 1947–1948 Hekla and 1961 Askja eruptions were examined. Although volcanogenic encrustations probably form during or after all subaerial volcanic eruptions, knowledge of the encrustation mineralogy in Iceland has been limited.

The geological environment at each volcano is described. The encrustations from lava surfaces, lava caves and craters were formed in thermal systems which usually were active for a few decades. Chemical leaching of all elements except SiO_2 and TiO_2 was found to be extensive at Eldfell and probably has been effective at all localities. Most of the major elements leached out of the rocks are represented in the encrustation minerals.

At Surtsey, 34 mineral species were identified, most common were gypsum, opal-A, calcite, fluorite, halite, ralstonite, thenardite, anhydrite and hematite. At Eldfell, 31 mineral species were identified, the most common were anhydrite, opal-CT, ralstonite, gypsum, hematite, mineral EB, mineral HA and opal-A. At Hekla, 36 mineral species were identified, the most common were ralstonite, mineral HA, opal-A, malladrite, mineral HB and hematite.

Our survey revealed 27 mineral species which are unknown as natural minerals. They have been divided into four groups: newly accepted minerals; new, partly defined minerals; probable new minerals; and, suspected new minerals. The minerals which have been accepted as new world minerals by the International Mineralogical Association are eldfellite ($NaFe(SO_4)_2$) and heklaite ($KNaSiF_6$).

The majority of the encrustation minerals are mixed halides and sulfates, followed by oxides and carbonates. Minerals rich in water dominate in all mineral classes but the carbonates. It appears that 32 of the minerals are new for Iceland. Our study has therefore added considerably to the mineralogy of Iceland, which now holds 262 minerals.

In Surtsey and Eldfell, sulfates are prominent, in Hekla, fluorides dominate and sulfates are rare. It is suggested that the abundance of fluorides at Hekla is explained by the high content of fluorine in the original magma. The abundance of the chlorine- and sulfur-rich minerals in Surtsey and Eldfell may be due to infiltration of sea water, although a magmatic cause is more likely. The encrustations divide into three groups, a Surtsey-Askja group, an Eldfell group and a Hekla group.

It appears reasonable to divide fumarolic mineral associations in Iceland into two types, volcanogenic and solfataric. The volcanogenic encrustations are formed by short-lived, thermal (fumarolic) systems. These systems are connected with recent volcanic activity at the surface, and the encrustations are primarily the products of magmatic degassing. Mineralogical characteristics are a great diversity of mineral species, no clay minerals and little free sulfur. On the other hand, solfataric encrustations are the surface exposures of high-temperature hydrothermal activity and are characterized by extensive water-rock interaction. Mineralogical characteristics are relatively few mineral species, abundant deposits of clay minerals, subsurface deposits of hematite and gypsum, and free sulfur at surface.

INTRODUCTION

A survey of 131 volcanogenic encrustations from Iceland was undertaken, using the X-ray powder diffraction method. Samples were collected from the extrusives of three recent Icelandic volcanic eruptions, the 1963–1967 Surtsey, the 1973 Eldfell and the 1991 Hekla eruptions. Available encrustation samples from the 1947–1948 Hekla and 1961 Askja volcanic eruptions, nine samples, were also studied. All the encrustation samples are kept in the mineral collection of the Icelandic Institute of Natural History in Reykjavík. The encrustations occur in colors of white, yellow, brown and red. They often are loosely coherent, some are water soluble and they are easily eroded by wind and water.

Altogether 140 samples of volcanogenic encrustations from the five above-mentioned eruptions were examined by the X-ray powder diffraction method. The bulk chemistry of seven rock samples from Eldfell was also examined. In this report we use the term encrustation to cover both sublimates deposited as a solid phase directly from a gaseous state, and formed by evaporation of a liquid phase. By volcanogenic encrustations we mean fumarolic deposits, formed by short-lived, shallow-rooted, thermal (fumarolic) systems, which are directly connected with volcanic processes at the surface.

PREVIOUS RESEARCH

Although volcanogenic encrustations probably form during or after all subaerial volcanic eruptions in

Iceland, knowledge on the mineralogy and paragenesis of these encrustations in Iceland has been very limited until recently. Óskarsson (1981) gave an account of the mineralogy and chemistry of encrustations of five recent volcanic eruptions, including Surtsey and Eldfell, and discussed their genesis. Jakobsson et al. (1992) described the mineralogy of encrustations of volcanogenic and evaporitic origin in Surtsey. Other references on volcanogenic encrustations in Iceland are limited (Schythe 1847; Kjartansson 1949, and Sigvaldason 1959, 1964). On a global basis significant studies include those of Naboko (1959) on the Kamchatka-Kuriles volcanoes, Stoiber & Rose (1974) on Central American volcanoes, Naughton et al. (1974) on Kilauea Volcano, Hawaii, Keith et al. (1981) on Mount St. Helens, Washington, Fedotov (1984) on Tolbachik, Kamchatka, Kodovsky & Keskinen (1990) on Mount St. Augustine, Alaska, and Garavelli et al. (1997a) on Vulcano, Italy.

METHODS

Each encrustation sample was allowed to cool down and dry, before packing it into a porous package. An exception is the sample NI 21541 collected in Surtsey in August 1998, see p. 17. Each encrustation sample was examined under the binocular microscope and discernable phases separated by hand-picking.

The X-ray powder diffraction analyses were performed at the Department of Geography and Geology, University of Copenhagen, with a Philips vertical powder diffractometer, using CuKα radiation. Several small samples were identified with the Guinier and Gandolfi cameras. On average three analyses were performed on each encrustation sample. The mineral identifications were performed with the aid of the ICDD Powder Diffraction File, sets 1–43, CD-ROM edition. The X-ray powder diffraction analyses on the Surtsey sample NI 21541 were performed at the Iceland GeoSurvey in Reykjavík (ÍSOR), with a Philips PW1710 powder diffractometer, using CuKα radiation. Reference patterns were obtained from the ICDD PDF-2 database, sets 1–46.

The whole rock chemical analyses were performed at the Department of Geography and Geology, University of Copenhagen. The major elements were determined by X-ray fluorescence spectrometry on fused glass discs, except Na_2O which was determined by atomic absorption spectrometry. FeO was determined by automatic potentiometric titration, using Cr(VII) as a titrant. LOI is the loss on ignition corrected for the calculated gain of weight due to oxidation of iron during ignition (Kystol & Larsen 1999).

Only ideal mineral compositions are given in this report, following Mandarino & Back (2004).

THE 1963–1967 SURTSEY ERUPTION

Eruption history

Surtsey island is part of the Vestmannaeyjar archipelago, at the south coast of Iceland (Fig. 1). It was constructed from the sea floor in a volcanic eruption occurring from 1963 to 1967 (Þórarinsson et al. 1964; Þórarinsson 1966, 1969). During the hydromagmatic explosive submarine phase of the eruption, from November 14 1963 to April 4 1964, alkali basalt tephra was produced. The tephra layers formed two crescent-shaped cones which merged.

The Surtsey eruption evolved from an explosive phase into an effusive basalt lava phase at the western crater in April 1964. Altogether, seven craters and crater fissures emitted lava between April 4 1964 and June 5 1967. The first major effusive phase (1964–1965) produced a 100 m thick lava shield to the southwest and south, while the second phase (1966–1967) produced a 70 m thick lava shield to the south and east. However, individual lava flow units are thin, usually only a few meters thick. Added to this are five small lava flows on the slopes of the eastern tephra crater (Fig. 2). The maximum height of Surtsey was 175 m a. s. l. at the end of the eruption, and as sea water depth before the eruption had been about 130 m, the total height of the volcano was 305 m. Due to marine abrasion the surface area of Surtsey has been reduced from a maximum of 2.65 km^2 in 1967 to 1.40 km^2 in 2006. It is estimated that the total output of the 1963–1967 Surtsey eruption was 1.1 km^3 of basalt tephra and lava (Þórarinsson 1969).

The encrustation samples discussed below were collected in 13 expeditions from 1965 to 1998. Several of the cave mineral findings have been reported by Jakobsson et al. (1992).

Geological environment

Abundant volcanogenic encrustations formed at the surface of lava and scoria during the effusion phase of the Surtsey eruption, especially at Surtungur, the western lava crater (Fig. 3). The lava at this site is relatively smooth lava of the pahoehoe type. At a few places, encrustations have been deposited

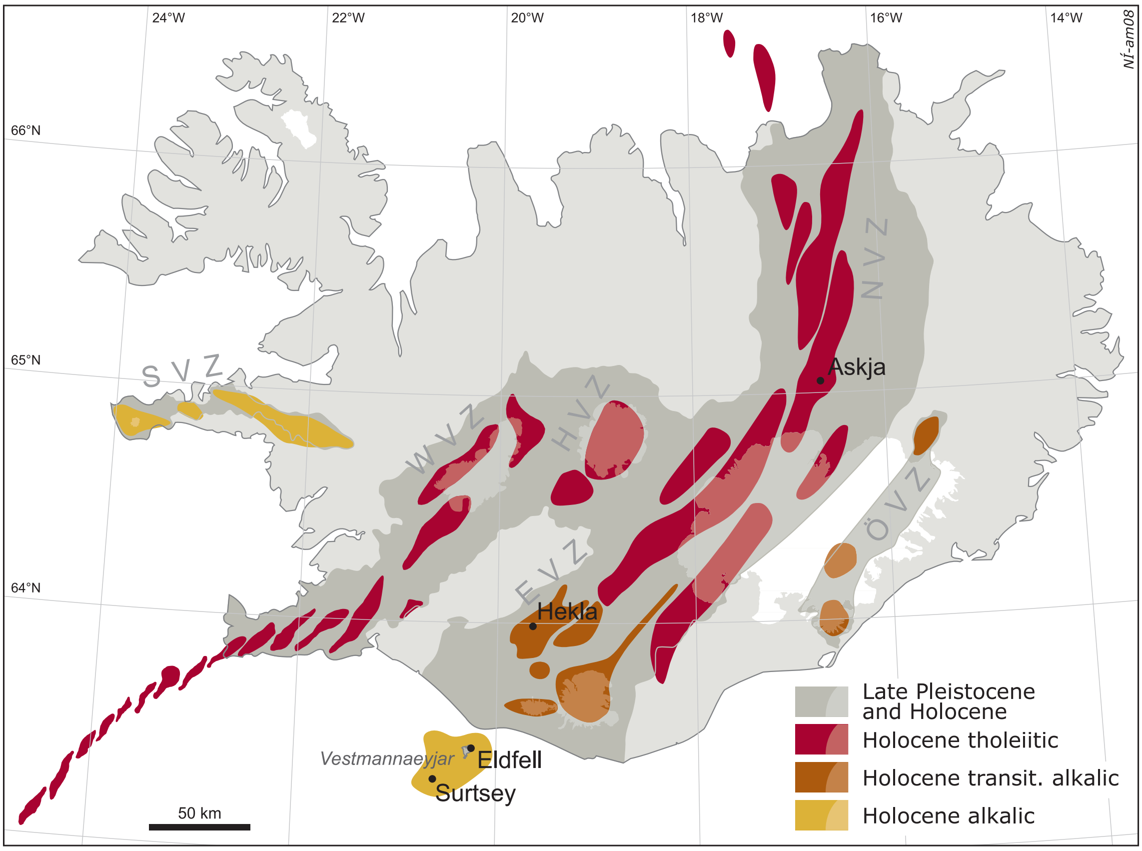

Fig. 1. The volcanic systems of Iceland and its insular shelf active during Late-Pleistocene and Holocene, after Jakobsson et al. (2008). WVZ: Western Volcanic Zone, HVZ: Hofsjökull Volcanic Zone, EVZ: Eastern Volcanic Zone, NVZ: Northern Volcanic Zone, SVZ: Snæfellsnes Volcanic Zone, and ÖVZ: Öræfajökull Volcanic Zone. Distinction is made between tholeiitic, transitional alkalic, and alkalic volcanic systems. The encrustation localities discussed in the text are highlighted.

in fissures on tephra or tuff. However, since most of the surface encrustations in Surtsey decompose quickly, relatively few samples were collected.

The encrustations were probably deposited at a range of temperatures. The surface cooling history of a 30x40 m area at the south-southwest rim of the Surtungur lava crater has been known since 1971 (Table 1, Fig. 4). The last basalt lavas flowed at this site in the spring of 1965, their eruptive temperature being about 1140–1180 °C. Measured maximum temperatures at this site declined from 370 to 126 °C between 1971 and 1982. However, an unexpected rise in temperature to 297 °C was observed in July 1986 and was apparently caused by subsidence of the lava pile, opening up of fissures, and conduction of hot gases from below (Jakobsson et al. 2000). After 1986 surface temperatures declined rapidly and had reached ambient temperatures in 1997. Aerial infrared images taken in November 1995 (Jakobsson & Árnason, unpubl. data) revealed that the entire lava field had cooled down, minor thermal emmission was only observed at the small lava craters (Fig. 2).

It follows that the maximum time of deposition of these surface encrustations at Surtungur is 2–3 decades, in many cases the time is probably to be counted in years. Temperature measurements at other surface sites in the Surtsey lavas indicate a similar time span. It should be noted that weather conditions in Surtsey are unfavorable for the survival of surface and subsurface encrustations. High winds and sandstorms are common and the precipitation is very high, the average annual precipitation 1961–1990 at the nearby Stórhöfði on Heimaey being about 1600 mm (Icelandic Meteorological Office 2008). It appears that the encrustation phases most likely to survive under these conditions are gypsum, calcite and hematite.

The Surtsey basalt lavas were of low viscosity and they tended to flow in tubes, especially from the Surtungur lava crater (Fig. 2). Lava caves are com-

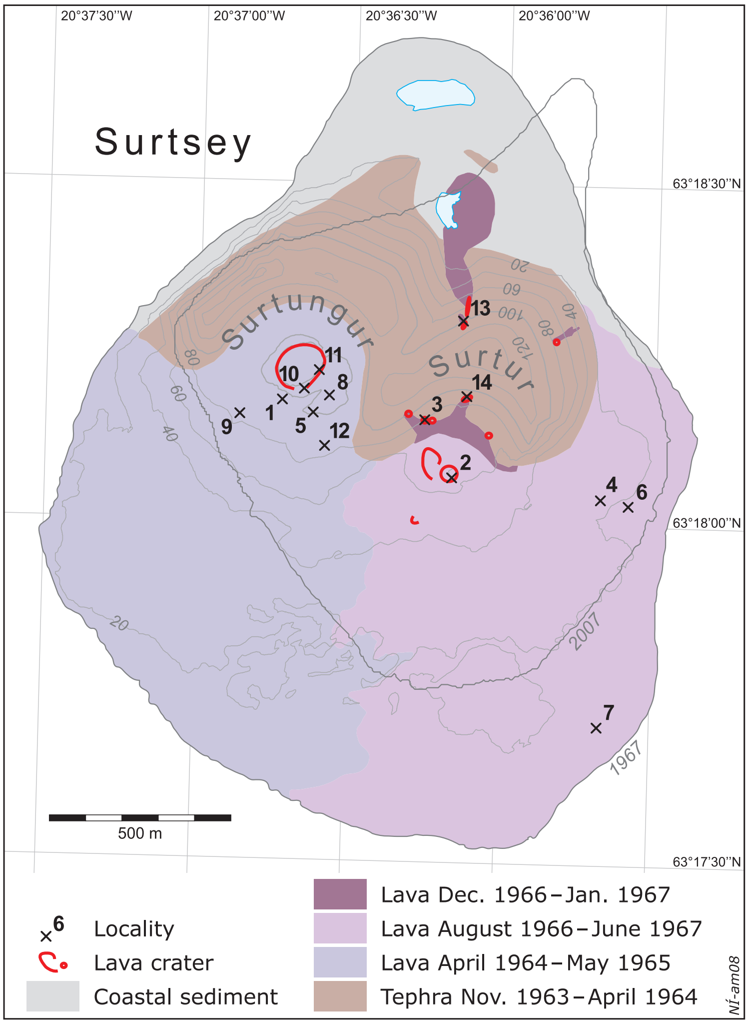

Fig. 2. Geological map of Surtsey. Topography is based on aerial photographs from 1967. Sampling localities of encrustations are indicated by crosses. The thin line shows the outline of the island as in 2007. Modified after Jakobsson et al. (1992).

Table 1. Surtsey, temperature measurements at surface at the southwest rim of the lava crater Surtungur, locality 1 in Fig. 2. The maximum temperature recorded each time is listed. Ambient temperatures are at 10 °C. See Fig. 4.

Date, Decimal year	Temperature °C
1971.7	370
1973.7	215
1974.6	160
1976.7	160
1979.6	137
1980.7	125
1982.6	126
1986.5	297
1988.6	178
1990.7	77
1991.6	38
1992.6	33
1994.6	15
1997.5	10
1998.6	10
2008.6	10

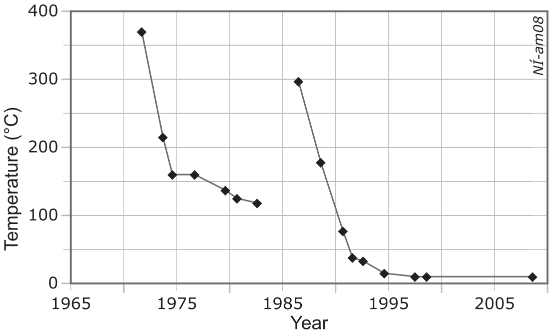

Fig. 4. Temperature measurements at the southwest rim of Surtungur, locality 1 on Surtsey. See Table 1. The maximum temperature measured each time at surface is shown. Modified after Jakobsson et al. (2000).

Fig. 3. A view of Surtungur, the western lava crater in Surtsey, looking to the northwest. The entrance of the lava cave SUR-04 is to the right of the figure. The yellowish encrustation on the lava surface is presumably ralstonite, and the red-brown hematite. The photo was taken on May 10, 1967. Photogr. H. Bárðarson.

Table 2. Surtsey, temperature measurements at the entrance of the lava cave SUR-04 ("Grillið"), locality 5 in Fig. 2. The maximum temperature recorded each time is listed. Ambient temperatures are at 10 °C. See Fig. 5.

Date, Decimal year	Temperature °C
1971.5	80–90
1972.4	65
1979.6	30
1988.6	10
2008.6	10

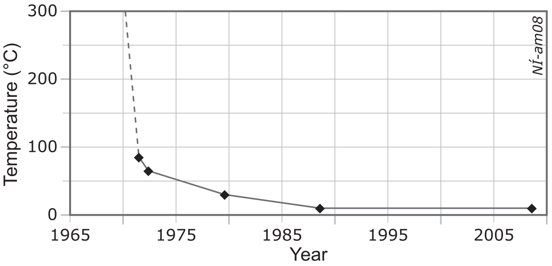

Fig. 5. Temperature measurements at the entrance of the lava cave SUR-04 ("Grillið"), locality 5 on Surtsey. The maximum temperature measured each time in the cave is shown. See Table 2.

mon and most of them are emptied sub-horizontal lava tubes, others are emptied near vertical lava feeder-channels in the eastern lava craters (Jónsson & Hróarsson 1990; Hróarsson 1991).

The cooling history of the entrance of the lava cave SUR-04, which has been called “Grillið” is known to some extent (Table 2, Fig. 5). When it was first visited and sampled in July 1971, about six years after it formed, temperatures up to 70 °C were measured and the thermometer was still rising when the geologists had to retreat to the surface. It was estimated that the real air temperature was at 80–90 °C. The cave was visited again and sampled in June 1972, when it had cooled down to 65 °C. During the following years temperatures declined further in the entrance of this cave. In August 1979 temperatures at 30 °C were prevalent and no traces of water soluble encrustations could be found. In August 1988 only ambient temperatures were measured (Jakobsson et al. 1992) and the cave was then partly filled with wind-blown tephra. The time of deposition of encrustations in the shallow caves is therefore probably also short. The time of deposition in the deeper caves is more difficult to determine, but is most probably to be counted in decades.

Although emmission of steam has been vigorous at Surtsey, especially during the first years after the eruption, no thermal water has been issued in the island except at the northwestern shore (Ólafsson & Jakobsson, in press). It is assumed that thermal water was present at depths of 60 to 100 m below the surface of the lavas (Jakobsson & Moore 1986).

It is suggested that the surface encrustations in Surtsey were mainly deposited in two types of environments, as sublimates deposited directly from a gaseous state on lava and scoria at relatively high temperatures, and in a vapor-dominated system in lava craters and shallow lava caves, where steam emanation was vigorous (Jakobsson et al. 1992).

The encrustation samples which were collected at the surface are listed in Table 3 under localities 1–4, the samples from the shallow caves under localities 5–11 in the same table, and the samples from the deeper caves under localities 12–14.

Table 3. Encrustation samples collected in Surtsey 1965–1998, locality list. Localities are shown on Fig. 2. Identified minerals are arranged roughly in order of abundance in each sample.

A. ON SURFACE OF LAVA AND SCORIA		
1. AT THE SOUTHWEST RIM OF SURTUNGUR. Locality 1 in Fig. 2.		
NI 1012	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ malladrite Na_2SiF_6 mineral HD $NH_4(Fe,Co)_2F_6$ (?) chukhrovite? $Ca_4AlSi(SO_4)F_{13}\cdot 12H_2O$ unidentified sp.	Soft crust on lava, brownish yellow, 1–2 mm thick. Collected in 1965.
NI 15567	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ opal-A $SiO_2\cdot nH_2O$ unidentified sp.	Crust on lava, red-yellow-brown, about 1 mm thick. Collected in the summer of 1971.
NI 15568	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ chukhrovite? $Ca_4AlSi(SO_4)F_{13}\cdot 12H_2O$	Crust on lava, brownish, <1 mm thick. Collected in the summer of 1971.
NI 11601	halite NaCl anhydrite $CaSO_4$	Crust on downward side of lava slab, white, <3 mm thick. Subsurface temperature ≤290 °C. Collected on July 18, 1986.
NI 11604	halite NaCl hematite Fe_2O_3 anhydrite $CaSO_4$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ opal-A? $SiO_2\cdot nH_2O$	Crust on downward side of lava slab, white, <3 mm thick. Subsurface temperature ≤260 °C. Collected on July 18, 1986.

2. ÁGÚSTGÍGAR. The eastern inside wall of the easternmost lava crater of Surtur. Locality 2 in Fig. 2.		
NI 7459	gypsum $CaSO_4\cdot 2H_2O$	Massive crust on lava, grayish brown, impregnated with tephra, botryoidal on surface, 1–5 mm thick. Ambient surface temperatures. Collected on August 17, 1979.
3. DESEMBERGÍGAR. At the lowermost lava crater of the small crater row on the northwest inside slope of Surtur. At surface. Locality 3 in Fig. 2		
NI 12387	calcite $CaCO_3$ opal-A $SiO_2\cdot nH_2O$	Crust on the downward side of a thin lava slab, white, up to 1–2 mm thick. Temperatures 63–67 °C at 5 cm depth. Collected on August 10, 1988.
4. AT CAVE SUR-01. Locality 4 in Fig. 2.		
NI 12383	sulfur S	Massive crust on the downward side of a lava slab, yellow, up to 2 mm thick, at the entrance of the cave. Ambient surface temperatures. Collected on August 10, 1988.
B. IN LAVA CAVES AND CAVITIES		
5. CAVE SUR-04, ENTRANCE (“Grillið”). Subhorizontal lava tube, south southeast of the Surtungur crater. At the entrance, 1–2 m below surface. Locality 5 in Fig. 2.		
NI 1962	halite NaCl anhydrite $CaSO_4$ glauberite $Na_2Ca(SO_4)_2$ kainite $KMg(SO_4)Cl\cdot 3H_2O$ mineral SA $Ca_{0.83}Na_{0.33}(SO_4)\cdot 0.5H_2O$ mineral SH $Na_2Mg_3(SO_4)_2(OH)_2\cdot 4H_2O$ (?) mineral SF (comp. unknown) mineral SG (comp. unknown)	Solid crust on the lava floor, white to colorless, <3.5 cm thick. Surface temperature >70 °C. Collected on July 9, 1971.
NI 7484	halite NaCl löweite $Na_{12}Mg_7(SO_4)_{13}\cdot 15H_2O$ mineral SH $Na_2Mg_3(SO_4)_2(OH)_2\cdot 4H_2O$ (?) unidentified sp.	Stalactites, colorless, length up to 45 cm. Air temperature >70 °C. Collected on July 9, 1971.
NI 1963	halite NaCl thenardite Na_2SO_4 blödite $Na_2Mg(SO_4)_2\cdot 4H_2O$ glauberite $Na_2Ca(SO_4)_2$ eugsterite? $Na_4Ca(SO_4)_3\cdot 2H_2O$	Stalactites, white to colorless, length up to 25 cm. Air temperature 65 °C. Collected on June 13, 1972.
NI 1964	halite NaCl kainite $KMg(SO_4)Cl\cdot 3H_2O$ kieserite $MgSO_4\cdot H_2O$ löweite $Na_{12}Mg_7(SO_4)_{13}\cdot 15H_2O$ pentahydrite? $MgSO_4\cdot 5H_2O$ unidentified sp.	Stalactites, white to colorless, length up to 10 cm. Air temperature 65 °C. Collected on June 13, 1972.
6. CAVE SUR-01. Subhorizontal lava tube, at the coast east of Surtur. Part of this cave has now disappeared due to marine abrasion. From the roof of the cave, about 1 m below surface. Locality 6 in Fig. 2.		
NI 12382	halite NaCl calcite $CaCO_3$ gypsum $CaSO_4\cdot 2H_2O$	Powdery crust on the roof, white, up to 2 mm thick. Ambient surface temperatures. Collected on August 10, 1988.

7. CAVE AT THE SOUTHEAST COAST. A small lava cave close to the surface; the cave has now disappeared due to marine abrasion. Locality 7 (approx.) in Fig. 2.		
NI 1092	halite $NaCl$ carnallite $KMgCl_3\cdot 6H_2O$ mineral SB (comp. unknown)	Stalactite, yellow-brown, length 9.5 cm. Collected on January 3, 1967.
8. CAVE SOUTHEAST OF SURTUNGUR. A small lava cave, samples collected close to the surface. Locality 8 in Fig. 2.		
NI 1027	thenardite Na_2SO_4 gypsum $CaSO_4\cdot 2H_2O$	Powdery crust on lava, white, <1 cm thick. Collected on September 11, 1969.
NI 6382	gypsum $CaSO_4\cdot 2H_2O$ anhydrite $CaSO_4$ halite $NaCl$ unidentified sp.	Crust on lava, white, <3 mm thick. Collected on September 7, 1973.
9. CAVE SUR-03. Subhorizontal lava tube, to the southwest of the Surtungur crater. From the floor on the western side of the cave, some 15 m below surface. Locality 9 in Fig. 2.		
NI 15100	gypsum $CaSO_4\cdot 2H_2O$	Crust of minute crystals on lava, grayish-white, <2–3 mm thick. About 25 m from the entrance; ambient surface temperatures. Collected on July 12, 1990.
NI 15101	thenardite Na_2SO_4 gypsum $CaSO_4\cdot 2H_2O$	Powdery crust on lava, white, <3 cm thick. About 50 m from the entrance; ambient surface temperatures. Collected on July 12, 1990.
NI 15374	gypsum $CaSO_4\cdot 2H_2O$ unidentified sp.	Crust on lava, colorless, <2 mm thick. On the floor of the cave, 30 m from the entrance. Collected on August 10, 1992.
NI 19011	mineral SC (comp. unknown) unidentified sp.	Crust on lava, white and yellow-brown, <2 mm thick. In a fissure in the wall, 30 m from the entrance. Collected on August 12, 1994.
NI 19012	calcite $CaCO_3$ ralstonite? $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral SC (comp. unknown) unidentified sp.	Crust on lava, white and yellow-brown, <2 mm thick. In a fissure in the wall, 30 m from the entrance. Collected on August 12, 1994.
NI 21541	mirabilite $Na_2SO_4\cdot 10H_2O$ thenardite Na_2SO_4	Crust on lava, colorless, <5 mm thick. Some 30 m from the entrance. Colorless and compact when collected, became powdery and white, see main text p. 17. Collected on August 29, 1998.
10. SURTUNGUR. Cavities deep in the southern inside wall of the large lava crater. Locality 10 in Fig. 2.		
NI 1965	thenardite Na_2SO_4 gypsum $CaSO_4\cdot 2H_2O$	Powdery crust on scoria, white, <0.5 cm thick. Ambient surface temperatures. Collected on June 13, 1972.
NI 12389	anhydrite $CaSO_4$ calcite $CaCO_3$ bassanite? $CaSO_4\cdot 0.5H_2O$	Crust on lava, white, < 1 mm thick. Surface temperature 135 °C. Collected on August 10, 1988.

