Fifty year evolution of thermal manifestations at Surtsey Volcano, 1968 – 2018

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ABSTRACT
The geothermal activity in Surtsey over the decades provides a very valuable record of the evolution of a volcanic geothermal system following its development and its relation to the process of palagonitization. The present study compiles all published as well as unpublished data on the surface manifestations of geothermal activity and measurements in the drill hole completed in 1979, to give a comprehensive account of the evolution of the thermal area at Surtsey during the period of 1968-2018. Most of this work was done by the late Sveinn P. Jakobsson. Overall, the time series demonstrates a slow but clear trend of cooling of Surtsey with time: the thermal activity within the lava rapidly cooled from recorded emission temperatures in fumaroles of up to 460°C in 1970, to ambient temperatures within 30-40 years after emplacement. In contrast, the thermal area within the tephra/tuff exhibits a gradual onset of geothermal activity. The onset on Surtur (Austurbunki) was first detected in 1968 and high temperatures still prevail at the surface where temperatures have only declined from 100 to 80-90 °C in 50 years. The onset on Surtungur (Vesturbunki) was detected in 1974 and the maximum temperatures recorded have remained within the 90-100 °C range since 1979. The intermediate area between Surtur/Austurbunki and Surtungur/Vesturbunki has exhibited activity broadly in the same way as Surtur/Austurbunki and maximum temperatures that remained within the 90-100 °C range from 1979-2000, are now clearly declining. Maximum temperatures in the 1979 drillhole were 141 °C in 1980 but they have been steadily declining, reaching 123 °C in 2018.

INTRODUCTION
The volcanic island of Surtsey forms part of the Vestmannaeyjar volcanic system at the southern end of Iceland's Eastern Volcanic Zone. Surtsey's volcanic eruption is estimated to have started about 40 hours before the first visible explosive activity broke the sea surface on November 14, 1963 (Sayyadi *et al*. 2021). During this four and a half month long phreatomagmatic explosive phase, tephra of alkali olivine-basalt composition was produced. The deposition of the tephra resulted in the formation of the two crescent-shaped cones (Fig. 1) of Austurbunki (at the time of the eruption the name Surtur I was used - Thorarinsson, 1965) and Vesturbunki (previously named Surtur II), each with a diameter of about 400 m and a height of 150 – 170 m above sea level. (Jakobsson & Moore 1982).

The names of localities have evolved with time since the Surtsey eruption. The two vents that formed on Surtsey were originally called Surtur I and Surtur II. This was then changed to Surtur for the eastern lava crater and Surtungur for the western lava crater, and in later years, the tephra cones have been called Austurbunki and Vesturbunki, while Surtur and Surtungur are still used for the lava vents. For simplicity, and ease of reference to some of the early publications, we use the names Surtur for the

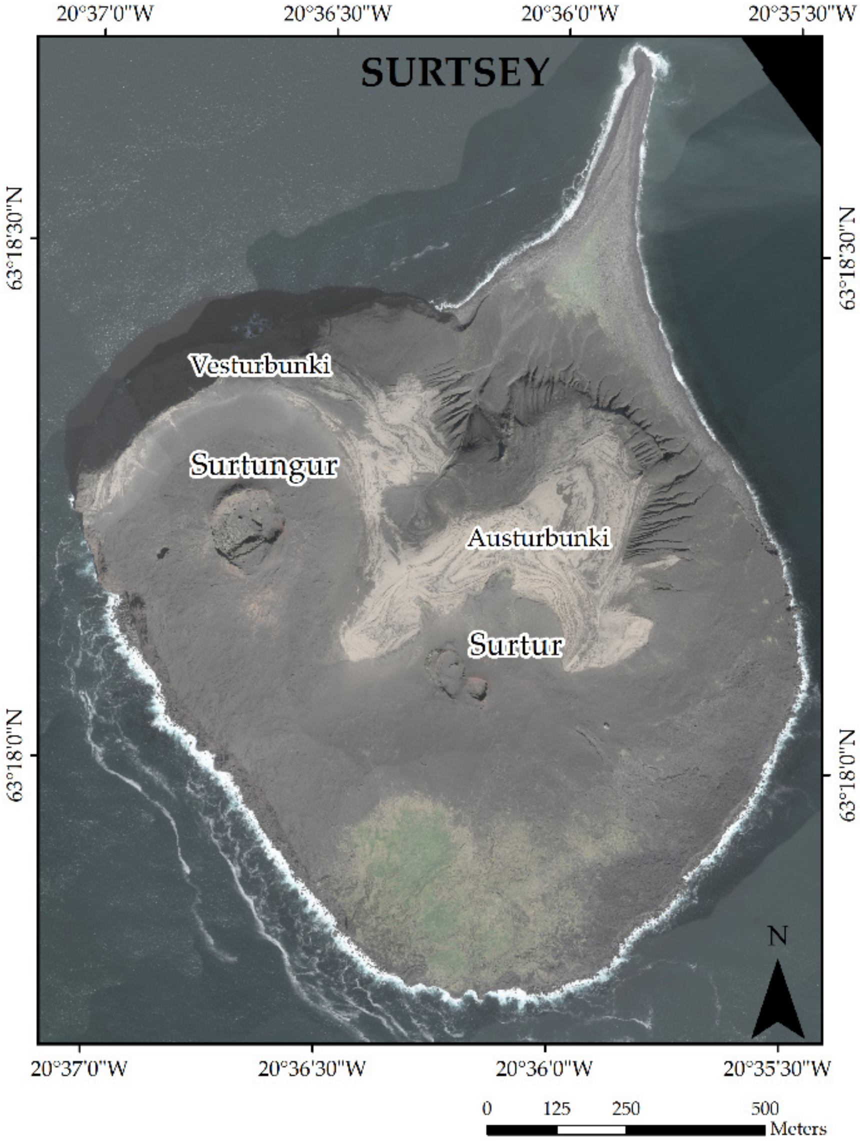

Figure 1. Aerial photograph of Surtsey taken in September 2018 (Loftmyndir ehf. 2018).

present day Austurbunki+Surtur, and Surtungur for Vesturbunki+Surtungur. Care is taken to differentiate between the tephra cones and the lava craters in the text.

