Chemical composition of hydrothermal water and water-rock interactions on Surtsey volcanic island. A preliminary report

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ABSTRACT

A continuously cored drill hole was drilled on Surtsey in 1979 in order to study the structure of the volcano and the hydrothermal alteration of tephra formed during the Surtsey eruption. The drill hole has provided important insights into the character of the hydrothermal system in the volcano. The basalt tephra in Surtsey has been observed to alter rapidly within the hydrothermal system, concluding with the consolidation of the tephra into palagonite tuff. The temperature in the drill hole has been measured regularly, and samples of water for chemical analysis have been collected occasionally. The composition of the water in the well is basically that of seawater, but shows slight water-rock interaction. In 2002 a hot spring with a temperature of 82°C was discovered on the northwestern shore of the island. The chemical composition of the water in the hot spring shows direct mixing of seawater and rainwater, with some water-rock interaction.

INTRODUCTION

Surtsey island is a part of the Vestmannaeyjar archipelago. It was constructed from the sea floor in a volcanic eruption that lasted from 1963 to 1967 (Thórarinsson 1966, 1969, Thórarinsson et al. 1964). During the hydromagmatic explosive submarine phase of the eruption, from November 1963 to April 1964, 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 phase at the western crater in April 1964. Altogether, seven craters and crater fissures emitted lava between April 1964 and June 1967. The first major effusive phase (1964–1965) produced a lava shield reaching 100 m above sea level, while the second phase (1966–1967) produced a 70 m high lava shield. Together they form a lava field that slopes gently to the south and east. In addition there are five small lava flows on the slopes of Austurbunki (Fig. 1).

Apart from Surtsey, eruptions occurred on the sea floor at three sites. About 2.5 km north-northeast of Surtsey, a submarine tephra ridge, Surtla, was built up in December 1963 and January 1964. At a distance of 0.6 km to the east-northeast of Surtsey, explosive activity formed the island of Syrtlingur in 1965. In 1965–1966 yet another island, called Jólnir, was formed by explosive activity 1 km southwest of Surtsey. Today, however, only submarine platforms remain of these two islands.

Due to heavy marine erosion (Jakobsson et al. 2000), 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, and high tuff and lava cliffs have formed. Marine erosion had worn its way to the tuff core at the northwestern cliffs of the island by 1980.

DRILL HOLE SE-1 ON SURTSEY

In the summer of 1979 a continuously cored drill hole was drilled in Surtsey (Jakobsson & Moore 1982). The drill site (Fig. 1) is located at

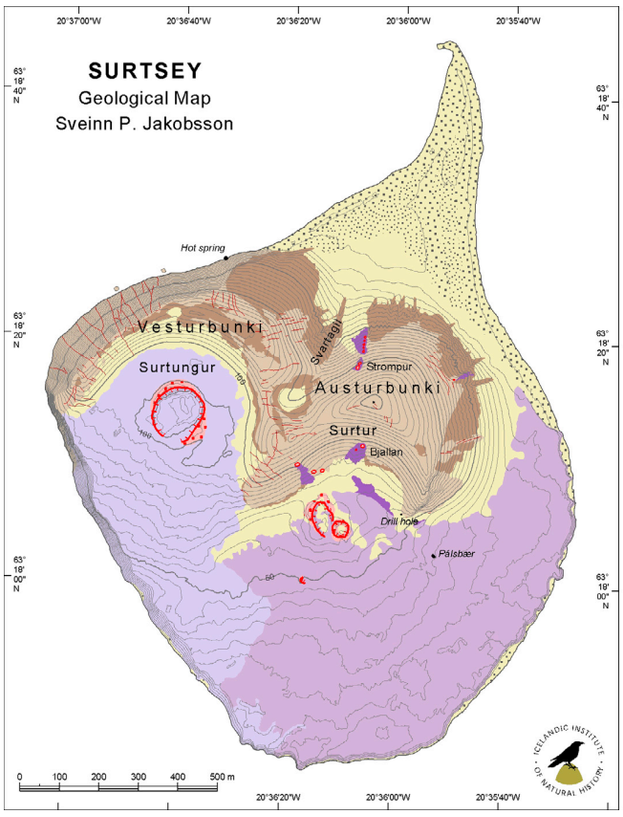

Fig. 1. Geological map of Surtsey, as in 2006. Topography is based on aerial photographs from August 2004. The locations of the drill hole SE-1 and the hot spring are indicated.