11. CAVE SUR-07. A vertical lava feeder-channel in the east part of the Surtungur crater. In a by-cave at some 12 m below surface. Locality 11 in Fig. 2.		
NI 19004	gypsum $CaSO_4\cdot 2H_2O$ mineral SG (comp. unknown) mineral SC (comp. unknown) unidentified sp.	Crust on lava, white, <2 mm thick. Collected on August 12, 1994.
NI 19006	gypsum $CaSO_4\cdot 2H_2O$ calcite $CaCO_3$	Crust on lava, white, 7 mm thick. Collected on August 12, 1994.
NI 19008	thenardite Na_2SO_4 gypsum? $CaSO_4\cdot 2H_2O$ unidentified sp.	Crust on the lava floor, white, <3 cm thick. Collected on August 12, 1994.
NI 19009	thenardite Na_2SO_4 gypsum $CaSO_4\cdot 2H_2O$	Soft crust on the lava floor, white, 8 cm thick. Collected on August 12, 1994.
NI 19010	thenardite Na_2SO_4 gypsum $CaSO_4\cdot 2H_2O$ unidentified sp.	Crust on the lava floor, white, <3 cm thick. Collected on August 12, 1994.
12. CAVE SUR-04, INNER PART. Subhorizontal lava tube, south southeast of the Surtungur crater. About 15 to 55 m from the entrance, about 2–4 m below surface. Locality 12 in Fig. 2.		
NI 15105	gypsum $CaSO_4\cdot 2H_2O$	Crust on a lava shelf, white and yellow-brown, 1–2 mm thick. About 15 m from the entrance. Surface temperature 35–40 °C. Collected on July 12, 1990.
NI 15107	opal-A $SiO_2\cdot nH_2O$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ fluorite CaF_2	Crust on a lava shelf, white and yellow-brown, 1–2 mm thick. About 15 m from the entrance. Surface temperature 35–40 °C. Collected on July 12, 1990.
NI 15102	gypsum $CaSO_4\cdot 2H_2O$ unidentified sp.	Crust of crystals on a lava shelf, white to colorless, <3 mm thick. About 17 m from the entrance. Surface temperature 35–40 °C Collected on July 12, 1990.
NI 15103	gypsum $CaSO_4\cdot 2H_2O$ fluorite CaF_2 opal-A $SiO_2\cdot nH_2O$	Layered crust on a lava shelf, white to yellow, up to 2 cm thick. About 20 m from the entrance. Surface temperature 35–40 °C. Collected on July 12, 1990.
NI 15368	calcite $CaCO_3$ hydromagnesite $Mg_5(CO_3)_4(OH)_2\cdot 4H_2O$ fluorite CaF_2 unidentified sp.	Crust on lava, white, botryoidal, <0.5 cm thick. On a shelf 30 m from the entrance of the cave. Surface temperature at 25 °C. Collected on August 9, 1992.
NI 15369	opal-A $SiO_2\cdot nH_2O$ fluorite CaF_2	Crust on lava, white and yellow-brown, <1 mm thick. On the roof, about 30 m from the entrance of the cave. Surface temperature at 25 °C. Collected on August 9, 1992.
NI 15370	fluorite CaF_2 halite NaCl	Crust on lava, white and brownish yellow, <4 mm thick. On a shelf about 30 m from the entrance of the cave. Surface temperature at 25 °C. Collected on August 9, 1992.
NI 15371	opal-A $SiO_2\cdot nH_2O$ calcite $CaCO_3$ fluorite CaF_2 gypsum $CaSO_4\cdot 2H_2O$	Crust on lava, white and brownish, <1 mm thick. On a shelf, about 30 m from the entrance of the cave. Surface temperature at 25 °C. Collected on August 9, 1992.

NI 15372	opal-A $SiO_2\cdot nH_2O$ gypsum $CaSO_4\cdot 2H_2O$ akaganeite? $Fe_8O_{8-x}(OH)_{8+x}Cl_x$ unidentified sp.	Crust on lava, light brown, <1 mm thick. On a shelf 30 m from the entrance of the cave. Surface temperature at 25 °C. Collected on August 9, 1992.
NI 15373	fluorite CaF_2	Crust on lava, white-yellow, <0.5 cm thick. About 35 m from the entrance of the cave. Surface temperature at 25 °C. Collected on August 9, 1992.
NI 15364	gypsum $CaSO_4\cdot 2H_2O$ fluorite CaF_2 opal-A $SiO_2\cdot nH_2O$ unidentified sp.	Crust on lava, white-colorless, <1.5 cm thick. On a shelf, 40 m from the entrance of the cave. Surface temperature at 25 °C. Collected on August 9, 1992.
NI 15365	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ hematite Fe_2O_3	Crust on lava, red-yellow, <1 mm thick. On the floor, approx. 40–50 m from the entrance of the cave. Surface temperature at 25 °C. Collected on August 9, 1992.
NI 15359	gypsum $CaSO_4\cdot 2H_2O$ fluorite CaF_2 calcite $CaCO_3$	Crust on lava, white to yellow white, <3 mm thick. From the roof, 50 m from the entrance of the cave. Surface temperature at 25 °C. Collected on August 9, 1992.
NI 15360	gypsum $CaSO_4\cdot 2H_2O$ unidentified sp.	Crust on lava, white, <3 mm thick. From the roof, 50 m from the entrance of the cave. Surface temperature at 25 °C. Collected on August 9, 1992.
NI 15361	gypsum $CaSO_4\cdot 2H_2O$ fluorite CaF_2 calcite $CaCO_3$ unidentified sp.	Crust on lava, white, <3 mm thick. From the roof, 50 m from the entrance of the cave. Surface temperature at 25 °C. Collected on August 9, 1992.
NI 15363	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ hematite Fe_2O_3 cryptohalite? $(NH_4)_2SiF_6$	Crust on lava, pink, <1 mm thick. On a shelf 55 m from the entrance of the cave. Surface temperature at 25 °C. Collected on August 9, 1992.
13. STROMPUR (cave SUR-08). Vertical feeder channel. The lava crater on the northern outer side of Surtur. On the bottom of the crater, about 20 m below the crater rim. Locality 13 in Fig. 2.		
NI 16923	gypsum $CaSO_4\cdot 2H_2O$ opal-A $SiO_2\cdot nH_2O$ calcite $CaCO_3$ halite $NaCl$	Crust on lava, white, <1 mm thick. Ambient surface temperature. Collected on July 31, 1993.
NI 16925	calcite $CaCO_3$ opal-A $SiO_2\cdot nH_2O$ gypsum $CaSO_4\cdot 2H_2O$	Crust on lava, white to marine green, <1 mm thick. Ambient surface temperatures. Collected on July 31, 1993.
NI 16926	opal-A $SiO_2\cdot nH_2O$ fluorite CaF_2 calcite $CaCO_3$ gypsum $CaSO_4\cdot 2H_2O$	Powdery crust on lava, white, <2 mm thick. Ambient surface temperatures. Collected on July 31, 1993.
NI 21555	glauberite $Na_2Ca(SO_4)_2$ anhydrite $CaSO_4$ gypsum $CaSO_4\cdot 2H_2O$ thenardite Na_2SO_4 blödite $Na_2Mg(SO_4)_2\cdot 4H_2O$ eugsterite $Na_4Ca(SO_4)_3\cdot 2H_2O$	Soft crust on lava, white-yellow, <1 cm thick. Collected on September 5, 1998.

14. BJALLAN (cave SUR-11). The uppermost lava crater of the small crater row on the northeast inside slope of Surtur. On the inner wall of the nearly closed crater, at 2 m depth. Locality 14 in Fig. 2.		
NI 19015	natroalunite $NaAl_3(SO_4)_2(OH)_6$ opal-A $SiO_2 \cdot nH_2O$ gypsum $CaSO_4 \cdot 2H_2O$ fluorite CaF_2	Crust on lava, white to grayish, <7 mm thick. Surface temperature 30 °C. Collected on August 13, 1994.
NI 19016	opal-A $SiO_2 \cdot nH_2O$ fluorite CaF_2	Crust on lava, white, <3 mm thick. Surface temperature 30 °C. Collected on August 13, 1994.
NI 19017	gypsum $CaSO_4 \cdot 2H_2O$ fluorite CaF_2 calcite $CaCO_3$ opal-A $SiO_2 \cdot nH_2O$	Crust on lava, white, 3 mm thick. Surface temperature 24 °C. Collected on August 13, 1994.
NI 19020	opal-A $SiO_2 \cdot nH_2O$ unidentified sp.	Crust on lava, botroyidal, white, <6 mm. Surface temperature 24 °C. Collected on August 13, 1994.
NI 19021	doyleite $Al(OH)_3$ opal-A $SiO_2 \cdot nH_2O$ hematite Fe_2O_3	Crust on lava, white, <1.5 mm thick. Surface temperature 24 °C. Collected on August 13, 1994.
NI 19022	calcite $CaCO_3$ opal-A $SiO_2 \cdot nH_2O$	Crust on lava, white, <1.5 mm thick. Surface temperature 18 °C. Collected on August 13, 1994.

Mineralogy of the encrustations

The 55 encrustation samples collected in Surtsey are described in Table 3 and the localities are shown in Fig. 2. The minerals identified in each sample are arranged roughly in order of abundance. The surface encrustation samples are generally less than 5 mm in thickness, whereas the samples from the lava caves may reach a thickness of several centimeters. Encrustation stalactites from the caves are usually less than 10 cm long and reach a maximum length of 45 cm (Fig. 6). A few of the minerals, such as gypsum, halite and thenardite, can reach a size of several centimeters, but the size of most of the rare or very rare minerals is of the order of millimeters or even micrometers.

The 34 mineral species which were identified in the Surtsey encrustations are listed in Table 4, arranged roughly in order of abundance. It should be noted that hematite, glauberite (Fig. 7) and mirabilite probably were more common in Surtsey than indicated in Table 4, due to a possible sampling bias. As regards the identification of chukhrovite, with reference to the Surtsey environment, it is probable that the observed species corresponds to the synthetic chukhrovite with composition $Ca_4AlSi(SO_4)F_{13} \cdot 12H_2O$ (Mathew et al. 1981), and not to the REE-containing chukhrovite described from natural occurences.

Seven mineral species are not known as minerals in nature. Two of them, minerals SA and SH, have X-ray powder diffraction patterns which are nearly identical to described synthetic compounds

Fig. 6. Encrustation sample NI 1963 from Surtsey, from the entrance of cave SUR-04 (“Grillið”), see Table 3. A stalactite of halite, also containing thenardite, blödite, glauberite and eugsterite(?). The stalactite is partly covered by brownish wind-blown tephra.

Table 4. Identified encrustation minerals of the 1963–1967 Surtsey eruption. The minerals are arranged roughly in order of abundance.

Mineral	Composition	Abundance
Gypsum	$CaSO_4\cdot 2H_2O$	common
Opal-A	$SiO_2\cdot nH_2O$	common
Calcite	$CaCO_3$	common
Fluorite	CaF_2	common
Halite	NaCl	common
Ralstonite	$Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$	common
Thenardite	Na_2SO_4	common
Anhydrite	$CaSO_4$	fairly common
Hematite	Fe_2O_3	fairly common
Blödite	$Na_2Mg(SO_4)_2\cdot 4H_2O$	rare
Chukhrovite?	$Ca_4AlSi(SO_4)F_{13}\cdot 12H_2O$	rare
Eugsterite	$Na_4Ca(SO4)_3\cdot 2H_2O$	rare
Glauberite	$Na_2Ca(SO_4)_2$	rare
Kainite	$KMg(SO_4)Cl\cdot 3H_2O$	rare
Löweite	$Na_{12}Mg_7(SO_4)_{13}\cdot 15H_2O$	rare
Mineral SC	(comp. unknown)	rare
Mineral SH	$Na_2Mg_3(SO_4)_2(OH)_2\cdot 4H_2O$ (?)	rare
Carnallite	$KMgCl_3\cdot 6H_2O$	very rare
Doyleite	$Al(OH)_3$	very rare
Hydromagnesite	$Mg_5(CO_3)_4(OH)_2\cdot 4H_2O$	very rare
Kieserite	$MgSO_4\cdot H_2O$	very rare
Malladrite	Na_2SiF_6	very rare
Mineral HD	$NH_4(Fe,Co)_2F_6$ (?)	very rare
Mineral SA	$Ca_{0.83}Na_{0.33}(SO_4)\cdot 0.5H_2O$	very rare
Mineral SB	(comp. unknown)	very rare
Mineral SF	(comp. unknown)	very rare
Mineral SG	(comp. unknown)	very rare
Mirabilite	$Na_2SO_4\cdot 10H_2O$	very rare
Natroalunite	$NaAl_3(SO_4)_2(OH)_6$	very rare
Sulfur	S	very rare
Akaganeite?	$Fe_8O_{8-x}(OH)_{8+x}Cl_x$	very rare
Bassanite?	$CaSO_4\cdot 0.5H_2O$	very rare
Cryptohalite?	$(NH_4)_2SiF_6$	very rare
Pentahydrite?	$MgSO_4\cdot 5H_2O$	very rare

and are probably their mineral analogues. Mineral HD is also a probable new mineral. Four other species, minerals SB, SC, SF and SG, are possibly new minerals. It should be noted that the X-ray powder diffraction diagrams indicate that there are even more unidentified species among the encrustations (Table 3), although they are not listed in Table 4. The minerals which appear to be unknown to science will be discussed in a later chapter.

In addition to the 34 mineral species determined by us, Óskarsson (1981) had identified galeite ($Na_{15}(SO_4)_5ClF_4$), aphthitalite ($(K,Na)_3Na(SO_4)_2$) and metathenardite (Na_2SO_4) at lava surfaces in Surtsey.

The encrustations at most sites probably formed at a range of temperatures, cf. Figures 4 & 5. As the extrusives at Surtsey appear to be cooling slowly and at an even rate, measured temperatures at the time of sampling will indicate the minimum temperature of deposition. For example, samples NI 11601 and NI 11604 (Table 3) where the measured temperatures indicate that halite, anhydrite, hematite, ralstonite and opal-A formed at or above 260–290 °C. And sample NI 12389 indicates that

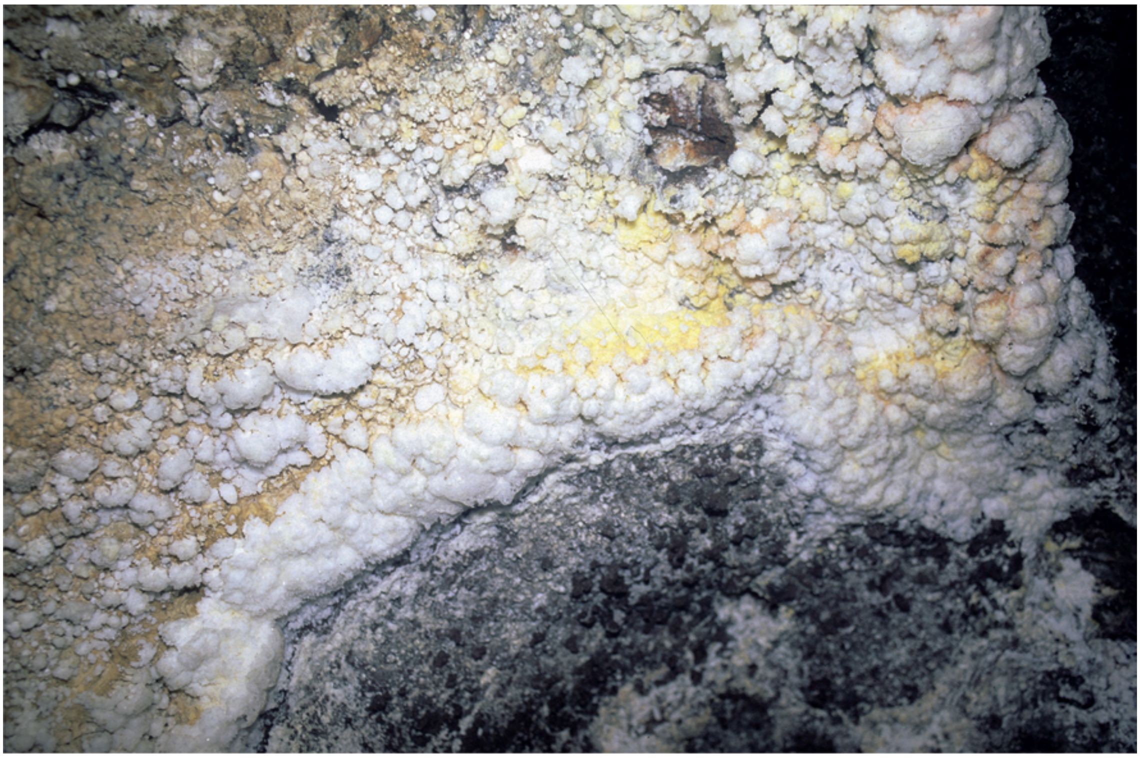

Fig. 7. Encrustations on the wall of the lava cave SUR-08 (Strompur) in Surtsey, August 1998, spanning about 40 cm. Mainly glauberite, anhydrite, gypsum, thenardite, and probably ralstonite.

anhydrite, bassanite and calcite formed at or above 135 °C.

It is tentatively suggested that ralstonite and hematite are type minerals of the encrustations at lava surfaces (localities 1–4 in Table 3). These minerals are presumably formed at comparatively high temperatures. At lower temperatures during the cooling process, minerals such as anhydrite and gypsum may be deposited.

In the shallow caves and entrances of larger caves in Surtsey (localities 5–11 in Table 3), halite, kainite, löweite, gypsum and thenardite can possibly be labeled as type minerals. It is noteworthy that a very similar mineralogy was found in the two shallow caves in the 1961 Askja lava, see Table 12. Since Askja is practically at the center of Iceland, there is little reason to link the occurrence of for example halite in Surtsey to the presence of sea water at the latter locality. With reference to Jakobsson et al. (1992) the main temperature range of formation for these minerals in Surtsey may be 65–100 °C.

In the deeper parts of the lava caves (localities 12–14 in Table 3), which have cooled at a relatively slow rate, fluorite, opal-A, calcite and gypsum may be labeled as type minerals. These minerals may have formed at quite a range of temperatures, at or above some 330 °C (fluorite) and down to some 35–100 °C (opal-A, calcite and gypsum).

The transformation of mirabilite to thenardite

In Surtsey, it was noted that colorless to white encrustations in some cases became powdery after they were collected. In order to investigate this transformation, an encrustation of this type was collected on August 29, 1998 in the lava cave SUR-03 (NI 21541, Table 3). The sample was compact and colorless when sampled and was immediately packed into a water-tight, sealed container. Three days after arriving in Reykjavík, on September 7, the sample had remained intact in its container and was prepared for X-ray powder diffraction at the Iceland GeoSurvey.

The first analysis, immediately after the unpacking, yielded mirabilite, $Na_2SO_4 \cdot 10H_2O$ (mon.), see Figure 8. However, the sample gradually changed structure in the laboratory, and after one hour a considerable part of the sample had changed to

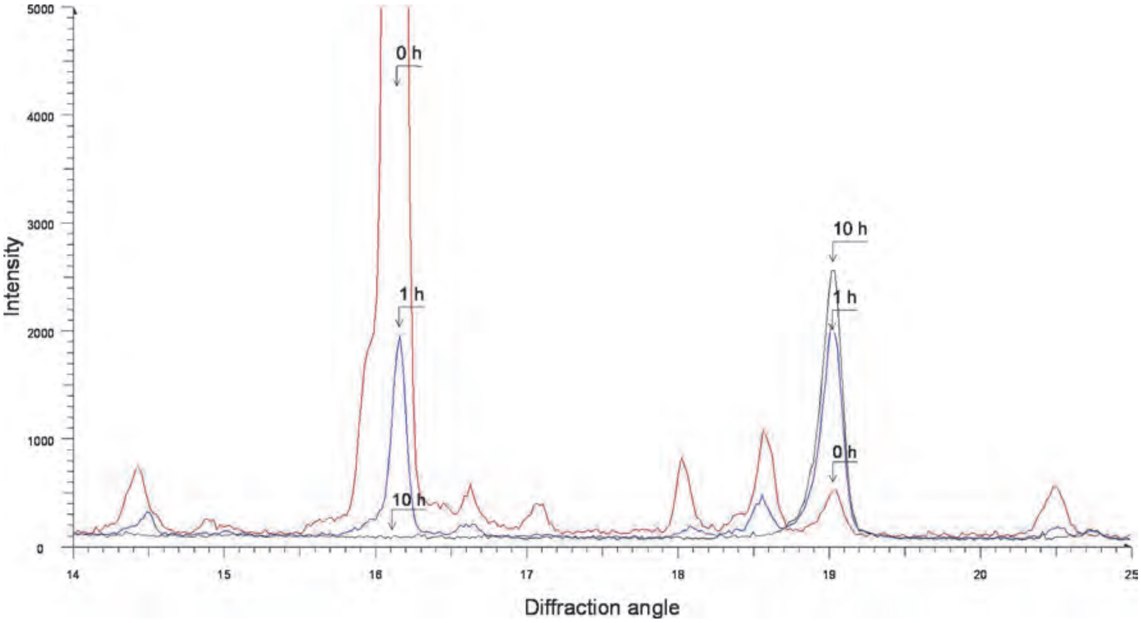

Fig. 8. XRD powder diagrams of sample NI 21541, showing the transformation of mirabilite to thenardite. Red diagram: analysis of wet sample; blue diagram: analysis of sample after 1 hour; and black diagram: analysis after 10 hours.

thenardite, Na_2SO_4 (orth.), and after 10 hours it had completely changed to thenardite, with evaporation of water at ambient laboratory conditions. The sample had then become white and powdery. It therefore appears probable that Surtsey samples determined as thenardite, originally were made of mirabilite. However, it is also possible that thenardite, Na_2SO_4 (orth.), was formed by transformation of metathenardite, Na_2SO_4 (trig.), which has been reported at 271 °C (Strunz & Nickel 2001).

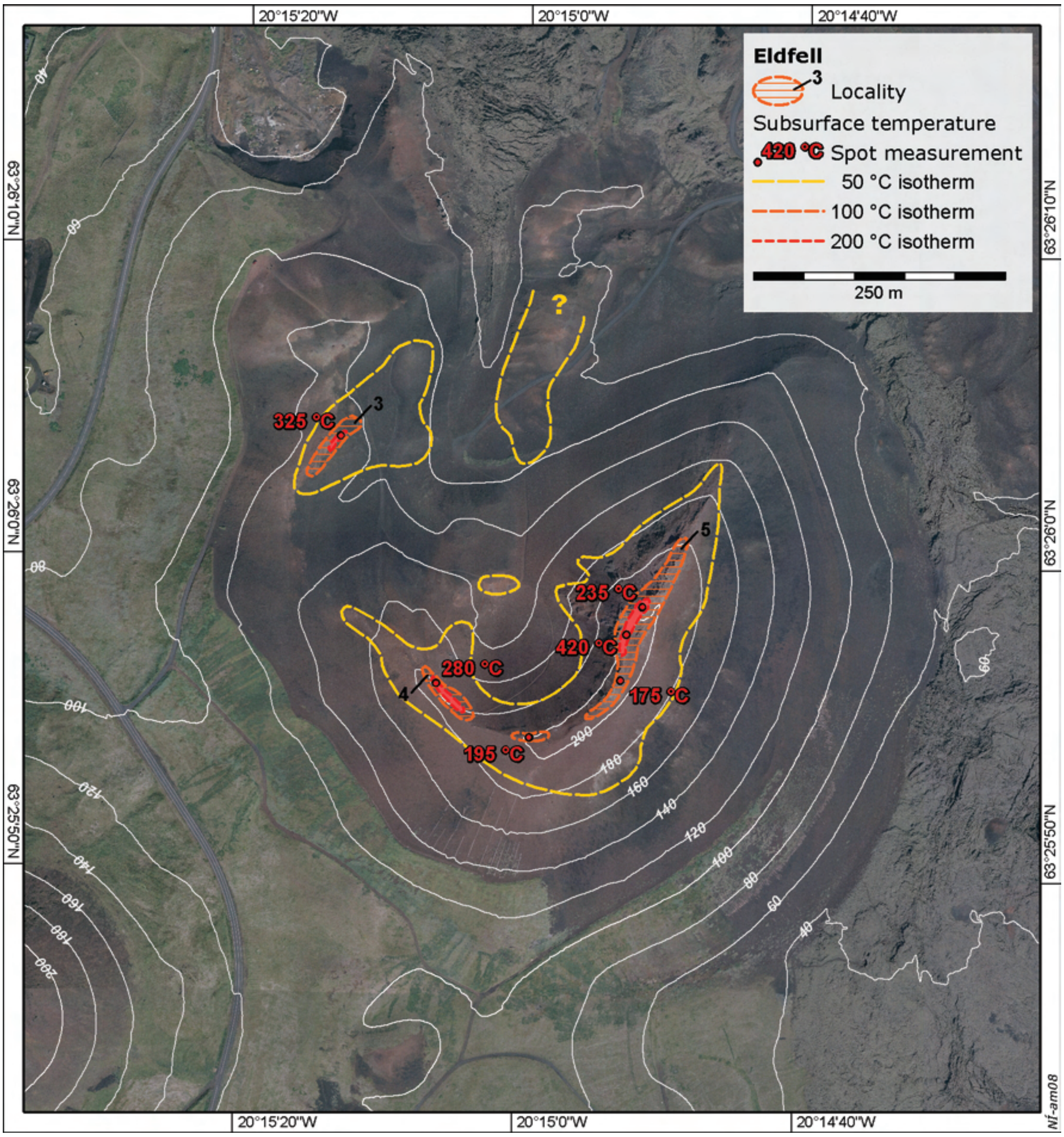

Fig. 9. Eldfell, Heimaey, after aerial photographs from 2007. The extent of the thermal (fumarolic) area in Eldfell as in July 1990 is shown, with reference to the approximate positions of the 50, 100 and 200 °C isotherms. The three sampling localities on Eldfell, cf. Table 7, are indicated.

THE 1973 ELDFELL ERUPTION

Eruption history

The Eldfell volcano (Fig. 9) is situated on Heimaey, the largest and the only inhabited island of the Vestmannaeyjar archipelago, off the south coast of Iceland (Fig. 1). Both Eldfell and Surtsey belong to the Vestmannaeyjar volcanic system. The Eldfell eruption started on January 23 1973, on a 1.5 km long fissure that opened up at the outskirts of the town of Vestmannaeyjar, producing lava along its entire length. Eruptive activity quickly concentrated at the central part of the fissure and a scoria cone, Eldfell, was built up, reaching a height of 245 m a. s. l. (Þórarinsson et al. 1973). The Eldfell eruption was last seen active on June 26, 1973 and is considered to be among the most destructive volcanic eruptions in the history of Iceland due to the proximity to the town.

The magma was of hawaiite-mugearite composition (Jakobsson et al. 1973). At the end of the eruption the Eldfell lava covered 3.2 km^2, and the total output of lava and scoria was estimated to be

Fig. 10. A view of the northeastern rim of the Eldfell crater, looking to the northeast. The photo was taken on July 5, 1990.

0.25 km^3 (Sigurðsson 1974). The temperature of the lava was measured at 1030 °C at the beginning of the eruption (Þórarinsson et al. 1973), as compared with 1140–1180 °C in Surtsey. The Eldfell lava reaches a thickness of about 110 m at the eastern side of Eldfell and large sections of the lava are 40–60 m thick.

The Eldfell magma was more evolved than the magma erupted at Surtsey and as a result the Eldfell eruption released a larger amount of volatiles than the Surtsey eruption. After the cessation of the Eldfell eruption the extrusives have continued to release a considerable amount of gases, especially at the Eldfell scoria cone. The specimens of the encrustation minerals discussed below were collected on the Eldfell lava in 1973 and 1975, and at Eldfell between 1988 and 1995.

Geological environment

The Eldfell lava is a block lava, although large parts of it are covered with an apron of scoria. Early on volcanic gases formed extensive encrustations on the surface of the lava and the first encrustations were already collected in February 1973 (Óskarsson 1981). As in Surtsey, the lava encrustations on the Eldfell lava were probably deposited at a range of temperatures. Due to the thickness of the Eldfell lava, it has been cooling down at a considerably slower rate than the Surtsey lavas. According to aerial infrared images taken in November 1995 (Jakobsson & Árnason, unpubl. data), there still were considerable thermal emmissions from large parts of the lava north of Eldfell. Due to the weather conditions on Heimaey, which in several respects are comparable to those of Surtsey, much of the encrustations on the lava have disappeared.

The Eldfell crater (Fig. 10) is made up of coarse scoria mixed with volcanic bombs and lava fragments. When the crater was visited for sampling purposes in April 1988, a large section of the upper part of the crater was very hot and subsurface temperatures were measured at 260 °C. Figure 9 shows a sketch of the fumarolic area in Eldfell made on July 5, 1990. Maximum temperatures of 420 °C were found at 50 cm depth and emission of steam was still vigorous from the crater rims. Table 5 shows the results of temperature measurements made on November 15, 1995 and the results are plotted in Figure 11. A similar temperature range as a function of depth was recorded in 1990.

Table 5. Temperature measurements (°C) at Eldfell, the northeast crater rim, on November 15, 1995, see Fig. 11.