On April 4, 1964, when seawater could no longer access the Surtungur vent (Surtur II), the eruption style changed from explosive to effusive, forming the Surtungur lava crater. Lava deposition on Surtsey occurred in three distinct phases (Jakobsson & Moore 1982). The first one lasted 13 months (April 1964-May 1965), building a lava shield. This eruptive phase was followed by a 15-month hiatus of activity on the Surtsey island, as explosive, phreatomagmatic activity built the new islands of Syrtlingur and Jólnir, both of which were quickly washed away by marine erosion (e.g., Thorarinsson 1968). The second phase of effusive activity on Surtsey lasted about 10 months (August 1966-June 1967), when a 220 m long fissure opened along the floor of Surtsey's eastern crater. The third phase occurred in December 1966-January 1967 when new fissures became active, and lava broke through at four additional sites in Austurbunki tephra cone. These third phase eruptions were all very minor (Baldursson & Ingadóttir 2007). When the volcanic activity on Surtsey finally ceased on June 5, 1967, the oceanic island that formed reached 175 m above sea level. Considering that the sea water depth before the eruption had been about 130 m, the total height of Surtsey volcano was 305 m in 1967 (Jakobsson 1972).

The island of Surtsey has changed considerably since the end of the eruption in 1967. Its shape is constantly modified by the harsh conditions of intense wave action in winter, prevailing in the sea south of Iceland (Jakobsson & Moore 1982). In 1968, Thorarinsson estimated that by the end of the eruption in 1967, Surtsey had reached a size of 2.65 km^2 and that the total production of eruptives during the eruption was 1.1 km^3, about 60-70 % of which was tephra (Thorarinsson 1969). By 2019, gradual erosion of the island had reduced its size to 1.22 km^2 (Óskarsson *et al.* 2020).

One of the main objectives of the initial studies at Surtsey was to closely follow the processes of consolidation and palagonitization of basaltic tephra to describe how these processes take place under the local physical conditions (Jakobsson & Moore 1982). Since its formation, Sveinn P. Jakobsson visited the island almost every year. He frequently inspected the area of primary tephra and sampled various localities to determine the start and the conditions of the expected process of consolidation and palagonitization of the tephra (Jakobsson & Moore 1982).

The first signs of consolidation in the tephra were observed in August 1966 in a few places such as the top of Surtur. When this observation was made, only the outermost 10-15 cm of the exposed tephra layers were consolidated. This was believed to be the result of the frequent oscillations in temperature and moisture that the surface experienced, as it faced the main direction of precipitation and sun exposure (Jakobsson & Moore 1982). In April of 1968, Sigurður Thorarinsson discovered heating of tephra with emanations of steam at the surface of Surtur (Jakobsson 1978). Additionally, this thermal anomaly was also observed in the infrared images taken on August 22, 1968, during a study conducted by Friedman and Williams (1970). It was then suggested that a geothermal system was being developed as a consequence of intrusive activity in the eastern tephra crater during December 1966-January 1967 (Jakobsson & Moore 1986).

A year after the thermal anomalies were discovered, Sveinn P. Jakobsson observed the first signs of palagonitization on the surface at the southeast corner of Surtur in September 1969. The geothermal activity caused the basalt tephra to alter rapidly into palagonite. Consequently, upon the discovery of the first signs of palagonitization, a program was established to monitor the expansion of palagonite tuff on Surtsey (Jakobsson 1972). This was the first time that the process of palagonitization was monitored in a natural setting (Jakobsson 1972, Jakobsson 1978). The program consisted of measuring areas of tephra and tuff on average every third year. Rock samples were taken and the expanding area of palagonite tuff was mapped in every expedition (Jakobsson 1978, Jakobsson *et al.* 2000).

The palagonitization and consolidation rates of the Surtsey tephra were estimated by Sveinn P. Jakobsson based on surface observations made during the period of 1969 – 1977. The results indicated that at 100 °C, it takes one to two years for the tephra within the greater part of the tephra cone above sea level, to convert into dense palagonitized tuff with the volume fraction of palagonite exceeding 10%. However, the rate of palagonitization was considerably slower at lower temperatures, particularly where the temperature had dropped below 40 °C (Jakobsson 1978).

In 1979, a 181 m deep hole was drilled, and a core extracted through the eastern rim of the Surtur tephra cone (present day Austurbunki), reaching close to the pre-eruption seafloor. This scientific drilling project was originated because of the exceptional opportunity to study the development of a historic, well-studied, oceanic volcano from its inception on the seafloor, through the formation of a volcanic island, to the modification of the volcanic edifice by geothermal processes (Jakobsson & Moore 1982). A second drilling program took place in 2017, the ICDP-supported SUSTAIN project where three cores were extracted at the same location as the 1979 drillhole to further study the structure and evolution of the island (Jackson *et al.* 2019, Weisenberger *et al.* 2019, Prause *et al.* 2020, Kleine *et al.* 2020, McPhie *et al.* 2020, Bergsten *et al.* 2021). The present study contributes to the overall aim of this work of documenting and further understanding the evolution of a volcanic island after its formation.

METHODS

During these geologic expeditions, the surface of Surtsey has been mapped in detail using conventional methods to follow the extent of the thermal area and the extent of the palagonite tuff. The first temperature measurements were performed by Sveinn P. Jakobsson in September 1969, and by August 1970, the thermal field was mapped in detail for the first time (Jakobsson 1972). Ævar Jóhannesson, at the Science Institute of the University of Iceland, contributed significantly to the mapping of the thermal area in 1970 and 1975, by making temperature measurements on both Surtur and Surtungur's tephra and lava fields (Jóhannesson 1972, Jóhannesson 1978).

Throughout four decades, Sveinn P. Jakobsson continued to perform thermal surveys and contribute to the logging of the surficial temperatures of the geothermal area. His records show that conventional mapping was performed until 2006, when more modern techniques started to be implemented. After Jakobsson's last visit to Surtsey in 2008, Icelandic Institute of Natural History (IINH) geologists, Lovísa Ásbjörnsdóttir and Kristján Jónasson, took over the thermal monitoring. Additionally, the 2018 survey was conducted by Velveth Perez, as a part of her master's by research project at the University of Iceland.