Fig. 2. Water sample collected downhole from drill hole SE-1 at Austurbunki in 1990.

the southeastern edge of the Surtur tephra crater, at 58 m above sea level. Figure 2 shows the top of the drill hole in 1990. The total depth of the well was 181 m, and it is believed that the bottom of the hole is only a few meters from the old sea floor. Drilling had to be terminated at this depth due to very loose material from which cores could not be recovered. The well has an steel casing to 165 m depth. The main purpose of the drilling was to obtain a core for studying the structure of the island and the hydrothermal alteration of the tephra formed during the Surtsey eruption. The core has been described in detail by Jakobsson & Moore (1982, 1986).

HYDROTHERMAL ANOMALY

In the spring of 1967, a mild hydrothermal anomaly was discovered at the surface in Austurbunki. The extent of this anomaly is clearly related to the distribution of lava craters (Friedman and Williams 1970). The hydrothermal area at the surface continued to expand until approximately 1979, when the expansion ceased, presumably because tephra consolidation had started to affect the heat flux through the rock. Since about 1995, surface temperatures appear to have been on the decline. Vapour emissions are, however, still visible from many open fissures. In the tuff cones, the highest near-surface temperatures within the hydrothermal area have typically been about 97–

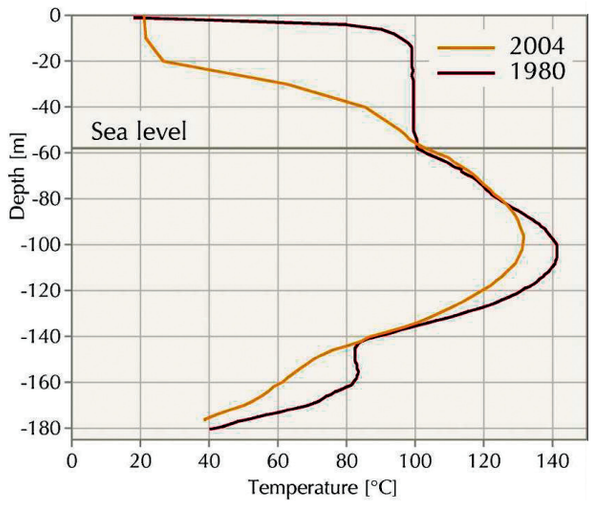

Fig. 3. Temperature measurements in the drill hole in September 1980 and August 2004. The seawater level is at a depth of 58 m. The drill hole is cased down to a depth of 165 m.

100°C, indicating how vapour dominates the heat flux above sea level.

The basalt tephra has been observed to alter rapidly within the hydrothermal portions of Surtsey, concluding with consolidation of the tephra into palagonite tuff, first observed at the surface in 1969. During the alteration process, the original glass shards in the tephra are chemically altered and hydrated to produce palagonite (Jakobsson 1978). A number of chemical elements are released from the original glass in the tephra to form an array of new secondary minerals, which eventually fill the voids in the rock and cement its particles together (Jakobsson & Moore 1986). It is estimated that some 85–90% of the volume of the tephra cones above sea level had been changed to dense palagonite tuff by 2006. Because of this alteration and compaction of the tephra, the rock is considerd to become gradually impermeable, with heat flux mainly taking place along fractures in the rock.

The drill hole has provided important insights into the character of the hydrothermal system in the volcano. These data, along with studies at the surface, strongly suggest that the heat in the hydrothermal system was provided by intrusions which formed both below and above sea level in 1965 and 1966 at Vesturbunki, and in December 1966 and January 1967 at Austurbunki. Lava extrusions in these areas probably contributed as well (Jakobsson & Moore 1982, 1986, Stefánsson et al. 1985, Jakobsson et al. 2000). Temperature logs in the drill hole, shown in Figure 3, indicate a general cooling of the hydrothermal system, with the maximum temperature at 105–110 m depth declining from a calculated value of 154°C in 1966 and 1967 to a measured temperature of 130°C in 2004 (Jakobsson et al. 2000).

Figure 4 shows a cross section of Surtsey, from northwest to southeast. The information on the geometry of the hydrothermal system and the alteration of the tephra is based on observations during the eruption, surface geology, sea floor topography, and drill hole data. It is inferred that cold sea water enters the hydrothermal system through deep porous layers. The water is heated by contact with dikes and intrusions, produces alteration of the tephra, and then rises and presumably flows back into the sea.