Depth	Hole number						
cm	1	2	3	4	5	6	7
8							82
20							222
28	291						
30		295		320		230	
35							295
40			410				
85						450	
90					585		

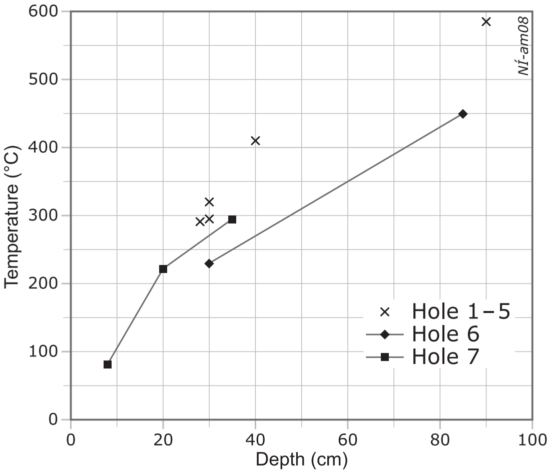

Fig. 11. Temperature measurements at the northeastern rim of the Eldfell crater, on November 15 1995. See Table 5.

The aerial infrared images of 1995 reveal that the heat flux in the Eldfell crater is mainly along concentric lines aligned with the rims of the crater. The Eldfell crater was revisited in August 2007. The field of fumarolic activity at the northeast crater rim had narrowed considerably since it was last measured in 1995, and only a minor emission of steam was observed. Although no exact measurements were made in 2007, the cooling of the crater since 1995 was clearly evident. It may be tentatively suggested that the fumarolic system in Eldfell, which now is 35 years old, has a life time at the surface of some 100 years at maximum.

Thermal water has not been observed anywhere at the surface in the Eldfell lava. With reference to the thickness of the Eldfell lava, the high porosity of the hawaiite/mugearite lava and the underlying basaltic Helgafell lava, it is assumed that the groundwater (or sea water) table is at depths of 40 to 100 m below the collection sites of the lava. It is suggested that the Eldfell lava encrustations were all deposited directly as sublimates from a gaseous phase discharged from the cooling lava. At the Eldfell crater, however, the water table may be some 240 m below the rim, and the water which is in contact with the feeder dikes of Eldfell may be assumed hot or even boiling.

Leaching of rocks

In Eldfell a white coating on rock fragments and scoria can be observed at several sites. At the top of the crater, where the gas discharge has been vigorous, parts of the scoria and even large lumps of volcanic bombs are altered to a white or light-yellow material (Fig. 12), in some cases throughout. Zoning is frequently seen. Other parts of the top section of the Eldfell crater on the other hand consist of bright red layers of scoria (Fig. 13). The altered rocks have been exposed by wind erosion which has removed the uppermost 0.3–0.8 m of the rim of the crater.

Bulk chemical analyses of these altered rocks are presented in Table 6. Unaltered extrusives (analyses A–C, Table 6) are presented for comparison. As regards the white or white-yellow rocks, an analysis of sample NI 20638, indicates zoned leaching of the major elements except silica (Fig. 12). The red-brown center part of the bomb (analysis D, Table 6, D in Fig. 12) has only suffered minor leaching. Although Fe has been oxidised, it is very similar in composition to the unaltered extrusives. The outermost zone (analysis E, Table 6) is extensively leached of almost all components except SiO_2 and TiO_2. An X-ray powder diffraction analysis of this section indicated only the presence of opal-CT. A thin section study of the rock reveals that opal-CT has replaced the primary minerals plagioclase, pyroxene, olivine and magnetite. Opal-A was, however, found as secondary crust in holes of the rock.

A chemical analysis of a bright-white scoria sample NI 13557 (analysis F in Table 6) shows a near complete leaching of all elements, with the exception of SiO_2 and part of TiO_2. An X-ray powder diffraction analysis of this sample only indicated the presence of opal-CT. Another white-yellow sample of scoria, NI 20631 in Table 7, where an X-ray powder diffraction analysis showed only opal-CT, was collected at 222 °C which indicates that the process of leaching was effective at or above that temperature.

Several other X-ray powder diffraction analyses showed that the extensively leached, white rocks at the top of Eldfell had altered to opal-CT, cf. Table 7. The secondary colorless or white crusts depos-

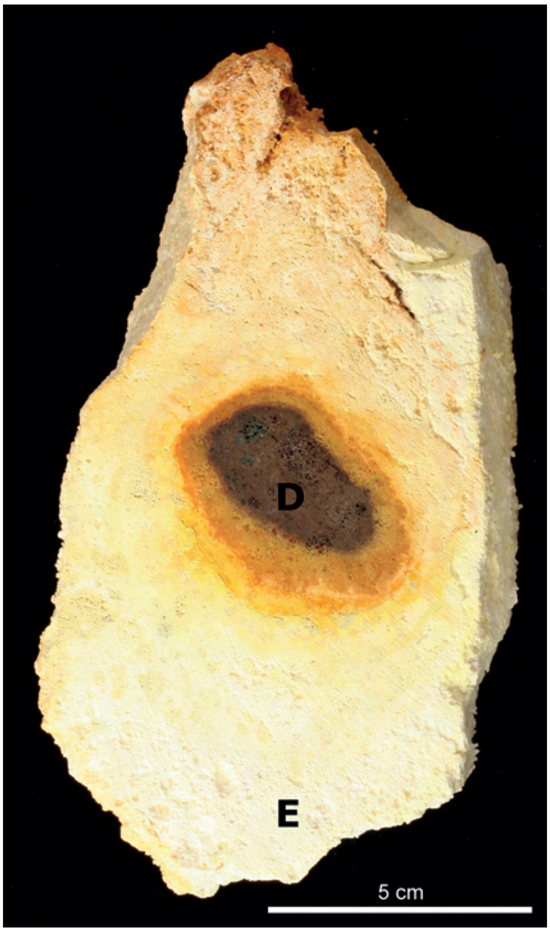

Fig. 12. A leached bomb fragment of hawaiite from the Eldfell crater, NI 20638. Letters D and E refer to the two sections which were chemically analyzed, see Table 6. An X-ray powder diffraction analysis of section E indicated only opal-CT, and frothy colorless crusts in holes of the rock in the same section turned out to be opal-A, see Table 7.

Fig. 13. A hematized scoria of hawaiite from the Eldfell crater, with encrustations of anhydrite, NI 20624. The letter G refers to the section which was chemically analyzed, see Table 6. An X-ray powder diffraction analysis of the red mass (954) indicated only hematite, and the white crust only anhydrite (955), see Table 7.

Table 6. Whole rock chemical analyses. Composition (wt.%) of the unaltered Eldfell extrusives collected during March–June 1973 (columns A–C), and the altered extrusives in Eldfell (columns D–G), cf. Fig. 14. LOI refers to loss on ignition, and primarily indicates the content of H_2O, Cl and S in the rock.

	A	B	C	D	E	F	G
	4802	4692	5995	20638-1	20638-2	13557	20624
SiO_2	47.54	47.57	47.64	46.40	85.94	93.68	33.34
TiO_2	3.18	3.16	3.10	3.10	3.90	1.19	2.72
Al_2O_3	16.20	16.16	16.18	17.97	1.10	0.18	19.60
Fe_2O_3	2.84	2.62	3.04	8.40	0.01	0.00	15.64
FeO	11.00	11.32	10.72	3.47	0.35	0.14	0.10
MnO	0.25	0.24	0.23	0.15	0.01	0.00	0.06
MgO	4.70	4.64	4.51	3.22	0.11	0.03	0.81
CaO	8.33	8.46	8.41	7.69	0.17	0.02	7.02
Na_2O	4.67	4.53	4.60	3.72	0.20	0.00	1.55
K_2O	1.03	1.00	1.02	0.74	0.11	0.01	0.77
P_2O_6	0.52	0.52	0.52	0.49	0.12	0.02	0.68
LOI	0.16	0.04	0.28	3.91	6.45	1.62	14.99
Total	100.42	100.26	100.26	99.25	98.47	96.88	97.28

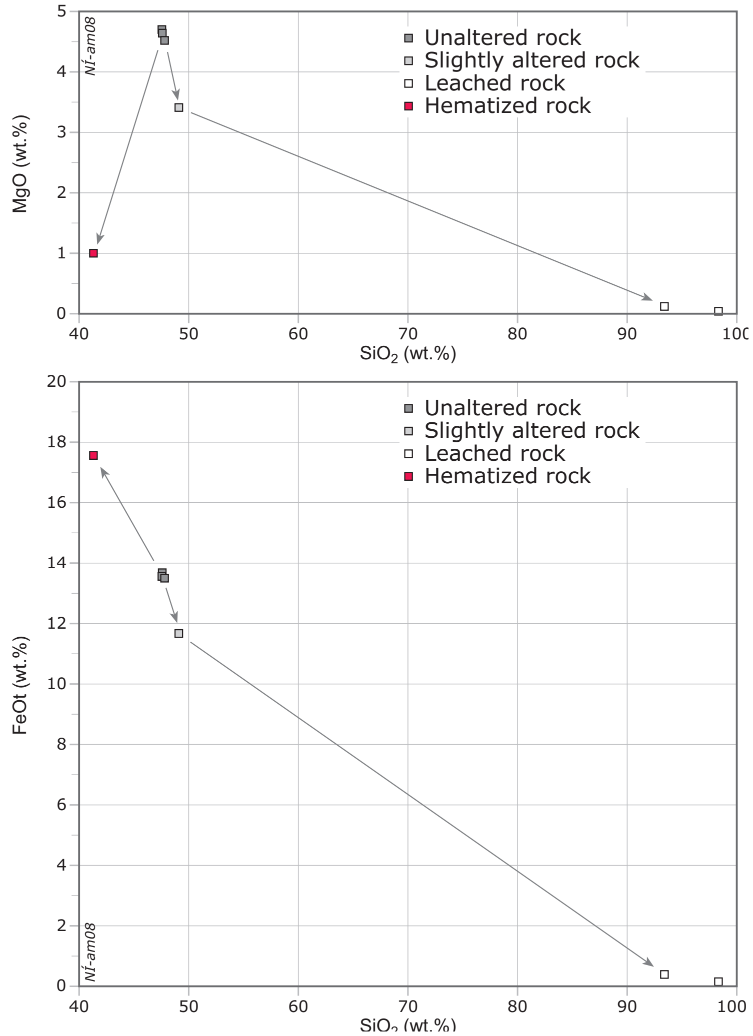

Fig. 14. Plot of MgO and total Fe as FeO, versus SiO_2, to illustrate the changes in bulk chemistry of the volcanic bomb (NI 20638), white scoria (NI 13557) and red scoria (NI 20624), see Table 6. The chemical analyses have been normalized to 100%, excluding LOI.

ited on the surface or in holes in these rocks are always made of opal-A.

As regards the bright-red sample NI 20624 (G in Fig. 13 and Table 6) an extensive leaching of Mg is indicated, and a partial leaching of Si, Na and K, whereas Fe and Al have been added to the rock. An X-ray powder diffraction analysis of the main red mass of this sample only indicated hematite and an unidentified species, the white crust being anhydrite. It is thus not yet possible to explain the fate of the elements Al, Ti and Ca.

Figure 14 illustrates the bulk rock changes in the three rock samples from the top of Eldfell, NI 20638, NI 13557 and NI 20624, the analyses have been normalized to 100%, leaving out LOI. The three analyses of unaltered extrusives (Table 6) from the Eldfell eruption serve as a comparison.

The thickness of the leached layers at the top of Eldfell is very uneven, with an average thickness estimated at 20–30 cm. The elements which have been leached out of the rocks are all represented in the encrustation minerals with the exception of Ti and P, no encrustation minerals containing the latter elements have been identified. Furthermore, Mg appears rarely to be represented among the encrustation minerals.

Sigvaldason (1964) reported on opal coating on lava formed in the 1961 Askja volcanic eruption. He suggested it to be a residue by the attack of hydrochloric and/or hydrofluoric acid on the cooling lava surface. Leaching of rocks, leaving opaline masses, has also been reported in several other cases, as for example in Central American volcanoes (Stoiber & Rose 1974) and in the Tolbachik volcano on Kamchatka (Fedotov 1984).

The encrustation samples which were collected at the surface of the lava are listed in Table 7 under localities 1–2, and the samples from the Eldfell crater are listed under localities 3–5.

Table 7. Encrustation samples collected at Eldfell 1973–1995, locality list. Localities are shown on Fig. 9. Identified minerals are arranged roughly in order of abundance in each sample.

A. ON SURFACE OF LAVA		
1. 0.5 KM SOUTHEAST OF ELDFELL. On surface of lava which flowed during January 30–February 3, 1973. Locality 1, to the north of Eldfell crater.		
NI 11989	sal ammoniac NH_4Cl cryptohalite $(NH_4)_2SiF_6$	Crust on lava, white to yellow, <5 mm thick. Collected on February 3, 1973.
2. AT THE HEATING INSTALLATION, NORTH OF ELDFELL. On surface of lava which flowed during March–April 1973. Locality 2, to the southeast of Eldfell crater.		
NI 7457	sal ammoniac NH_4Cl	Crust on altered lava, white, 1.2 cm thick. Collected on September 6, 1975.
NI 7458	jarosite $KFe_3(SO_4)_2(OH)_6$ gypsum $CaSO_4{\cdot}2H_2O$ opal-CT $SiO_2{\cdot}nH_2O$	Crust on lava, white, grayish and yellow, 5 cm thick. Collected on September 6, 1975.
B. IN ELDFELL SCORIA CRATER		
3. NORTHWEST RIM. On scoria formed in March–June 1973. Locality 3 in Fig. 9.		
NI 12246	halite $NaCl$ sylvite KCl	Crust on scoria, white, <1 cm thick. Ambient surface temperature. Collected on April 30, 1988.
NI 19732	opal-A $SiO_2{\cdot}nH_2O$	Colorless encrustations, white and yellow, in holes of leached volcanic bomb. At surface. Collected on April 7, 1995.
4. CENTER CREST OF RIM. On scoria formed in March–June 1973. Locality 4 in Fig. 9.		
NI 13560	anhydrite $CaSO_4$ gypsum $CaSO_4{\cdot}2H_2O$ hematite Fe_2O_3 ankerite? $Ca(Fe,Mg,Mn)(CO_3)_2$	Crust on altered scoria, white and black crystals. At surface. Ambient temperatures. Collected on July 5, 1990.
NI 13561	hematite Fe_2O_3 anhydrite $CaSO_4$ bassanite $CaSO_4{\cdot}0.5H_2O$ gypsum $CaSO_4{\cdot}2H_2O$ alunite? $KAl_3(SO_4)_2(OH)_6$ unidentified sp.	Scoria, fine grained, rusty-red, with white encrustation. At surface. Subsurface temperature 260 °C. Collected on July 5, 1990.
5. NORTHEAST RIM. On scoria formed in March–June 1973. Locality 5 in Fig. 9. A temperature profile for the central part of the area, as on November 15, 1995, is shown in Fig. 11.		
NI 12251	anhydrite $CaSO_4$ opal-CT $SiO_2{\cdot}nH_2O$ hematite? Fe_2O_3	Crust on altered scoria, brownish yellow, <1 mm thick. Collected on April 30, 1988.
NI 12252	anhydrite $CaSO_4$ gypsum $CaSO_4{\cdot}2H_2O$ sulfur S	Massive crust, white and yellow, 6 cm thick. Collected on April 30, 1988.
NI 12256	mineral HA (comp. unknown) mineral HB (comp. unknown) anhydrite $CaSO_4$ mineral HR $MgAlF_5{\cdot}2H_2O$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6{\cdot}H_2O$ jarosite $KFe_3(SO_4)_2(OH)_6$ mineral HH (comp. unknown) unidentified sp.	Crust on altered scoria, white and yellow brown, 3 cm thick. Collected on April 30, 1988.

NI 13548	gypsum $CaSO_4 \cdot 2H_2O$ bassanite $CaSO_4 \cdot 0.5H_2O$ anhydrite $CaSO_4$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ chessexite $Na_4Ca_2Mg_3Al_8(SiO_4)_2(SO_4)_{10}(OH)_{10} \cdot 40H_2O$	Crust on altered scoria, white to grayish, <6 mm. At 15 cm depth, temperature 94 °C. Collected on July 5, 1990.
NI 13550	anhydrite $CaSO_4$ gypsum $CaSO_4 \cdot 2H_2O$ mineral HN (comp. unknown) jarosite $KFe_3(SO_4)_2(OH)_6$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ hematite Fe_2O_3	Crust on altered scoria, white and yellow, 6.5 cm thick. Temperature 144 °C. Collected on July 5, 1990.
NI 13553	anhydrite $CaSO_4$ bassanite $CaSO_4 \cdot 0.5H_2O$ ralstonite? $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ unidentified sp.	Crust on altered scoria, yellow-brown and white, <1.2 cm thick. Temperature 235 °C. Collected on July 5, 1990.
NI 13554	gypsum $CaSO_4 \cdot 2H_2O$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ mineral HA (comp. unknown)	Crust on altered scoria, multicolored, <0.5 cm. Temperature 235 °C. Collected on July 5, 1990.
NI 13556	eldfellite $NaFe(SO_4)_2$ tamarugite $NaAl(SO_4)_2 \cdot 6H_20$ mineral EN $Na_3Fe(SO_4)_3$ anhydrite $CaSO_4$	Frothy crust on altered scoria, brownish to greenish yellow, <2.5 cm thick. Temperature approx. 200 °C. Collected on July 5, 1990.
NI 13557	opal-CT $SiO_2 \cdot nH_2O$ quartz SiO_2	Leached, fine grained scoria, yellow to white; with minor white encrustations. Temperature 56 °C. Collected on July 5, 1990.
NI 13558	opal-CT $SiO_2 \cdot nH_2O$ anhydrite $CaSO_4$	Leached, fine grained scoria, yellow to white; with minor white encrustations. Temperature 56 °C. Collected on July 5, 1990.
NI 13559	gypsum $CaSO_4 \cdot 2H_2O$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ chessexite $Na_4Ca_2Mg_3Al_8(SiO_4)_2(SO_4)_{10}(OH)_{10} \cdot 40H_2O$	Crust on altered scoria, white, <6 mm. Temperature 80 °C. Collected on July 5, 1990.
NI 19736	anhydrite $CaSO_4$ hematite Fe_2O_3 gypsum $CaSO_4 \cdot 2H_2O$ mineral HD? $NH_4(Fe,Co)_2F_6$ (?) unidentified sp.	Stalactites on altered scoria, brownish, <2 cm in length; and greenish-yellow encrustation. Temperature 420 °C. Collected on April 7, 1995.
NI 20624	hematite Fe_2O_3 anhydrite $CaSO_4$ unidentified sp.	Scoria, fine grained, rusty red, with white encrustations. At 30 cm depth, temperature 230 °C. Collected on November 15, 1995.
NI 20625	hematite Fe_2O_3 anhydrite $CaSO_4$ mineral EI (comp. unknown) mineral EB (comp. unknown) mineral EA (comp. unknown) mineral HA (comp. unknown) mineral HB (comp. unknown) unidentified sp.	Scoria, fine grained, rusty red, with white encrustations. At 30 cm depth, temperature approx. 230 °C. Collected on November 15, 1995.

NI 20626	hematite Fe_2O_3 anhydrite $CaSO_4$ opal-A $SiO_2\cdot nH_2O$ mineral EA (comp. unknown) mineral HA (comp. unknown) mineral EB (comp. unknown)	Scoria, fine grained, rusty red, with white encrustations. At 30 cm depth, temperature approx. 230 °C. Collected on November 15, 1995.
NI 20627	mineral EA (comp. unknown) mineral HA (comp. unknown) mineral EB (comp. unknown) anhydrite $CaSO_4$ hematite Fe_2O_3 mineral HD $NH_4(Fe,Co)_2F_6$ (?)	Frothy crust on altered scoria, white and rusty red, <7 mm thick. At 30 cm depth, temperature 220 °C. Collected on November 15, 1995.
NI 20628	opal-A $SiO_2\cdot nH_2O$	Crust on leached scoria, colorless, <5 mm thick. At 8 cm depth, temperature 82 °C. Collected on November 15, 1995.
NI 20629	opal-A $SiO_2\cdot nH_2O$ ralstonite? $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$	Crust on leached scoria, white, <5 mm. At 8 cm depth, temperature 82 °C. Collected on November 15, 1995.
NI 20630	opal-A $SiO_2\cdot nH_2O$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral HR $MgAlF_5\cdot 2H_2O$ mineral HB (comp. unknown) mineral HA (comp. unknown) mineral EB (comp. unknown) mineral EH (comp. unknown) unidentified sp.	Crust on altered scoria, white, <5 mm thick. At 8 cm depth, temperature 82 °C. Collected on November 15, 1995.
NI 20631	opal-CT $SiO_2\cdot nH_2O$	Leached scoria, white to yellow. At 20 cm depth, temperature 222 °C. Collected on November 15, 1995.
NI 20633	opal-CT $SiO_2\cdot nH_2O$	Leached scoria, white to yellow, colorless to white precipitations in holes. At 20 cm depth, temperature 222 °C. Collected on November 15, 1995.
NI 20635	opal-CT $SiO_2\cdot nH_2O$ unidentified sp.	Leached scoria, white to yellow, colorless to white precipitations in holes. At 40 cm depth. Collected on November 15, 1995.
NI 20637	opal-CT $SiO_2\cdot nH_2O$	Leached scoria, white to yellow. Ambient temperatures. Collected on November 15, 1995.
NI 20638	opal-CT $SiO_2\cdot nH_2O$ opal-A $SiO_2\cdot nH_2O$ unidentified sp.	Leached volcanic bomb, light yellow, with white encrustations. At 25 cm depth, ambient temperatures. Collected on November 15, 1995.

Mineralogy of the encrustations

Altogether 31 encrustation samples were collected at Eldfell and they are described in Table 7, the localities are shown in Figure 9. The minerals identified in each sample are arranged roughly in order of abundance. Only three samples of encrustations from the lava surface were examined by us, however, Óskarsson (1981) studied 11 samples which were collected in 1973. The encrustation samples are generally larger than in Surtsey, often several centimeters in thickness. A few of the minerals, like sal ammoniac (on lava surface), anhydrite and gypsum can reach a size of several centimeters. However, the size of most of the rare or very rare minerals is of the order of millimeters or even micrometers.

The 30 mineral species which have been identified by us in the Eldfell encrustations are listed in Table 8, arranged roughly in order of abundance. It should be noted that Óskarsson (1981), states that sal ammoniac, cryptohalite and halite, which are listed as rare or very rare in Table 8, are among the most common encrustation minerals collected on the surface of the lava in 1973, although these encrustations may gradually have disappeared as the lava cooled down.

Our investigation indicated that thirteen mineral species in the Eldfell encrustations were not previously registered as minerals. Opal–CT is included here, although it has a certain status, as mentioned above, in replacing the primary minerals of the rock, and therefore not being a true encrustation mineral.

One of these minerals, eldfellite ($NaFe(SO_4)_2$), has been accepted as a new mineral (IMA 2007-051) by the International Mineralogical Association, Commission on New Minerals, Nomenclature and Classification. A detailed description of this mineral is presented on p. 40–41. Eldfellite (Fig. 15) is isostructural with yavapaiite ($KFe(SO_4)_2$) and is monoclinic. The crystals are yellowish-green, platy, with diameters up to 15 µm and a thickness of 2–3 µm. They occur in mixture with tamarugite and mineral EN ($Na_3Fe(SO_4)_3$). The holotype of eldfellite is kept in the mineral collection of the Icelandic Institute of Natural History in Reykjavík under the sample number NI 13556. Part of the holotype is also temporarily deposited at Museum C. L. Garavelli, Dipartimento Geomineralogico, Università di Bari, Italy.

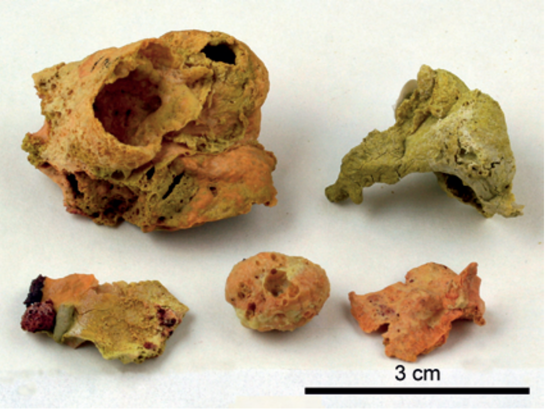

Fig. 15. Eldfellite, sample NI 13556. A new mineral species, $NaFe(SO_4)_2$, accepted by the International Mineralogical Association in February 2008. XRD and SEM analyses indicate that the crust is formed of comparable amounts of eldfellite, tamarugite and mineral EN. The red color is probably due to a minor admixture of hematite.

Another species, named mineral HR (see description on the Hekla encrustations), has an X-ray powder diffraction pattern identical to a known synthetic compound listed in the Powder Diffraction File. This strongly suggests that also in this case we have a new mineral with a known composition ($MgAlF_5\ 2H_2O$). Species named mineral HD has an X-ray powder diffraction pattern nearly identical to synthetic NH_4FeCoF_6 described in the Powder Diffraction File. Nine other species, named minerals EA, EB, EH, EI, EN, HA, HB, HH and HN, are identified among the Eldfell encrustations and possibly are new minerals. As in Surtsey and Hekla the X-ray powder diffraction diagrams indicate, however, that there may be other unidentified species among the encrustations (see Table 7), although they are not listed in Table 8.

Six of the new mineral species found in Hekla, minerals HA, HB, HD, HH, HN and HR, were also identified in samples from the Eldfell crater. One of the new mineral species found in Eldfell, mineral EA (and possibly mineral EB), was also found in one sample from Breiðaskarð at Hekla. The two new minerals and those which are unknown to science will be discussed in a later chapter.

As the fumarolic system at the Eldfell scoria crater is slowly cooling and probably at an even rate, the measured temperatures at the time of sampling will in most cases indicate the minimum temperature of deposition of the minerals in question. For example, anhydrite, hematite and mineral HD(?) were identified in sample NI 19736 (Table 7) which was collected at 420 °C; bassanite, along with anhydrite, was identified in sample NI 13561, which was collected at 260 °C; ralstonite, mineral HA, opal-A, mineral EB, mineral EI, mineral EA, min-

Table 8. Identified encrustation minerals of the 1973 Eldfell eruption. The minerals are arranged roughly in order of abundance, according to the present survey. According to Óskarsson (1981) halite, sal ammoniac and cryptohalite were common as encrustations on the Eldfell lava in 1973.

Mineral	Composition	Abundance
Anhydrite	$CaSO_4$	common
Opal-CT	$SiO_2 \cdot nH_2O$	common
Ralstonite	$Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$	common
Gypsum	$CaSO_4 \cdot 2H_2O$	common
Hematite	Fe_2O_3	common
Mineral EB	(comp. unknown)	fairly common
Mineral HA	(comp. unknown)	fairly common
Opal-A	$SiO_2 \cdot nH_2O$	fairly common
Bassanite	$CaSO_4 \cdot 0.5H_2O$	rare
Chessexite	$Na_4Ca_2Mg_3Al_8(SiO_4)_2(SO_4)_{10}(OH)_{10} \cdot 40H_2O$	rare
Jarosite	$KFe_3(SO_4)_2(OH)_6$	rare
Mineral EA	(comp. unknown)	rare
Mineral HB	(comp. unknown)	rare
Mineral HD	$NH_4(Fe,Co)_2F_6$ (?)	rare
Mineral HR	$MgAlF_5 \cdot 2H_2O$	rare
Sal ammoniac	NH_4Cl	rare
Sulfur	S	rare
Sylvite	KCl	rare
Eldfellite	$NaFe(SO_4)_2$	very rare
Cryptohalite	$(NH_4)_2SiF_6$	very rare
Halite	NaCl	very rare
Mineral EH	(comp. unknown)	very rare
Mineral EI	(comp. unknown)	very rare
Mineral EN	$Na_3Fe(SO_4)_3$	very rare
Mineral HH	(comp. unknown)	very rare
Mineral HN	(comp. unknown)	very rare
Quartz	SiO_2	very rare
Tamarugite	$NaAl(SO_4)_2 \cdot 6H_20$	very rare
Alunite?	$KAl_3(SO_4)_2(OH)_6$	very rare
Ankerite?	$Ca(Fe,Mg,Mn)(CO_3)_2$	very rare

eral HA and mineral HB were identified in samples NI 13553, 13554, 20625, 20626 and 20627, which were collected at 230–235 °C; and eldfellite and tamarugite were identified in sample NI 13556, which was collected at 200 °C.

At the scoria crater of Eldfell, where the highest temperatures of formation are encountered, ralstonite and hematite appear to be typical minerals, although they are not found in all the samples. At lower temperatures, anhydrite and gypsum appear to be the most common. Opal-CT is common and is considered to replace the minerals in the rock in most, if not all, cases. It probably forms at high temperatures as mentioned above. On the lava surface to the north and southeast of Eldfell, halite, sal ammoniac and cryptohalite, were common as encrustations in 1973, according to Óskarsson (1981).