Here the term palagonite is used as a synonym for altered, hydrated, basaltic glass, of brown or yellow color. The term is related to the alteration process,

Figure 2. Images taken during the 2018 thermal survey: A) Photograph of a steaming fissure located at the top of Surtungur tephra cone (Vesturbunki). B) Temperature measurement taken with the thermocouple sensor-stick. C) Trimble tablet with integrated GPS allows logging of the temperature reading. D) Additional record of the temperature measurement coordinates made with handheld GPS.

called palagonitization. Móberg (palagonite tuff), is an Icelandic term for brownish, consolidated tephra, of basaltic or intermediate composition (Jakobsson 1978, Stroncik & Schmincke 2002). Thermal field refers to the area at the surface of Surtsey that presents thermal anomalies.

During the most recent geologic expeditions at Surtsey, the thermal surveys are completed using an electronic thermometer that features an infrared sensor with a laser pointer, and a temperature-sensor thermocouple stick attachment (Fig. 2). In addition to a Trimble tablet with integrated GPS, the exact location of the temperature measurements is logged with the aid of a handheld GPS. This technology has improved the monitoring surveys by replacing the conventional mercury thermometers and the topographic paper maps that were used in the past.

As a consequence of the highly consolidated state of the palagonite tuff, temperature measurements are taken along a network of open fissures that are located throughout Surtur and Surtungur's palagonitized tuff cones. This network is clearly noticeable due to their elevated topography in contrast with the surrounding area, as well as the altered coloration of most of the fissures. In some cases, these active fissures also present condensation and emanation of steam. The temperature measurements in the open active fissures are performed by introducing the thermocouple temperature-sensor stick deep (approx. 15-20 cm) into the ground. A fair number of fissures are non-active and have been closed by scaling that has been deposited along the opening. Surface temperatures of these closed fissures were logged using an infrared laser gun thermometer.

Nineteen original paper maps that are part of the unpublished data by Sveinn P. Jakobsson on the surface manifestations of the thermal activity were digitized using GIS software. Nine additional maps were created with the temperature data that is available in the digital record of the IINH. Jakobsson's geological maps of Surtsey in scale 1:5000 were used and different features of the thermal manifestations that he tracked during the thermal monitoring surveys include: the palagonite tuff, thermal area extension, steaming fissures and temperature measurements. Additionally, the extent of the palagonite tuff was mapped with the aid of aerial photographs taken usually every other year.

The extent of the thermal area and how it changes with time is an important parameter in describing the evolution of Surtsey. In this study, the area at any given time is defined with three methods: when available, with the 20 °C isotherm line; with the defined area according to Jóhannesson's (1972) and Jakobsson's field data; and with thermal data extrapolation to 20 °C.

During the spatial and temporal analysis of the thermal area at Surtsey, the maximum temperatures recorded for the lava and the tephra are listed separately to monitor their course individually. For better comprehension and due to its volume and extent, the tephra thermal region is further subdivided into three separate areas: the Surtur (Austurbunki) tephra cone, the Surtungur (Vesturbunki) tephra cone, and the intermediate tephra zone. Six thermal survey maps from the following years were chosen for further analysis due to their substantial amount of thermal data in comparison with the rest: 1970, 1979, 1988, 2000, 2011, and 2018. The time elapsed between these surveys is suitable for analysis of the progression of the thermal area and its manifestations.

Additionally, the temperature in the 181-m-deep drill hole from 1979 has been monitored regularly for the past forty years by measuring the temperature. The record shows seventeen logs. However, only five of these will be used in this study to tie the evolution of the surface manifestations of the geothermal system to the subsurface temperatures: 1980, 1990, 2000, 2009, 2018. These surveys were strategically chosen to be about one decade apart.

RESULTS

The lava fields

Surtungur: The thermal data shows that the maximum recorded temperature of vapor/gas emitting from fissures in the Surtungur's lava pile was 460 °C in 1970 (Fig. 3) (Jóhannesson 1972), about 40% of the initial magma temperature estimation of 1150 °C. Vapor emissions decreased rapidly, and in 1974, the highest temperature recorded reached 160 °C (data not shown).

Temperatures remained constant for some years, until a slow increase was observed between 1983 – 1985 (data not shown). An even slower but steady decrease in temperature began after that. A substantial gap in the thermal record of the entire lava thermal region was observed for most of the 1990's, and by the year 2000, the maximum temperature recorded was already down to near-ambient values with a maximum of 16 °C (Fig. 3). No thermal anomalies were observed in the lava fields in 2018.

Surtur: The thermal record for Surtur's lava field was not as consistent nor as complete as the monitoring of the thermal area on Surtungur. The maximum temperature found within Surtur's lava field in 1970 reached 63 °C, at a location within a fissure that had been active in January 1967 (Fig. 3). Additionally, Jakobsson's thermal records from this area focused on the fissures located at the slopes of the tephra cone (Austurbunki). The highest maximum temperature value of 100 °C was recorded in 1979-1980 (Fig. 3). This temperature measurement was not from the lava field and was taken from vapor emitted from a fissure that is located within Surtur's cone inner wall.

The maximum temperature values oscillate during the following years and the recorded temperature never reached similarly high values again. Regardless of these temperature fluctuations, an overall decrease in temperature was observed in the thermal record and the last surface temperature measurement was taken in 2008, at a value of 55 °C (data not shown).

The Surtur (Austurbunki) tephra cone

The first thermal survey made on the tephra formation was done in November 1969. At that time, the maximum temperature at the surface of Surtur´s tephra cone was 84 °C. By the following year, temperature values between 98 °C and 100 °C were reported by Ævar Jóhannesson (1972) and Sveinn P. Jakobsson (1972), near the location where the first signs of palagonitization were observed (Fig. 3). In August 1970, only the inner wall of Surtur's tephra cone showed consolidation, and within this consolidated area, an even smaller volume of tephra showed signs of palagonitization.

The thermal records of the following years showed a period of substantial temperature fluctuations during the first decade after the onset of the thermal activity. Surface temperature values gained stability in 1979 and temperatures stayed within 90– 98 °C until 1992. There was a substantial gap in the data for the following years, but a survey performed in 2000 placed the maximum temperature value at 98 °C (Fig. 3). Another period of stable temperatures within the 84 – 100 °C range began in 2008 (data not shown). Surface temperature measurements made in 2018, placed the maximum temperature value at 88.9 °C (Fig. 3). Additionally, most of Surtur's tephra cone had been palagonitized, except for the distal parts of the eastern and the north-facing slopes where the tephra still presented a very low degree of consolidation.