In the summer of 2002 a hot spring with a temperature of 78°C was discovered on the northwestern shore (Figs. 5 and 6), where hot water was flowing from a 15–20 m long fissure with a northeasterly trend. In 2006 the temperature was 82°C, but in the summer of 2008 the hot spring proved to be inaccessible, as it was now below sea level, due to marine erosion.

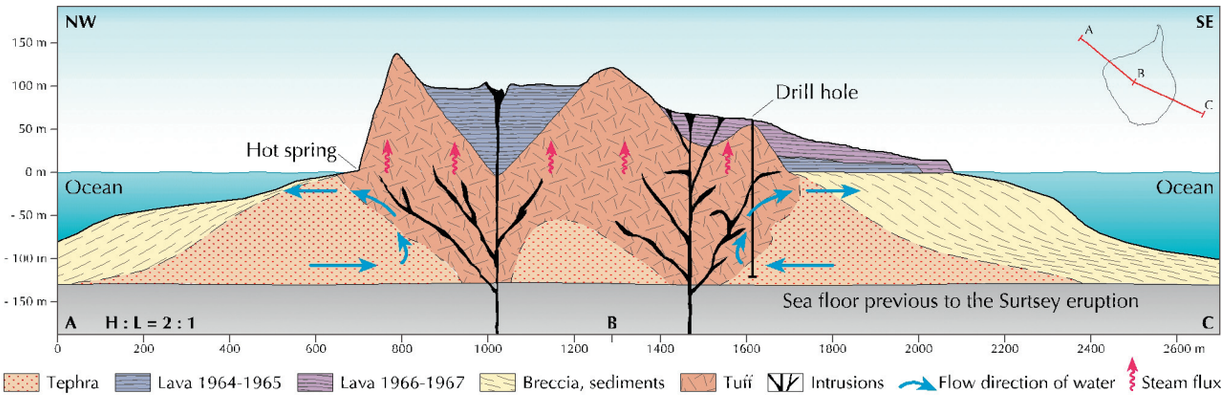

Fig. 4. A cross section through the Surtsey volcano, from northwest to southeast. It is inferred that the tephra within the suggested hydrothermal system is transformed into palagonite tuff.

Fig. 5. The hot spring at the northwestern shore of Surtsey in August 2006. The cliff to the left is made up of palagonite tuff, originally formed as tephra in hydromagmatic explosions in 1964.

Fig. 6. A closer view of the hot spring.

WATER SAMPLES

Sample locations

Samples for chemical analysis of water were collected at several locations on Surtsey from 1985 to 2006. On four occasions samples were collected from drill hole SE-1 (Fig. 2). The samples were collected by a downhole sampler at two depth intervals in the drill hole, at 55 to 65 m depth, close to the water level, and at 167 to 177 m depth, below the well casing. All the samples from the drill hole are listed in Table 1. Water level monitoring has revealed that the tidal amplitude in the well is about 80% of the amplitude in the surrounding ocean.

Table 1. Water samples collected on Surtsey 1985 to 2006.

Sample id.	*Date*	*Depth (m)*	*Sample id.*	*Date*
Drill hole ~ 55 m depth			*Dug pit*	
19850230	1985-08-05	55	19850234	1985-08-06
19850231	1985-08-05	65	19860099	1986-07-17
19850232	1985-08-05	55	19860100	1986-07-18
19860094	1986-07-17	58	19860101	1986-07-18
			19880100	1988-08-11
Drill hole ~ 175 m depth			*Seawater*	
19860095	1986-07-16	167	19850233	1985-08-05
19860096	1986-07-16	170	19880101	1988-08-10
19860097	1986-07-17	177	*Rainwater*	
19880103	1988-08-10	176	19880102	1988-08-10
19900241	1990-09-24	176	*Hot spring*	
			20020204	2002-08-17
			20060517	2006-08-12