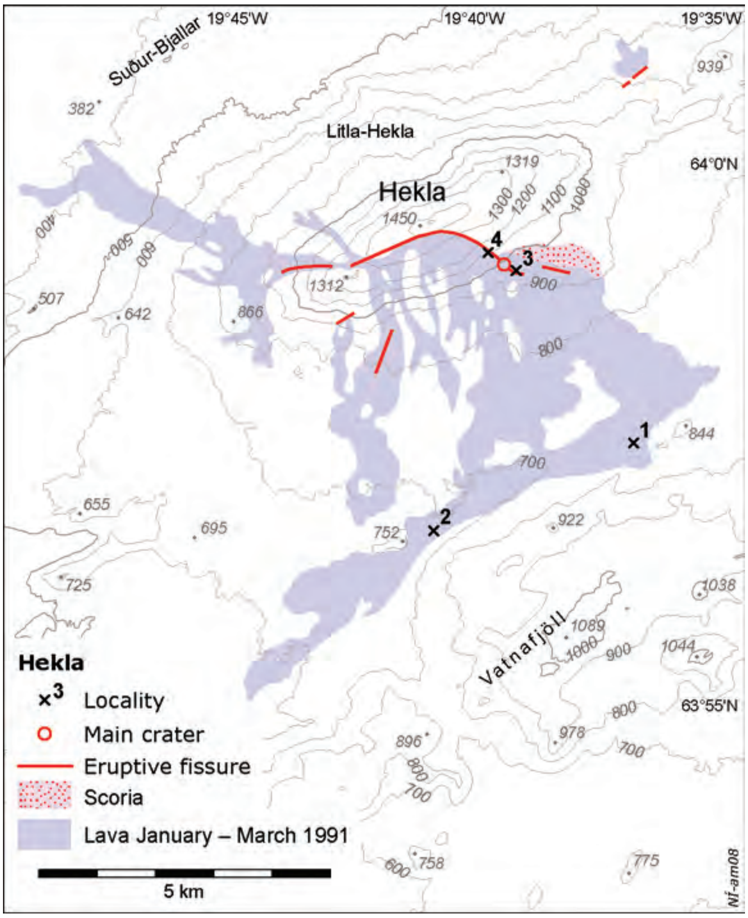

Fig. 16. Eruptive fissures and extrusives of the 1991 Hekla eruption, slightly modified after Guðmundsson et al. 1992. The sampling localities of encrustations are indicated by crosses.

THE 1991 HEKLA ERUPTION

Eruption history

The Hekla central volcano is one of the most active volcanoes in Iceland, with more than 18 eruptions recorded in historical time. It is the production center of the Hekla volcanic system in south Iceland (Fig. 1). The 1991 Hekla eruption started on January 17 with a short-lived plinian phase which was accompanied with an effusive lava phase (Guðmundsson et al. 1992). After two days of eruption the volcanic activity was mainly restricted to a single fissure trending east-southeast from the top of the mountain (Fig. 16). The eruption came to an end on March 11, 1991.

The 1991 Hekla extrusives are transitional mugearite belonging to the transitional alkalic rock series of Iceland (Jakobsson et al. 2008). The lava has commonly a thickness of only 4–8 m on flat ground and covers about 23 km^2. The total amount of tephra and lava produced is estimated to be 0.15 km^3.

A considerable amount of volcanic gases and vapor was released during the eruption. Pollution of groundwater and rivers around the volcano was observed already a few days after the onset of the eruption, by the rise of concentration of carbonate, sulfate and other dissolved solids. In the river Ytri-Rangá to the west of Hekla the fluorine concentration rose from an average of 0.7 ppm to 4.1 ppm on the 5th day of the eruption, and then fell back to the pre-eruption level on the 6th day (Guðmundsson et al. 1992). The average content of soluble fluorine from the tephra formed on January 17 was 1600 ppm (Guðmundsson et al. 1992). A new volcanic eruption occurred in Hekla between February 26 and March 8, 2000.

Geological environment

On flat ground the 1991 Hekla lava is of a block lava type, however, on the slopes of the mountain it is mainly of an aa type. Two lava surface localities were visited in January and March 1991. One lava cave, Hrossahellir, just below the main crater of the eruption, was sampled. The eastern main crater of the 1991 Hekla eruption is made up of coarse scoria mixed with volcanic bombs (Guðmundsson et al. 1992). The most prolific area with respect to encrustations was on the eruption fissure above

Fig. 17. An overview of the encrustation field on the eastern 1991 eruption fissure, Hekla, looking to the east, locality 4 on Fig. 16. The black lava in the background to the right is part of the 1991 Hekla lava field. The photo was taken on September 15, 1993. This locality was covered by scoria from the following Hekla volcanic eruption, during February 26 – March 8, 2000.

the main crater at 1105 m a. s. l. (Fig. 17).

According to aerial infrared images taken in 1995 (Jakobsson & Árnason, unpubl. data), the 1991 Hekla lavas on flat ground had cooled down to ambient temperatures, whereas the linear eruption fissure above the main crater still showed strong thermal emission. In August 2007 the 1991 Hekla eruption fissure was revisited. The linear encrustation field above the main crater of the eruption was found to be completely covered by coarse tephra during the Hekla eruption in February–March 2000 and no encrustations were found. No steam emanations were seen, so probably the fissure had cooled down to ambient temperatures since it was last measured in 1995. It is therefore suggested that the lavas, the main crater and the linear eruption fissure of the 1991 Hekla eruption cooled down to ambient temperatures at the surface in less than 10 years.

Thermal water has not been observed anywhere at the surface in the Hekla area. Thus, with reference to the high porosity of the basalt-andesitic lavas and thick layers of scoria, the water table is assumed at depths far below the collection sites of the 1991 Hekla lava, the main crater and the eruption fissures.

It is suggested that the surface encrustations at Hekla were mainly deposited in two types of environments, as sublimates deposited directly from a gaseous state at relatively high temperatures on lava and scoria at the linear eruption fissure, and in a vapor-dominated system in the shallow lava cave of Hrossahellir where steam emanation was vigorous. Encrustations have been observed in many of the eruptions in Hekla. Schythe (1847) reports for example large deposits of encrustations at the craters which erupted in 1845–1846.

Conditions for the survival of encrustations are very harsh at Hekla. The annual average precipitation is very high, at the northeast side of Hekla it is estimated to be about 2500–3000 mm (Icelandic Meteorological Office 2008). The area, especially the top of the mountain, frequently has high-wind storms.

The encrustation samples which were collected on lava at the surface are listed in Table 9 under localities 1–2, the samples from the shallow cave under locality 3, and the samples from the linear eruption fissure above the main crater under locality 4.

Table 9. Encrustation samples collected at Hekla 1991–1993, locality list. Localities are shown on Fig. 16. Identified minerals are arranged roughly in order of abundance in each sample.

A. ON SURFACE OF LAVA		
1. BREIÐASKARÐ. On lava which flowed on January 18–19, 1991. Locality 1 on Fig. 16.		
NI 15202	sal ammoniac NH_4Cl cryptohalite $(NH_4)_2SiF_6$	Crust on lava, white, <3 mm thick. Surface temperatures 40–60 °C. Collected on July 12, 1991.
NI 15204	cryptohalite $(NH_4)_2SiF_6$ sal ammoniac NH_4Cl calcite $CaCO_3$	Crust on lava, brownish yellow and white, <4 mm thick. Surface temperatures 100–200 °C. Collected on July 12, 1991.
NI 15205	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ unidentified sp.	Crust on lava, red-brown, <0.5 cm thick. Surface temperatures 30–40 °C. Collected on July 12, 1991.
NI 15206	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral HA (comp. unknown) mineral EA (comp. unknown) mineral EB? (comp. unknown)	Crust on lava, white-yellow, <0.5 cm thick. Surface temperatures 100–200 °C. Collected on July 12, 1991.
NI 15208	cryptohalite $(NH_4)_2SiF_6$ sal ammoniac NH_4Cl malladrite Na_2SiF_6	Crust on lava, brownish yellow, <0.5 cm thick. Surface temperatures 100–200 °C. Collected on July 12, 1991.
NI 15209	cryptohalite $(NH_4)_2SiF_6$ sal ammoniac NH_4Cl malladrite Na_2SiF_6 fluorite CaF_2 unidentified sp.	Crust on lava, brownish yellow, <4 mm thick. Surface temperatures 100–200 °C. Collected on July 12, 1991.
NI 15210	cryptohalite $(NH_4)_2SiF_6$ sal ammoniac NH_4Cl malladrite Na_2SiF_6 ralstonite? $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$	Crust on lava, yellow, <0.5 cm thick. Surface temperatures 100–200 °C. Collected on July 12, 1991.
2. LAMBAFELL. On lava which flowed in early March 1991. Locality 2 on Fig. 16.		
NI 15201	malladrite Na_2SiF_6 hematite Fe_2O_3 mineral HD $NH_4(Fe,Co)_2F_6$ (?) unidentified sp.	Crust on lava, white to yellow, <0.5 cm in thickness. Collected on July 7, 1991.
B. IN LAVA CAVE		
3. HROSSAHELLIR. On surface of lava on the floor of the cave at the eastern main crater. Locality 3 on Fig. 16.		
NI 15114	thenardite Na_2SO_4 glauberite $Na_2Ca(SO_4)_2$ hydroglauberite $Na_{10}Ca_3(SO_4)_8\ 6H_2O$	Crust on lava, yellow-white to grayish, <1.5 cm thick. Collected on August 3, 1991.
NI 15522	thenardite Na_2SO_4 gypsum $CaSO_4\cdot 2H_2O$	Crust on lava, white, <1.5 cm thick. Ambient surface temperatures. About 10 m from the entrance of the cave. Collected on September 16, 1992.

C . IN SCORIA CRATER

4. NORTHEAST SCORIA CRATER FISSURE. On scoria at the linear eruption fissure above the eastern main crater, formed in January–March 1991. Locality 4 on Fig. 16.

NI 15505	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ mineral HA (comp. unknown) hematite Fe_2O_3 mineral HB (comp. unknown) ilmenite $FeTiO_3$ mineral HD $NH_4(Fe,Co)_2F_6$ (?) mineral HC (comp. unknown) unidentified sp.	Crust on altered scoria, white, yellowish and brownish, <0.5 cm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15506	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ mineral HA (comp. unknown) heklaite KNaSiF6 mineral HB (comp. unknown) mineral HC (comp. unknown) mineral HD $NH_4(Fe,Co)_2F_6$ (?) malladrite Na_2SiF_6 unidentified sp.	Crust on altered scoria, white, yellowish and brownish, <4 mm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15507	opal-A $SiO_2 \cdot nH_2O$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ mineral HD $NH_4(Fe,Co)_2F_6$ (?) mineral HA (comp. unknown) mineral HB (comp. unknown) unidentified sp.	Crust on altered scoria, white, yellowish and brownish, <0.5 cm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15508	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ opal-A $SiO_2 \cdot nH_2O$ mineral HA (comp. unknown) mineral HC (comp. unknown) mineral HB (comp. unknown)	Crust on altered scoria, white-yellow, <0.5 cm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15509	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ hematite Fe_2O_3 mineral HA (comp. unknown) opal-A $SiO_2 \cdot nH_2O$ mineral HG $Na_2Ca_3Al_2F_{14}$ malladrite Na_2SiF_6 mineral HB (comp. unknown) heklaite $KNaSiF_6$ mineral HC (comp. unknown) mineral HK (comp. unknown) mineral HR? $MgAlF_5 \cdot 2H_2O$	Crust on altered scoria, multicolored, <0.5 cm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15510	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ mineral HT $FeSiF_6 \cdot 6H_2O$ opal-A $SiO_2 \cdot nH_2O$ malladrite? Na_2SiF_6 mineral HU $AlF_3 \cdot 3H_2O$ (?)	Crust on altered scoria, light yellow to pink, 2 mm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15511	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ mineral HT $FeSiF_6 \cdot 6H_2O$ malladrite Na_2SiF_6 mineral HM (comp. unknown) mineral HU $AlF_3 \cdot 3H_2O$ (?)	Crust on altered scoria, light yellow, <3 mm thick. Temperatures at 170 °C. Collected on September 16, 1992.

NI 15512	opal-A $SiO_2\cdot nH_2O$ mineral HA (comp. unknown) ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral HD $NH_4(Fe,Co)_2F_6$ (?) malladrite Na_2SiF_6 mineral HB? (comp. unknown)	Crust on altered scoria, brownish, <0.5 cm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15513	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral HA (comp. unknown) heklaite $KNaSiF_6$ malladrite Na_2SiF_6 hieratite / demartinite K_2SiF_6 mineral HB (comp. unknown) unidentified sp.	Crust on altered scoria, white to yellow, <0.8 cm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15514	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral HA (comp. unknown) malladrite Na_2SiF_6 heklaite $KNaSiF_6$	Crust on altered scoria, brown and yellow, <2 mm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15515	malladrite Na_2SiF_6 hematite Fe_2O_3 mineral HI $\beta\text{-}FeF_3\cdot 3H_2O$ (?) opal-A $SiO_2\cdot nH_2O$ heklaite $KNaSiF_6$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral HM (comp. unknown) mineral HK (comp. unknown) mineral HD $NH_4(Fe,Co)_2F_6$ (?) mineral HH (comp. unknown) opal-CT? $SiO_2\cdot nH_2O$ unidentified sp.	Crust on altered scoria, brown to yellow, <3 mm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15516	opal-A $SiO_2\cdot nH_2O$	Crust on altered scoria, colorless, <2 mm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15517	opal-A $SiO_2\cdot nH_2O$	Crust on altered scoria, colorless, <1 mm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15518	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ hematite Fe_2O_3 mineral HA (comp. unknown) mineral HG $Na_2Ca_3Al_2F_{14}$ unidentified sp.	Crust on altered scoria, brownish and white, <0.5 cm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15519	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral HA (comp. unknown) mineral HB (comp. unknown)	Crust on altered scoria, brownish, <2 mm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15520	malladrite Na_2SiF_6 heklaite $KNaSiF_6$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral HA (comp. unknown)	Crust on altered scoria, brownish to yellow, <2 mm thick. Temperatures at 170 °C. Collected on September 16, 1992.
NI 15521	gypsum $CaSO_4\cdot 2H_2O$ unidentified sp.	Crust on altered scoria, white and yellow, <3 mm thick. Temperature 40 °C. Collected on September 16, 1992.

NI 15524	anhydrite $CaSO_4$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ gypsum $CaSO_4\cdot 2H_2O$ hematite Fe_2O_3	Crust on altered scoria, white, grayish and yellow, <6 mm thick. In a fissure in the scoria cone 0.8 m below surface. Temperature at 500 °C. Collected on September 16, 1992.
NI 17062	anhydrite $CaSO_4$ fluorite CaF_2 ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ unidentified sp.	Crust on altered scoria, white to yellow-brown, <3 mm thick. In a fissure in the scoria cone. Temperature 325 °C. Collected on September 15, 1993.
NI 17063	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral HA (comp. unknown) mineral HB (comp. unknown)	Crust on altered scoria, brownish and white, <2 mm thick. Temperature 155 °C. Collected on September 15, 1993.
NI 17064	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral HA (comp. unknown) mineral HG $Na_2Ca_3Al_2F_{14}$ mineral HB (comp. unknown) opal-A $SiO_2\cdot nH_2O$ fluorite CaF_2 hematite Fe_2O_3 unidentified sp.	Crust on altered scoria, brownish, white and yellow, <3 mm in thickness. Collected on September 15, 1993.
NI 17065	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ fluorite CaF_2 mineral HB (comp. unknown) sulfur? S	Crust on altered scoria, white, yellowish and brownish, <3 mm thick. Temperature 195 °C. Collected on September 15, 1993.
NI 17066	opal-A $SiO_2\cdot nH_2O$ mineral HB (comp. unknown) ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral HA? (comp. unknown)	Crust on leached scoria, white, yellowish and brownish, <2 mm thick. Temperature 190 °C. Collected on September 15, 1993.
NI 17067	opal-A $SiO_2\cdot nH_2O$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral HA (comp. unknown) mineral HB (comp. unknown) mineral HR $MgAlF_5\cdot 2H_2O$ malladrite Na_2SiF_6	Crust on leached scoria, white, yellowish and brownish, <4 mm thick. Temperature 190 °C. Collected on September 15, 1993.
NI 17068	opal-A $SiO_2\cdot nH_2O$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral HB (comp. unknown) mineral HA (comp. unknown) mineral HC (comp. unknown)	Crust on leached scoria, white, yellowish and brownish, <2 mm in thickness. Temperature 190 °C. Collected on September 15, 1993.
NI 17069	opal-A $SiO_2\cdot nH_2O$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ mineral HA (comp. unknown) mineral HB (comp. unknown)	Crust on leached scoria, white, yellow and brownish, <3 mm thick. Temperature 190 °C. Collected on September 15, 1993.
NI 17070	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ unidentified sp.	Crust on altered scoria, multicolored, <3 mm thick. Temperature 232 °C. Collected on September 15, 1993.
NI 17071	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$ malladrite Na_2SiF_6 mineral HA (comp. unknown)	Crust on altered scoria, multicolored, <3 mm thick. Temperature 275 °C. Collected on September 15, 1993.

NI 17072	heklaite $KNaSiF_6$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ opal-A $SiO_2 \cdot nH_2O$ hematite Fe_2O_3 mineral HA (comp. unknown) malladrite? Na_2SiF_6 mineral HB? (comp. unknown) unidentified sp.	Crust on altered scoria, multicolored, <2 mm thick. Temperature 333 °C. Collected on September 15, 1993.
NI 17073	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ mineral HN (comp. unknown) fluorite CaF_2 mineral HR $MgAlF_5 \cdot 2H_2O$ unidentified sp.	Crust on altered scoria, yellow to brown, <1 cm thick. Temperature 190 °C. Collected on September 15, 1993.
NI 17074	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ mineral HN (comp. unknown) mineral HR $MgAlF_5 \cdot 2H_2O$ mineral HS (comp. unknown)	Crust on altered scoria, brownish and white, <2 mm thick. Temperature 190 °C. Collected on September 15, 1993.
NI 17075	opal-A $SiO_2 \cdot nH_2O$	Crust on altered scoria, white, yellow and brownish, <3 mm thick. Temperature 190 °C. Collected on September 15, 1993.
NI 17076	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ pachnolite / thomsenolite $NaCaAlF_6 \cdot H_2O$ opal-A $SiO_2 \cdot nH_2O$ mineral HK? (comp. unknown)	Crust on altered scoria, brown, yellow and greenish, <1.5 cm thick. Temperature 190 °C. Collected on September 15, 1993.
NI 17077	opal-A $SiO_2 \cdot nH_2O$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ mineral HA (comp. unknown) mineral HN (comp. unknown) mineral HH (comp. unknown) unidentified sp.	Crust on altered scoria, white, yellow to brown, <2 mm thick. Temperature 190 °C. Collected on September 15, 1993.
NI 17078	hematite Fe_2O_3 ralstonite? $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ halite $NaCl$ fluorite CaF_2	Crust on altered scoria, dark brown to yellow, <0.5 cm thick. Temperature 190 °C. Collected on September 15, 1993.

Mineralogy of the encrustations

The 45 encrustation samples collected from the 1991 Hekla eruption are described in Table 9 and the localities are given in Figure 16. The minerals identified in each sample are arranged roughly in order of abundance. The thickness of each sample is generally of the order 0.3–1 cm (Fig. 18), and the minerals generally occur in intergrown aggregates a few millimeters or micrometers in thickness, except thenardite in the cave, which formed layers several centimeters thick. The 36 mineral species which were identified in the 1991 Hekla encrustations are listed in Table 10, arranged roughly in order of abundance.

During the course of our study on the Hekla encrustations, some 17 species were identified which

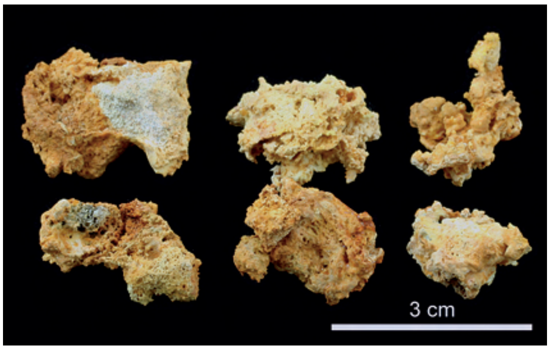

Fig. 18. Encrustation sample NI 15507 from Hekla. Scoria fragments coated with irregular layers of sublimates. Identified minerals are opal-A, ralstonite, and minerals HD, HA and HB. See Table 9.

Table 10. Identified encrustation species of the 1991 Hekla eruption. The minerals are arranged roughly in order of abundance.

Mineral	Composition	Abundance
Ralstonite	$Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$	common
Mineral HA	(comp. unknown)	common
Opal-A	$SiO_2 \cdot nH_2O$	common
Malladrite	Na_2SiF_6	common
Mineral HB	(comp. unknown)	common
Hematite	Fe_2O_3	common
Cryptohalite	$(NH_4)_2SiF_6$	fairly common
Fluorite	CaF_2	fairly common
Heklaite	$KNaSiF_6$	fairly common
Mineral HC	(comp. unknown)	fairly common
Mineral HD	$NH_4(Fe,Co)_2F_6$ (?)	fairly common
Mineral HR	$MgAlF_5 \cdot 2H_2O$	fairly common
Sal ammoniac	NH_4Cl	fairly common
Anhydrite	$CaSO_4$	rare
Gypsum	$CaSO_4 \cdot 2H_2O$	rare
Mineral HG	$Na_2Ca_3Al_2F_{14}$	rare
Mineral HI	$\beta\text{-}FeF_3 \cdot 3H_2O$ (?)	rare
Mineral HK	(comp. unknown)	rare
Mineral HM	(comp. unknown)	rare
Mineral HN	(comp. unknown)	rare
Mineral HT	$FeSiF_6 \cdot 6H_2O$	rare
Mineral HU	$AlF_3 \cdot 3H_2O$ (?)	rare
Thenardite	Na_2SO_4	rare
Calcite	$CaCO_3$	very rare
Glauberite	$Na_2Ca(SO_4)_2$	very rare
Halite	NaCl	very rare
Hydroglauberite	$Na_{10}Ca_3(SO_4)_8 \cdot 6H_2O$	very rare
Mineral EA	(comp. unknown)	very rare
Mineral HH	(comp. unknown)	very rare
Mineral HS	(comp. unknown)	very rare
Pachnolite / thomsenolite	$NaCaAlF_6 \cdot H_2O$	very rare
Hieratite / demartinite	K_2SiF_6	very rare
Ilmenite	$FeTiO_3$	very rare
Mineral EB?	(comp. unknown)	very rare
Opal-CT?	$SiO_2 \cdot nH_2O$	very rare
Sulfur?	S	very rare

appear not to be known as natural minerals. Mineral EA and mineral EB have already been discussed in the chapter on Eldfell.

One of the new species, heklaite ($KNaSiF_6$), has been accepted as a new mineral (IMA 2008-052) by the International Mineralogical Association, Commission on New Minerals, Nomenclature and Classification. The mineral was investigated by X-ray powder diffraction and scanning electron microscopy. The corresponding standard diagram in the Powder Diffraction File (PDF) has the label 38-0686. Heklaite is orthorhombic and the crystals are colorless. It typically occurs with malladrite (Na_2SiF_6) and is possibly intergrown with it, in some parts of the sample NI 15513 (Fig. 19) heklaite appears to be intergrown with hieratite or demartinite (polymorphs of K_2SiF_6). A detailed description of this mineral is presented on p. 41. The holotype of heklaite is kept in the mineral collection of the Icelandic Institute of Natural History in Reykjavík under the sample number NI 15513. Part of the holotype is also temporarily deposited at Museum C. L. Garavelli, Dipartimento Geomineralogico, Università di Bari, Italy.

As will be discussed in a later chapter, minerals HG, HR and HT are considered to be new, partly defined

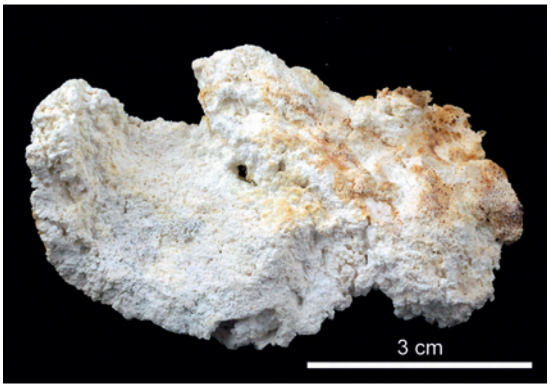

Fig. 19. Encrustation sample NI 15513 from Hekla. Identified minerals are ralstonite, mineral HA, heklaite, malladrite, hieratite/demartinite and mineral HB. See Table 9.

minerals as they can be identified with well-known synthetic compounds; minerals HU, HI and HD are probable new minerals; and finally, minerals HA, HB, HC, HK, HM, HN, HS and HH, are considered to be possible new minerals.

With reference to the observations at Surtsey and Eldfell, the eruption fissure at Hekla probably was cooling slowly and at an even rate. The measured temperatures at the time of sampling will therefore indicate the minimum temperature of deposition of the minerals in question. For example, anhydrite, ralstonite and hematite were identified in sample NI 15524 (Table 9) which was collected at 500 °C; heklaite, opal-A, mineral HA, malladrite and mineral HB were identified in samples NI 17070-17072 which were collected at 330 °C; and fluorite, sulfur, mineral HR, mineral HC, mineral HN, mineral HS, pachnolite and halite, were identified in samples NI 17065-17069 and 17073-17078, which were collected at 190–195 °C.

The encrustation mineralogy of the lava surface and the lava cave is quite distinct from that of the lava eruption fissure. The most common encrustation minerals collected on the surface of cooling lava at Hekla during 1991–1993, are cryptohalite, sal ammoniac and malladrite. The first two were also common on the Eldfell lava (Table 8; Óskarsson 1981). The most common minerals on the lava fissure are ralstonite, opal-A, hematite and malladrite, and surprisingly enough, also the unknown minerals HA and HB.

Only minor leaching of rocks was observed at the surface in the 1991 Hekla encrustation fields, although it was common in Eldfell, and only one questionable case of the identification of opal-CT was registered, although it was among the most common phases at Eldfell. The reason probably is a difference in age, as the encrustation field at Eldfell has now been active for about 35 years and wind erosion has removed the uppermost part of the rim of the Eldfell crater.

OTHER VOLCANIC ERUPTIONS

For comparative purposes, X-ray powder diffraction analyses were made on the main encrustation samples from the 1947–1948 Hekla and 1961 Askja eruptions, which are kept in the collections of the Icelandic Institute of Natural History in Reykjavík. Previously, little information was available on these samples.

The 1947–1948 Hekla eruption. This volcanic eruption occurred solely within the top fissure (Heklugjá) of the central volcano Hekla (Fig. 1). The eruption started on March 29, 1947 and lasted until April 21, 1948. About 0.2 km³ of tephra was produced during the plinian phase of the eruption. Lava covered 40 km² and its volume was about 0.8 km³ (Þórarinsson 1976). The chemical composition of the extrusives changed from transitional benmoreite (SiO_2 63%) at the beginning of the eruption, to transitional mugearite (SiO_2 54%) at the end.

A large amount of gas and vapor emanated from the craters, especially Axlargígur at the southwestern shoulder of the volcano. Líndal & Sigurgeirsson (1976) measured the temperatures of emerging gas at Axlargígur between November 1951 and September 1954, and found that maximum temperatures declined from approximately 630 °C to 385 °C during that period. Abundant encrustations were still found at Axlargígur in 1952, four years after the cessation of the eruption.

The encrustation samples from the 1947–1948 Hekla eruption were collected from five localities during 1947–1952. One sample was collected at 530 °C in August 1952. In Table 11 the minerals are arranged roughly in order of abundance in each sample. In this context it is of interest to note that the encrustation sample NI 1939 (Table 11), which was collected in the 1947–1948 Hekla lava in September 1949, was originally determined chemically as being glauber's salt, i.e. mirabilite (Kjartansson 1949). An X-ray powder diffraction analysis carried out by the present authors in 1995 (Table 11) gave thenardite and gypsum. It appears likely that this sample originally was put into a sealed, water-tight container before it was analyzed in 1949. It has been kept in an open container in the mineral collection of the Institute of Natural History in Reykjavík since 1949.

All the eight minerals (excluding mirabilite) identified in encrustations from the Hekla 1947–1948 eruption (Table 11) were also found in encrustations from the Hekla 1991 eruption.

Table 11. The 1947–1948 Hekla eruption, locality list with identified minerals.

AXLARGÍGUR.		
NI 15969	anhydrite $CaSO_4$ ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ unidentified sp.	Crust on scoria, white and brownish yellow, <2 mm thick. Temperatures >100 °C. Collected on June 5, 1949.
AXLARGÍGUR.		
NI 15989	opal-A $SiO_2 \cdot nH_2O$ opal-CT? $SiO_2 \cdot nH_2O$	Crust on leached volcanic bomb, white to brownish, <1 mm thick. Temperatures at 530 °C. Collected on August 10, 1952.
HRAUNGÍGUR.		
NI 15981	ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$ unidentified sp.	Crust on scoria, brownish yellow, <1 mm thick. Collected on May 1, 1947.
0.3 KM SOUTHWEST OF HRAUNGÍGUR.		
NI 16015	malladrite Na_2SiF_6 ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$	Crust on lava, brownish yellow, <1 mm thick. Collected on June 20, 1947.
SURFACE OF LAVA, UNSPECIFIED.		
NI 15992	hematite Fe_2O_3	Powdery crust on lava, red-brown, <1 mm thick. Collected in 1947.
KARELSHELLIR, A LAVA CAVE.		
NI 1939	mirabilite? $Na_2SO_4 \cdot 10H_2O$ thenardite Na_2SO_4 gypsum $CaSO_4 \cdot 2H_2O$	Powdery crust on the floor of the cave, white. Collected in September 1949.

