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The SUSTAIN ICDP Drilling Project on Surtsey

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ABSTRACT

In 1963, a submarine eruption was observed off the south coast off Iceland. Eruptive activity continued until 1967 and subsequently the island of Surtsey was born. In 1968, the first indications of hydrothermal activity were observed on the surface of the island. In 1969, the first signs of palagonitization of the basaltic glass were spotted. In 1979, a vertical drill hole (SE-01, 181 m) was cored. Studies of the core revealed that the Surtsey tephra had undergone a progressive alteration resulting in advanced lithification. In the seawater-dominated hydrothermal system, primary basaltic glass experiences intensive palagonitization and formation of secondary minerals, including analcime and phillipsite. In 2015, an international research group initiated a new drilling project on Surtsey, where one of the aims was to study the time-lapse evolution of the hydrothermal system and the associated mineralogical, geochemical, and microbiological processes. In July – September 2017, three cored boreholes were drilled on Surtsey by the International Continental Scientific Drilling Program-supported SUSTAIN drilling project. Two vertical holes (SE-02a, SE-02b), 152 and 192 m deep respectively, are parallel and adjacent (< 8 m distance) to the 1979 (SE-01) borehole. In addition, a 35° angled cored borehole (SE-03) was drilled from the same drilling platform to the west, under the Surtur I crater. This core extends to a measured depth of 354 m, which corresponds to a vertical depth of about 290 m. Wireline downhole logging was carried out in SE-02b before installation of a Surtsey Subsurface Observatory for in situ incubations experiments. Core processing took place on the nearby island of Heimaey during the drilling operation in August-September and at the Icelandic Institute of Natural History, near Reykjavík, in October-November. Observation of the newly retrieved core material indicate that the consolidation of the Surtsey tephra has progressed since 1979 by ongoing palagonitization of basaltic glass, alteration of primary magmatic olivine and plagioclase and the formation of secondary minerals including clay minerals and zeolites.

1. INTRODUCTION

In summer 2017, the Surtsey Underwater volcanic System for Thermophiles, Alteration processes and Innovative Concretes (SUSTAIN) drilling project (Jackson et al., 2015, 2019; Weisenberger et al. 2019), drilled three cored boreholes through Surtsey Volcano (Figure. 1), a very young oceanic island, nature preserve and UNESCO World Heritage site (https://whc.unesco.org/en/list/1267). Four years of planning and preparation resulted in the successful acquisition of nearly 650 m of drill core from the still hot volcano, through a project sponsored by the International Continental Scientific Drilling Program (ICDP). The 2017 cores will provide a unique opportunity to compare with a 181 m vertical core through the volcano, acquired in 1979 (Jakobsson and Moore, 1982, 1986). The three 2017 wellheads are situated within 10 m distance from the 1979 cored borehole. Fluid compositions and temperatures in the 1979 borehole have been monitored many times by scientists and by members of the Surtsey Research Society since 1980. The 1979 and 2017 time-lapse drilling projects therefore provide a record of global significance for studying the early progression of processes and properties in the young oceanic crust. During preparation and operation, a great deal of attention was given to creating a zero-impact drilling operation that would fully preserve the sensitive surface and subsurface environments on Surtsey, adhering to the strict protection of the island. The plan was set up in accordance with guidelines set by the Iceland Environment Agency and Surtsey Research Society to avoid any risk to the vegetation, birds and sea life that inhabit the island and the marine preserve that surrounds it.

An overview of the project and first results are given in Jackson et al. (2019) while a detailed description of the operation is given in Weisenberger et al. (2019). This paper is meant to complement the above publications by giving a short overview of the drilling operation into the Surtsey low-temperature geothermal area. In addition, new temperature logs are presented that were acquired during a field expedition in 2018. They represent the recent thermal conditions after the well had regained equilibrium with the surrounding rocks after the drilling disturbance.

2. GEOLOGICAL SETTING

Surtsey is a volcanic island that was created by basaltic eruptions from 1963 to 1967, approximately 32 km from the south coast of Iceland (Thorarinsson et al., 1964; Thorarinsson, 1967). Surtsey forms part of the Vestmannaeyjar archipelago, a young volcanic system that marks the southern offshore tip of Iceland's SE rift zone (Figure 1). The island was constructed from an original seawater depth of 130 m, and eventually attained a height of 150 m above sea level (a.s.l.). At the termination of activity in June 1967 the total erupted volume was about 1 km^3. Explosive eruptions followed by basaltic lava flows (Thorarinsson, 1967). Surtsey "has been protected since its birth, providing the world with a pristine natural laboratory" and a unique scientific record of colonization of new land by plants, animals and marine organisms through long term studies of primary biological succession (Baldursson and Ingadóttir, 2007). Subsurface processes were first explored in 1979 by a 181 m deep cored drill hole through the rim of the eastern tephra cone

(Figure 1) (Jakobsson and Moore, 1982). Subsurface microbiota of bacteria and archaea have recently been observed in fluids extracted from the deeper zones of the 1979 drill hole below a 120 – 140 °C thermal barrier at about 100 m b.s. (Marteinsson et al., 2015). Below this horizon, microbial life could be derived from the seafloor and, therefore, be potentially indigenous to the oceanic environment.