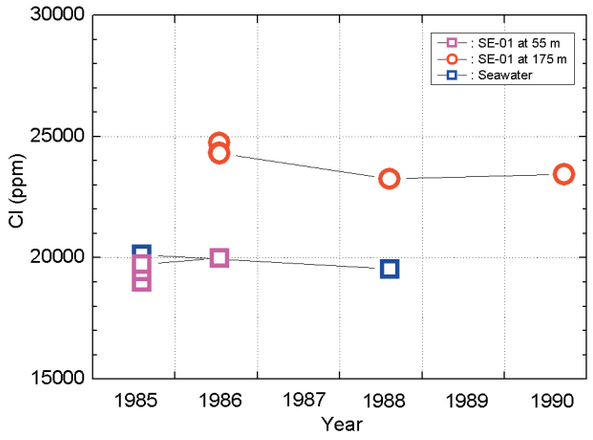

Fig. 7. Chloride content of samples from drill hole SE-1 at the depth intervals 55–65 m and 167–177 m. The concentration of chloride in coastal seawater at Surtsey is shown for comparison.

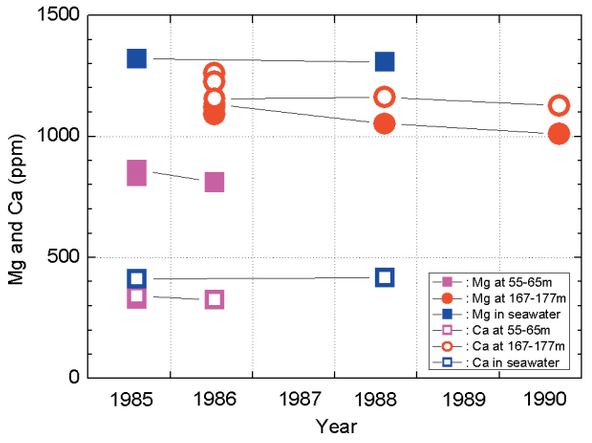

Fig. 8. Magnesium and calcium content of samples from drill hole SE-1 at the depth intervals 55–65 m and 167–177 m. The concentration of these elements in coastal seawater at Surtsey is shown for comparison.

Samples for chemical analysis were also collected from a pit that was dug on the flat northern end of Surtsey. The pit was dug primarily to study the tidal phase delay and amplitude difference between Surtsey and the Vestmannaeyjar harbour. Samples of coastal seawater were also collected, as were samples of rainwater from the roof of the Pálsbaer hut. Finally, two samples from a recently discovered hot spring at Vesturbunki were collected in 2002 and 2006 (Fig. 4). These samples are also listed in Table 1.

The water samples collected on Surtsey were analysed for various elements. Some were analysed for all major elements including pH and carbonates, whereas others were only analysed for salinity and a few other components.

Samples from drill hole SE-1

Water samples for chemical analysis were collected from the drill hole with a downhole sampler in 1985, 1986, 1988 and 1990. Four samples were collected at the depth interval 55 to 65 m, a few meters below the water level in the well. The water at this level is not in any direct contact with the rock, since the drill hole is cased to 165 m, as previously stated. These samples are thus not thought to participate in any water-rock interaction, and they were only collected because of difficulties with

Table 2. Chemical composition of water samples from the drill hole SE-1 at 55 to 65 m depth (ppm).

Sample id.	*19850230*	*19850231*	*19850232*	*19860094*
Date	1985-08-05	1985-08-05	1985-08-05	1986-07-17
Depth (m)	55	65	55	58
SiO_2	11.4	10.2	11.0	7.47
B				5.0
Li				0.27
Na	10940	10970	11033	11210
K	475	493	494	580
Mg	835	861	861	810
Ca	327	346	340	325
Sr				7.34
F	0.69	0.70	0.70	0.63
Cl	19003	19440	19732	19980
Br	68.9	69.9	70.2	
SO_4	1460	1407	1436	1342
Fe				1.04
TDS	35760	36574	36634	36650
$\delta^{18}O$ ‰				6.72

Table 3. Chemical composition of water samples from the drill hole SE-1 at 167 to 177 m depth (ppm).