The 1961 Askja eruption. This volcanic eruption occurred within the large Askja caldera (45 km^2) in the northern volcanic zone (Fig. 1). The 1961 eruption was preceded by the formation of big solfataras on a N-S line along the eastern caldera wall of Askja, about 10 days before the eruption (Sigvaldason 1964). This was a solfatara area with little or no water discharge, but with fuming and vigorously boiling mud pits and mud suspension.

The volcanic eruption started along a fissure northwest of the solfatara area on October 26 and lasted until November 28 (Þórarinsson & Sigvaldason 1962). The 1961 Askja eruption was a small eruption, only producing about 0.1 km^3 of tholeiitic basalt lava. The lava, Vikrahraun, covered 11 km^2 and large parts of it are estimated to be only a few meters in thickness. According to Sigvaldason (1964) temperatures at 420 °C were still measured at a depth of 20 cm at the crater in June 1962, however, in August 1962 all soluble salts had been washed away and apparently no new encrustations were being formed.

Encrustations formed both at the lava surface and in caves, but were apparently not widespread (Þórarinsson 1963). Sigvaldason (1964) reported that opal formed thin coating on lava, and suggested that it is a residue by the attack of hydrochloric and/or hydrofluoric acid on the cooling lava surface. This is evidently a leaching process of rocks comparable to that which was observed on a larger scale in Eldfell.

In Table 12 the minerals are arranged roughly in order of abundance in each sample. Óskarsson (1981) studied samples collected in June 1962 and found encrustations of sulfur, sal ammoniac and an NH-Fe-Cl-compound at the surface, and stalactites of metathenardite in lava caves. The 1961 Askja samples available to us derive from two shallow lava caves, all of which were presumably collected during the summer of 1962 (Table 12).

In our study, only six mineral species were identified in the encrustations of Askja. The similarity of the Askja mineralogy to that of the entrance of cave SUR-04 and other shallow cave features on Surtsey (Table 3) is noteworthy.

Table 12. The 1961 Askja eruption, locality list with identified minerals.

LAVA CAVE SOUTHWEST OF “THE SCIENCE HOLE” IN VIKRAHRAUN.		
NI 718	thenardite Na_2SO_4 dansite $Na_{21}Mg(SO_4)_{10}Cl_3$ löweite $Na_{12}Mg_7(SO_4)_{13}\cdot15H_2O$ blödite $Na_2Mg(SO_4)_2\cdot4H_2O$ halite NaCl unidentified sp.	Stalactites, white, up to 9 cm long. Collected on July 2, 1962.
GLÓFI, A LAVA CAVE IN VIKRAHRAUN.		
NI 688	thenardite Na_2SO_4	Crust on lava, white, 1–3 mm thick. Collected on July 29, 1962.
NI 1428	thenardite Na_2SO_4 halite NaCl kainite $KMg(SO_4)Cl\cdot3H_2O$	Stalactites. white, up to 9 cm long. Probably collected in the summer of 1962.

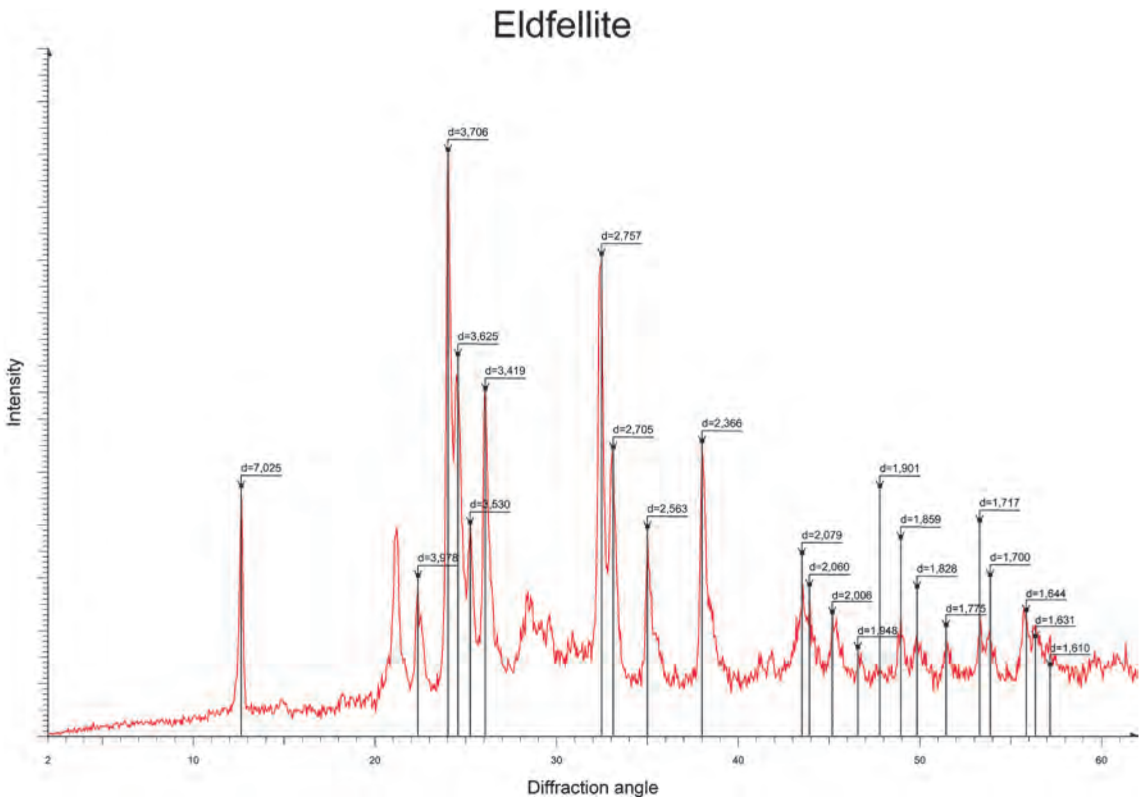

Fig. 20. X-ray powder diffraction diagram of eldfellite ($NaFe(SO_4)_2$), diagram no. LD191911. Accompanying phases are tamarugite and mineral EN ($Na_3Fe(SO_4)_3$).

NEWLY ACCEPTED, PARTLY DEFINED, PROBABLE, AND SUSPECTED NEW MINERALS

During the course of the present survey, many mineral species, unknown to science as minerals, were revealed. Before the publishing of this report, two of them, eldfellite (IMA 2007-051) and heklaite (IMA 2008-052), have been accepted by the International Mineralogical Association, Commission on New Minerals, Nomenclature and Classification, as new mineral species.

A description of the unknown minerals follows below, where they have been divided into four groups, Newly accepted minerals, New, partly defined minerals, Probable new minerals, and Suspected new minerals. Most of these minerals are rare or very rare, except a few of the unknown minerals among the encrustations at the eruption fissure in Hekla (Table 10), although they now are covered by extrusives of the 2000 Hekla eruption.

Newly accepted minerals. Species accepted by the International Mineralogical Association, Commission on New Minerals, Nomenclature and Classification.

Eldfellite (IMA 2007-051), $NaFe(SO_4)_2$. Aggregate has a frothy structure. Greenish yellow. Soluble in water. Found in one sample from Eldfell; NI 13556 (XRD LD191911/1004). The X-ray powder diffraction pattern is shown in Figure 20. This mineral was also investigated by scanning electron microscopy (SEM) and energy dispersive spectrometer (EDS) at Università di Bari (A. Garavelli and P. Acquafredda, pers. comm.). Occurs with tamarugite and mineral EN ($Na_3Fe(SO_4)_3$). The main diffraction maxima were first matched to the PDF 27-718 diagram for $NaFe(SO_4)_2$. It was confirmed by the match with a more detailed powder pattern obtained on synthetic $NaFe(SO_4)_2$ by E. Leonardsen in 1996. The calculated unit cell was a = 8.038(3), b = 5.1640(2) and c = 7.1660(3) Å, found by least square refinement of unambiguously indexed powder lines. XRD data suggest that the compound is isostructural with $NaFe(SeO_4)_2$ (Giester 1993). A Rietveld refinement based on the same structure type reveals that the LD191911 X-ray diffraction diagram represents a mixture of eldfellite as the major, and tamarugite as the minor phase and for the former gives the following crystal lattice parameters: 8.029(4), 5.138(3), 7.137(4) Å, 92.12(2)°, space group

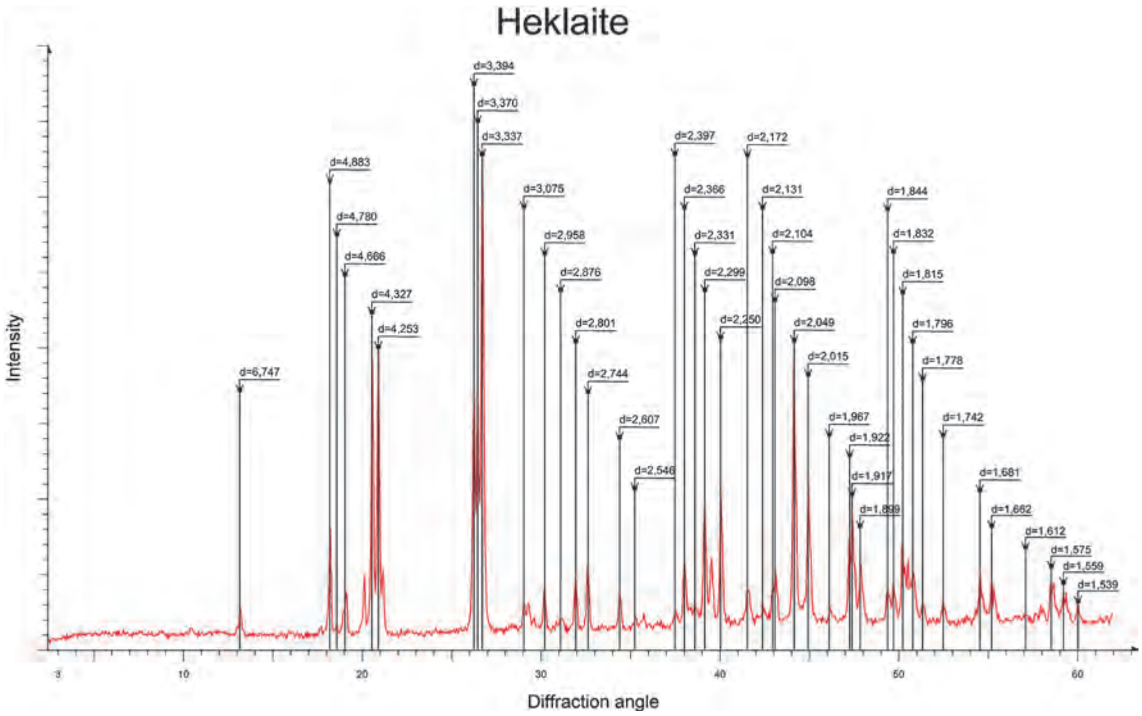

Fig. 21. X-ray powder diffraction diagram of heklaite ($KNaSiF_6$), diagram no. IE192321. Accompanying phase is malladrite.

C2/m. Like $NaFe(SeO_4)_2$, eldfellite is isostructural with yavapaiite ($KFe(SO_4)_2$). Originally run in 1996, the powdered sample 1004, which contained eldfellite, EN and tamarugite, was rerun in 2000 showing that eldfellite and EN had largely diminished in amount and ferrinatrite ($Na_3Fe(SO_4)_3 \cdot 3H_2O$) appeared in the sample. This indicates that both minerals are unstable under laboratory humidity conditions. However, a check done by X-ray diffraction and SEM on the uncrushed sample kept for 17 years in the institute in Reykjavík, reveals fresh eldfellite without signs of alteration.

Heklaite (IMA 2008-052), $KNaSiF_6$. Colorless. Found in seven samples from Hekla; main sample NI 15513 (XRD IE192321/15513D), where it can be collected in nearly pure condition. The X-ray powder diffraction pattern is shown in Figure 21. Occurs typically with malladrite (Na_2SiF_6) and is possibly intergrown with it. Occurs also with ralstonite, HA, HB and HG. In some parts of the sample it appears to be intergrown with hieratite or demartinite (polymorphs of K_2SiF_6). Originally run in 1993, the powdered preparate 15513D was rerun in 2000, showing that heklaite is stable at laboratory conditions. The chemical composition is confirmed by SEM/EDS (A. Garavelli and P. Acquafredda, pers. comm.) and the powder diagrams match excellently the one calculated from the known structure of $KNaSiF_6$ (Fischer & Kraemer 1991). The corresponding standard diagram in the Powder Diffraction File (PDF) has the label 38-0686.

New, partly defined minerals. Species for which the natural occurrences have not been reported, but which can be identified with well-known synthetic compounds.

Mineral HG, $Na_2Ca_3Al_2F_{14}$. Brownish? Found in three samples from Hekla in small amounts; main sample NI 15509 (XRD IE192216/15509K). The X-ray powder diffraction pattern is shown in Figure 22. Always occurs with ralstonite and HA, also occurs with HB, malladrite and heklaite. Originally run in 1993, the preparate 15509K was rerun in 2000, showing that the mineral HG is stable at laboratory conditions. This is a well characterized compound and the powder diagrams of HG match excellently the one calculated from the known structure of $Na_2Ca_3Al_2F_{14}$ (Courbion & Ferey 1988). The corresponding standard diagram in PDF has the label 36-1496.

Mineral HR, $MgAlF_5 \cdot 2H_2O$. White. Found in four samples from Hekla and two from Eldfell; main sample (Eldfell) NI 12256 (XRD LD211641/1015). The X-ray powder diffraction pattern is shown in Figure 23. Always mixed with ralstonite, also occurs with HA, HN and HB. Originally run in 1996,

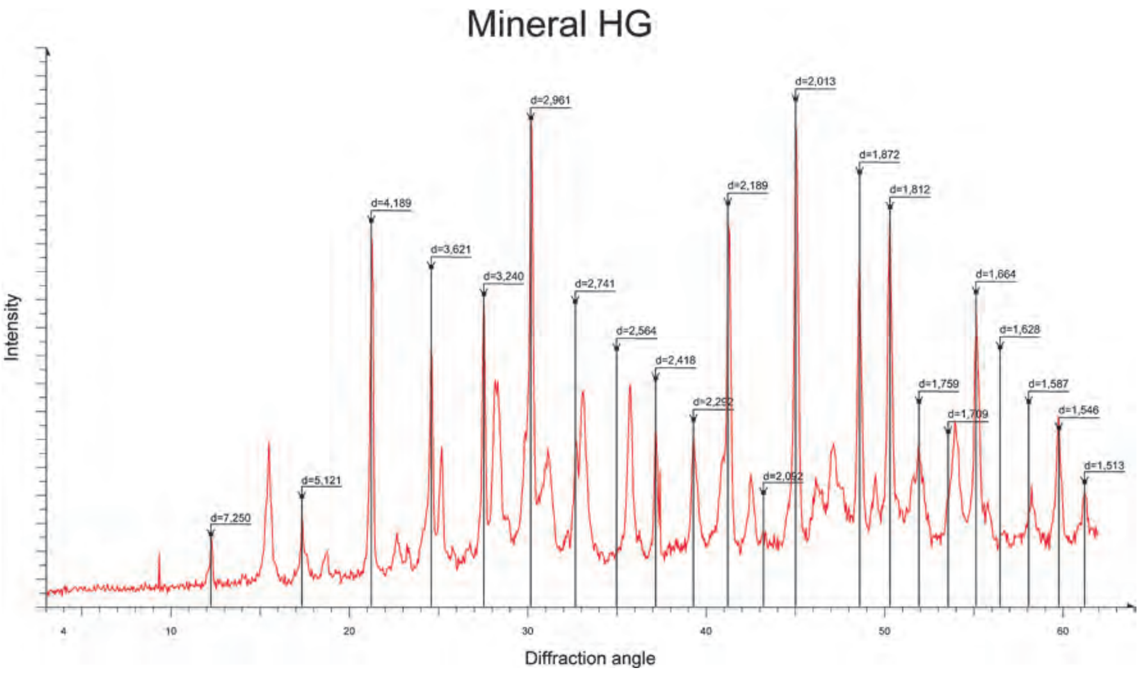

Fig. 22. X-ray powder diffraction diagram of mineral HG ($Na_2Ca_3Al_2F_{14}$), diagram no. IE192216. Accompanying phases are ralstonite, hematite and mineral HB.

the powdered preparate 1015 was rerun in 2000, showing that the mineral HR is stable at laboratory conditions. This is a well characterized compound and the powder diagrams of HR match well the one calculated from the known structure of $MgAlF_5 \cdot 2H_2O$ (Weil & Werner 2001). The corresponding standard diagram in PDF has the label 39-0655. Note, however, that the composition specified in 39-0655 has a different content of water per formula unit (1.5 instead of 2 as found by crystal structure analysis).

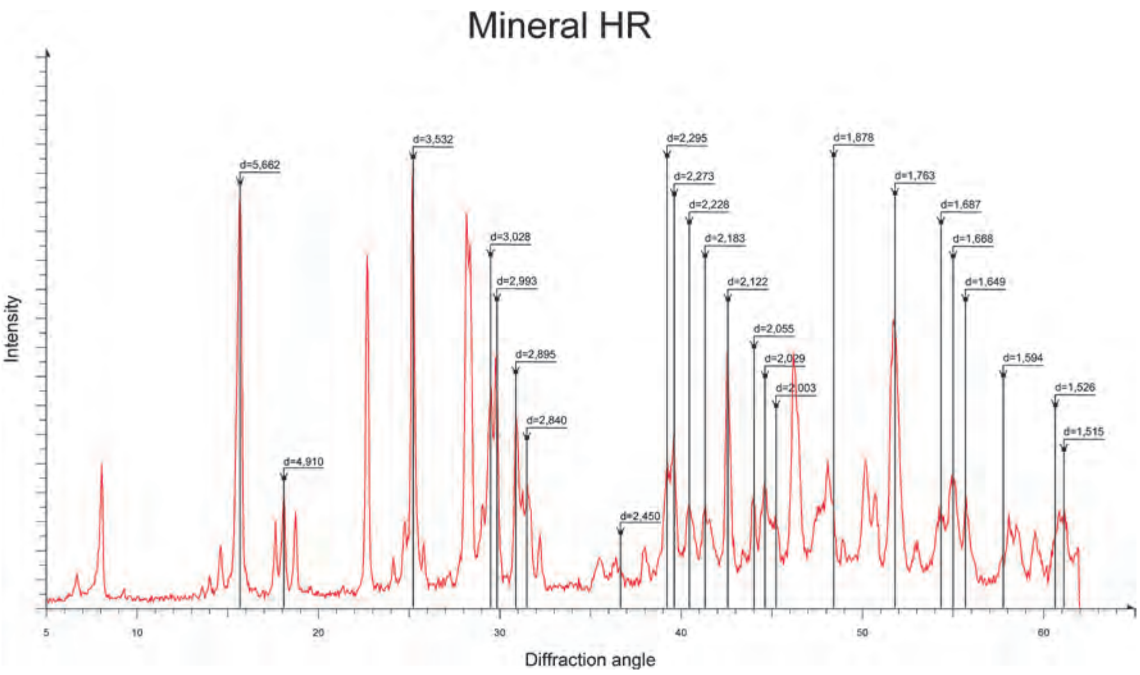

Fig. 23. X-ray powder diffraction diagram of mineral HR ($MgAlF_5 \cdot 2H_2O$), diagram no. LD211641. Accompanying phases are mineral HA and some other unidentified minerals.

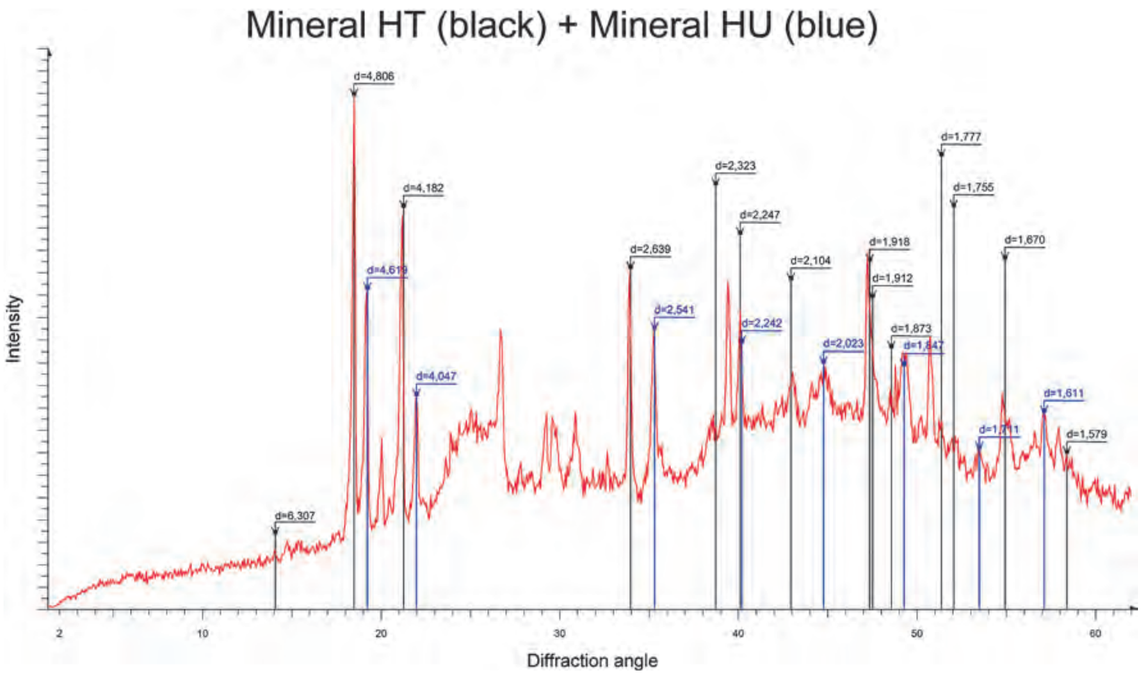

Fig. 24. X-ray powder diffraction diagram of mineral HT and HU ($FeSiF_6 \cdot 6H_2O$) and mineral HU, diagram no. JJ110146. Accompanying phases are malladrite and some amorphous material.

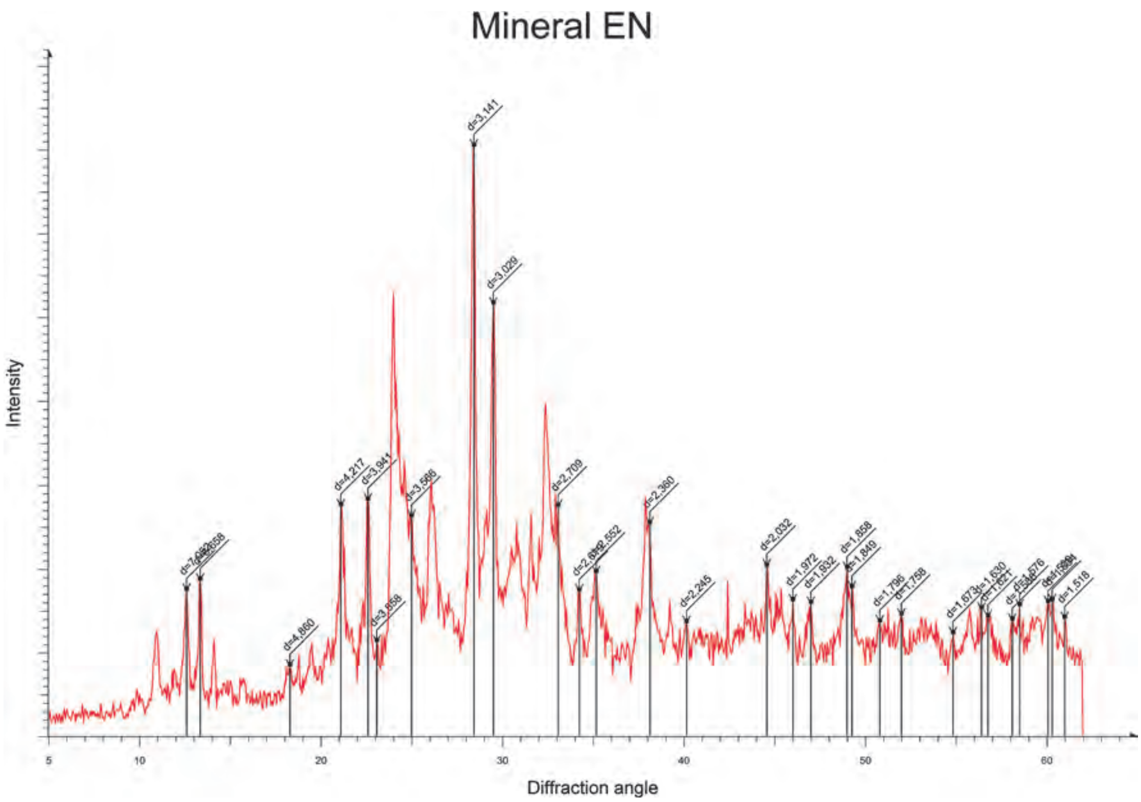

Fig. 25. X-ray powder diffraction diagram of mineral EN ($Na_3Fe(SO_4)_3$), diagram no. LD191707. Accompanying phases are eldfellite, tamarugite, probably blödite and some other unidentified minerals.

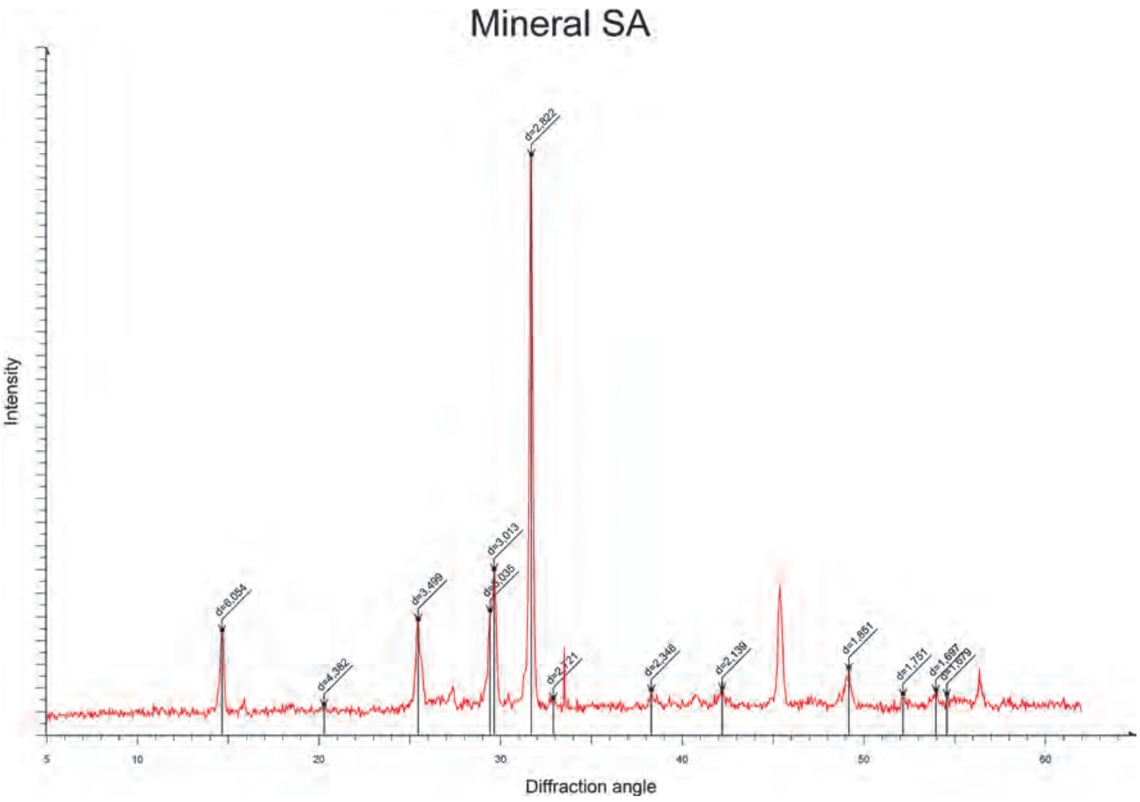

Fig. 26. X-ray powder diffraction diagram of mineral SA, diagram no. HD150037. Accompanying phase is halite.

Mineral HT, $FeSiF_6·6H_2O$. Yellow. Found in two samples from Hekla, main sample NI 15511 (XRD JJ110146/922). The X-ray powder diffraction pattern is shown in Figure 24. Occurs with malladrite, ralstonite, HM and HU. This is a well characterized compound and the powder diagrams of HT match well the one calculated from the known structure of $FeSiF_6·6H_2O$ (Chevrier et al. 1981). The corresponding standard diagram in PDF has the label 26-0799.

