Encrustations from Lava Caves in Surtsey, Iceland. A Preliminary Report

By

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INTRODUCTION

During the Surtsey eruption off the south coast of Iceland (Thorarinsson 1967), abundant volcanogenic encrustations formed at the lava craters of Surtsey, especially at the large western lava crater (Fig.1). Nine samples of high-temperature encrustations, which were collected from the surface of lava in Surtsey during the eruptions in 1963-1967, were analysed in detail by Óskarsson (1981). He recognized four minerals in these encrustations, sulfur, galeite, thenardite and aphthitalite, the two last-named being most abundant. Torssander (1988) determined the sulfur isotope ratios in some of these samples. Jakobsson & Moore (1986) further identified gypsum and halite as common low-temperature encrustations.

Since the cessation of the eruptions in 1967, samples of encrustations have been collected during the many trips to the island, mainly from lava caves, since surface encrustations quickly started to decompose. The present report is a preliminary account of the encrustation samples from Surtsey which are kept in the mineral collection of the Icelandic Museum of Natural History in Reykjavík. The samples were collected during the years 1967-1990.

LAVA CAVES IN SURTSEY

The Surtsey lavas are of alkali basaltic composition and because of their low viscosity they tended to flow in tubes and closed trenches, especially from the western lava crater (Fig. 1), where the lavas formed a 100 m thick shield. Although lava caves were discovered by visitors at least as early as 1966, the speleology of Surtsey did not really attract the attention of scientists until recently, when two members of the Icelandic Speleological Society visited Surtsey to investigate the lava caves (Jónsson & Hróarsson 1990 & 1991). In addition to two lava caves recorded by Ólafsson (1982), eight new lava caves were investigated. Most of the caves are emptied sub-horizontal lava tubes, others are emptied near vertical lava feeder-channels in the eastern lava craters. The location of the largest lava caves in Surtsey along with a few profiles is shown in Jónsson & Hróarsson (1990) and some of the caves are described by Hróarsson (1990). Encrustations presumably formed in most of these caves, at least during the initial cooling period of the la-

TABLE I

Encrustations from lava caves and caverns in Surtsey, collected 1967-1990. Minerals are listed in estimated order of abundance for each sample. Localities are shown on Fig. 1.

IMNH 1092. Stalactite, length 9,5 cm, from a lava cave somewhere on the south shore. Collected on January 3, 1967; no temperature data.
HALITE, yellow, stalactitic.
CARNALLITE, brownish, powdery coating.
Unidentified species.

IMNH 1027. Powdery crust, up to 1 cm thick, from a lava cave at the western lava crater. Locality 1 in Fig. 1. Collected in Sept. 1969; no temperature data.
THENARDITE, white, powdery.
GYPSUM (trace), white.

IMNH 1962. Solid crust, up to 3,5 cm thick, from the floor of „Grillid", the entrance to the lava cave S-4, 80 m SE of the western lava crater. Locality 1 in Fig. 1. Collected on July 9, 1971; temperature ≥70°C.
HALITE, colorless, massive.
ANHYDRITE, white.
KAINITE, colorless.
GLAUBERITE, white.
$Na_2Ca_3(S0_4)_6 \cdot 3H_20$ (JCPDS no. 35-137).
Unidentified species.

IMNH 7484. Stalacites, length up to 45 cm, from „Grillid", the entrance to the lava cave S-4, 80 m SE of the western lava crater, cf. IMNH 1962. Locality 1 in Fig. 1. Collected on July 9, 1971; temperature ≥70°C.
HALITE, colorless, stalactitic
LOEWEITE, colorless.
Unidentified species.

IMNH 1963. Stalactites, length up to 25 cm, from „Grillid", the entrance to the lava cave S-4, 80 m SE of the western lava crater. Locality 1 in Fig. 1. Collected on June 13, 1972; temperature 65°C.
HALITE, colorless, stalactitic.
BLOEDITE, colorless.
THENARDITE, white.
GLAUBERITE, white.
Unidentified species.

IMNH 1964. Stalactites, length up to 10 cm, from „Grillid", the entrance to the lava cave S-4, 80 m SE of the western lava crater, cf. IMNH 1963. Locality 1 in Fig. 1. Collected on June 13, 1972; temperature 65°C.
HALITE, colorless, stalactitic.
KAINITE, colorless.
KIESERITE, white, botryoidal.
LOEWEITE, white, massive.
Unidentified species.