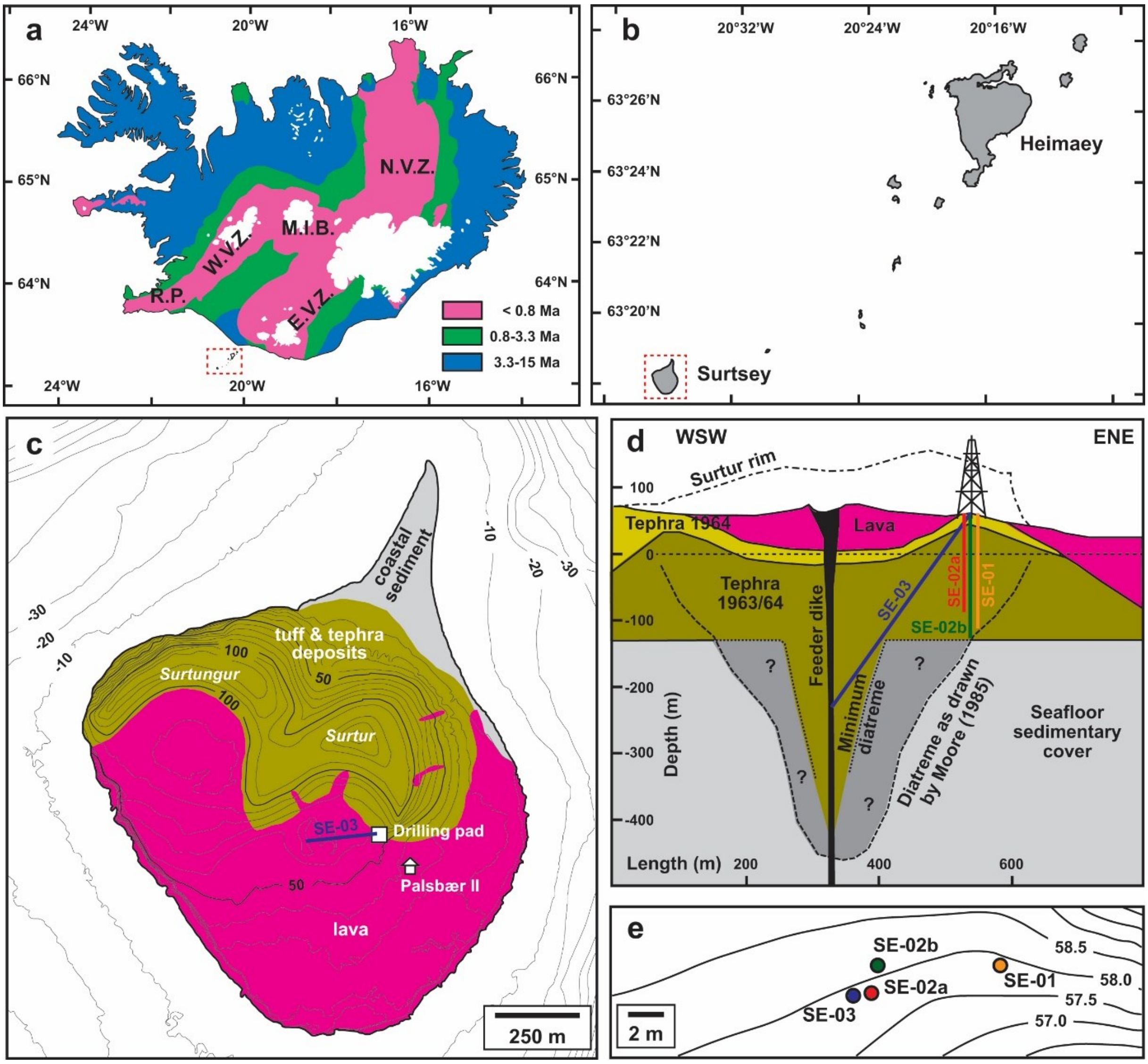

Figure 1: Outline of Surtsey's position as the southernmost member of the Westman Island Archipelago, which marks the off-shore extension of Iceland's East Volcanic Zone (E.V.Z.) into the North Atlantic Ocean and geologic overview of the island. a) Simplified geological map of Iceland (after Jóhannesson and Saemundsson, 2009), b) Westman Island Archipelago and location of Surtsey, c) Geological map of Surtsey (modified after Baldursson and Ingadóttir, 2007), d) Simplified cross section of Surtsey (modified after Jackson et al. 2019). e) Location of the wellheads (adapted from Weisenberger et al. 2019)

3. DRILLING OPERATION

3.1 Previous drilling

Initial coring of Surtsey took place between June and August 1979, as described by Jakobsson and Moore (1982). The hole was collared at an elevation of 58.4 m and drilled to a total depth of 180.6 m. The hole was cored using NQ diameter (75.7 mm outside diameter, 47.6 mm core diameter) until the bit got stuck at 176.5 m. It was then completed with a BQ diameter (60 mm outside diameter, 36.5 core diameter) for the additional four meters retrieved. Core recovery was very good (97.9%) to 138 m. Below that point, drilling was more difficult and core recovery was lower mainly due to unconsolidated tephra (Jakobsson and Moore, 1982). The steel drill casing remained in the hole.

3.2 Site selection

The 1979 drilling program on Surtsey provided exceptionally well-constrained information about the structure, stratigraphy, temperature, and hydrothermal system of a 181 m vertical section through the SE sector of the eastern crater (Jakobsson and Moore, 1982, 1986). The opportunity to determine in situ rates of alteration and other changes over the last 38 years strongly influenced the decision to locate the new drill holes within 10 m of the 1979 SE-01 hole (Figure 1). Figure 2 shows the layout of the logistical components of the drilling expedition. Seawater was used for circulation, pumped over a distance of 1.4 km from a sheltered location on the western side of the northern peninsula.