The Surtungur (Vesturbunki) tephra cone

In 1970, the maximum temperature recorded in Surtungur's tephra only went as high as 10 °C (Fig. 3). Temperature values for the next few years presented an overall increase and by 1979, the temperature reached 98 °C (Fig. 3). There was a period of stable values, within the 90-99 °C range, during the following decade, and a temperature of 100 °C was reached in 1992 and 2008 (data not shown). The maximum temperature value that was measured during the 2018 thermal survey reached 92.4 °C (Fig. 3) and by then, palagonitization had altered Surtungur's entire inner wall. If the geothermal activity continues in this area, palagonitization can be expected to fully cover the north-facing slope of the cone in the years to come. Additionally, a value of 88.9 °C was measured at the top of Surtungur's rim during the thermal survey performed in 2018 (Fig. 3).

The intermediate tephra zone

The thermal record for the zone where the Surtungur tuff cone overlaps the Surtur cone is referred in this study as the intermediate tephra geothermal area. Thermal activity has been observed within this zone since the onset of the thermal manifestations at the surface of the tephra in 1968. The first thermal monitoring performed in 1969 covered this area and placed the maximum temperature value at 80 °C (data not shown). Between 1969 and 1976 the thermal record showed a substantial temperature fluctuation around 85 °C, within the 15 – 100 °C range. In 1979, maximum temperatures gained stability, with values staying within the 90 – 100 °C range (Fig. 3). This continued until 2000, when the maximum temperature value dropped to 80 °C (Fig. 3). Fluctuations were also observed in the following years, but in 2018 the maximum temperature value was still 80 °C (Fig. 3).

Changes in the extent of Surtsey's thermal field

Using a combination of Jakobsson and Jóhannesson's (1972) records, the surface area of the thermal heat anomaly was calculated to be around 0.42 km^2 in 1970 (Fig. 4e). At this time, most of the anomaly was concentrated within the lava thermal region, specifically that of Surtungur's lava field and in the small craters in the tephra cone that erupted for a few days in 1966/67. The surface manifestations were present on Surtur's tephra cone as well as the intermediate tephra zone, but only ambient temperatures were recorded at the surface of Surtungur's tephra cone (Fig. 3).

In 1979, the surface manifestations of the thermal heat anomaly covered a surface area of about 0.39 km^2 (Fig. 4e) Spatial analysis placed the largest extent of the thermal anomalies within the entire tephra region. A decrease in surface area was observed in the following years, especially within the lava thermal region (Fig. 3). By 1988, the extent of the thermal heat only covered about 0.01 km^2 of the lava region (Fig. 4a), and the entire thermal field had been reduced to 0.33 km^2 (Fig. 4e).

In 2000, the lava thermal region presented only ambient temperatures (Fig. 3). At this time, the thermal field was 0.21 km^2 (Fig. 4e) and most of its manifestations were localized at the surface of Surtur's tephra cone (Fig. 3). A considerable change in the extent of the thermal field was also observed in 2011. The entire thermal field was then confined to 0.04 km^2 (Fig.4e) along the rim of both tephra cones (Fig. 3). Additionally, the thermal anomaly of the lava field region had completely disappeared (Fig. 3).

The 2018 spatial and temporal analysis of the field observations and temperature measurements placed the extent of the thermal field at about 0.021 km^2 (Fig. 4e). Most of the manifestations were still observed along the rims of both tephra cones.

Surtsey 1979 drill hole analysis

The temperature measurements that have been gathered in the 181-m-deep drill hole since 1980 have shown a general cooling trend of the geothermal system deep inside the island with a

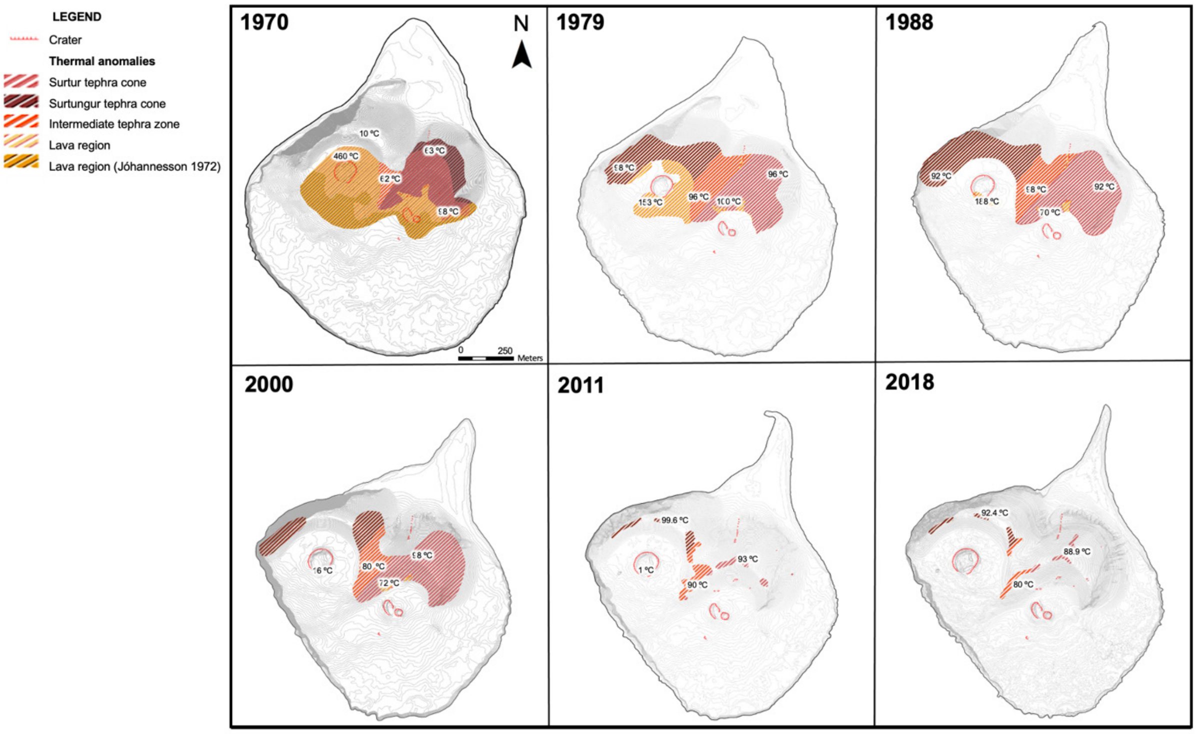

Figure 3. Extent of thermal field from 1970 to 2018, according to Jakobsson's map records and later survey data, and Jóhannesson's thermal survey (1972). Different colors correspond to different locations.

