Fifty Year Evolution of Thermal Manifestations at Surtsey Volcano, 1968 – 2018

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Declaration

Hereby I declare that this thesis is written by me and that it has neither by part nor the whole been submitted previously to a higher degree.

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Abstract

The tephra making up the tuff cones in Surtsey, formed in 1963-1964 in the phreatomagmatic phase of the Surtsey eruption and showed the first signs of palagonitization at the surface in 1969, a year after the onset of the geothermal system was detected. The early work on Surtsey established that at 100 °C, it takes one to two years for the tephra to convert into dense palagonitized tuff while the rate of palagonitization is considerably slower at lower temperatures. The present study compiles all published as well as unpublished data on the surface manifestations of geothermal activity and measurements in the drill hole completed in 1979, to give a comprehensive account of the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 demonstrate 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 was 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 was detected in 1974 and the maximum temperatures recorded have remained within the 90 – 100 °C range since 1979. The intermediate area between Surtur and Surtungur has exhibited activity broadly in the same way as Surtur 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.

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# Table of Contents

List of Figures .................................................................................................................. x

List of Tables ....................................................................................................................... xii

Abbreviations ...................................................................................................................... xiii

Acknowledgements .............................................................................................................. xiv

Chapter 1: Introduction ....................................................................................................... 1

Chapter 2: Geological background .................................................................................... 5
  2.1 Geological setting ........................................................................................................ 5
  2.2 The 1963-1967 Surtsey eruption ............................................................................... 6
  2.3 The formation of the Surtsey tephra ....................................................................... 7
  2.4 The formation of the lava field ................................................................................. 8

Chapter 3: Previous studies ............................................................................................... 9
  3.1 Consolidation and palagonitization of the Surtsey tephra ....................................... 10
  3.2 Surface measurements of the thermal area on Surtsey .......................................... 12
    Work of Ævar Jóhannesson 1970 – 1975 ................................................................. 12
    Work of Sveinn Jakobsson and coworkers since 1969 ......................................... 13
    Surface measurements in 2018 ............................................................................ 14
    The 1979 Surtsey drilling project ....................................................................... 19

Chapter 4: Methodology .................................................................................................. 23
  4.1 Field work – Surface temperature measurement survey ...................................... 23
  4.2 Digitization of map record ..................................................................................... 25
  4.3 Spatial and temporal analyses ............................................................................... 26
  4.4 Surtsey 1979 drill hole analysis ............................................................................. 29

Chapter 5: Results .............................................................................................................. 31
  5.1 Evolution of thermal anomalies in the lava fields ................................................. 31
  5.2 Evolution of thermal activity in Surtur tephra/tuff cone ....................................... 34
  5.3 Evolution of thermal activity in Surtungur tephra/tuff geothermal area ............. 37
  5.4 Evolution of thermal activity in the intermediate tephra/tuff geothermal area ...... 38
  5.5 Changes in the extent of Surtsey’s thermal field ..................................................... 39
  5.6 Surtsey 1979 drill hole analysis ............................................................................. 51
List of Figures

Figure 1.1 Iceland’s tectonic setting and location of Surtsey within the Vestmannaeyjar archipelago ................................................................. 1

Figure 1.2 Aerial photograph of Surtsey ................................................................................................................................. 3

Figure 1.3 Cross-section of geothermal area on Surtsey ............................................................................................................. 4

Figure 2.1 Map of active volcanic systems in Iceland and the location of the Eastern Volcanic Zone ................................................................. 5

Figure 2.2 Photograph of intermittent “cocks-tail” explosions during phreatomagmatic activity of Surtsey volcano ............................................. 8

Figure 3.1 Geological map of Surtsey ................................................................................................................................. 9

Figure 3.2 Field photograph of poorly consolidated tephra outcrop ..................................................................................... 11

Figure 3.3: Ævar Jóhannesson’s map of thermal area on Surtsey ..................................................................................... 13

Figure 3.4: Measurement locations of 2018 thermal survey ..................................................................................... 14

Figure 3.5 Thermal survey performed on July 2018 ............................................................................................................. 15

Figure 3.6 Thermal survey map from 1979 and drill site location ..................................................................................... 20

Figure 3.7 1979 and 1980 temperature profiles based on study by Axelsson et al. (1982) .................................................... 21

Figure 4.1 Methods and instrumentation used during 2018 thermal survey ................................................................ 24

Figure 4.2 Jakobsson’s original survey map from 1982 used for digitization ................................................................ 26

Figure 4.3 Partitioning of the thermal area according to spatial and temporal analyses ............................................................ 28

Figure 5.1 Thermal survey performed in 1970 ............................................................................................................. 32

Figure 5.2 Maximum temperature recorded in Surtur and Surtungur’s lava field .................................................................... 34

Figure 5.3 Thermal survey performed in August 1970 showing the extent of the palagonite tuff .................................................... 35

Figure 5.4 Maximum temperature recorded in Surtur and Surtungur’s tephra/tuff cones .................................................... 37
List of Tables

Table 3.1: List of thermal surveys made on Surtsey since 1969.......................... 16 -18
Table 5.1: Thermal record of Surtsey’s lava region ............................................. 33
Table 5.2: Thermal record of Surtsey’s tephra/tuff region ................................. 36
Table 5.3: The surface extent of the different zones within Surtsey’s thermal field ......................................................................................................................... 41
Table 5.4: Evolution of the thermal surface area ............................................... 48
Table 5.5. Maximum temperature values within the 1979 drill hole and their depth .................................................................................................................. 55
Abbreviations

SUSTAIN - Surtsey Underwater volcanic System for Thermophiles, Alteration processes and Innovation

IINH - Icelandic Institute of Natural History

GIS - Geographic Information Systems
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Chapter 1: Introduction

Iceland is the largest subaerial component of the Mid-Atlantic Ridge. The boundary between the North American and Eurasian tectonic plates is marked by the crest of the ridge that crosses the country from south west to northeast. Iceland is constructed almost exclusively of volcanic rocks due to the high volcanic activity that creates new land as the major rift belt expands continuously (Jakobsson et al., 2008).