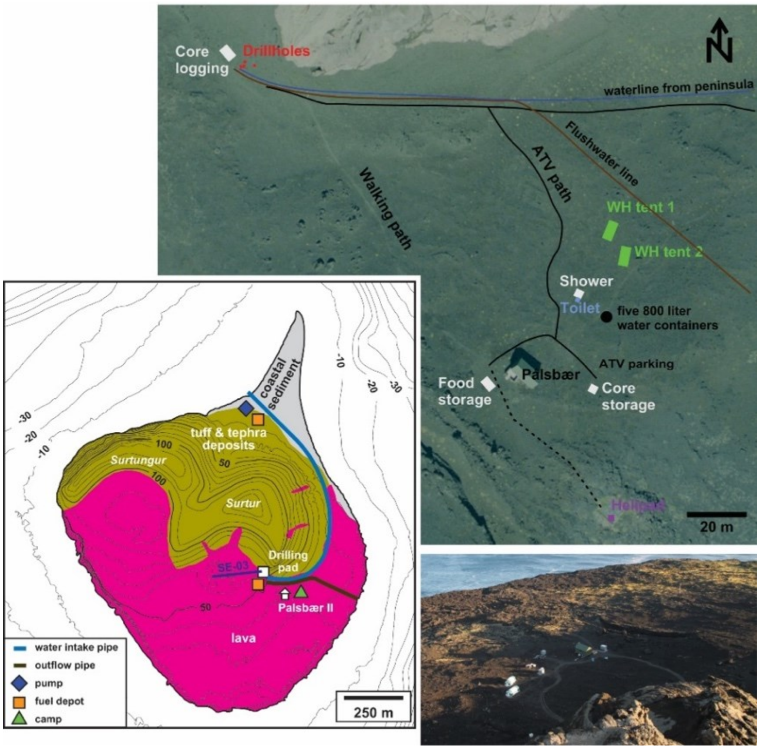

Figure 2: Map of the SUSTAIN Surtsey camp set up at end of July and taken down in September. WH: Weather Heaven tents (modified after Weisenberger et al., 2019).

3.3 Logistics of drilling on Surtsey

To obtain permission for the drilling operation, an application was submitted in April 2016 to the Iceland Environment Agency (Umhverfisstofnun). The SUSTAIN team worked closely with representatives of the Agency to develop best practices for every aspect of the drilling operation. To overcome the logistical challenges, we sought assistance and cooperation with institutions and companies with the necessary expertise and experience to operate effectively in the Surtsey Natural Reserve. Comprehensive planning and preparation of equipment for shipment to Iceland was critical to ensuring a functional operation in Surtsey's remote and protected environment. The absence of a harbor on the island required that the entire transport of materials and provisions took place via helicopter or landings via dinghy from a larger boat offshore. The logistics of delivering the equipment, personnel and facilities to keep the operation running effectively was one of the most challenging aspects of the drilling project.

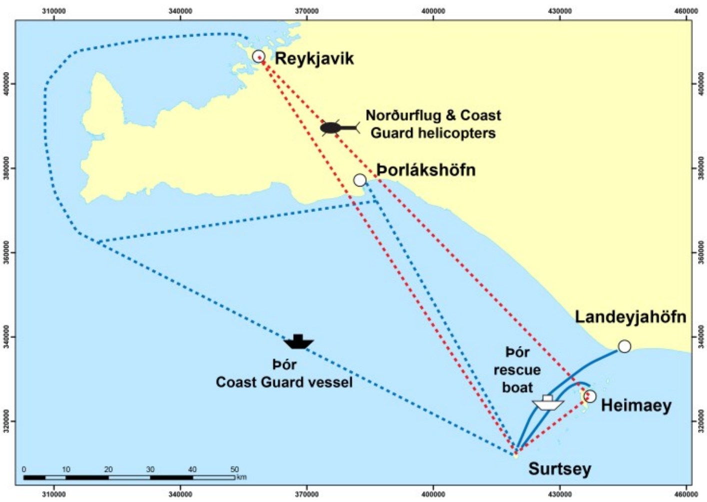

Figure 3: Map of transport modes and routes during the 2017 Surtsey drilling operation (adapted from Weisenberger et al. 2019).

For transport of the expected 60 – 65 metric tons of equipment, fuel, provisions and camp materials from Þorlákshöfn to Surtsey and then to Reykjavík, after demobilization we sought the assistance of the Icelandic Coast Guard. The Coast Guard was the only operator in Iceland with the organizational and technical capabilities needed to carry out the maritime helicopter sling-lift equipment transport for the expedition. For helicopter transport of personnel and general servicing during the operation, we secured the services of the

Norðurflug helicopter company, which has a twin-engine Dauphin and highly experienced pilots. Finally, for occasional boat transport and the needed on-sea support we sought the assistance of the rescue group in Heimaey (Björgunarfélag Vestmannaeyja) which has a high-speed rescue boat and well-trained crews for sea rescue and transport operations. The cooperation with all parties worked well with everybody involved doing their best, at the time needed and sometimes at short notice. This positive attitude towards the project was of major importance and contributed greatly to the success of the expedition. Transport routes during the SUSTAIN drilling operations are shown Figure 3.