Mineral EN, $Na_3Fe(SO_4)_3$. White to yellow. Found in small amounts in one sample from Eldfell; NI 13556 (XRD LD191707/1002). The X-ray powder diffraction pattern is shown in Figure 25. Occurs with eldfellite and tamarugite and several other not well defined minerals. Its powder diffraction data match well the theoretical diagram calculated assuming the crystal structure type of $Na_3V(SO_4)_3$. The corresponding standard diagram in PDF has the label 39-0243. Mineral EN is unstable at laboratory conditions most probably due to a reaction with the atmospheric water (see eldfellite).

Probable new minerals. Species for which the natural occurrences have not been reported, but which can be matched to known synthetic compounds. However, the questions of chemical composition and crystal structure are still not fully resolved.

Mineral SA, $Ca_{0.83}Na_{0.33}(SO_4)·0.5H_2O$. Colorless-white. Found in one sample from Surtsey; NI 1962 (XRD HD150037/1962C). The X-ray powder diffraction pattern is shown in Figure 26. Occurs with halite, kainite, anhydrite and mineral SG. This mineral is closely related to bassanite. It has the same structure with an ordered substitution where each substituted Ca atom is replaced by 2Na. It is still not clear if SA can be considered a separate mineral species or just a Na-rich bassanite. For this the chemical composition should be directly confirmed and the structural relation to bassanite clarified. The formula given here corresponds to the maximum recorded substitution in a study of the phase system (Freyer et al. 1999). The powder diagram calculated from the known structure of this compound shows small but significant differences to the powder diagram of bassanite. It is possible on the basis of these differences to prove that the diagram HD150037 contains SA (plus halite) and not bassanite, whereas the identity of bassanite can be verified the same way in some other diagrams (e.g. Eldfell NI 13548, KL062021).

Mineral HU, matches the PDF diagram 43-0436, described as $AlF_3·3H_2O$. White? Found in two samples from Hekla; main sample NI 15511 (XRD

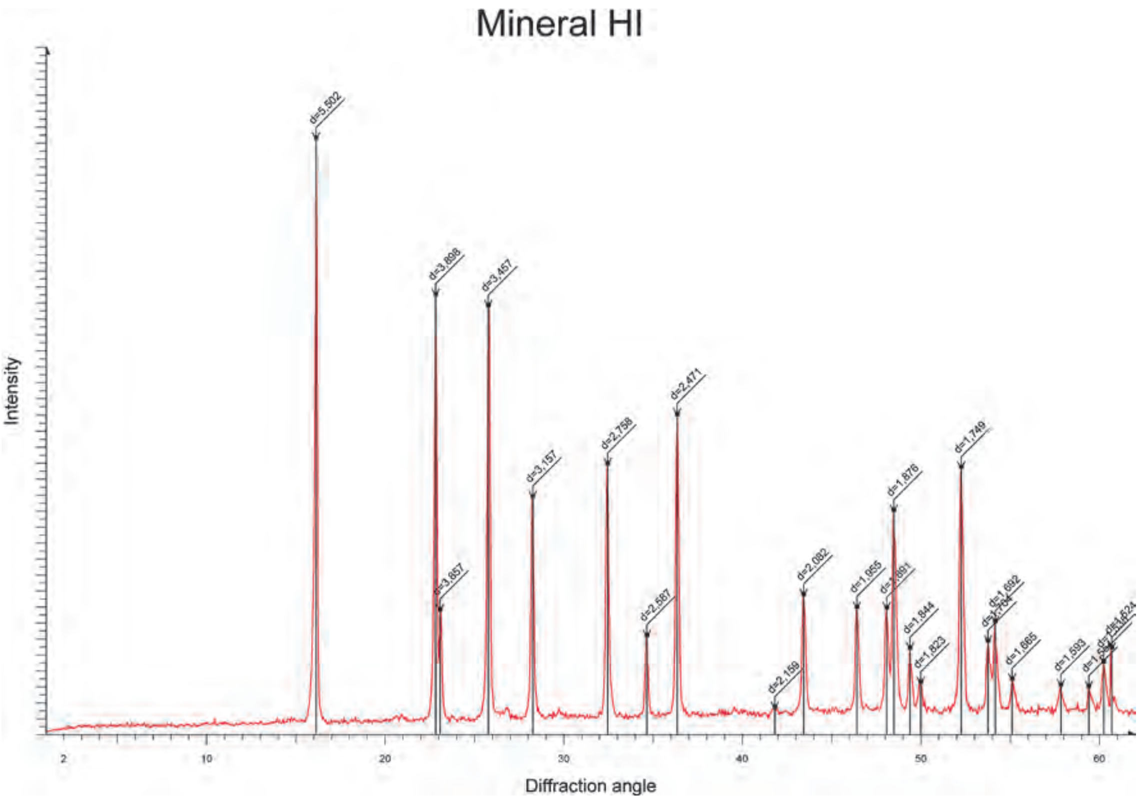

Fig. 27. X-ray powder diffraction diagram of mineral HI, diagram no. IE200446.

JJ110146/922). The X-ray powder diffraction pattern is shown in Figure 24. Occurs with ralstonite, HT and malladrite. This mineral needs a chemical analysis. The reference for PDF 43-0436 is from a patent and not an article for a well characterized compound. $AlF_3 \cdot 3H_2O$ is known in nature as the mineral rosenbergite which has a completely different powder diffraction diagram from that of HU.

Mineral HI, β-$FeF_3 \cdot 3H_2O$ (?). White to light yellow. Found in one sample from Hekla, where it can be collected in pure condition; NI 15515 (XRD IE200446/15515I). The X-ray powder diffraction pattern is shown in Figure 27. Occurs with HD. The sample was collected in 1992 and analyzed in 1993. However, it changed colors at laboratory conditions from white to light yellow during 1993–1996. The powder diagram matches well the PDF 32-0464 (specified as β-$FeF_3 \cdot 3H_2O$). β-$FeF_3 \cdot 3H_2O$ is isostructural with rosenbergite ($AlF_3 \cdot 3H_2O$). The powder diagram calculated from the structure data of β-$FeF_3 \cdot 3H_2O$ (Teufer 1964) matches the diagram of HI in the position of diffraction maxima, however, there are large differences in relative intensities. This mineral needs an independent chemical analysis for the confirmation of composition (a solid solution with rosenbergite or other isostructural fluoride can not be excluded). A SEM study can also help in detecting eventual impurities which also can be a reason for discrepancies in intensities in XRD diagrams.

Mineral HD, $NH_4(Fe,Co)_2F_6$ (?). Brownish. Found in six samples from Hekla and one from Eldfell; main sample NI 15507 (XRD LD252110/1030), where it can be collected in nearly pure condition. The X-ray powder diffraction pattern is shown in Figure 28. Occurs mainly with HA, ralstonite, malladrite, also HB; usually in minor amounts. Originally run in 1996, the preparate 1030 was rerun in 2000, showing that the mineral HD is stable at laboratory conditions. The diffraction pattern resembles in main features those of PDF 39-1148 (NH_4CoFeF_6) and 24-1219 ($NH_4Fe_2F_6$). The powder diagram calculated from the structure of $NH_4Fe_2F_6$ (Ferey et al. 1981) also resembles the diagram of HD, but with some differences in positions of diffraction maxima and intensities. A comparison suggests that the crystal lattice of HD is tetragonal, in contrast to $NH_4Fe_2F_6$ which has a close to tetragonal, but orthorhombic crystal lattice. It can be concluded from similarities that HD also has a crystal structure of the pyrochlore type. A reliable chemical analysis is needed to give the composition of this mineral.

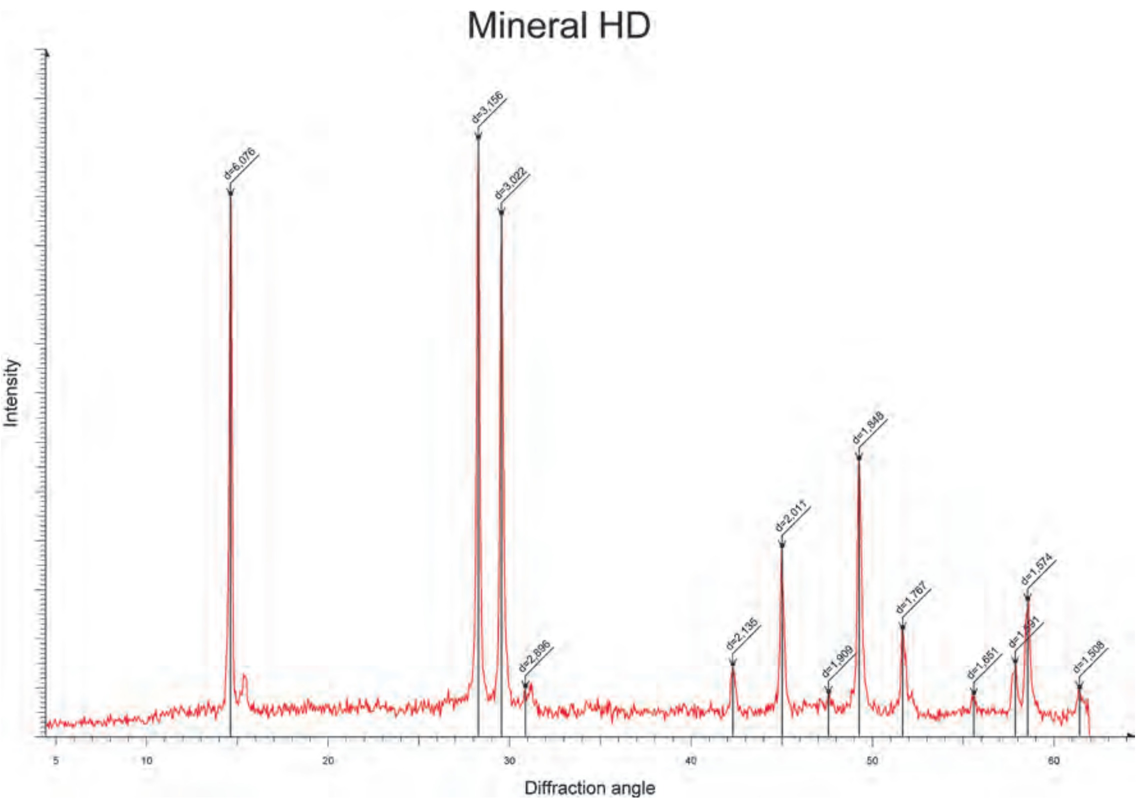

Fig. 28. X-ray powder diffraction diagram of mineral HD, diagram no. LD252110. Accompanying phase is ralstonite.

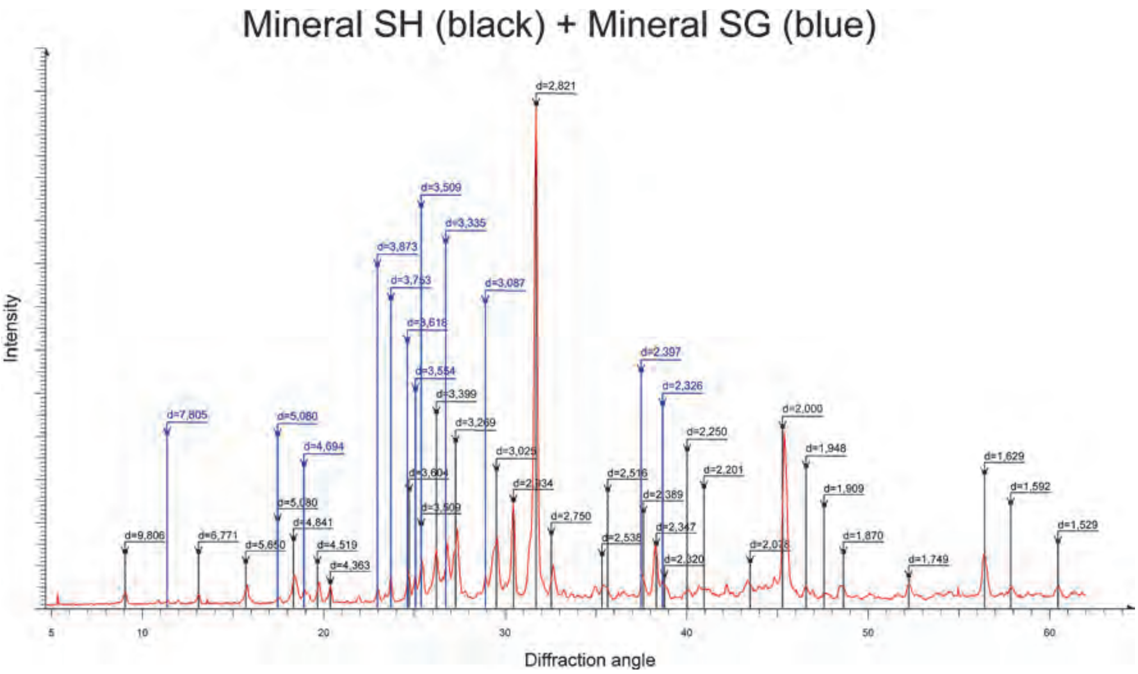

Fig. 29. X-ray powder diffraction diagram of minerals SH and SG, diagram no. HD142233. Accompanying phase is halite.

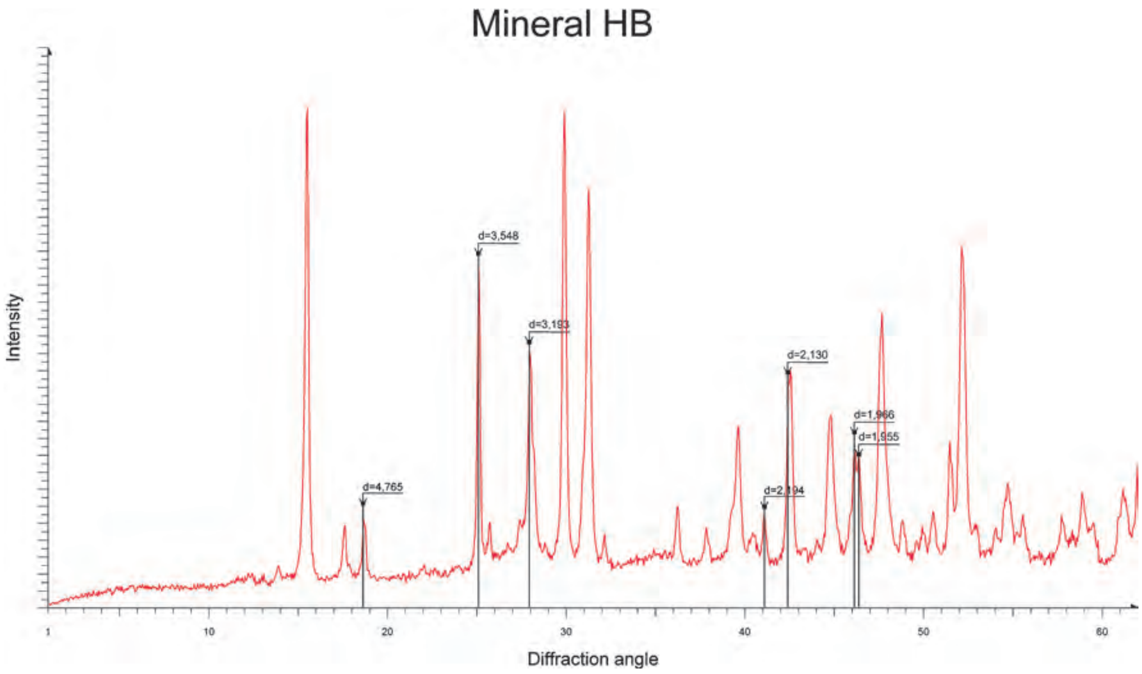

Fig. 30. X-ray powder diffraction diagram of mineral HB, diagram no. IE191651. The main phase in the diagram is ralstonite.

The atomic substitutions in this structure type can include both NH_4 and Fe/Co.

Mineral SH, $Na_2Mg_3(SO_4)_2(OH)_2 \cdot 4H_2O$ (?). Colorless-white. Found in two samples from Surtsey; main sample NI 1962 (XRD HD142233/1962B). The X-ray powder diffraction pattern is shown in Figure 29. Occurs with halite, anhydrite, kainite and SA. The composition written here is the one given with the PDF diagram 23-0686 with which SH shows a good match. However, the reference is not very reliable (has a low confidence mark in PDF, and no crystal structure data have ever been produced for a compound of this composition) and this mineral surely needs a detailed analysis, to prove its composition and homogeneity.

Suspected new minerals. Phases which do not match (to our knowledge) any of the diagrams in PDF. The observed XRD lines are given as d-spacings in Å (with corresponding relative intensities in parentheses on a scale from 1 to 10). The measurements were made with a variable divergence slit which emphasizes the intensities at lower d-values.

Mineral HB, composition unknown. Brownish? Identified lines 4.78 (3), 3.56 (10), 3.19 (7), 2.19 (3), 2.13 (7), 1.97 (5) and 1.96 (5). Found in 16 samples from Hekla and three from Eldfell; main sample NI 15507 (XRD IE191651/5507D). The X-ray powder diffraction pattern is shown in Figure 30. Occurs in most cases with ralstonite and HA, occasionally with HD, HR and HG. Possibly intergrown with ralstonite and HA. Originally run in 1993, the preparate 15507D was rerun in 2000, showing that the mineral HB is stable at laboratory conditions.

Mineral SB, composition unknown. White. Identified lines 5.77 (3), 4.26 (3), 4.11 (9), 3.96 (4), 2.89 (8), 2.73 (7), 2.65 (10) and 1.85 (4). Found in one sample from Surtsey; NI 1092 (XRD HD141825/1092B2). The X-ray powder diffraction pattern is shown in Figure 31. Occurs with halite and carnallite. Originally run in 1992, the preparate 1092 was rerun in 2000, indicating that it is stable at laboratory conditions.

Mineral SC, composition unknown. White or yellow-brown. Identified lines 5.02 (5), 4.57 (1), 4.35 (1), 3.73 (10), 3.28 (3), 2.89 (4), 2.63 (7), 2.44 (2), 2.35 (2), 2.28 (1), 2.24 (1), 2.15 (4), 1.79 (2) and 1.56 (2). Found in three samples from Surtsey; main sample NI 19011 (XRD JI281656/823). The X-ray powder diffraction pattern is shown in Figure 32. Occurs with gypsum.

Mineral SF, composition unknown. White-gray. Identified lines 5.97 (1), 3.18 (10), 3.16 (7), 2.91 (7). Found in one sample from Surtsey; NI 1962 (XRD GL070836/1962B). The X-ray powder diffraction pattern is shown in Figure 33. Occurs with halite, anhydrite, kainite and SG.

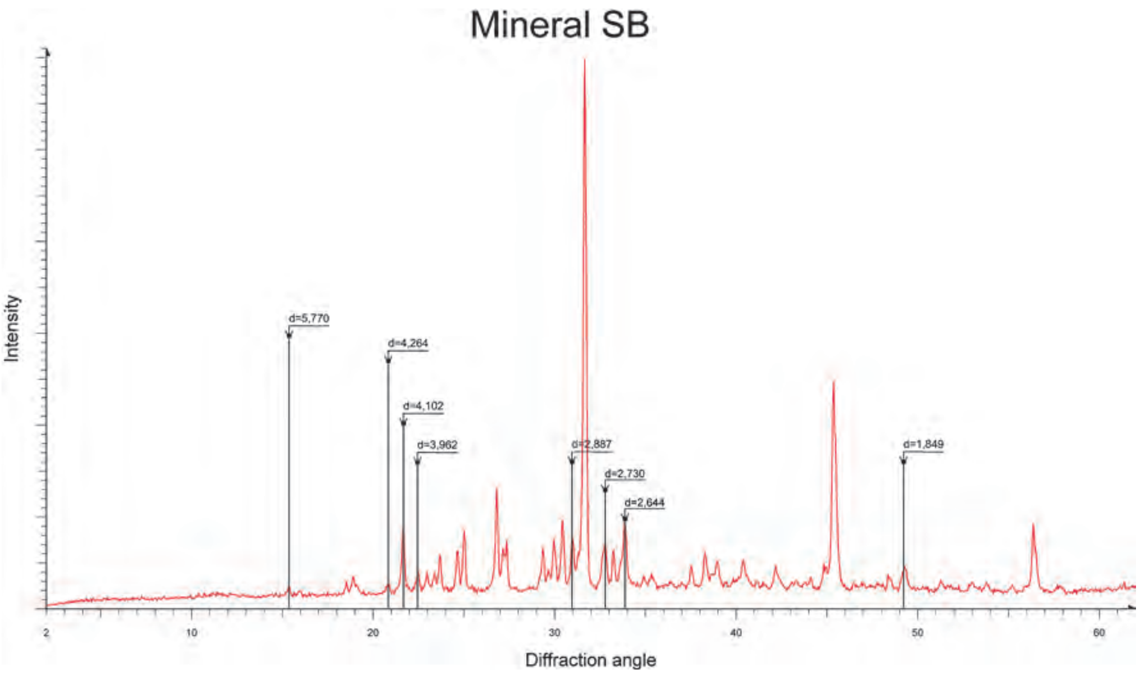

Fig. 31. X-ray powder diffraction diagram of mineral SB, diagram no. HD141825. The main phases are carnallite and halite.

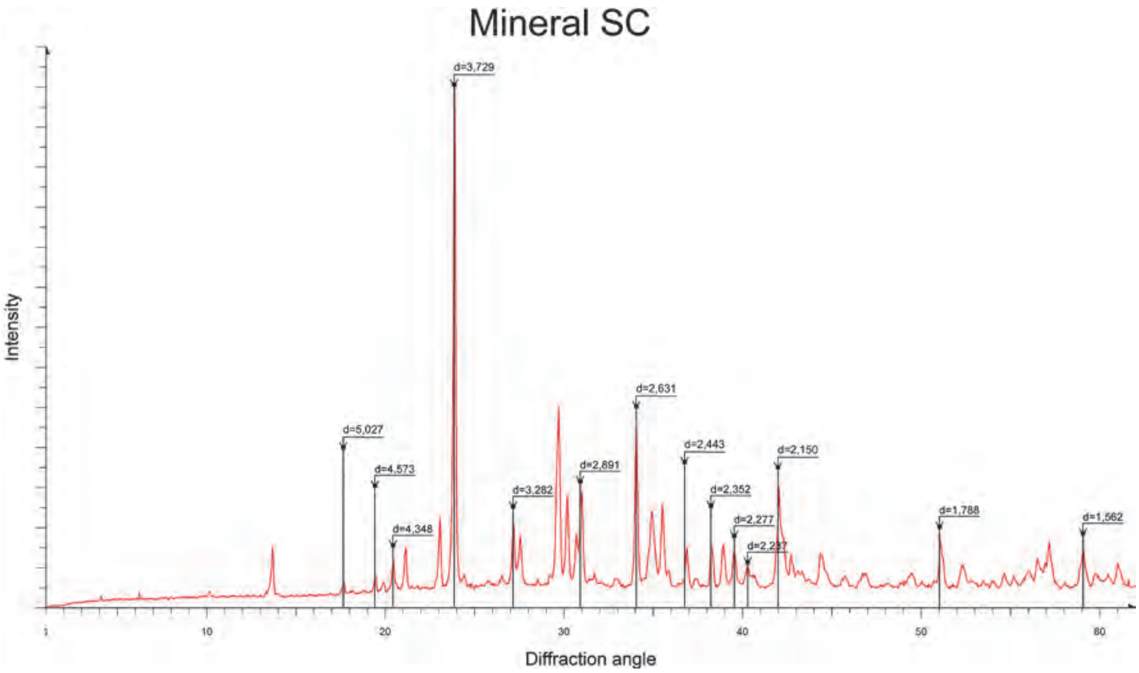

Fig. 32. X-ray powder diffraction diagram of mineral SC, diagram no. JI281656. Accompanying phase is a pyroxene (augite) probably from the base rock.

<u>Mineral SG</u>, composition unknown. White-gray. Identified lines 7.79 (1), 5.07 (2), 4.69 (3), 3.87 (3), 3.76 (5), 3.61 (5), 3.56 (5), 3.51 (7), 3.33 (10), 3.09 (5), 2.39 (5) and 2.33 (4). Found in one sample from Surtsey; NI 1962 (XRD HD142233/1962B). The X-ray powder diffraction pattern is shown in Figure 29. Occurs with halite, anhydrite and SH.

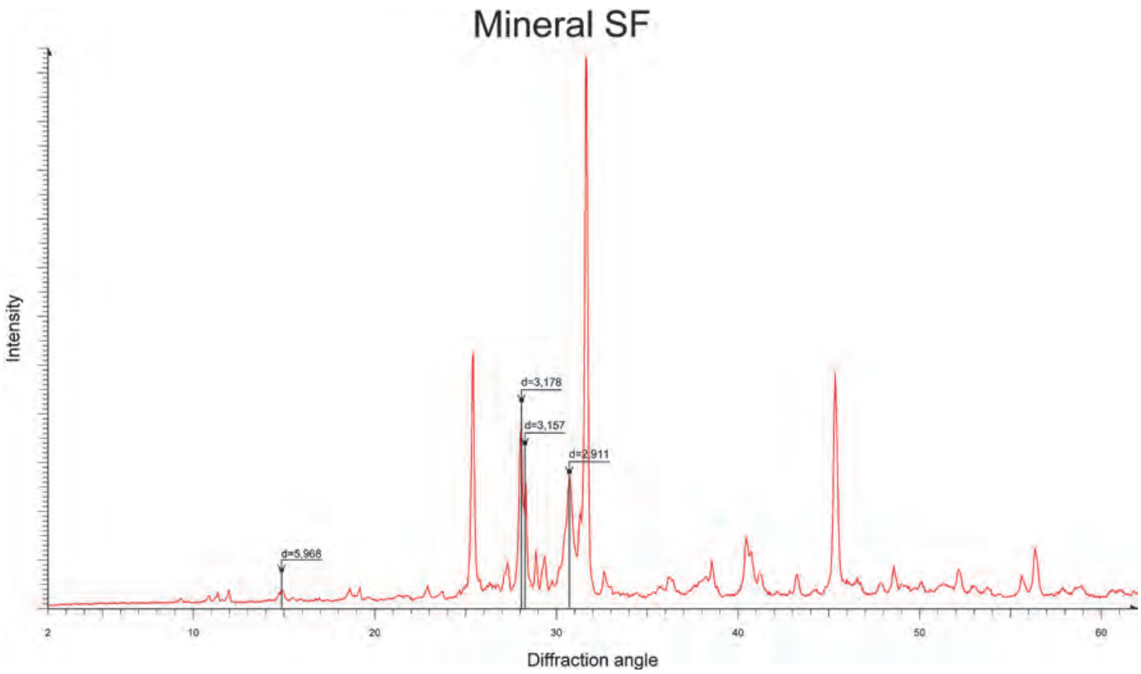

Fig. 33. X-ray powder diffraction diagram of mineral SF, diagram no. GL070836. Accompanying phases are halite and anhydrite.

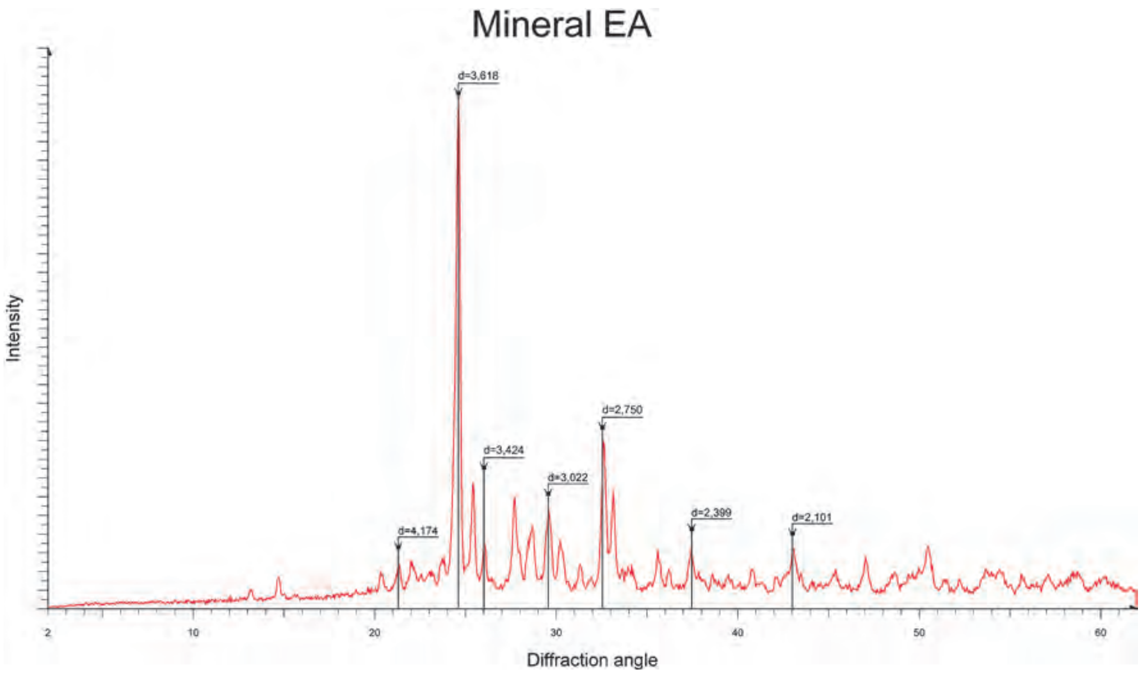

Fig. 34. X-ray powder diffraction diagram of mineral EA, diagram no. LD212353. Accompanying phases are hematite, anhydrite and mineral HA.