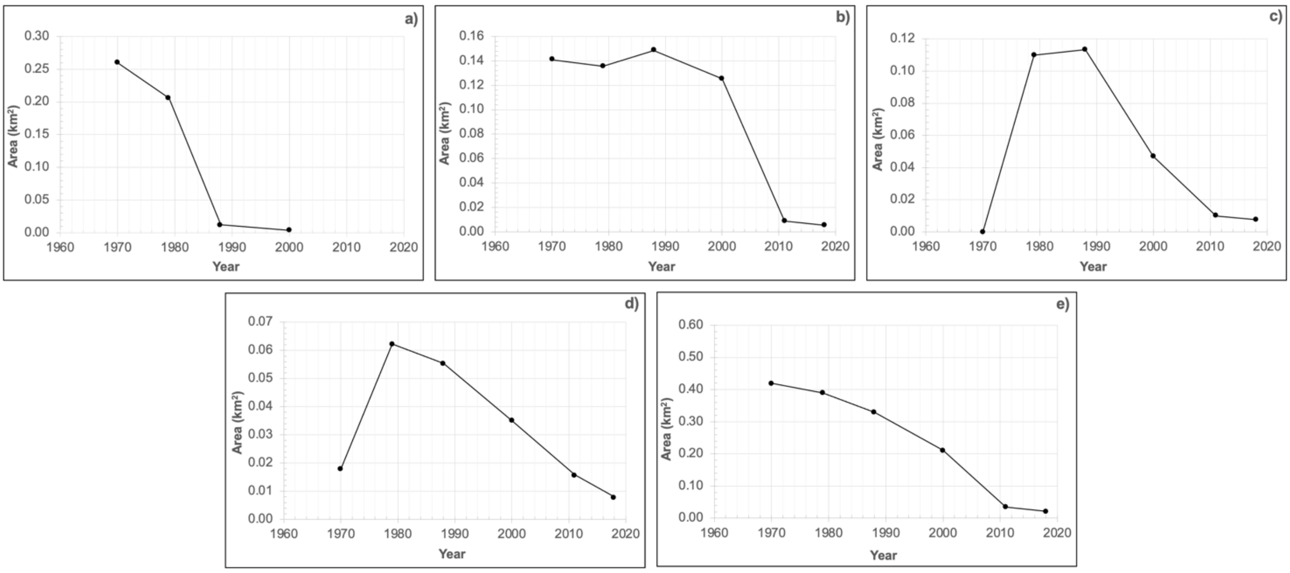

Figure 4. a) Extent evolution of the thermal area in the lava field region. The largest surface area is observed in 1970. A markedly decrease in surface area follows and by 2000, the thermal anomalies at the surface of the lava fields are about to disappear. **b)** Thermal evolution of Surtur's tephra/tuff geothermal area from 1969-2018. A gradual decrease in surface area is observed since 1969 with a marked decrease in the period from 1988-2011. **c)** Thermal evolution of Surtungur's tephra/tuff geothermal area from 1969-2018. A steep increase in the surface area is observed from 1969–1988, followed by a gradual decrease that is still observed by 2018 when the thermal manifestations on Surtungur declined to 0.008 km^2. **d)** Thermal evolution of the intermediate tephra/tuff zone geothermal area from 1969-2018. A steep increase in the surface area is observed from 1969–1979, followed by a gradual decrease that is still observed by 2018 when the thermal manifestations only extended as far as 0.008 km^2. **e)** The surface evolution of the extent of the entire thermal field on Surtsey. The surface area was largest in 1970, 0.42 km^2, but gradually decreased after that. Based on the thermal survey performed in 2018, the extent of the thermal field is about 0.02 km^2. Note the different scaling on the y-axes of the diagram.

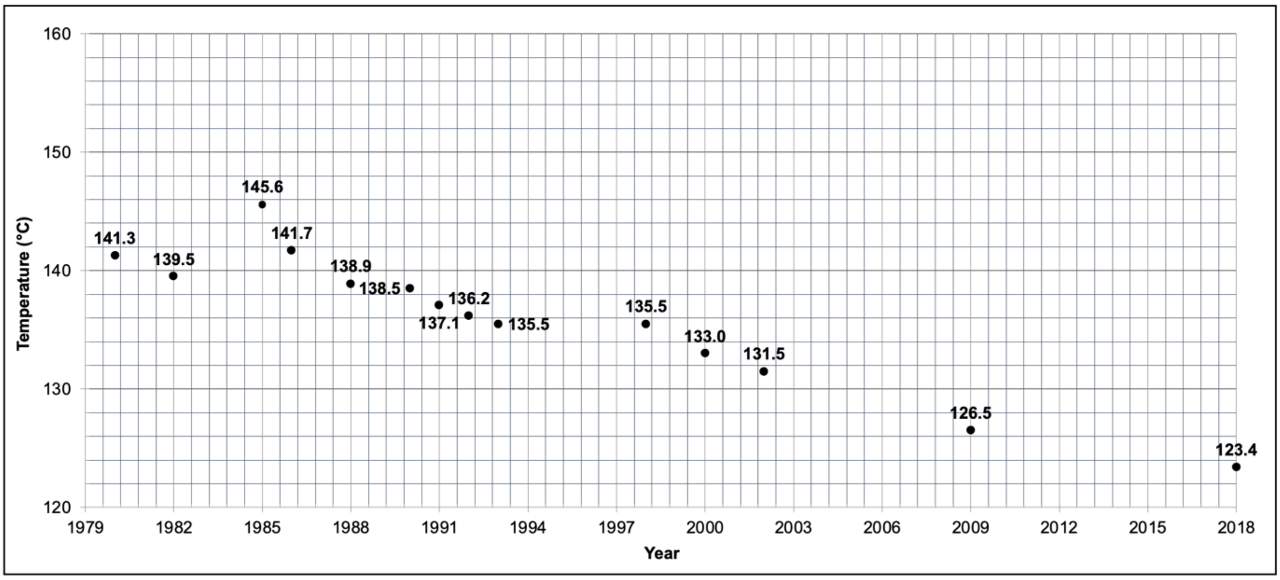

Figure 5. Graph showing the maximum temperatures measured in the 1979 drill hole during 39 years of thermal monitoring. Note that the y-axis only shows 120-150 °C.