IMNH 1965. Powdery crust, up to 1,5 cm thick, from a cavern in the southwestern wall of the western lava crater. Locality 2 in Fig. 1. Collected on June 13, 1972; ambient temperatures.
THENARDITE, white, powdery.
GYPSUM, white.

IMNH 6382. Crust, up to 3 mm thick, on lava from a lava cave at the western lava crater. Locality 1 in Fig. 1. Collected on Sept. 7, 1973; no temperature data.
GYPSUM, white, prismatic.
ANHYDRITE, white.
HALITE, white.
Unidentified species.

IMNH 7459. Grayish crust (impregnated with basalt tephra), botryoidal on surface, 1-3 mm thick, from a vertical feeder-channel to the easternmost Ágústgígar. Locality 3 in Fig. 1. Collected on August 17, 1979; ambient temperatures.
GYPSUM, colorless, massive.

IMNH 12382. Powdery crust, up to 2 mm thick, from the roof of lava cave S-1 on the east shore. Locality 4 in Fig. 1. Collected on August 10, 1988; ambient temperatures.
HALITE, white, powdery.
CALCITE, white, powdery.
GYPSUM (trace), white.

IMNH 12383. Massive crust, up to 2 mm thick, on the under side of a lava slab, at the entrance to lava cave S-1 on the east shore, cf. IMNH 12382. Locality 4 in Fig. 1. Collected on August 10, 1988; ambient temperatures.
SULPHUR, light yellow, massive.

IMNH 12387. Crust, up to 1-2 mm thick, on the under side of a lava slab, at lava craters from Dec. 1966. Locality 5 in Fig. 1. Collected on August 10, 1988; temperatures 63°-67°C.
CALCITE, white, crusty.
OPAL-A, white, massive.

IMNH 15100. Crust, up to 2-3 mm thick, of minute crystals from the floor of cave S-3 on the western side. Locality 6 in Fig. 1. Collected on July 12, 1990; ambient temperatures.
GYPSUM, grayish-white, diamond-shaped.

IMNH 15101. Powdery crust, up to 3 cm thick, from the floor of cave S-3 on the western side, cf. IMNH 15100. Locality 6 on Fig. 1. Collected on July 12, 1990; ambient temperatures.
THENARDITE, white, powdery or platy
GYPSUM (trace), white.

IMNH 15102. Crust of crystals, up to 3 mm thick, from a shelf in cave S-4 on the western side. Locality 7 in Fig. 1. Collected on July 12, 1990; temperatures 35°-40°C.
GYPSUM, colorless-white, prismatic crystals
FLUORITE, white.
Unidentified species.

IMNH 15103. Layered crust, up to 2 cm thick, from a shelf in cave S-4 on the western side, cf. IMNH 15102. Locality 7 in Fig. 1. Collected on July 12, 1990; temperatures 35°-40°C
GYPSUM, white, prismatic crystals.
FLUORITE, white, powdery.
OPAL-A, white.

IMNH 15104. Efflorescence, up to 2 mm thick, from the wall in cave S-4 on the western side, cf. above. Locality 7 in Fig. 1. Collected on July 12, 1990; temperatures 35°-40°C.
FLUORITE, white, fibrous or platy.
OPAL-A, white.

IMNH 15105. Layered crust, up to 5 mm thick, from a shelf in cave S-4 on the western side, cf. above Locality 7 in Fig. 1. Collected on July 12, 1990; temperatures 35°-40°C.
GYPSUM, white, prismatic to tabular crystals.

IMNH 15106. Layered crust, up to 1 cm thick, from the floor in cave S-4 on the western side, cf. above. Locality 7 in Fig. 1. Collected on July 12, 1990; temperatures 35°-40°C.
GYPSUM, white, prismatic to tabular crystals.

IMNH 15107. Crust, about 1-2 mm thick, from a shelf in cave S-4 on the western side, cf. above. Locality 7 in Fig. 1. Collected on July 12, 1990; temperatures 35°-40°C.
OPAL-A, white.
FLUORITE, white.
RALSTONITE, yellow-brown.