Sample id.	*19860095*	*19860096*	*19860097*	*19880103*	*19900241*
Date	1986-07-16	1986-07-16	1986-07-17	1988-08-10	1990-09-24
Depth (m)	167	170	177	176	176
pH / °C	8.59/24.1	8.56/23.9	8.12/24.5	8.34/22.6	8.31/23.8
CO_2 (total carbonate)	15.8	15.8	46.5	14.9	8.8
H_2S (total sulphide)	< 0.03	< 0.03	< 0.03	< 0,03	< 0.03
SiO_2	0.99	1.10	9.54	2.47	8.40
B	4.36	4.42	4.54		4.10
Li	0.22	0.20	0.20	0.24	
Na	13291	13426	13245	12715	12337
K	662	679	695	564	520
Mg	1091	1120	1134	1052	1010
Ca	1226	1261	1156	1162	1127
Sr	12.1	11.7	10.1		
F	0.37	0.36	0.48	0.39	0.40
Cl	24322	24745	24296	23250	23440
SO_4	2972	3097	3057	2581	2726
Br				78.9	79.3
Fe	0.20	0.17	0.14	0.025	
TDS	48310	49390	48610	42950	43730
$\delta^{18}O$ ‰	1.37	1.13	1.38	1.25	

sampling the well at deeper levels. However, five samples were collected in the depth interval of 167 to 177 m. The temperature in the upper depth interval is approximately 100°C but the temperature at 167 to 177 m depth is approximately 50 to 70°C, as shown in Figure 3. The results of the chemical analyses from the drill hole are presented in Tables 2 and 3.

The thermal water from the drill hole is seawater with a chloride concentration similar to that of

Table 4. Chemical composition of water samples from the dug pit (ppm).

Sample id.	*19850234*	*19860099*	*19860100*	*19860101*	*19880100*
Date	1985-08-06	1986-07-17	1986-07-18	1986-07-18	1988-08-11
pH / °C	8.30 / 23.9				8.33 / 22.2
CO_2 (total carbonate)	87.5				46.1
H_2S (total sulphide)	< 0.03				< 0.03
SiO_2	4.97	5.41	6.89	6.89	6.38
B		3.30			
Li		0.13	0.04	0.04	0.05
Na	7037	6899	1380	1462	2207
K	319	321	69.8	75.5	106
Mg	847	771	154	154	209
Ca	258	260	46.9	49.1	75.6
Sr		3.92	0.80	0.80	
F	1.22	0.80	1.43	1.43	2.52
Cl	12555	12432	2501	2638	3553
SO_4	1822	1615	342	358	838
Br	44.3				12.1
NO_3					2.13
Fe		0.30			0.025
TDS	24737	24630	4965	5265	7141

Table 5. Chemical composition of samples of seawater and rainwater collected on Surtsey (ppm).

Sample id.	*19850233*	*19880101*	*19880102*
Date	1985-08-05	1988-08-10	1988-08-10
	seawater	seawater	rainwater
pH / °C	8.25/23.3	8.22/22.1	
CO_2 (total carbonate)	102	103	
H_2S (total sulphide)	< 0.03	< 0.03	
SiO_2	0.03	0.27	0.52
Li		19.0	
Na	10757	10836	153
K	452	452	6.28
Mg	1320	1307	17.9
Ca	410	417	7.26
F	0.86	0.63	0.017
Cl	20130	19530	281
SO_4	2684	2738	34.9
Br	70.6	68.1	0.83
NO_3			0.28
Fe	0.17	< 0.025	
TDS	39512	38040	503

Table 6. Chemical composition of water samples from the hot spring (ppm).

Sample id.	*20020204*	*20060517*
Date	2002-08-17	2006-08-12
Flow rate (L/s)	~0.1	~0.1
Temp. (°C)	78.0	82.4
pH / °C		7.53 / 23.9
CO_2 (total carbonate)		30.5
H_2S (total sulphide)		< 0.03
TDS		22410
SiO_2	43.8	25.9
Na	3035	6730
K	134	327
Mg	55.3	261
Ca	386	726
Sr		4.66
F	6.51	2.12
Cl	3160	11360
SO_4	3120	2160
Br	10.2	
Fe		0.0296
Al		0.111
Ba		0.0528
Co		0.00006
Cr		0.00041
Cu		0.00105
Mn		0.0454
Mo		1.03
Ni		0.00051
Pb		0.00033
Zn		0.00211

the seawater at the island shore. The samples show that the concentration of the major elements at these two depth intervals is relatively stable over the period studied. Figure 7 shows the chloride concentration in the water, and Figure 8 shows the magnesium and calcium content of the water. The content of these elements in seawater at Surtsey are also shown for comparison.