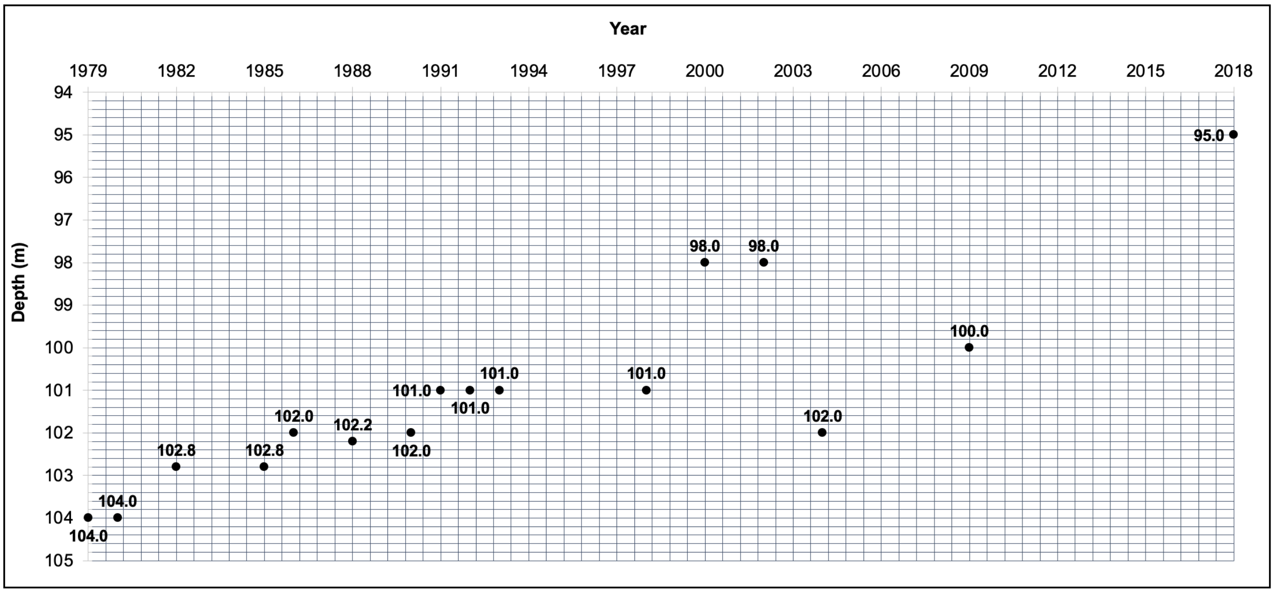

Figure 6. Graph showing the depth at which the maximum temperature zone is reached during 39 years of thermal monitoring. Note that the y-axis only shows the depth range of 94-105 m.

general cooling rate of less than 1° C per year (Fig. 5). The initial temperature measurement placed the maximum temperature of the geothermal system at about 100 m depth with values that measured up to 141.3 °C in 1980 (Fig. 5) while the maximum temperature recorded in 2018 was only as high as 123.4 °C at 95 m (Figs. 5 and 6). This accounts for an 18 °C drop in the maximum temperature in a 38-year period, giving a mean decrease of ~0.5 °C per year. Temperature profiles from 1980, 1990, 2000, 2009, and 2018 reached a maximum temperature zone at about 100 m depth (Fig. 6 and 7). Temperatures decreased below that to about 40 °C as depth reached 180 m (Fig. 7).

DISCUSSION

During the fifty years period of observations, it has not only been possible to document the evolution of the thermal activity at the surface of Surtsey, but also to follow closely the processes of consolidation and palagonitization of basaltic tephra and describe how they take place under the local physical conditions.

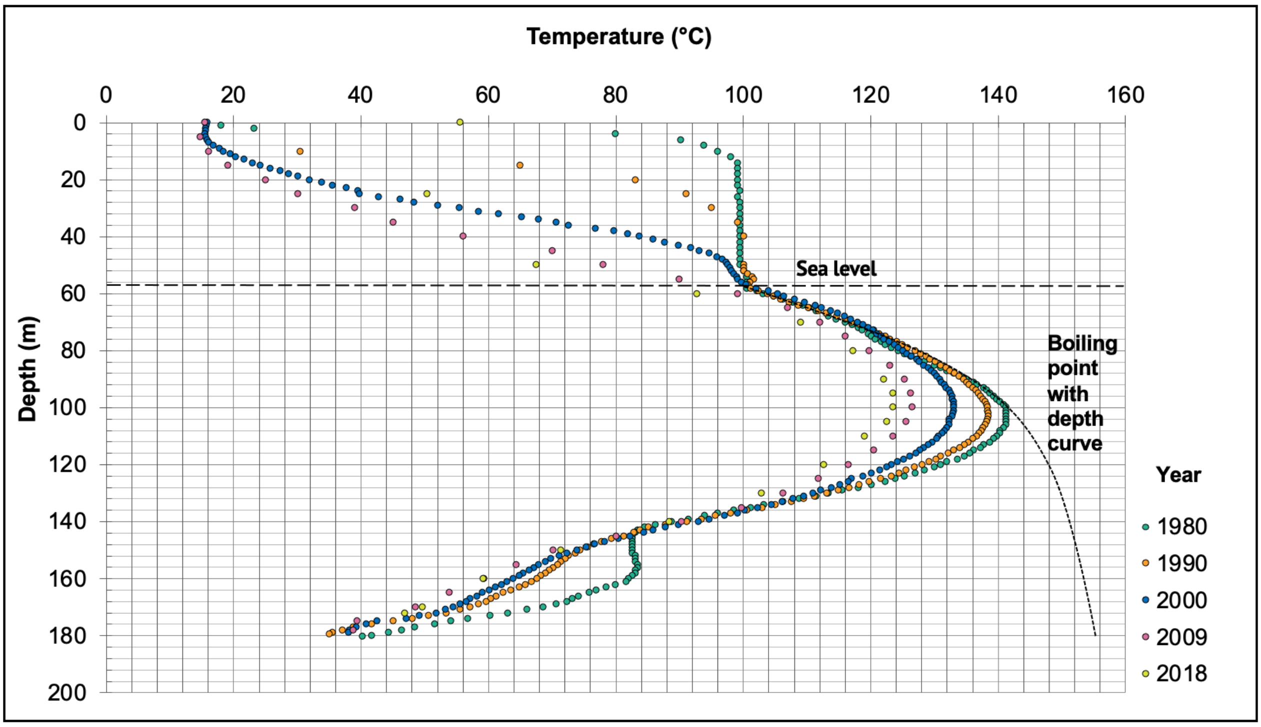

Figure 7. Temperature profiles from 1980, 1990, 2000, 2009 and 2018. The overall trend shows a decrease in temperature since 1980. The 2018 profile is from Prause et al. (2022).