3.4 Drill rig and drilling technique

Drilling was carried out by DOSECC Exploration Service (DES) of Salt Lake City, Utah, USA, using a helicopter-transportable Atlas Copco CS-1000 drill rig (Figure 4). Predrilling for all three boreholes (SE-02a, SE-02b, SE-03) involved rotary drilling with a 6⅛" (15.88 cm) tricone rotary drill-bit. The pilot hole was drilled to install and cement in place a 4½" (11.43 cm) HWT conductor casing. Individual HWT casing pipes were 3.05 m in length. The conductor casing had an HWT casing shoe of 16 cm in length affixed.

After cementing the conductor casing, coring and drilling operations were performed using a standard wire-line coring technique. The cored rock was captured and collected in an inner tube assembly, and then retrieved and brought to the surface by an overshot device attached to a wireline cable. The maximum length of a core run was 3.05 m. The core was recovered by using plastic liners inside the inner tubes similar to practices that use aluminum splits. Boreholes SE-02a and SE-02b were cored solely with a HQ3 size drilling bit. Borehole SE-03 was cored initially with an HQ3 size bit, but then reduced at about 213 m to NQ3 when the supply of HQ rods was fully consumed.

In boreholes SE-02b and SE-03, attapulgite drilling mud (Florigel High-Yield Salt Water Stable Drilling Clay) was occasionally employed to stabilize the borehole and improve lifting of rock fragments within the circulating seawater fluid. The use of this product was approved by the Environment Agency. A discharge line attached to the mud diverter on top of the HW casing ran from the drill site to a plastic catchment basin near the camp. Cuttings settled out, and a line at the top of the basin discharged clear fluid to the ocean on the eastern shore of the island. Drilling was conducted 24 hours per day, seven days a week through a two-shift system. Each shift consisted of one driller and one helper. In addition, the drilling supervisor was on site for the entire drilling operation.

Figure 4: Photograph of the CS-1000 drill rig on Surtsey.

<u>3.4.1 Water supply line</u>

The water line was designed to transport seawater drilling fluid from the western shore of the northern peninsula to the drill site (Figure 2). This is a location relatively sheltered from wave action, which is most intense on the eastern and southern coast of the island. The water system initially consisted of a submerged electric pump, a generator to run the pump, and a 1.4 km long water pipe to the drill site. After breakdown of the submerged pump, it had to be replaced by two mobile pumps that due to the semi-diurnal tides had sometimes to be moved twice per day.

<u>3.4.2 Water filtering system</u>

Seawater pumped from the northern peninsula was used as the circulating drilling fluid. At the drill site, the seawater was stored in 1000-liter reservoir tanks, and then pumped to the drilling head. Before entering the final storage reservoir, the seawater used in boreholes SE-02a and SE-02b was passed through a PENTEK Big Blue filtration unit, with a 30 µm cartridge filter that removed fine debris. The seawater was then passed through a UV light AQUA4ALT system from WEDECO (Aquaculture systems, Xylem Water Solutions Herford GmbH, Germany) with maximum flow rate of 1.58 L/s or 5.7 m^3/h, and stored in three 1000-liter reservoir tanks for subsequent use. During pumping to the drill head, the treated seawater was then passed through another UV light WEDCO AQUA4ALT system. The inclined drill hole, SE-03, was cored with untreated seawater.

3.5 Time line

Table 1 provides a chronological summary of the drilling activity on Surtsey in 2017. Figure 5 shows the drilling operation and entire drilling progress. An advance team arrived on 23 July, transported by the Vestmannaeyjar rescue boat Þór, to prepare the drilling platform, camp, and other sites before the mobilization operation. Meanwhile, other team members continued equipment preparations in Reykjavik. On 26 July the drilling equipment was transported by trucks from the warehouse to Þorlákshöfn harbor. About one-half of the load was then loaded on the Icelandic Coast Guard vessel VS Þór. After sailing to Surtsey, the Icelandic Coast Guard Super Puma helicopter TF-LÍF lifted equipment from the VS Þór to Surtsey. The vessel returned to Þorlákshöfn harbor, was loaded a second time, and returned to Surtsey. The Icelandic Coast Guard TF-LÍF helicopter delivered in total 107 loads from VS Þór on 28-30 July. Installation of the camp and rigging up activities continued for several days. On 7 August, the drillers spud in borehole SE-02 (later named SE-02a) and drilling was officially underway. Major problems soon developed with the water pumping system which required additional helicopter operations to remove and repair the submersible pump and reset it into the ocean. On 13 August, the Rescue boat Þór brought additional equipment to Surtsey from Heimaey to repair and improve the water supply system. In the morning of 16 August, the drilling string got stuck at about 151 m b.s., due to hole collapse. Attempts to free the rods were partially successful. On 17 August, no further progress was achieved in freeing the stuck rods, and it was decided to terminate borehole SE-02a, without the planned installation of the Surtsey Subsurface Observatory. The pilot hole for a second vertical hole, SE-02b, began on 19 August. There were initial problems with seawater supply, but this was resolved with the addition of a second camp manager so that the seawater pumping system was maintained over both 12-hour shifts. Coring reached a total depth of about 192 m on 26 August. Borehole logging operations were carried out by the ICDP Operational Support Group on 27 August. This was followed by installation of the anodized aluminum tubing for the Surtsey Subsurface Observatory on 27 August. The pilot hole for the inclined SE-03 borehole was drilled on 28 August, and core drilling operations began on 29 August. These operations proceeded efficiently, since cementing of the conductor casing and water supply problems had been effectively resolved. On 4 September, the angled hole reached total measured depth at about 354 m, and rigging down activities began.