<u>Mineral EA</u>, composition unknown. White, acicular. Identified lines 4.17 (1), 3.62 (10), 3.42 (1), 3.02 (2), 2.75 (3), 2.40 (1) and 2.10 (1). Found in three samples from Eldfell and one sample from Hekla; main sample NI 20625 (XRD LD212353/1022). The X-ray powder diffraction pattern is shown in Figure 34. Occurs most often with EB, HA and anhydrite. Originally run in 1996, the preparate 1022 was re-

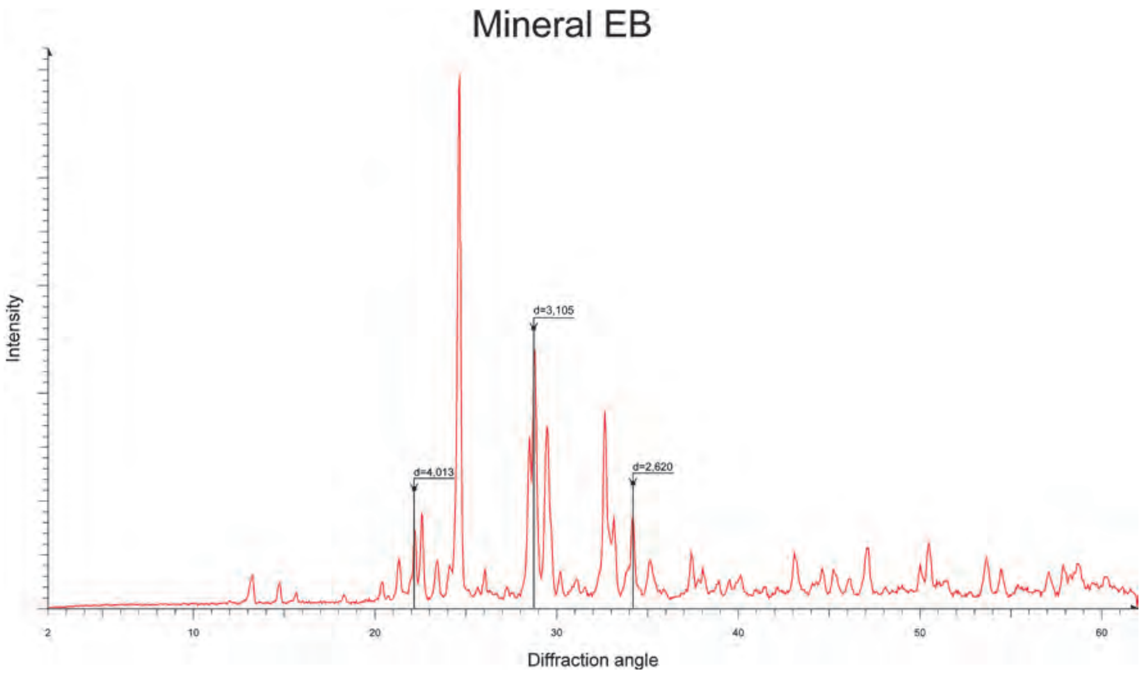

Fig. 35. X-ray powder diffraction diagram of mineral EB, diagram no. LD192114. Accompanying phases are minerals EA, HA and HD.

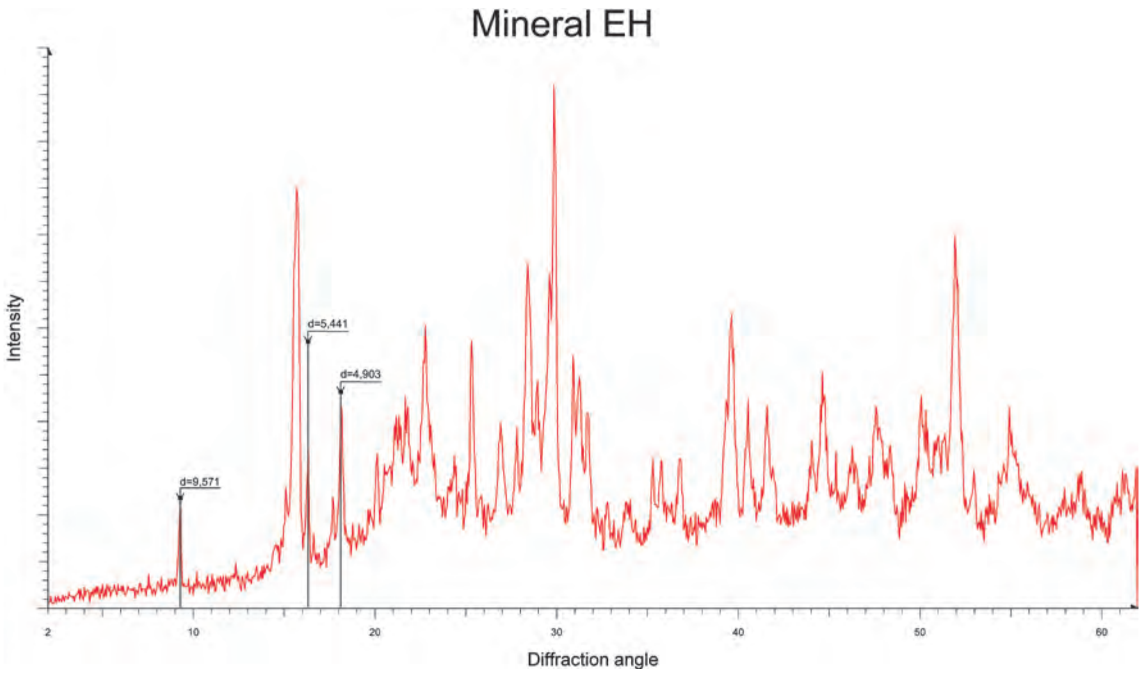

Fig. 36. X-ray powder diffraction diagram of mineral EH, diagram no. KL052127. Accompanying phases are minerals HR, EH, HB, HA and EB.

run in 2000, indicating that the mineral EA is stable at laboratory conditions.

Mineral EB, composition unknown. Botryoidal, white. Identified lines 4.01 (3), 3.10 (10) and 2.62 (3). Found in four samples from Eldfell and possibly one from Hekla; main sample NI 20627 (XRD LD192114/1006). The X-ray powder diffraction pattern is shown in Figure 35. Occurs with HA in

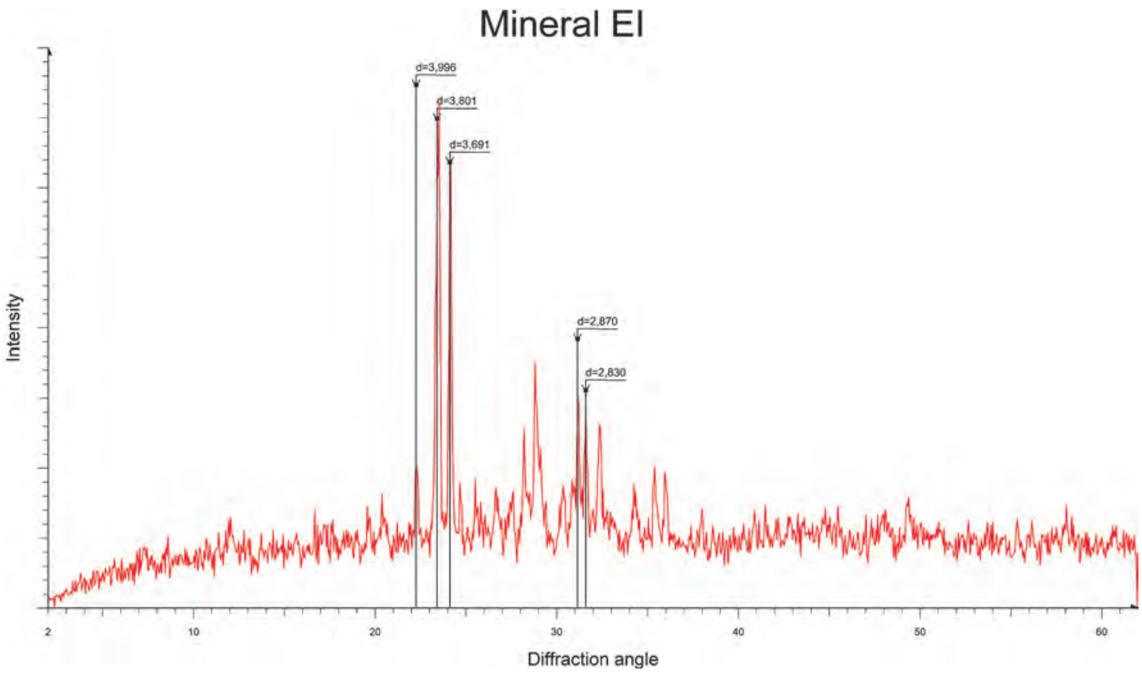

Fig. 37. X-ray powder diffraction diagram of mineral EI, diagram no. LD212150. Accompanying phases are minerals EA and EB and anhydrite.

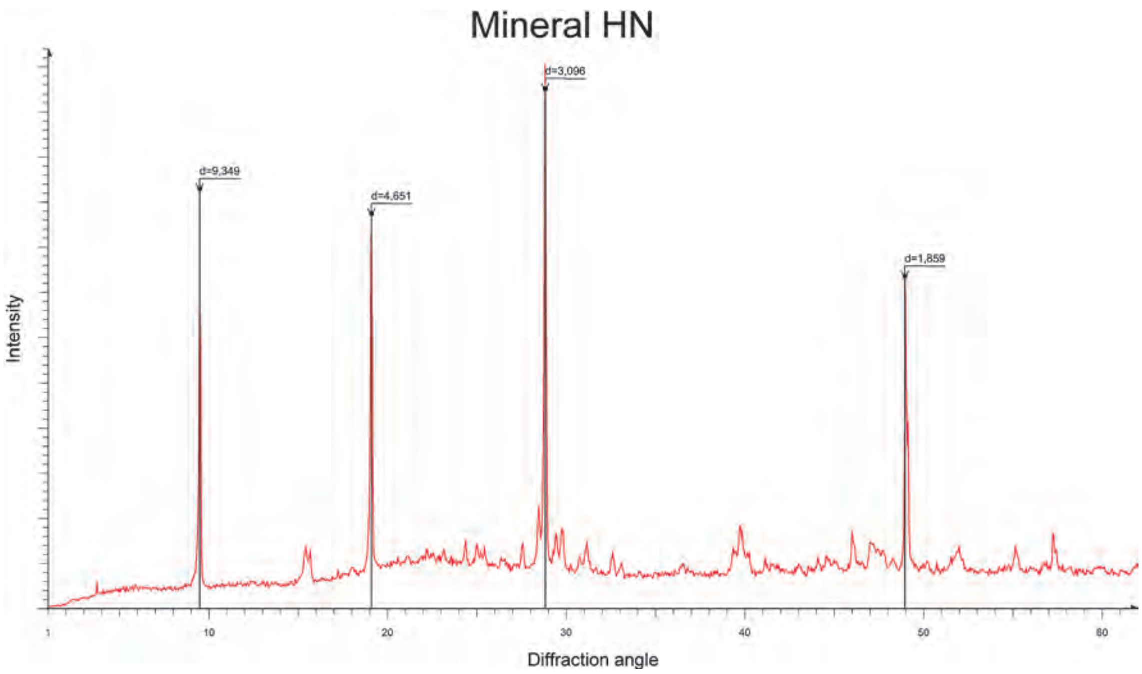

Fig. 38. X-ray powder diffraction diagram of mineral HN, diagram no. JJ012341. Accompanying phases are ralstonite and unidentified species.

all cases, also with EA, HD and anhydrite. Originally run in 1996, the preparate 1006 was rerun in 2000, indicating that the mineral EB is stable at laboratory conditions.

Mineral EH, composition unknown. Identified lines 9.58 (5), 5.44 (8) and 4.90 (10). Found in one sample from Eldfell; NI 20630 (XRD KL052127/965). The X-ray powder diffraction pattern is shown in

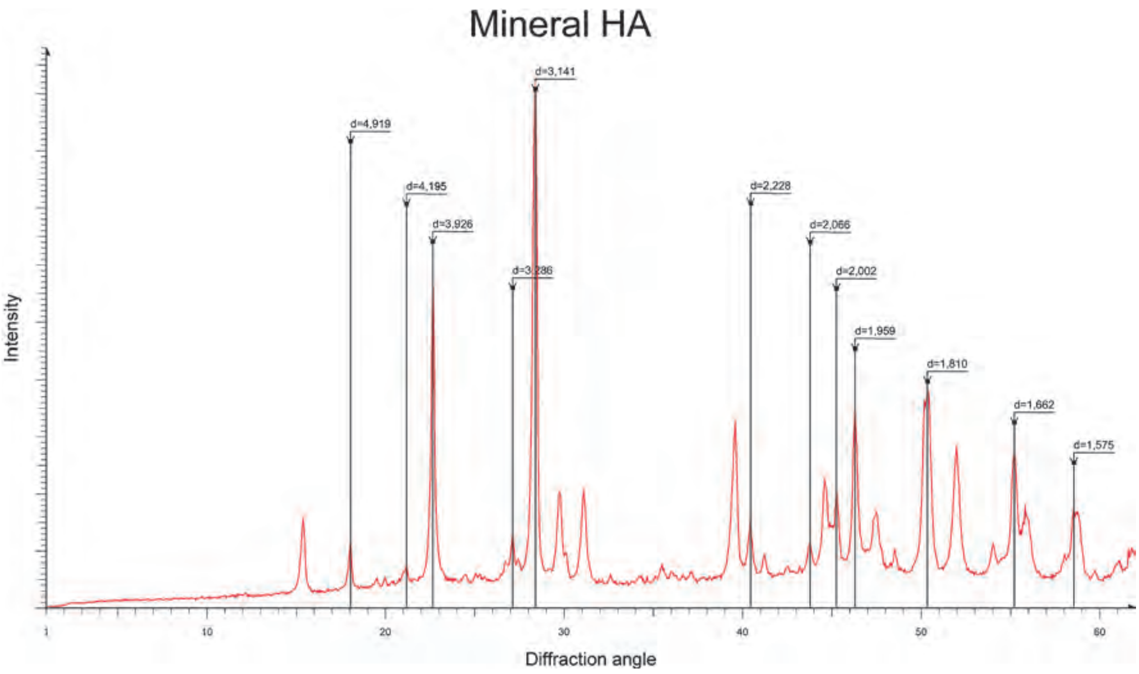

Fig. 39. X-ray powder diffraction diagram of mineral HA, diagram no. JJ301749. Accompanying phase is ralstonite.

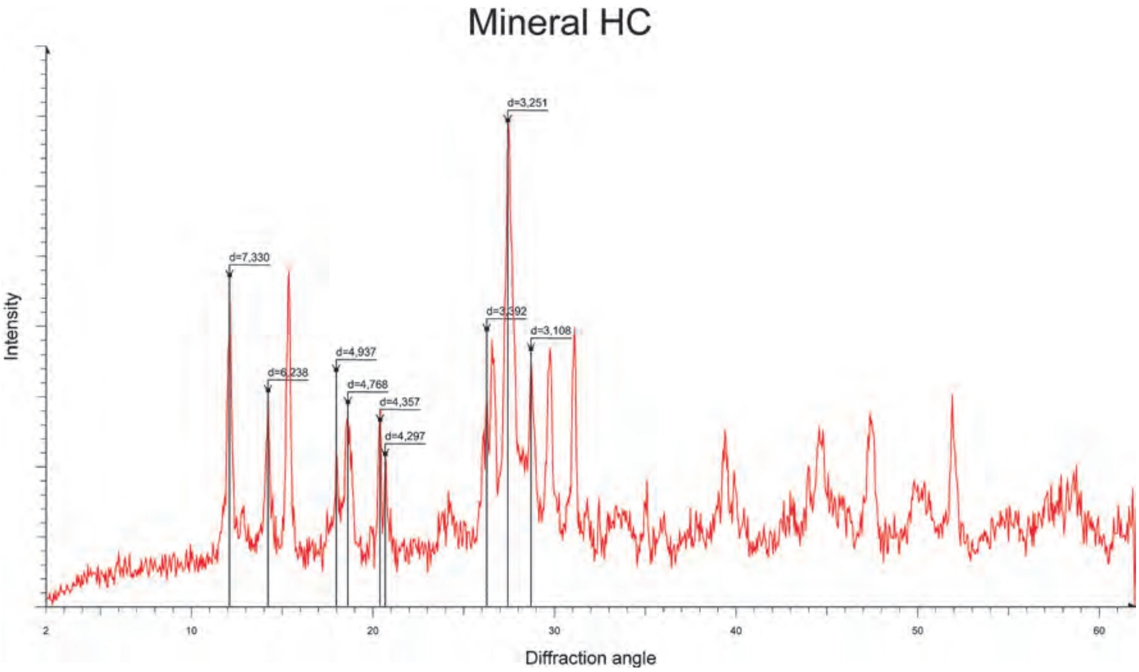

Fig. 40. X-ray powder diffraction diagram of mineral HC, diagram no. LD251906. Accompanying phases are ralstonite and some unidentified mineral(s).

Figure 36. Occurs with HR, HA, HB and EB. Originally run in 1995, the preparate 965 was rerun in 2000, indicating that it is stable at laboratory conditions.

Mineral EI, composition unknown. Gray? Identified lines 3.99 (2), 3.80 (10), 3.69 (8), 2.87 (4) and 2.83 (3). Found in one sample from Eldfell; NI 20625 (XRD LD212150/1020). The X-ray powder diffrac-

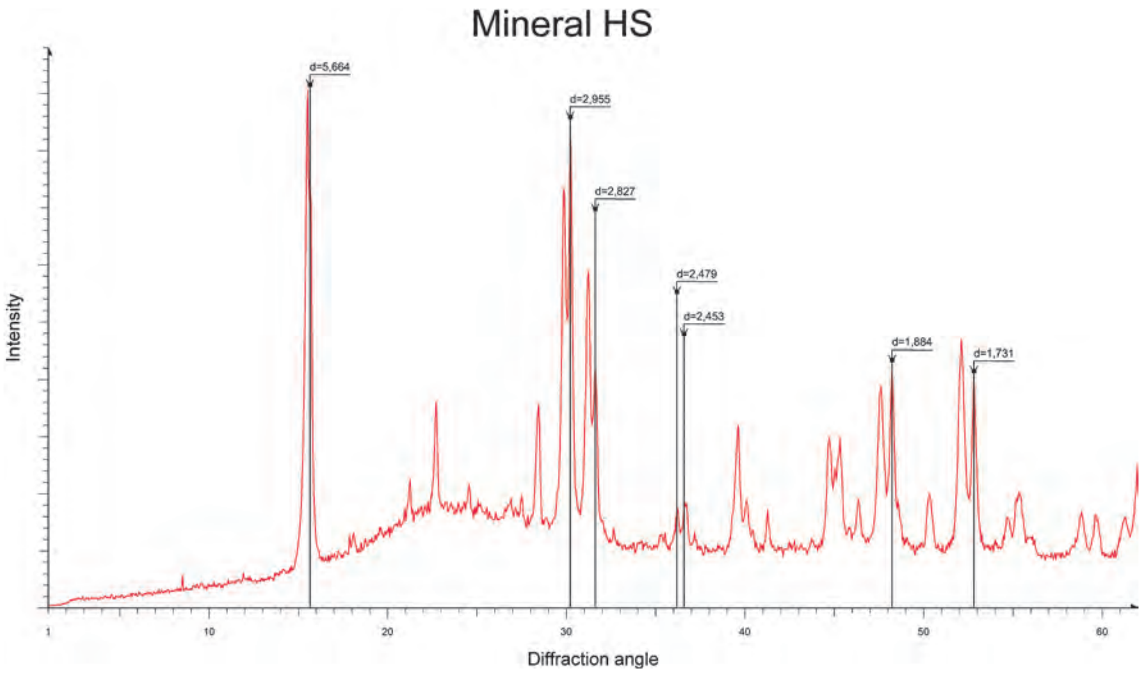

Fig. 41. X-ray powder diffraction diagram of mineral HS, diagram no. JJ031102. Accompanying phases are ralstonite and mineral HA.

tion pattern is shown in Figure 37. Occurs with anhydrite, EB, EA and HA. Originally run in 1996, the preparate 1020 was rerun in 2000, indicating that mineral EI is stable at laboratory conditions.

Mineral HN, composition unknown. White. Identified lines 9.34 (6), 4.65 (7), 3.10 (10), and 1.86 (6). Found in three samples from Hekla and one from Eldfell; main sample NI 17074 (XRD JJ012341/866) where it is almost in pure condition. The X-ray powder diffraction pattern is shown in Figure 38. Occurs with ralstonite, HR and HA.

Mineral HA, composition unknown. White-yellow? Identified lines 4.92 (1), 4.20 (1), 3.93 (6), 3.29 (1), 3.14 (10), 2.23 (2), 2.07 (1), 2.00 (2), 1.96 (4), 1.81 (4), 1.66 (3) and 1.58 (2). Being the most common of the unknown species, it is found in 21 samples from Hekla and six from Eldfell; main sample NI 17072 (XRD JJ301749/865). The X-ray powder diffraction pattern is shown in Figure 39. Is nearly always associated with ralstonite and is possibly intergrown with it. Occurs also often with HB, besides HC and HG, and EA (in Eldfell). Originally run in 1993, the preparate 15505E was rerun in 2000, showing that the mineral HA is stable at laboratory conditions.

Mineral HC, composition unknown. Colorless crystals. Identified lines 7.32 (6), 6.24 (4), 4.94 (3), 4.77 (4), 4.36 (4), 4.30 (3), 3.39 (4), 3.25 (10) and 3.11 (5). Found in five samples from Hekla, most often in trace amounts; main sample NI 15505 (XRD LD251906/1028). The X-ray powder diffraction pattern is shown in Figure 40. Occurs with ralstonite, HA and sometimes HB. Originally run in 1996, the preparate 1028 was rerun in 2000, showing that the mineral HC is stable at laboratory conditions.

Mineral HS, composition unknown. Identified lines 5.66 (9), 2.96 (10), 2.83 (5), 2.48 (2), 2.46 (3), 1.89 (5) and 1.73 (5). Found in one sample from Hekla; NI 17074 (XRD JJ031102/867). The X-ray powder diffraction pattern is shown in Figure 41. Occurs with ralstonite, HA, HN and HR.

Mineral HM, composition unknown. Identified lines 5.45 (10), 3.86 (9), 2.44 (10) and 1.73 (9). Found in trace amounts in two samples from Hekla; main sample NI 15515 (XRD IE111156/15515E). The X-ray powder diffraction pattern is shown in Figure 42. Occurs with malladrite and heklaite. Originally run in 1993, the preparate 15515E was rerun in 2000, showing that the mineral HM is stable at laboratory conditions.

Mineral HH, composition unknown. Only one distinct line is identified (11.05 Å). Found in trace amounts in two samples from Hekla and one from Eldfell; main sample NI 15515 (XRD IE200236/15515G). Occurs with HA and ralstonite, also HB and HR.

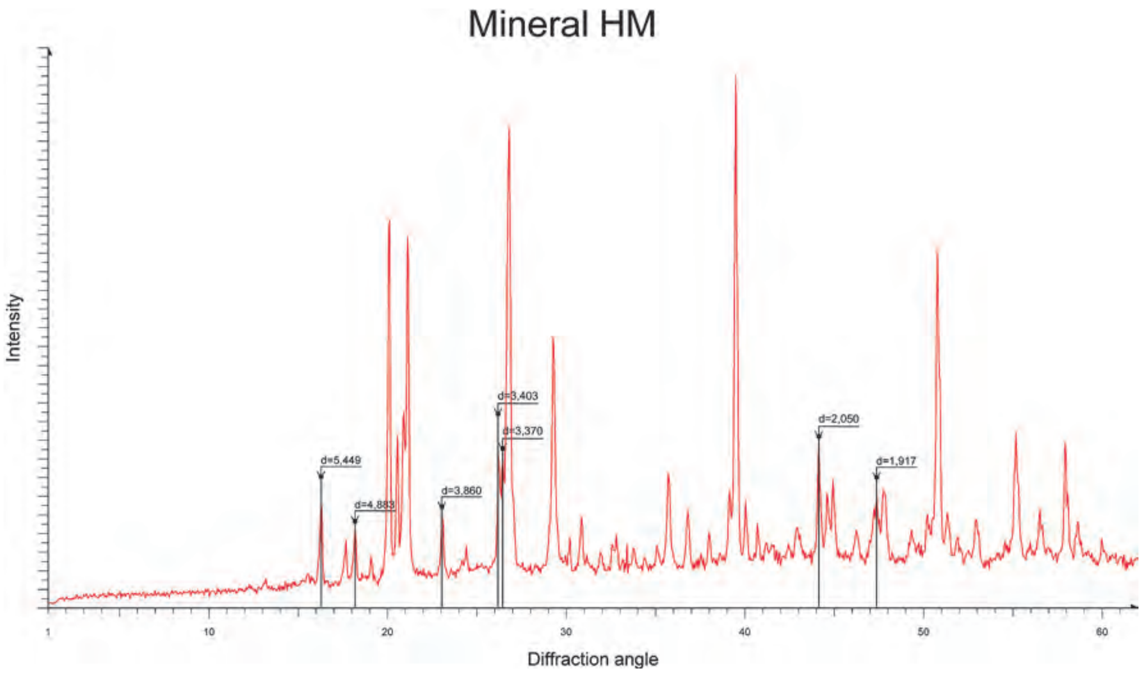

Fig. 42. X-ray powder diffraction diagram of mineral HM, diagram no. IE111156. Accompanying phases are malladrite and heklaite.

Originally run in 1993, the preparate 15515G was rerun in 2000, showing that the mineral HH is stable at laboratory conditions.

Mineral HK, composition unknown. Only one distinct line is identified (7.88 Å). Found in trace amounts in two samples from Hekla; main sample NI 15509 (XRD IE101907/15509F). Occurs with ralstonite, malladrite and HA. Originally run in 1993, the preparate 15509F was rerun in 2000, indicating that the mineral HK is stable at laboratory conditions.

GENERAL MINERALOGY OF THE ENCRUSTATIONS

The minerals which were identified in our survey of volcanogenic encrustations from three recent volcanic eruptions in Iceland, the 1963–1967 Surtsey, the 1973 Eldfell and the 1991 Hekla eruptions, are listed in Table 13. Those minerals which were labeled as “Newly accepted minerals”, “New, partly defined”, and “Probable new minerals”, in the preceding chapter, have been included in the table. In addition to these species, Óskarsson (1981) had reported metathenardite (Na_2SO_4) in Surtsey, Eldfell and Hekla (1970 eruption); and aphthitalite ($(K,Na)_3Na(SO_4)_2$) and galeiite ($Na_{15}(SO_4)_5F_4Cl$) in Surtsey. A considerable diversity in mineralogy of the encrustations is indicated, as has been observed for example at the Kamchatka volcanoes (Naboko 1959) and at Etna (Garavelli et al. 1997b).

Table 13 shows how the encrustation minerals, whose chemistry is known, divide between the main mineral classes. The majority of the minerals are mixed halides and sulfates, followed by oxides and carbonates. Minerals rich in water dominate in all classes except the carbonates. The abundance of ralstonite at all three volcanoes came as a surprise as this mineral has not been reported from Iceland previously. The mineral is a common encrustation mineral at other volcanoes, for example the Central American volcanoes (Stoiber & Rose 1974). It is also noteworthy that only one sample of sulfur was found in Surtsey, two in Eldfell and one in Hekla, see Table 13. This is contrary to what has been written in various geological and popular publications on these volcanic eruptions. The probable explanation is that even geologists frequently mistake ralstonite for sulfur because of their similar color.

It appears that 32 of the minerals are new for Iceland, including those determined by Jakobsson et al. (1992). Prior to our study on the volcanogenic encrustations, the mineral register of the Icelandic Institute of Natural History in Reykjavík contained descriptions of 230 mineral species found in Iceland, excluding varieties. The majority of these minerals are of igneous origin. Our study has therefore added considerably to the mineralogy of Iceland which now holds 262 mineral species.

Table 13. The encrustation minerals of the 1963-1967 Surtsey, 1973 Eldfell and 1991 Hekla eruptions. The number of determinations of each mineral at each volcano is shown in the columns to the right. Those minerals which were labeled as “Newly accepted minerals”, “New, partly defined minerals” and “Probable new minerals” in the preceding chapter, are included. The estimated position of the new mineral species in the main classes in the Strunz system (Strunz & Nickel 2001) is shown. New mineral species for Iceland, including those in Jakobsson et al. (1992), are shown in italics.