Samples from the dug pit

During the expeditions to Surtsey in 1985, 1986, and 1988, pits were dug into the central part of the peninsula extending north from the main part of the island. The main purpose of the pits was to study differences in tidal amplitude and phase between Surtsey and the Vestmannaeyjar harbour. The pits were deep enough to collect water for chemical analysis, and the results are shown in Table 4. The water samples collected from the pit had chloride content ranging from 2500 to 12500 ppm, which indicated direct mixing between rain water and seawater as discussed below.

Samples of coastal seawater and rainwater

Two samples of seawater were collected on the eastern shore of Surtsey, one in 1985 and another one in 1988. A sample of rainwater was collected from the roof of the Pálsbaer hut in 1988. The results are shown in Table 5. The chloride content of the seawater at Surtsey is slightly higher than that of standard mean ocean water (SMOW), which has a chloride content of 19400 ppm. The rainwater samples displayed a high concentration of dissolved solids, indicating the influence of seawater spray.

Samples from the hot spring at Vesturbunki

In the summer of 2002, a hot spring with a temperature of 78°C was discovered at sea level at the nortwestern shore of Vesturbunki. The spring is shown in Figs. 4 and 5. A water sample was collected from the spring, see Table 6. In the summer of 2006, another sample was collected from the same spring. At this time the temperature was found to be 82°C, and the flow rate was estimated as 0.1 L/s. The sampling was difficult, and the chemical analyses show the mixing of seawater and spring water. In the summer of 2008 the hot spring was inaccessible, as it was then below sea level.

CHEMICAL COMPOSITION OF THE WATER SAMPLES

The thermal waters collected on Surtsey are of seawater origin. The chemical composition of some samples can best be explained by the direct

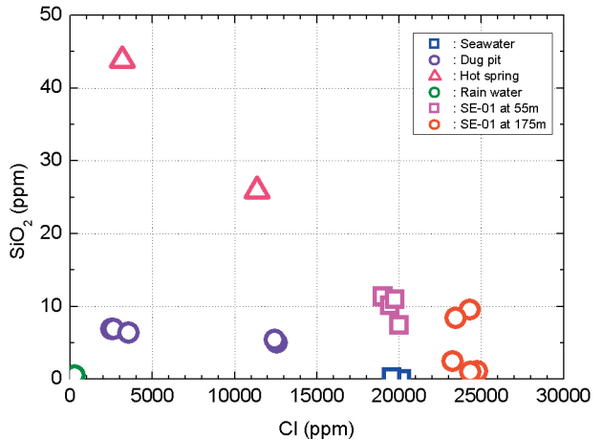

Fig. 9. The relationship between chloride and silica in all water samples.

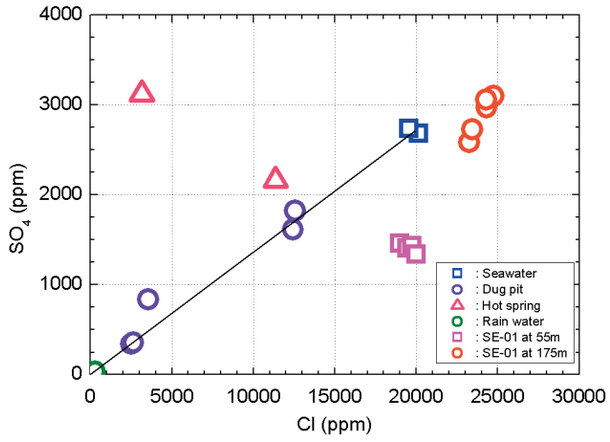

Fig. 10. The relationship between chloride and sulphate in all water samples. The line indicates direct mixing of rainwater and seawater.

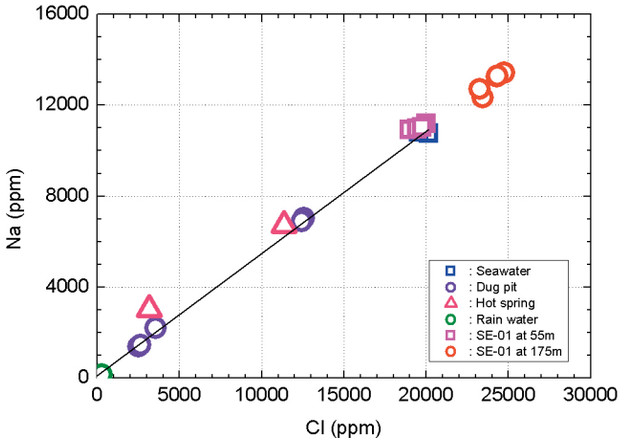

Fig. 11. The relationship between chloride and sodium in all water samples. The line indicates direct mixing of rainwater and seawater.