Table 1: Chronological summary of drilling activity.

Phase	Time
Mobilization	23.07-30.07.2017
Drilling SE-02a	30.07-18.08.2017
Drilling SE-02b	18.08-28.08.2017
Drilling SE-03	28.08-05.09.2017
Fluid sampling	05.09-06.09.2017
Demobilization	06.09-12.09.2017

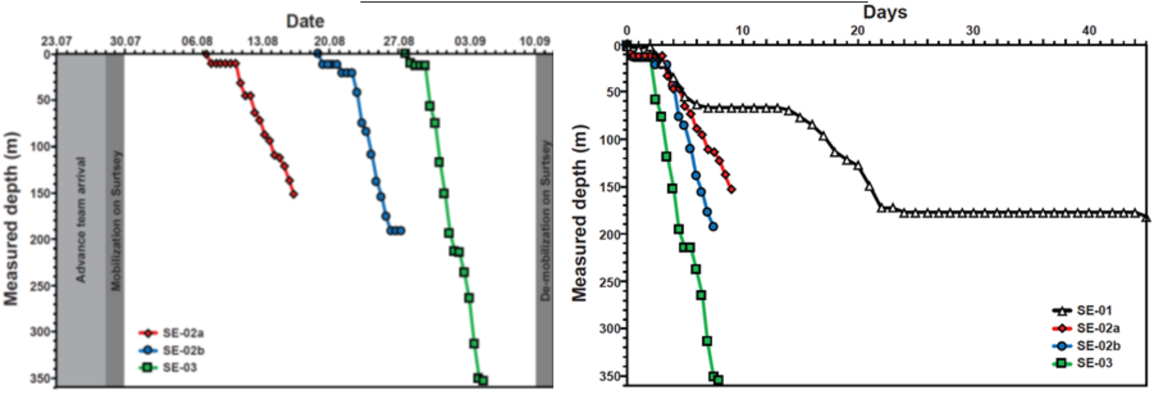

Figure 5: Timeline for activities on Surtsey in 2017 and drilling progress of the three boreholes (left graph). The right graph compares the relative drilling progress for the 2017 boreholes and with the 1979 borehole (after Jakobsson and Moore, 1982).

3.6 Drilling progress

Drilling progress for the 2017 boreholes are given in Figure 5. Although the rate of penetration (ROP, in m/hour) that appears constant at about 3 m/hour, the true progress varied substantially, mainly due to problems with the supply of seawater drilling fluid. The relative daily drilling progress for the three 2017 boreholes (Figures 5) is compared with daily progress of the 1979 borehole (Jakobsson and Moore, 1982).

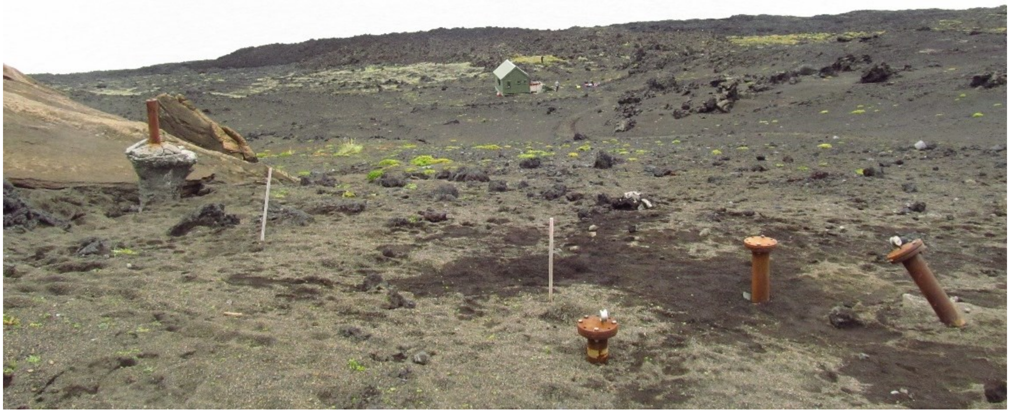

Figure 6: Photograph showing the wellheads of the three 2017 boreholes and the 1979 borehole (to the left).

Table 2: Boreholes drilled in Surtsey in 1979 (SE-01) and 2017 (SE-02a, SE-02b, SE-03) (after Weisenberger et al., 2019).

Bore-hole name	Hole ID	Coordinates (WGS84)	Flange height a.s.l.)*	Reference level (mduring drilling (m a.s.l.)*	East** North** (m)	Horizontal Distance from SE-01 (m)	Depth** * (m)
SE-01	73552	63° 18.09749'N	58.40	-	419756.79	0.00	180.6
		20° 35.98221'W			311669.86		
SE-02a	73553	63° 18.09659'N	58.01	57.57	419749.70	7.08	152.01
		20° 35.99063'W			311668.38		
SE-02b	73554	63 18.09739'N	57.86	57.65	419750.11	6.86	191.85
		20° 35.99020'W			311669.85		
SE-03	73555	63° 18.09649'N	58.13	57.65	419748.81	9.92	354.64
		20° 35.99170'W			311668.22		

* a.s.l.: above sea level; ** Reference coordinate system: ÍSN93; *** SE-03 is inclined 35° from vertical; depth is along hole axis.