Mineral	Composition	Surtsey	Eldfell	Hekla
Elements				
Sulfur	S	1	2	1
Halides				
Halite	NaCl	11	1	1
Sylvite	KCl		2	
Sal ammoniac	NH_4Cl		1	5
Fluorite	CaF_2	14		6
Carnallite	$KMgCl_3 \cdot 6H_2O$	1		
Mineral HD	$NH_4(Fe,Co)_2F_6$ (?)	1	2	6
Pachnolite / thomsenolite	$NaCaAlF_6 \cdot H_2O$			1
Mineral HR	$MgAlF_5 \cdot 2H_2O$		2	4
Mineral HU	$AlF_3 \cdot 3H_2O$ (?)			2
Mineral HG	$Na_2Ca_3Al_2F_{14}$			3
Ralstonite	$Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$	8	8	34
Mineral HI	$\beta\text{-}FeF_3 \cdot 3H_2O$ (?)			1
Chukhrovite?	$Ca_4AlSi(SO_4)F_{13} \cdot 12H_2O$	2		
Malladrite	Na_2SiF_6	1		16
Heklaite	$KNaSiF_6$			7
Hieratite / demartinite	K_2SiF_6			1
Cryptohalite	$(NH_4)_2SiF_6$	1	1	5
Mineral HT	$FeSiF_6 \cdot 6H_2O$			2

Mineral	Composition	Surtsey	Eldfell	Hekla
Oxides				
Hematite	Fe_2O_3		49	9
Ilmenite	$FeTiO_3$			1
Quartz	SiO_2		1	
Opal-A	$SiO_2\cdot nH_2O$	17	6	17
Opal-CT	$SiO_2\cdot nH_2O$		9	1
Akaganeite?	$Fe_8O_{8-x}(OH)_{8+x}Cl_x$	1		
Hydroxides				
Doyleite	$Al(OH)_3$	1		
Carbonates				
Calcite	$CaCO_3$	14		1
Ankerite?	$Ca(Fe,Mg,Mn)(CO_3)_2$		1	
Hydromagnesite	$Mg_5(CO_3)_4(OH)_2\cdot 4H_2O$	1		
Sulfates				
Eldfellite	$NaFe(SO_4)_2$		1	
Mineral EN	$Na_3Fe(SO_4)_3$		1	
Thenardite	Na_2SO_4	8		2
Glauberite	$Na_2Ca(SO_4)_2$	3		1
Anhydrite	$CaSO_4$	6	15	2
Alunite?	$KAl_3(SO_4)_2(OH)_6$		1	
Natroalunite	$NaAl_3(SO_4)_2(OH)_6$	1		
Jarosite	$KFe_3(SO_4)_2(OH)_6$		3	
Kieserite	$MgSO_4\cdot H_2O$	1		
Pentahydrite?	$MgSO_4\cdot 5H_2O$	1		
Löweite	$Na_{12}Mg_7(SO_4)_{13}\cdot 15H_2O$	2		
Tamarugite	NaAl(SO4)2·6H2O			1
Blödite	$Na_2Mg(SO_4)_2\cdot 4H_2O$	2		
Mirabilite	$Na_2SO_4\cdot 10H_2O$	1		
Hydroglauberite	$Na_{10}Ca_3(SO_4)_8\ 6H_2O$			1
Eugsterite	$Na_4Ca(SO_4)_3\cdot 2H_2O$	2		
Gypsum	$CaSO_4\cdot 2H_2O$	28	9	3
Bassanite	$CaSO_4\cdot 0.5H_2O$	1	3	
Mineral SA	$Ca_{0.83}Na_{0.33}(SO_4)\cdot 0.5H_2O$	1		
Kainite	$KMg(SO_4)Cl\cdot 3H_2O$	2		
Mineral SH	$Na_2Mg_3(SO_4)_2(OH)_2\cdot 4H_2O$ (?)	2		
Chessexite	$Na_4Ca_2Mg_3Al_8(SiO_4)_2(SO_4)_{10}(OH)_{10}\cdot 40H_2O$		2	
Total		**139**	**81**	**133**

MINERAL ASSEMBLAGES AND ASSOCIATIONS

As mentioned previously, the encrustation minerals discussed in this report obviously formed and equilibrated at a range of temperatures at each volcano, especially at Surtsey. We are therefore probably dealing with a range of equilibrium mineral assemblages at most localities. Due to the fine-grained nature of the encrustations, frequent intergrowths of mineral phases, and instability of several phases, a detailed survey of equilibrium mineral assemblages requires a special approach and will not be attempted here.

There are, however, some general characteristics of the mineral association in encrustations at each volcano which should be emphasized. Table 13 demonstrates that the minerals are unevenly distributed between the volcanoes. In Surtsey, sulfates are prominent, and calcite, halite and fluorite are also common. In Eldfell, sulfates dominate but carbonates are barely present. As regards Hekla, fluorides are characteristic and sulfates are rare. The encrustations from the 1947–1948 Hekla eruption can not be distinguished from those of the 1991 Hekla eruption.

Table 14 shows that encrustation minerals whose main cation is Ca or Na dominate. As regards Fe-rich species, hematite is common at all three volcanoes, probably more common than the survey indicates due to a possible sampling bias. Minerals whose main cation is Si are also common, however, it should be noted that opal–CT is probably residual. The survey shows that 47% of the mineral identifications from Surtsey are of Ca-rich species and 30% of Na-rich species. In Eldfell, 35% of the identifications are of Ca-rich species and 17% are of Na-rich species. In Hekla, 45% of the identifications indicate Na-rich species and 9% Ca-rich species. An explanation to the effect of this distribution of the cations will not be offered here.

The regional variations of chlorine and fluorine abundances in lavas from Iceland were investigated by Óskarsson (1981) and Sigvaldason & Óskarsson (1976, 1986). They showed that the abundance of the halides increases with alkalinity of the rocks, and suggested that the encrustation assemblages (associations) may reflect the original halide content of the respective magmas. In this regard it is of interest to note that Þórðarson et al. (1996) calculated that approximately half of the original fluorine and chlorine of the 1783–1784 Laki magma was released during the eruption.

Figure 43 shows the content of chlorine and fluorine in the lavas of the 1963–1967 Surtsey, 1973 Eldfell, 1970 Hekla and 1961 Askja eruptions, based on bulk rock chemical analyses on well documented samples (Sigvaldason & Óskarsson 1986). As data from the 1991 Hekla eruption are not available, data from the 1970 Hekla eruption are used instead, the whole-rock chemistry of the transitional mugearite lavas of these two eruptions being very similar.

It appears that the abundance of fluorides in the Hekla encrustations possibly is explained by the high content of fluorine in the rocks, and therefore

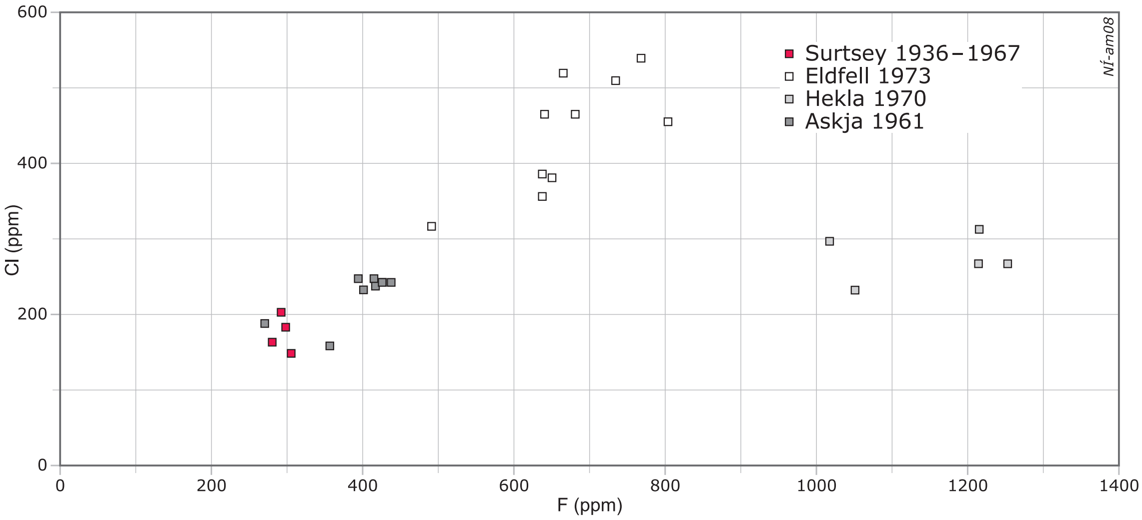

Fig. 43. Plot of F versus Cl to illustrate the differences in content of these halogenides in the lavas of the 1963–1967 Surtsey, 1973 Eldfell, 1970 Hekla and 1961 Askja eruptions. Based on data from Sigvaldason & Óskarsson (1986). Data from the 1991 Hekla eruption are not available, instead data from the 1970 Hekla eruption are used.

in the original magma. It would be tempting to ascribe the abundance of the chlorine- and sulfur-rich minerals in Surtsey and Eldfell to infiltration of sea water, however, this appears unlikely in light of the remarkable similarity of the encrustation mineralogy at Surtsey and the 1961 Askja eruption, as mentioned previously. A deep-rooted magmatic cause seems more likely. As regards sulfur, a comparison between the volcanoes cannot be made as few reliable determinations of the sulfur content of their extrusives are available. However, we are faced with the unexpected result that the encrustations explored in the present survey divide into three groups, a Surtsey-Askja group, an Eldfell group and a Hekla group.

Table 14. The encrustation minerals of the 1963-1967 Surtsey, 1973 Eldfell and 1991 Hekla eruptions, grouped according to the type of cation in the formula (except for hydrogene). The number of determinations of each mineral at each volcano is shown in the columns to the right.

Mineral	Composition	Surtsey	Eldfell	Hekla	Total
Al					
Doyleite	$Al(OH)_3$	1			1
Mineral HU	$AlF_3 \cdot 3H_2O$ (?)			2	2
Chukhrovite ?	$Ca_4AlSi(SO_4)F_{13}$ $12H_2O$	2			2
Alunite	$KAl_3(SO_4)_2(OH)_6$		1		1
Mineral HR	$MgAlF_5 \cdot 2H_2O$		2	4	6
Mineral HG	$Na_2Ca_3Al_2F_{14}$			3	3
Natroalunite	$NaAl_3(SO_4)_2(OH)_6$	1			1
Tamarugite	$NaAl(SO_4)_2 \cdot 6H_2O$		1		1
Pachnolite / thomsenolite	$NaCaAlF_6 \cdot H_2O$			1	1
Ralstonite	$Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$	8	8	34	50
Chessexite	$Na_4Ca_2Mg_3Al_8(SiO_4)_2(SO_4)_{10}(OH)_{10} \cdot 40H_2O$		2		2
C					
Calcite	$CaCO_3$	14		1	15
Ankerite	$Ca(Fe,Mg,Mn)(CO_3)_2$		1		1
Hydromagnesite	$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$	1			1
Ca					
Mineral SA	$Ca_{0.83}Na_{0.33}(SO_4) \cdot 0.5H_2O$	1			1
Chukhrovite ?	$Ca_4AlSi(SO_4)F_{13}$ $12H_2O$	2			2
Calcite	$CaCO_3$	14		1	15
Ankerite	$Ca(Fe,Mg,Mn)(CO_3)_2$		1		1
Fluorite	CaF_2	14		6	20
Anhydrite	$CaSO_4$	6	15	2	23
Bassanite	$CaSO_4 \cdot 0.5H_2O$	1	3		4
Gypsum	$CaSO_4 \cdot 2H_2O$	28	9	3	40
Glauberite	$Na_2Ca(SO_4)_2$	3		1	4
Mineral HG	$Na_2Ca_3Al_2F_{14}$			3	3
Eugsterite	$Na_4Ca(SO_4)_3 \cdot 2H_2O$	2			2
Pachnolite / thomsenolite	$NaCaAlF_6 \cdot H_2O$			1	1
Hydroglauberite	$Na_{10}Ca_3(SO_4)_8$ $6H_2O$			1	1
Chessexite	$Na_4Ca_2Mg_3Al_8(SiO_4)_2(SO_4)_{10}(OH)_{10} \cdot 40H_2O$		2		2
Fe					
Hematite	Fe_2O_3	4	9	9	22
Akaganeite ?	$Fe_8O_{8-x}(OH)_{8+x}Cl_x$	1			1
Ilmenite	$FeTiO_3$			1	1
Mineral HI	$\beta\text{-}FeF_3 \cdot 3H_2O$ (?)			1	1
Mineral HT	$FeSiF_6 \cdot 6H_2O$			2	2
Ankerite	$Ca(Fe,Mg,Mn)(CO_3)_2$		1		1
Jarosite	$KFe_3(SO_4)_2(OH)_6$		3		3
Eldfellite	$NaFe(SO_4)_2$		1		1
Mineral EN	$Na_3Fe(SO_4)_3$		1		1
Mineral HD	$NH_4(Fe,Co)_2F_6$ (?)	1	2	6	9

Mineral	Composition	Surtsey	Eldfell	Hekla	Total
K					
Sylvite	KCl		2		2
Jarosite	$KFe_3(SO_4)_2(OH)_6$		3		3
Alunite	$KAl_3(SO_4)_2(OH)_6$		1		1
Kainite	$KMg(SO_4)Cl\cdot3H_2O$	2			2
Carnallite	$KMgCl_3\cdot6H_2O$	1			1
Heklaite	$KNaSiF_6$			7	7
Hieratite / demartinite	K_2SiF_6			1	1
Mg					
Hydromagnesite	$Mg_5(CO_3)_4(OH)_2\cdot4H_2O$	1			1
Mineral HR	$MgAlF_5\cdot2H_2O$		2	4	6
Pentahydrite ?	$MgSO_4\cdot5H_2O$	1			1
Kieserite	$MgSO_4\cdot H_2O$	1			1
Kainite	$KMg(SO_4)Cl\cdot3H_2O$	2			2
Carnallite	$KMgCl_3\cdot6H_2O$	1			1
Ralstonite	$Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$	8	8	34	50
Chessexite	$Na_4Ca_2Mg_3Al_8(SiO_4)_2(SO_4)_{10}(OH)_{10}\cdot40H_2O$		2		2
Löweite	$Na_{12}Mg_7(SO_4)_{13}\cdot15H_2O$	2			2
Blödite	$Na_2Mg(SO_4)_2\cdot4H_2O$	2			2
Mineral SH	$Na_2Mg_3(SO_4)_2(OH)_2\cdot4H_2O$ (?)	2			2
Na					
Hydroglauberite	$Na_{10}Ca_3(SO_4)_8\ 6H_2O$			1	1
Löweite	$Na_{12}Mg_7(SO_4)_{13}\cdot15H_2O$	2			2
Glauberite	$Na_2Ca(SO_4)_2$	3		1	4
Mineral HG	$Na_2Ca_3Al_2F_{14}$			3	3
Blödite	$Na_2Mg(SO_4)_2\cdot4H_2O$	2			2
Mineral SH	$Na_2Mg_3(SO_4)_2(OH)_2\cdot4H_2O$ (?)	2			2
Mineral SA	$Ca_{0.83}Na_{0.33}(SO_4)\cdot0.5H_2O$	1			1
Malladrite	Na_2SiF_6	1		16	17
Heklaite	$KNaSiF_6$			7	7
Thenardite	Na_2SO_4	8		2	10
Mirabilite	$Na_2SO_4\cdot10H_2O$	1			1
Eugsterite	$Na_4Ca(SO_4)_3\cdot2H_2O$	2			2
Chessexite	$Na_4Ca_2Mg_3Al_8(SiO_4)_2(SO_4)_{10}(OH)_{10}\cdot40H_2O$		2		2
Natroalunite	$NaAl_3(SO_4)_2(OH)_6$	1			1
Tamarugite	$NaAl(SO_4)_2\cdot6H_2O$		1		1
Pachnolite / thomsenolite	$NaCaAlF_6\cdot H_2O$			1	1
Halite	$NaCl$	11	1	1	13
Eldfellite	$NaFe(SO_4)_2$		1		1
Mineral EN	$Na_3Fe(SO_4)_3$		1		1
Ralstonite	$Na_xMg_xAl_{2-x}(F,OH)_6\cdot H_2O$	8	8	34	50
NH_4					
Cryptohalite	$(NH_4)_2SiF_6$	1	1	5	7
Sal ammoniac	NH_4Cl		1	5	6
Mineral HD	$NH_4(Fe,Co)_2F_6$ (?)	1	2	6	9
S					
Sulfur	S	1	2	1	4
Anhydrite	$CaSO_4$	6	15	2	23
Thenardite	Na_2SO_4	8		2	10
Bassanite	$CaSO_4\cdot0.5H_2O$	1	3		4
Gypsum	$CaSO_4\cdot2H_2O$	28	9	3	40
Mirabilite	$Na_2SO_4\cdot10H_2O$	1			1
Jarosite	$KFe_3(SO_4)_2(OH)_6$		3		3
Alunite	$KAl_3(SO_4)_2(OH)_6$		1		1
Natroalunite	$NaAl_3(SO_4)_2(OH)_6$	1			1

Mineral	Composition	Surtsey	Eldfell	Hekla	Total
Tamarugite	$NaAl(SO_4)_2 \cdot 6H_2O$		1		1
Eugsterite	$Na_4Ca(SO_4)_3 \cdot 2H_2O$	2			2
Blödite	$Na_2Mg(SO_4)_2 \cdot 4H_2O$	2			2
Kainite	$KMg(SO_4)Cl \cdot 3H_2O$	2			2
Pentahydrite ?	$MgSO_4 \cdot 5H_2O$	1			1
Kieserite	$MgSO_4 \cdot H_2O$	1			1
Eldfellite	$NaFe(SO_4)_2$		1		1
Mineral EN	$Na_3Fe(SO_4)_3$		1		1
Mineral SA	$Ca_{0.83}Na_{0.33}(SO_4) \cdot 0.5H_2O$	1			1
Chukhrovite ?	$Ca_4AlSi(SO_4)F_{13} \cdot 12H_2O$	2			2
Hydroglauberite	$Na_{10}Ca_3(SO_4)_8\ 6H_2O$			1	1
Löweite	$Na_{12}Mg_7(SO_4)_{13} \cdot 15H_2O$	2			2
Mineral SH	$Na_2Mg_3(SO_4)_2(OH)_2 \cdot 4H_2O$ (?)	2			2
Chessexite	$Na_4Ca_2Mg_3Al_8(SiO_4)_2(SO_4)_{10}(OH)_{10} \cdot 40H_2O$		2		2
Glauberite	$Na_2Ca(SO_4)_2$	3		1	4
Si					
Quartz	SiO_2		1		1
Opal-A	$SiO_2 \cdot nH_2O$	17	6	17	40
Opal-CT	$SiO_2 \cdot nH_2O$		9	1	10
Mineral HT	$FeSiF_6 \cdot 6H_2O$			2	2
Malladrite	Na_2SiF_6	1		16	17
Heklaite	$KNaSiF_6$			7	7
Hieratite / demartinite	K_2SiF_6			1	1
Cryptohalite	$(NH_4)_2SiF_6$	1	1	5	7
Chukhrovite ?	$Ca_4AlSi(SO_4)F_{13} \cdot 12H_2O$	2			2
Chessexite	$Na_4Ca_2Mg_3Al_8(SiO_4)_2(SO_4)_{10}(OH)_{10} \cdot 40H_2O$		2		2
Ti					
Ilmenite	$FeTiO_3$			1	1

VOLCANOGENIC VERSUS SOLFATARIC ENCRUSTATIONS

It appears reasonable to divide fumarolic mineral associations in Iceland into two types, volcanogenic and solfataric, and Óskarsson (1981) has commented on this distinction. As mentioned previously the volcanogenic encrustations described in this report are formed by short-lived, probably shallow-rooted, thermal (fumarolic) systems, which usually only are active at the surface for a few years, or a few decades. These systems are characterized by no discharge of water at the surface, and steam discharge is generally limited. The volcanogenic systems are directly connected with recent volcanic activity at the surface, and the encrustations are primarily the products of magmatic degassing. General mineralogical characteristics appear to be a great diversity of mineral species, no clay minerals and little free sulfur. It may provisionally be suggested that the type minerals are ralstonite, anhydrite-gypsum, thenardite and halite.

The solfataric hydrothermal systems, as for example at Krísuvík, Torfajökull and Krafla, are long-lived, probably often active for thousands of years or more. This suggests a deep-rooted source. Recent surface, or subsurface, volcanic activity may, or may not, be connected to the solfataric activity. The solfataric systems are the surface exposures of high-temperature hydrothermal activity, with extensive water-rock interaction (Arnórsson et al. 2008). The solfataric activity is usually stable at the surface, but may shift from one place to another due to earthquakes or volcanic activity, as for example was seen in Askja in 1961 (Sigvaldason 1964). These systems are characterized by vigorous discharge of steam and/or water. Boiling mud pits and mud suspension are characteristic. Elements are possibly mainly transported to the surface by steam and boiling water. General mineralogical characteristics are relatively few mineral species, abundant deposits of clay minerals, subsurface deposits of hematite and gypsum, and usually free sulfur at surface. It may provisionally be suggested that type minerals are clay minerals, mainly montmorillonite and kaolinite (Sigvaldason 1959; Kristmannsdóttir 1979; Arnórsson 1997); gypsum, hematite, sulfur, and pickeringite, halotrichite and alunogen (Jakobsson 1988).

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ÚTDRÁTTUR Á ÍSLENSKU

Að jafnaði myndast ýmiss konar útfellingar í eldgosum, eða í kjölfar þeirra. Þessar eldfjallaútfellingar mynda skánir á yfirborði hrauna, í hraunhellum eða við gígop. Flestar útfellinganna myndast beint úr hraunkvikugasi sem streymir út um op í kólnandi berginu, aðrar myndast úr vatnsgufu og þá einkum í hraunhellum og gígum. Útfellingarnar eru margar viðkvæmar fyrir veðrun og endast því yfirleitt ekki lengi nema í hellum.

Við höfum rannsakað með röntgenbrotgreiningu samsetningu 131 eldfjallaútfellingar sem myndaðist í Surtseyjargosinu 1963–1967, Eldfellsgosinu 1973 og Heklugosinu 1991. Einnig höfum við athugað útfellingar sem til voru í steinasafni Náttúrufræðistofnunar Íslands úr Heklugosinu 1947–1948 og Öskjugosinu 1961. Þessar greiningar voru gerðar á steindafræðideild Háskólans í Kaupmannahöfn og hjá Íslenskum Orkurannsóknum.

Í greininni er sagt frá hverju eldgosi í stuttu máli og aðstæðum er lýst. Fylgst hefur verið með kólnun gosmyndana í Surtsey og Eldfelli. Þar hafa útfellingarnar myndast í aðgreindum, grunnum, jarðhitakerfum í hraunum og gígum. Þessi hitakerfi eru skammlíf, oftast kólna þau niður á nokkrum árum eða áratugum. Langlífasta hitakerfið er í Eldfelli á Heimaey, en það hefur nú verið virkt í ríflega 35 ár en fer hægt kólnandi. Þess ber að geta að hraunið við Eldfell er óvenju þykkt, allt að 110 metrar. Hitakerfin virðast hafa verið mun skammlífari í Surtsey, og líklega einnig í Heklu.

Hiti var yfirleitt mældur um leið og útfellingu var safnað. Hæstur hiti mældist í Eldfelli 1995, 420 °C, þá höfðu myndast þar anhydrít, gifs og hematít. Í helli í Surtsey sem kallaður hefur verið “Grillið”, mynduðust dropasteinar úr vatnsgufu við 65–100 °C, þeir voru úr halíti, kainíti, löweíti, gifsi og thenardíti og urðu allt að 45 cm langir.

Í Eldfelli má sjá hvernig eldfjallagasið hefur valdið ætingu á berginu og fjarlægt úr því flestar katjónir nema Si og hluta af Ti. Bergið verður þá hvítt eða hvítgult. Flestar þær katjónir sem þvegist hafa út úr berginu eru að finna í útfellingunum. Talið er líklegt að þetta ferli skýri að verulegu leyti tilurð útfellinganna í eldfjöllunum þremur. Aðrar útfellingar, t. d. í grunnum hellum í Surtsey og Öskju, hafa fallið út úr vatnsgufu sem líklega á rætur sínar að rekja til grunnvatns eða sjávar.

Í Surtsey greindust 34 tegundir útfellingasteinda, algengastar voru gifs, ópal-A, kalsít, halít, flúorít, ralstonít, thenardít, anhydrít og hematít. Í Eldfelli og Eldfellshrauni greindist 31 tegund, algengastar voru anhydrít, ópal-CT, ralstonít, gifs, hematít, ópal-A og tvær óþekktar steindategundir. Í útfellingum úr Heklugosinu 1991 greindust 36 tegundir, algengastar voru ralstonít, ópal-A, malladrít, hematít og tvær óþekktar steindategundir. Hinn mikli tegundafjöldi steinda í öllum þremur eldfjöllunum kom mjög á óvart. Þá reyndist tegund eins og ralstonít, sem ekki hafði áður fundist á landinu, óvænt algeng meðal útfellinganna, en aftur á móti var brennisteinn sjaldgæfur.

Í Heklugosinu 1947–1948 myndaðist mikið af útfellingum. Þær tegundir sem við greindum þaðan voru þær sömu og fundust í Heklugosinu 1991. Í Öskjugosinu 1961 myndaðist lítið af útfellingum og þar er um að ræða sömu eða sambærilegar steindir og var að finna í grunnum hellum í Surtsey.

Í eldfjöllunum þremur greindust 27 tegundir steinda sem ekki voru áður þekktar í náttúrunni. Nokkrar þeirra hafa áður verið búnar til í tilraunastofum. Við höfum skipt þessum steindum í fjóra hópa: nýjar, samþykktar heimssteindir (2 tegundir); nýjar, að hluta greindar sem nýjar steindir (4 tegundir); líklegar nýjar steindir (5 tegundir); og hugsanlegar nýjar steindir (16 tegundir).

Þær tvær tegundir sem þegar hafa verið samþykktar (2007 og 2008) sem nýjar heimssteindir af Alþjóða Steindafræðisambandinu (IMA), eru *eldfellít* $NaFe(SO_4)_2$ og *heklaít* $KNaSiF_6$. Eldfellít fannst í norðausturrima Eldfells, í 240 m hæð, og heklaít í austurgossprungunni sem var virk í Heklugosinu 1991, í 1105 m hæð. Eldfellít kristallast mónóklínt, kristallarnir eru plötulaga og gulgrænir, og meðalstærð þeirra er aðeins 15x3 míkrómetrar. Heklaít kristallast rombískt, kristallarnir eru litlausir og meðalstærð þeirra er 40x20 míkrómetrar.

Meirihluti útfellingasteindanna tilheyra þeim flokkum steinda er nefnast halíð og súlföt, en einnig er nokkuð um oxíð og karbónöt. Vatnsríkar steindir eru ríkjandi og allnokkrar steindanna leysast upp í vatni. Í ljós kom að 32 steindanna höfðu ekki áður fundist hér á landi. Í gagnagrunni Náttúrufræðistofnunar Íslands voru áður skráðar 230 íslenskar steindategundir, og þá eru afbrigði ekki talin með. Hér er því um verulega aukningu í fjölda íslenskra steindategunda að ræða.

Súlföt voru algeng í Surtsey, einnig nokkrar tegundir karbónata og halíða. Í Eldfelli voru súlföt sömuleiðis algeng en karbónöt voru aftur á móti mjög sjaldgæf. Ætla mætti að myndun súlfata og halíða í þessum eldfjöllum hafi verið tengd sjónum, en með vísun til þess að þessar tegundir útfellinga var einnig að finna í Öskju 1961, er líklegra að skýringa sé að leita í efnasamsetningu bergkvikunnar. Í Heklu voru flúoríð (undirflokkur halíða) yfirgnæfandi og súlföt voru sjaldgæf. Í gosbergi frá Heklu hefur ætíð mælst mikið af flúor og má ætla að bergkvikan undir Heklu sé óvenju rík af þessu reikula efni. Það er því talið að samsetning bergkvikunnar ráði samsetningu útfellinganna, a. m. k. að verulegu leyti.

Eldfjallaútfellingar myndast á hitasvæðum sem eru skammlíf og grunnstæð. Lítil gufuvirkni einkennir hitasvæði af þessu tagi og rennandi vatn sést ekki á yfirborði. Tegundaauðgi er mikil en þó hafa þar ekki fundist leirsteindir og brennisteinn er sjaldgæfur. Þessi hitasvæði eru tengd gosvirkni á yfirborði jarðar.

Útfellingar á yfirborði svokallaðra háhitasvæða, eins og t. d. í Krísuvík, Torfajökulssvæðinu og Kröflu, eru af öðrum toga. Hér er um að ræða langvarandi jarðhitavirkni sem á sér djúpar rætur. Vatns- eða gufumyndun er mikil, leirsteindir myndast í miklu magni og brennisteinn er yfirleitt algengur. Mun færri tegundir steinda myndast en þegar um eldfjallaútfellingar er að ræða.

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