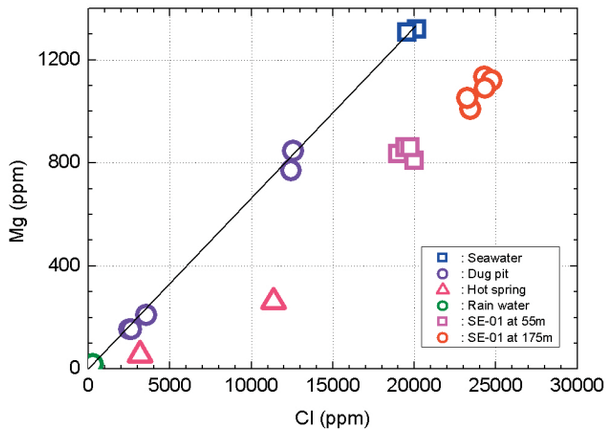

Fig. 12. The relationship between chloride and magnesium in all water samples. The line indicates direct mixing of rainwater and seawater.

mixing of seawater and rainwater. Other samples, however, show evidence of ion exchange with the host rock. This is especially true of the higher temperature waters.

The salinity of the water at the upper depth level, close to the water level in the drill hole, is almost identical to that of the coastal seawater, whereas the samples collected at lower temperature and close to the bottom of the well have approximately 20% higher salinity (Fig. 7).

This increase in salinity is probably an indirect consequence of the palagonitization of the tephra. During the alteration process, hydration of the basaltic glass removes some of the water from the pore fluid, leaving the chloride still dissolved. This, in effect, increases the chloride concentration in the fluid that is in contact with the tephra at the deeper level. The water at the upper depth level is unaffected, however, because it is wholly contained within the casing and has no direct contact with the tephra.

The relationship between chloride and some other major elements in the water samples is shown in Figs. 9 to 14. It is evident from these figures that the chemical composition of waters from the dug pits can best be explained by direct mixing of seawater with rainwater. Waters from drill hole SE-1 and from the hot spring at Vesturbunki show water-rock interactions, however.

The silica content shown in Figure 9 is slightly elevated with respect to seawater in samples from the drill hole, but it is below 10 ppm in all other samples expect the ones from the hot spring. The hot spring samples display an increase in the sulphate concentration, in contrast to the samples from the drill hole (Fig. 10), whose sulphate concentration falls below the mixing line. The concentration of sodium in all water samples (Fig. 11) falls directly on a mixing line between seawater and rain water. Samples from the hot spring and from the drill hole all show a decrease in Mg content (Fig. 12), most likely due to the formation of Mg-rich clays as an

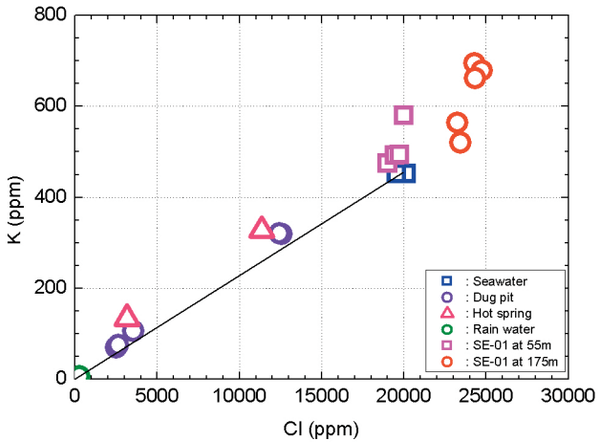

Fig. 13. The relationship between chloride and potassium in all water samples. The line indicates direct mixing of rainwater and seawater.

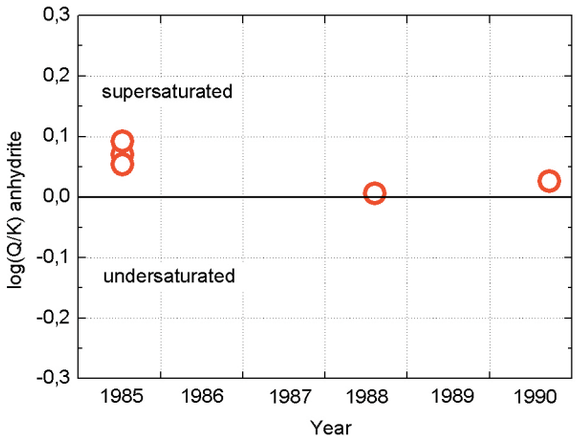

Fig. 15. Saturation index for anhydrite in water samples from 167 to 177 m depth in drill hole SE-1. Reference temperature for calculations is 50°C.