3.7 Borehole locations

Boreholes drilled in 2017 (SE-02a, SE-02b, SE-03) are drilled in close vicinity to the cored borehole drilled in 1979 (SE-01) (Figure 1, Table 2). The wellhead of the vertical SE-02a borehole lies 7.08 m WSW of SE-01 and the wellhead of the vertical SE-02b borehole lies 6.86 m WNW of SE-01. The wellhead of the inclined SE-03 cored borehole lies about 10 m WSW from SE-01. The azimuth is directed to the west (264°), and the horizontal displacement at the bottom of the well is about 203 m from the wellhead. The heights of the wellhead flanges were measured on 11 September 2017 and on 20 July 2018. Well-head heights relative to sea level are given in Table 2. Figure 6 shows the wellheads and after completion of the drilling activity for reference. The ground surface is loose unconsolidated tephra, and is expected to change with time.

3.8 Borehole design

Drilled depths, casing lengths, and borehole design are shown in Figure 7 The reference level during drilling was the local ground surface. However, due to the unconsolidated nature of the surficial tephra, the reference level differs among the individual boreholes.

3.8.1 Borehole SE-02a

The SE-02a cored borehole was vertically pre-drilled with a 6⅛" tricone rotary drill-bit to a measured depth of 9.55 m. A 4½" HWT conductor casing (outer diameter: 114.3 mm, inner diameter: 101.6 mm) was lowered to a casing shoe depth of 9.54 m and cemented. It was necessary to place and cement the conductor casing twice as caving of tephra prevented satisfactory cement displacement. After waiting on cement to set, coring with a HQ3 (outer diameter: 88.9 mm, inner diameter: 77.8 mm) bit reached a total depth of 151.57 m. Here, the string got stuck. The drill crew pulled the string free in three attempts, and raised the string by 6 rods. The string then got stuck again with the coring bit at 133.27 m measured depth, leaving an 18 m uncased section at depth. Five cuts were made at progressive depths to retrieve the HRQ rods at 122 m measured depth and at rods 37, 34, 18, and 15. The string could not be pulled from the uppermost cut at 46 m depth, however, and 43 HRQ drill rods and the bottom-hole assembly (4.14 m) remained in the borehole. Work on the borehole was terminated on 17 August 2017. An extension of the HWT conductor casing and a flange were installed 0.44 m above the reference ground level.

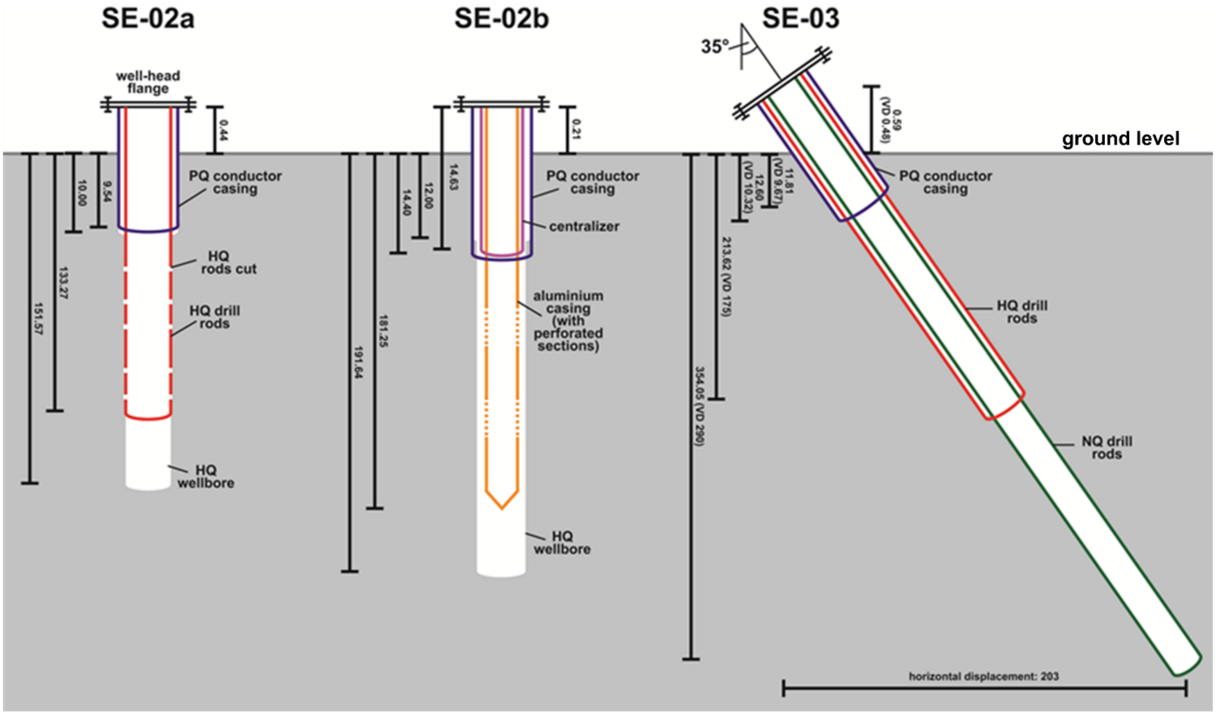

Figure 7: Schematic drawing of boreholes drilled on Surtsey in 2017. Although the ground surface is shown as a horizontal surface, variations exist in ground level. Measurements are recorded relative to the local ground level at each site at the time of drilling (adapted from Weisenberger et al., 2019).