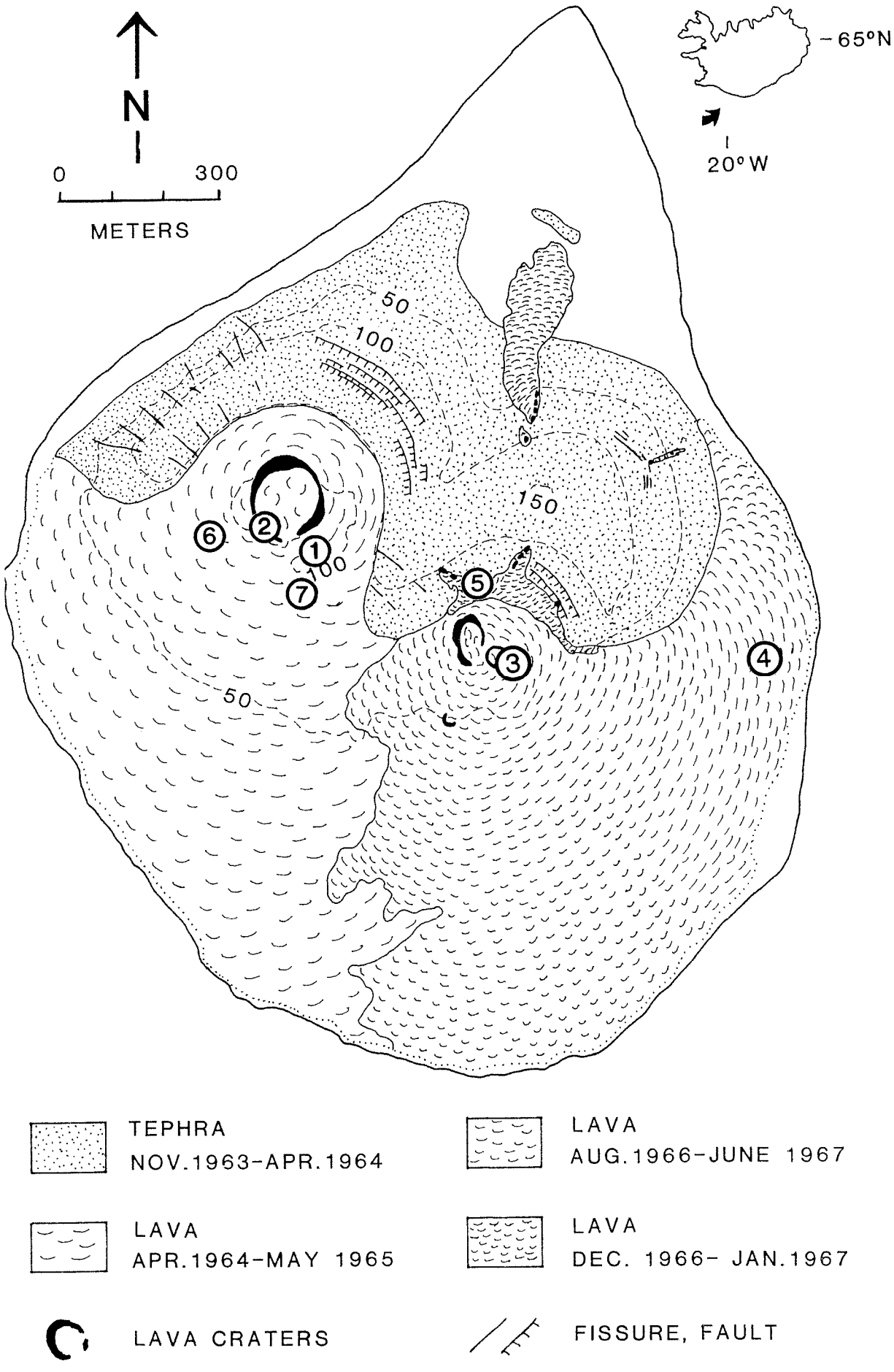

Fig. 1. Geologic map of Surtsey. Elevation contours are in meters. After Jakobsson & Moore (1986). Sample localities mentioned in TABLE I are marked with numbers.

vas. In 1990 abundant encrustations were still to be found in three of the caves, designated S-2, S-3 and S-4, while traces were found in one, S-1. Emptied lava tubes appear to be exceptionally common on Surtsey and in addition there are numerous caverns and voids in the Surtsey lavas where volcanogenic encrustations were deposited during cooling of the lavas.