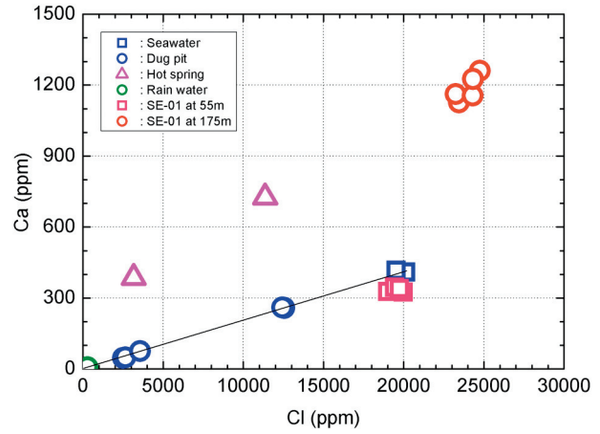

Fig. 14. The relationship between chloride and calcium in all water samples. The line indicates direct mixing of rainwater and seawater.

alteration product in the surrounding rock. There is a slight increase in potassium content compared to direct mixing as shown in Figure 13. The water samples from the lower depth interval in the drill hole and the hot spring samples all have a greatly increased concentration of calcium (Fig. 14).

The saturation index for anhydrite ($CaSO_4$) calculated for the samples from the lower depth interval in the drill hole is shown in Figure 15. The reference temperature is 50°C, which was approximately the temperature at 170 m depth in 1985. The calculations indicate that the water is very close to equilibrium with anhydrite in the rock.

Anhydrite is found scattered throughout the drill core of hole SE-1, and is most abundant near the bottom of the hole where the average alteration temperature of the tephra between 1967–1979 was < 40°C (Jakobsson & Moore 1986). The anhydrite apparently precipitated directly when inflowing sea water was heated, thus lowering the sulfate solubility. Comparable deposition of anhydrite occurs in the Reykjanes thermal brine (Tómasson & Kristmannsdóttir 1972).

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References

Friedman, J.D. & R.S. Williams 1970. Changing pattern of thermal emission from Surtsey, Iceland, between 1966 and 1969. U. S. Geol. Survey Prof. Paper 700-D: D116–D124.

Jakobsson, S.P. 1978. Environmental factors controlling the palagonitization of the Surtsey tephra, Iceland. Bull. Geol. Soc. Denmark 27: 91–105.

Jakobsson, S.P. & J.G. Moore 1982. The Surtsey research drilling project of 1979. Surtsey Res. Prog. Rep. 9: 76–93.

Jakobsson, S.P. & J.G. Moore 1986. Hydrothermal minerals and alteration rates at Surtsey volcano, Iceland. Geol. Soc. Amer. Bull. 97: 648–659.

Jakobsson, S.P., G. Gudmundsson & J.G. Moore 2000. Geological monitoring of Surtsey, Iceland, 1967–1998. Surtsey Res. 11: 99–108.

Stefánsson, V., G. Axelsson, Ó. Sigurdsson, G. Gudmundsson & B. Steingrímsson 1985. Thermal condition of Surtsey. Journ. Geodyn. 4: 91–106.

Thórarinsson, S. 1966. Sitt af hverju um Surtseyjargosid. (English summary: Some facts about the Surtsey eruption.) Náttúrufraedingurinn 35: 153–181.

Thórarinsson, S. 1969. Sídustu thaettir Eyjaelda. (English summary: The last phases of the Surtsey eruption.) Náttúrufraedingurinn 38: 113–135.

Thórarinsson, S., Th. Einarsson, G.E. Sigvaldason & G. Elísson 1964. The submarine eruption off the Vestmann Islands 1963–64. A preliminary report. Bull. Volcanol. 27: 435–445.

Tómasson, J. & H. Kristmannsdóttir 1972. High temperature alteration minerals and thermal brines, Reykjanes, Iceland. Contrib. Mineral. Petrol. 36: 123–134.