3.8.2 Borehole SE-02b

The SE-02b borehole was rotary drilled from the surface to about 13 m with a 6⅛" tricone bit. A 4½" HWT conductor casing was lowered into the hole and cemented in place with the casing shoe at 12.74 m measured depth. After waiting on cement to set, coring with a HQ3 began. At 20.84 m measured depth the conductor casing lifted up. This was pulled from the borehole and another cement job carried out. After waiting on cement, coring continued to 81.84 m measured depth when the conductor casing displaced downwards about one meter. An attempt to fish the HWT casing resulted in the recovery of only two casing segments. Two 10-foot HWT new segments were inserted, and a 5-foot segment added; the joints were welded together. Thus, twenty-five feet of new casing were threaded into the two remaining HWT casing segments. This extension resulted in a new casing shoe depth of 14.40 m. Coring then continued to a total depth of 191.64 m.

Wireline logging was conducted after pulling the coring string out of hole to a depth of about 40 m. The 2⅝" (66.675 mm) T-6061 anodized aluminum tubing for the Surtsey Subsurface Observatory was then run into the borehole to a landing depth of 181.25 m. This consists of fifty casing tubes in which five perforated segments were placed at 38, 63, 106, 136, and 161 m measured depth from the flange (Table 3). The perforated tubes have 29 rows of five ¼-inch punched perforations that extend over four feet, centered in the mid-section of the 12-foot long pipe. The flush joints of the tubes were wrapped with Teflon tape and wrenched together by hand. Teflon tape concentrates organic compounds at the joint, as compared with paste lubricants that could have been smeared along tubing surfaces, potentially contaminating the observatory. The aluminum tubing occurs in three lengths, due to sourcing constraints encountered by the provider. At the top of the borehole, PVC centralizer tubes were installed between the aluminum tubing and the steel HWT conductor casing to minimize corrosion over time. A flange was installed 0.21 m above the reference ground level. A custom wellhead cap and cover holds a Vectran rope that can be used for incubator experiments.

Table 3: Location of perforated sections for the 2¾" aluminum tubing in borehole SE-02b.

No	Perforated section (m)*
1	37.42 - 38.64
2	62.72 - 63.94
3	106.10 - 107.32
4	135.02 - 136.24
5	160.48 - 161.7

3.8.3 Borehole SE-03

The SE-03 cored borehole was pre-drilled at 35° from vertical with a 6⅛" tricone rotary drill bit to a measured depth of 12.6 m. After lowering the 4½" HWT conductor casing to a casing shoe depth of 11.91 m, the conductor casing was cemented in place. After waiting on cement, coring with a HQ3 bit tagged cement at 11.39 m. Coring continued to 213.89 m measured depth, when the supply of HRQ drilling rods was fully consumed. The HQ rods remained in the borehole to a measured depth of 213.62 m and coring continued with an NQR string (outer diameter: 66.9 mm, inner diameter: 60.3 mm). Coring with a NQ3 bit reached a total measured depth of 354.05 m. This corresponds 290 m vertical depth below the ground surface and a horizontal displacement of about 203 m (Figure 6). The NRQ coring string was left in the hole as permanent casing, including the NQ3 bottom-hole assembly. An extension of the HWT conductor casing was added and a flange was installed, at 0.48 m above the reference ground level. This corresponds to an additional well length of 0.59 cm.

4. CORE PROCESSING

4.1 Core processing in the Heimaey laboratory

The core processing operation on Heimaey started on 8 August, 2017 and took place in a large warehouse generously provided by the Vestmannaeyjar municipality. The workflow consisted of five principal tasks, whereas the workflow was elaborated based on lake core drilling protocols. (i.) Drill core inventory: cores were delivered to Heimaey via helicopter from Surtsey at intermittent intervals. The core inventory was verified with the driller reports, sample protocols, and core protocols and then entered into the DIS (Digital Information System). (ii.) Multi Sensor Core Logger (MSCL). (iii.) Drill core marking, cleaning with fresh seawater and packing in core trays (iv.) Digital core imaging: DMT CoreScan 3 instrument provided by ICDP generated high-resolution images of the drill core. (v.) Visual core descriptions: Macroscopic observations of the drill core were recorded in a visual core description template designated within the DIS. Core processing in Heimaey was continued until mid-September.

4.2 Core processing in Gardabaer

In order to complete the core processing, additional work took place at the Icelandic Institute of Natural History in Gardabaer, near Reykjavik. This included modifying procedures in line with hard rock drilling protocols. The core processing included the following tasks: (i.) All core in liners that were stored in fish bins for transportation from Heimaey to the IINH were assigned to core trays, based on individual core runs. (ii.) The core inventory for SE-02b and SE-03 was checked and corrections made where needed. (iii.) Database information for samples taken during the Heimaey core processing operation were updated and standardized. (iv.) All core was removed from liners, marked with blue/black and red reference lines, and washed with fresh seawater. (v.) Any mold was removed. (vi) Reference samples were imaged, documented, cut, and prepared for distribution. (vii.) Core from SE-02b and SE-03 was imaged with the ÍSOR core scanner smartCIS. Some sections already imaged in Heimaey needed to be imaged again, due to updating of the core inventory. (viii) New visual core descriptions were made for cores SE-02b and SE-03 within a time period of 3.5 weeks.