MINERALOGY OF THE ENCRUSTATIONS

Twenty samples of encrustations from the caves were examined, the samples being described in TABLE I and the localities given in Fig. 1. Each sample was examined under the binocular microscope and all discernible phases separated by hand-picking. The determination of the mineral phases was performed at the Department of Mineralogy, University of Copenhagen, with a Philips vertical powder diffractometer, using CuKα radiation. A few small samples were identified with the Gandolfi camera. The identifications were performed with aid of the JCPDS standard diffraction file, sets 1-39, CD-ROM edition.

Altogether 16 minerals could be determined leaving several species undetermined. The minerals are listed under each sample in Table I in estimated order of abundance. Halite, thenardite and gypsum proved to be abundant in the samples, although unevenly distributed. Opal-A (cf. Jones & Segnit 1971), fluorite, calcite and anhydrite are rarer and are found in much smaller amounts. Glauberite, kainite and loeweite are only found in small amounts and kieserite and bloedite in trace amounts in stalactites which mainly consist of halite. Carnallite, ralstonite and a mineral, corresponding to the synthetic compound $Na_2Ca_5(SO_4)_6 \cdot 3H_2O$ (JCPDS No. 35-137) are very rare, and sulfur was found at one locality. There appear to be at least five unidentified species. Seven of the above-mentioned minerals, glauberite, kainite, loeweite, kieserite, bloedite, carnallite and ralstonite, apparently have not been described from Iceland previously.

ENVIRONMENTAL FACTORS

Several of the encrustations appear to have been sampled at the time of deposition. Of special interest is „Grillid" the entrance to the lava cave S-4, which was visited in July 1971 (cf. TABLE I, samples IMNH 1962 and 7484) and again in June 1972 (samples IMNH 1963 and 1964). In 1971, stalactites of halite with anhydrite, kainite, glauberite and loeweite were sampled at $\geq$70°C and in 1972 halite, bloedite, thenardite, glauberite, kainite, kieserite and loeweite were sampled at 65°C. In these samples only thenardite and possibly halite appear to be decomposing. Since kainite, glauberite and loeweite could be sampled again in 1972 without signs of dissolution, it appears probable that these minerals were in equilibrium with the surroundings in „Grillid" in 1971 and 1972. The temperatures in 1971 may have been somewhat higher than 70°C (the thermometer was still rising when the geologists had to retreat to the surface because of the heat), and in places possibly as high as 90°-100°C. During the following years temperatures declined in „Grillid". In August 1979 temperatures of approx. 25°-35°C were prevalent and no traces of encrustations could be found. In August 1988 only ambient temperatures (10°-12°C) could be measured. It is tentatively suggested that kainite, glauberite, loeweite, bloedite, kieserite and probably halite were being deposited in the stalactites mainly at 65°-100°C. The lower limit of deposition of these minerals cannot be determined, it is, however, well above 35°C. It appears possible that thenardite, anhydrite, carnallite and $Na_2Ca_5(SO_4)_6 \cdot 3H_2O$ also were formed in the above-mentioned temperature range.

Most of the minerals identified in the stalactites are common in oceanic salt deposits. Deuterium measurements of steam condensates collected in 1971 in fissures in the Surtsey lavas (Jakobsson 1978) indicated a sea water origin where the steam emanation was vigorous, the steam being vaporized sea water. Presumably the sea water has been boiling at sea level where it comes into contact with hot intrusions inside Surtsey. Another possibility is that the stalactites originated in downseeping precipitation containing a high amount of ocean spray. Either way the stalactitic minerals probably are evaporitic.

In sample IMNH 12387 (TABLE I), collected in 1988, calcite and opal-A were identified. The encrustation appears fresh and temperatures at the time of sampling were measured at 63°-67°C. However, during 1979-1982 temperatures at this locality were measured at 80°-100°C. It appears certain that calcite and opal-A formed somewhere in the temperature range of 60°-100°C at this locality.