The palagonitization of the Surtsey tephra
Jakobsson and Moore (1986) suggested that the geothermal system was developing as a consequence of intrusive activity at Surtur (Austurbunki), during the period of December 1966-January 1967. The record presented here supports a relationship between the intrusive activity and the early development of the Surtur geothermal manifestations, but it does not explain the gradual onset of geothermal activity in Surtungur (Vesturbunki), appearing a decade or so later. The surface temperature measurements demonstrated that the thermal area expanded within the tephra craters since the first thermal anomalies were detected in 1968, and that basalt tephra took about 1-3 years to convert to palagonite tuff at 80-100 °C (Jakobsson 1978). The observations made in this study, along with the map record analysis, conform to this link between temperature and palagonitization. They also provide a comprehensive account of the evolution of the thermal area at Surtsey during the period of 1968-2018, where it can be noted that as a result of the development of the thermal activity, the basalt tephra was altered rapidly into palagonite tuff. Moreover, the palagonitized area in 1970 had substantially increased in only one year, after the first signs of palagonitization appeared on the surface in 1969.

Thermal manifestations in the lava fields
Field observations and temperature measurements taken at the surface, reveal a distinctive variation in thermal activity within the entire thermal field on Surtsey with different time scales and intensities for different areas. The main source of thermal heat in the lava field areas was the remnant heat of the lava, as it solidified and cooled down from its estimated erupting temperature of 1150°C. Due to the volumetric and emplacement time differences between the lava fields, it is convenient to discuss separately the thermal areas in Surtur and Surtungur.

The thermal anomaly at Surtungur's lava field
Lava effusion from Surtungur's vent ceased in May 1965. The lava shield, that reached 100 m above sea level, had been cooling down for over five years before the first temperature measurements were recorded in the thermal survey of 1970. The rapid decrease in maximum temperature that was observed in the 1970-1974 record, from 460 °C to 160 °C, reflects a rapid cooling rate during this specific period. A thick lava flow can have some molten or partially molten interior parts and in the first years after full solidification of thick lava bodies, temperatures above the boiling point of water are to be expected (e.g., Turcotte & Schubert 2002). With

time, as precipitation can percolate through the fully solidified lava, interior temperatures should drop fast. This may explain the rapid cooling of the lava piles compared with the tephra cones.

Following the very rapid initial cooling observed into the 1970s, the lava began to cool down slower. Subsidence of the southern part of the lava shield, along with 10-20 cm widening of fissures at the surface, are considered to account for the modest temperature increase that is observed in 1983 (Jakobsson *et al*. 2000). Despite the substantial gap in the thermal record for most of the 1990's, the ambient temperatures recorded by 2000 indicate that the thermal anomaly in the Surtungur lava field completely disappeared within 30-35 years from the end of the eruption.

The thermal anomaly at Surtur's lava field

A 70 m lava shield was formed during the effusive eruptive activity that took place in August 1966-June 1967 at Surtur (Jakobsson & Moore 1982). In addition, five very minor lava flows from five different fissures, located on the slopes of the tephra cone, erupted in December 1966-January 1967. The Surtur thermal area of the lava field comprises both eruption zones and it is worth mentioning that the thermal record does not include temperature measurements from or around the Surtur crater depression.

In 1970, when the initial maximum temperature of 63 °C was recorded, the lava that erupted at Surtur had been cooling down for three years. The substantial initial heat loss at Surtur's lava field is comparable to Surtungur's, and this was followed by a slower cooling rate. In 2008, when the last thermal survey of the lava region was recorded, Surtungur's maximum temperature was near ambient, a 55 °C maximum temperature was recorded in one of the fissures that opened up in 1966. However, a fissure that is located a few meters away only reached a maximum temperature of 27 °C. With this inference, it can still be concluded that the thermal anomaly in the Surtur lava field generally cooled down to ambient and eventually disappeared within 40-45 years.

The evolution of the thermal anomaly within the lava region

The thermal data recorded in Sveinn P. Jakobsson's thermal surveys (Fig. 3) and later data (Fig. 4) clearly showed a decrease in surface area, as the thermal manifestations that were found over an area of 0.26 km^2 in 1970, gradually decrease to ambient temperatures by 2000. This validates the source of the thermal anomaly within the lava region as the remnant heat of emplacement that is being lost by the natural process of cooling and advection of heat by water.

Thermal manifestations in the tephra cones

The thermal area of Surtsey is now confined to the tephra region of Surtur (Austurbunki) and Surtungur (Vesturbunki), and its characteristic thermal emission is steam issuing from fissures that formed in the tephra once it consolidated. As mentioned previously, the main source of thermal heat in the tephra is still up for debate but it has been hypothesized to be the intrusive activity in Surtur, during December 1966-January 1967 (Jakobsson & Moore 1986). However, as pointed out earlier, the onset of thermal activity in the Surtungur tephra cone (Vesturbunki) occurred several years after cessation of volcanic activity, suggesting that other processes may be important.

The thermal anomaly at Surtur (Austurbunki) tephra cone

The thermal values recorded in the monitoring surveys indicate that the thermal area at the surface of the Surtur tephra cone was established within 1-2 years. The area is still active with thermal manifestations concentrating along the top of the palagonite tuff rim. This concentration of thermal activity at topographic highs, that is also present at Surtungur's tephra cone, can be explained by a chimney effect that arises due to buoyancy. This is caused by the density difference between the hot fluid in the up-flow zone and the surrounding colder fluid; in the tephra cone the fluid is air (Stefánsson 1983). However, the thermal values also show that the temperature at the surface is declining slowly fifty years after its onset. The thermal activity on Surtur's tephra cone is expected to weaken and the thermal manifestations to eventually disappear in the future.