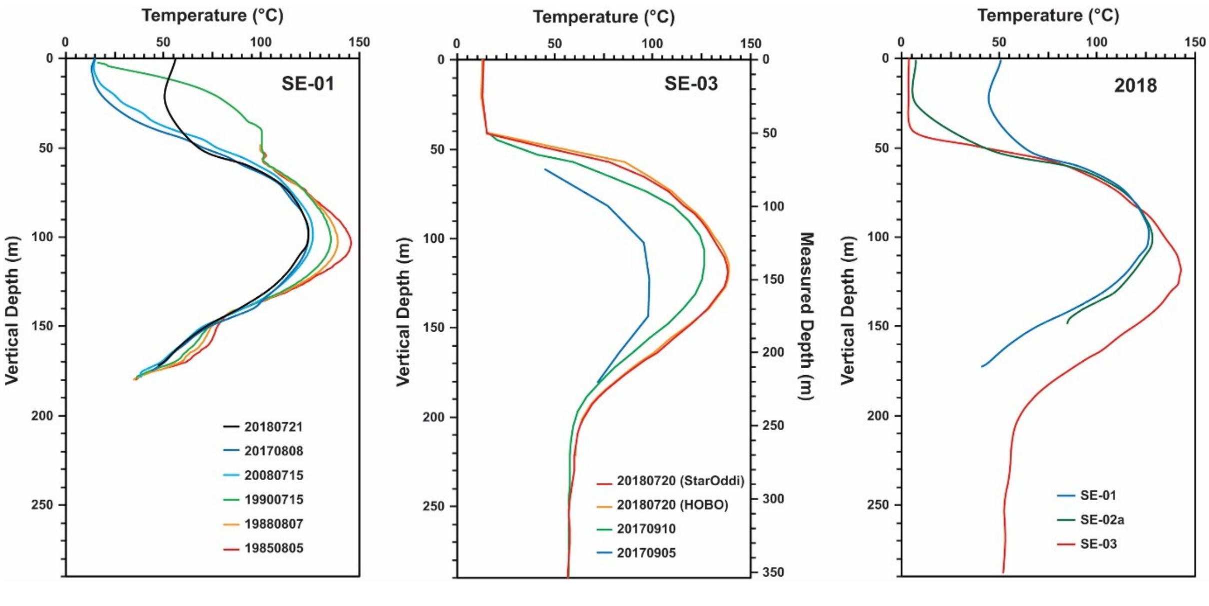

Figure 8: Temperature logs for wells on Surtsey (data before 2017 taken from the ÍSOR database, Data from 2017 derived from Weisenberger et al. 2019, data from 2018: this study). For the 2018 2 temperature memory tools have been used (StarOddi, HOBO).

5. THERMAL CONDTIONS

Figure 8 provides temperature logs of wells from Surtsey. Time serious measurement of well SE-01 show that the maximum temperature at a vertical depth of about 100 m has dropped since 1980 from about 140°C to 124°C, although the general shape of the temperature profile remains similar over the time period. The temperature profile of SE-02a shows similar trend than the profile of SE-01. However, the maximum temperature in SE-02a is about 1.5°C higher. Temperature logs of the vertical wells indicate an inflow of cold water at about 145 m below the surface. The temperature in the diatreme beneath the island (Jackson et al., 2019) is about 60°C, well above the expected ambient temperatures for the ocean floor.

The maximum measured temperatures in the angled well SE-03 during the annual Surtsey research expeditions 2018 yield a temperature of 138°C, which is 14°C hotter than in the vertical wells. The temperature maximum is also about 20 m deeper than in the vertical wells. Time series measurement started shortly after drilling was completed indicates that the well SE-03 had reached thermal equilibrium after drilling in 2017. The rise in temperature towards west suggests that the hottest part of the geothermal reservoir within the edifice lies under the main craters of the 1963-1967 eruption.

The thermal conditions of Surtsey were analyzed after the drilling in 1979 by Axelsson et al. (1982) and Stefánsson et al. (1985). These analyses suggested that the geothermal area in Surtsey could be explained by heat release from sizeable intrusive bodies within the edifice. The new data from Surtsey holds the potential for testing out this and other possible ideas on the sources of heat for this ocean-island geothermal system.

6. SUMMARY

The zero-impact drilling in the summer 2017 at the Surtsey UNESCO world heritage site resulted in the recovery of three cored boreholes and the installation of the Surtsey Subsurface Observatory. Two vertical holes (SE-02a, SE-02b), 152 and 192 m deep, respectively, are parallel and adjacent (< 8 m distance) to the 1979 (SE-01) borehole. In addition, a 35° angled cored borehole (SE-03) was drilled from the same drilling platform to the west, under the Surtur I crater. This core extends to a measured depth of 354 m, which corresponds to a vertical depth of about 290 m.

Although the tuffs drilled are soft compared to crystalline basalts, they are competent rocks and the procedures that best fitted the operation were those for hard rock. Therefore, we suggest to apply core processing protocols based on had core drilling standards, instead using protocols that follow lake core drilling procedures.

The new cores will reveal information about the cooling of the hydrothermal system, a possible location of the recharge zone and the water-rock interactions. These include the role of meteoric water within the seawater dominated system and the progressive palagonitization and consolidation of glassy basalt deposits through abiotic and/or biotic processes. Comparisons of the new core with the 1979 core will further quantify rates of reaction as function of time and temperature.

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