When samples were collected in the lava cave S-4 in July 1990 (IMNH 15102-15107), temperatures were measured at approximately 35°-40°C. Gypsum is abundant in this cave and appears to be very fresh. Aeolian sand which has fallen through a crack to the floor of the cave, forms a linear ridge and is covered with an extensive crust of fresh gypsum. This indicates that this mineral formed at a late stage. The fact that gypsum has not been identified in samples collected at temperatures above 63°C, see TABLE I, may indicate that it forms mainly in the temperature interval 35°-60°C in these lava caves. According to Posnjak (1938) the temperature of transition of gypsum to anhydrite is 42°C in pure water. Fluorite, ralstonite and sulfur, which were only found in small amounts, most probably formed at high temperatures, cf. Stoiber & Rose (1974).

It appears that the encrustations collected in the lava caves and caverns of Surtsey during 1967-1990 are mostly low-temperature encrustations, crystallizing from fumarolic gases. The encrustations are volcanogenic and evaporitic in origin (cf. Shopov 1989). The present survey does not permit any speculation on the paragenesis of the encrustation minerals. Table II gives a summary of secondary minerals identified in Surtsey, including alteration products of tephra at low temperatures.

TABLE II
Secondary minerals identified in Surtsey. Ideal mineral compositions after Fleischer & Mandarino (1991).

I. Formed as encrustations on lava and scoria, both on the surface and at depth, during cooling and degassing of magma.

A. At high temperatures (Óskarsson 1981 and this study).

sulfur S
aphthitalite $(K,Na)_3Na(SO_3)_2$
thenardite Na_2SO_4
galeite $Na_{15}(SO_4)_5F_4Cl$
fluorite CaF_2
ralstonite $Na_xMg_xAl_{2-x}(F,OH)_6 \cdot H_2O$

B. At temperatures between approx. 35°-100°C (this study).

halite NaCl
thenardite Na_2SO_4
gypsum $CaSO_4 \cdot 2H_2O$
opal-A $SiO_2 \cdot nH_2O$
calcite $CaCO_3$
anhydrite $CaSO_4$
glauberite $Na_2Ca(SO_4)_2$
kainite $MgSO_4 \cdot KCl \cdot 3H_2O$
loeweite $Na_{12}Mg_7(SO_4)_{13} \cdot 15H_2O$
kieserite $MgSO_4 \cdot H_2O$
bloedite $Na_2Mg(SO_4)_2 \cdot 4H_2O$
carnallite $KMgCl_3 \cdot 6H_2O$
$Na_2Ca_5(SO_4)_6 \cdot 3H_2O$ (JCPDS no. 35-137)

II. Formed as alteration products of basalt tephra within a hydrothermal system, both above and below sea level; at temperatures between 25°-150°C (Jakobsson & Moore 1986). Minerals listed in estimated order of abundance.

smectite (nontronite) Ca,Na,K; Al,Mg,Fe-silicate
analcime $NaAlSi_2O_6 \cdot H_2O$
phillipsite $(K,Na,Ca)_{1-2}(Si,Al)_8O_{16} \cdot 6H_2O$
tobermorite $Ca_9Si_{12}O_{30}(OH)_6 \cdot 4H_2O$
calcite $CaCO_3$
anhydrite $CaSO_4$
chabazite $CaAl_2Si_4O_{12} \cdot 6H_2O$
opal-A $SiO_2 \cdot nH_2O$
gypsum $CaSO_4 \cdot 2H_2O$
xonotlite $Ca_6Si_6O_{17} \cdot (OH)_2$

CONCLUSIONS

The encrustations from the lava caves and caverns of Surtsey collected in 1967-1990 are mainly low-temperature encrustations, crystallizing from fumarolic gases in cooling lavas. They are volcanogenic and evaporitic in origin.

Altogether sixteen mineral species were identified, leaving several species unidentified. Most abundant are halite, thenardite and gypsum. Seven of the minerals apparently have not been described from Iceland previously.

It is suggested that kainite, glauberite, loeweite, bloedite, kieserite and possibly halite were deposited mainly at 65°-100°C. Possibly all the stalactitic minerals were formed in this temperature interval. At another locality calcite and opal-A apparently were deposited somewhere in the range 60°-100°C. Gypsum may have formed mainly at 35°-60°C.

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