The thermal anomaly at Surtungur (Vesturbunki) tephra cone

The initial clear manifestations of thermal activity at the surface of the Surtungur tephra cone were finally observed on its western side in 1975. In contrast to Surtur, no intrusive activity was detected in the Surtungur tephra. It is therefore unlikely that the onset of geothermal activity in Surtungur can be explained by intrusions as for Surtur.

The thermal values recorded in the monitoring surveys indicate that even though the establishment of the thermal anomaly on the Surtungur tephra cone appears more gradually than that of Surtur, the latest thermal data indicates that the thermal activity on Surtsey is currently stronger within this thermal area, as the surface temperatures have stayed above 90 °C (Fig. 3). Thermal heat is expected to remain in this area for longer compared to Surtur and the intermediate zone, both of which are showing signs of weakening. Nonetheless the thermal manifestations at Surtungur are also expected to eventually diminish and disappear as the hydrothermal system in Surtsey begins to die down.

The thermal anomaly at intermediate tephra zone cone area

Overall, the intermediate zone between the well-defined Surtur and Surtungur tephra cones has shown relatively high temperatures since the first thermal survey was performed in 1969. The initial maximum temperature recorded within this area was 80 °C, and regardless of the fluctuations of the next five decades, the survey performed in 2018 still placed the maximum temperature value at 80 °C (Fig. 3). This suggests that the thermal activity at the intermediate tephra zone is still reasonably strong. Overall, the evolution of this area has resembled that of the Surtur cone. This may be related to the fact that the lower part of the tephra pile in this area is the eastern rim of Surtur, which was eventually covered by Surtungur tephra.

The evolution of the thermal anomaly within the tephra cones

The distinct difference of the evolution between the thermal region within the lava and the palagonitized tephra can be attributed to the fact that the tuff formation retains heat much better than the lava pile. This is best explained by the higher permeability of the lava that allows the sea water, as well as groundwater that accumulates due to precipitation, to easily seep through until the water reaches hot rock. At the interface, the water evaporates, effectively mining heat from the lava, with the steam generated emitted up through the lava pile until the heat is largely exhausted. In contrast, the permeability in the tephra decreases once consolidated, resulting in slow flow of groundwater through the tuff formation. This eventually allows the edifice to retain the thermal heat that is emitted by a heat source that may also lie deeper into the ground.

The thermal data from the 1979 Surtsey drill hole

The observations made during the analysis of the maximum temperature data recorded in the 1979 drill hole is essential to understand the thermal anomalies that are seen at the surface of Surtsey. Previous studies demonstrated that the heat transfer in Surtsey has been dominated by hydrothermal convection and that the system is vapor dominated above sea level (Friedman *et al*. 1976). The physical conditions found at the subsurface account for the thermal manifestations observed at the surface, which are characterized by vapor emissions that rise to 100 °C, as the water at sea level within parts of Surtsey boils and evaporates.

The hypothesis that intrusions account for the excess heat content of Surtsey has been previously favored (Friedman *et al.* 1976). The 13 m thick discontinuous intrusive complex, observed in the drill core from 1979 offered some support for this (Jakobsson & Moore 1982). However, the main source of thermal heat within the Surtur tephra cone is still up for debate, with the minor intrusions that happened from December 1966-January 1967 (Jakobsson & Moore 1986) being a contributing factor but probably not the main reason for the occurrence of a thermal area.

The difference between the onset of the thermal anomalies at the surface of the Surtur tephra cone (~1968) versus the Surtungur cone (mid 1970s) is interesting. The small intrusions in Surtur in 1966-67 presumably sped up the process and once the tephra began to consolidate, the transfer of vapor was affected. Micro cracks formed as the porosity and the micro permeability increased, and eventually the vapor was transferred to wider areas. The much later onset of visible thermal activity in the Surtungur tephra cone may be explained by the lack of late intrusive activity in that region.

The constant erosion of the island and the palagonitization of the tephra, which may have started at depth while the Surtsey eruption was still active and was eventually observed at the surface in 1969, have facilitated the formation and exposure of steaming fissures where the vapor emissions currently concentrate.

The temperature profiles of the 1979 drill hole show that the thermal heat that is concentrated within Surtsey is decreasing. As this heat dies down, it is expected that the thermal manifestations at the surface of Surtsey will also diminish and eventually disappear.

CONCLUSIONS

The monitoring of the surface thermal manifestations at Surtsey has revealed important information on the evolution of the entire thermal field. The record shows that thermal activity in the lavas and the tephra cones has followed noticeably different paths. The thermal activity on the lava fields initially exhibited very high heat loss followed by a further gradual cooling. Temperatures of up to 460 °C were recorded in fumaroles, five years after activity in the lava craters ceased. Overall, this thermal activity cooled down rapidly and the thermal anomaly disappeared in 30-40 years.

The thermal area within the tephra also exhibited a gradual onset of thermal activity, but the behavior between the two tephra cones is considerably different.

The onset of the geothermal activity at the surface of Surtur was detected in 1968. Temperatures between 80-90 °C still prevail at the surface but the size of the thermal area is now clearly declining and has been gradually doing so with time. The onset of the geothermal activity on Surtungur was detected in 1974. While there has been a significant decline in the extent of the thermal manifestations in this area, the maximum temperatures recorded have remained within the 90-100 °C range since 1979. The geothermal activity in the intermediate area, where the tephra cones of Surtur and Surtungur merge, has evolved broadly in the same way as Surtur. The 90-100 °C temperatures that were recorded there from 1979 have generally been declining since 2000.

Overall, the time series demonstrates a slow but clear trend of cooling of Surtsey with time. The record also demonstrates a clear distinction between the cooling and behavior of a pile of lava, which can cool fast as it is highly permeable, and palagonitized tuff, which has much lower permeability. The low permeability reduces the effectiveness of heat mining by convection and advection, thus retaining heat much better in the palagonitized tuff than in the lava. Additionally, temperatures measured within the 1979 drill hole also exhibit a decrease in the maximum temperature values since 1980. The drop was ca. 18 °C (141.3 to 123.4 °C) during the 38-year observation period. The abundant research on the geothermal system and the knowledge that has been gained from these studies have proven Surtsey to be an outstanding example on how post-eruptional geothermal processes can be studied under similar local physical conditions. Recent and future submarine eruptions may provide new monitoring opportunities and can benefit from programs similar to the one initiated by Sveinn P. Jakobsson, over 50 years ago on Surtsey volcano.

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