Surtsey formed during 1963-1967 in the southern part of the Vestmannaeyjar archipelago in the Vestmannaeyjar system, a young volcanic system in Iceland that comprises seventeen Holocene eruption sites. Alkaline rocks make up the Vestmannaeyjar archipelago where alkali olivine basalts dominate (Jakobsson, 1968). Only the Surtsey eruption in 1963-1967 and the 1973 Eldfell eruption on Heimaey are known to have occurred within this system during historical times. Heimaey forms a topographical high in the system as the main volcanic activity has been concentrated in that area, hence it is believed that Heimaey is evolving into a central volcano (Baldursson & Ingadóttir, 2007).

Figure 1.1: Left: The North-Atlantic and the Mid-Atlantic Ridge, with a thick red line showing the boundary between the North American and Eurasian tectonic plates. The red square shows the geographic location of Surtsey within the Vestmannaeyjar archipelago. Right: Map of Vestmannaeyjar archipelago. Surtsey (lower left-hand corner) is the second largest island after Heimaey (Baldrurson & Ingadottir, 2007).

Extensive research has taken place on Surtsey since the first signs of volcanic activity appeared on November 14, 1963. While Sigurður Þórarinsson detailed the
course and the morphology of the eruption (Þórarinsson et al., 1964; Þórarinsson 1966, 1968), and others worked on the petrography and the chemistry of the extruded alkali olivine basalt (Steinþórsson 1965, 1966), Sveinn P. Jakobsson paid increased attention to the formation of the palagonite tuff, partly because similar formations to the Icelandic Móberg are uncommon elsewhere on Earth. The conversion of tephra into palagonite tuff (Móberg) as a post-eruptional process occurring at relatively low temperatures (at or below 100 °C) and pressures was first demonstrated at Surtsey, where the process of palagonitization was shown to be highly temperature-dependent and to proceed much faster than previously anticipated (Jakobsson, 1972). The first signs of palagonitization at the surface of Surtsey were noticed in 1969 and by 2004, it was estimated that 85% of the tephra cone above sea level had been converted to palagonite tuff. While the process of palagonitization advanced, the thermal area at the surface also continued to expand. A decrease in the rate of expansion of the thermal area after 1979 has been attributed to the expansion of the palagonite tuff and its effect on the heat flux of the geothermal system by the consolidation of the tephra inside the island (Ólafsson & Jakobsson, 2009).
Figure 1.2: Aerial photograph of Surtsey taken in September 2018 (Loftmyndir ehf., 2018). The two main craters are called Surtur and Surtungur, while the terms Austurbunki and Vesturbunki refer only to their tephra piles (tuff cones). Surtur and Surtungur were originally referred to as Surtur I and Surtur II.

The post-eruptional temperature anomalies that were first discovered at the surface of the island in April of 1968 mark the visible onset of the thermal activity.
This thermal area has been monitored ever since as Surtsey provides a unique opportunity to study the evolution of a post-eruptional geothermal system.

Figure 1.3: NW-SE profile through the Surtsey volcano (Ólafsson & Jakobsson, 2009).

Comparable studies of post-eruptional geothermal systems include the monitoring of the geothermal activity of El Chichón volcano in Mexico which erupted in 1982. The thermal manifestations of El Chichón, such as the fumaroles that reached up to 98 °C and hot springs with temperatures that ranged from 20-71 °C, suggest the existence of a hot water hydrothermal convection system overlain by a relatively small volume vapor-dominated cap (Casadevall et al., 1984) like the one found on Surtsey. More recent submarine eruptions such as at the Nishinoshima volcano in Japan in July 2018, followed by Anak Krakatau in Indonesia later in 2018, may provide opportunities for similar monitoring programs. Surtsey, with its 50 years of monitoring, provides an example on how post-eruptional geothermal processes can be studied under similar local physical conditions.
Chapter 2: Geological background

2.1 Geological setting

The volcanic island of Surtsey forms part of the Vestmannaeyjar volcanic system which comprises the Vestmannaeyjar Archipelago at the southern end of Iceland’s Eastern Volcanic Zone (Figure 2.1). The Vestmannaeyjar volcanic system, with an estimated area of 875 km² (Jakobsson, 1979), produces rocks belonging to the alkali series, mainly alkali olivine basalts and alkali basalts. It comprises eighteen volcanic islands and several submarine eruption sites or remnants of short-lived volcanic islands. The archipelago is situated on a shallow shelf that dips gently to the southwest and has depths from around 50 to 140 m (Jakobsson, 1979).

With an original surface area of 2.65 km² (had declined to 1.23 km² in 2018), Surtsey is the second largest island in the Vestmannaeyjar Archipelago (Figure 1.1). It has been estimated that this young volcanic system probably commenced activity around 100,000 years ago and during the last 11,500 years, volcanism has remained at low intensity. Seventeen eruption sites have been identified above sea level and no high-temperature geothermal activity (temperature higher than 150 °C at 1 km depth) has been discovered in Vestmannaeyjar (Jakobsson, 1979).

Figure 2.1: The location of Surtsey Volcano at the southern end of Iceland’s Eastern Volcanic Zone (EVZ). The active volcanic systems are grouped according to petrological criteria. Surtsey volcano is located within a group of Holocene alkalic rocks (Jakobsson et al., 2008).
2.2 The 1963-1967 Surtsey eruption

Surtsey’s volcanic eruption is estimated to have started a couple of days before the first visible explosive activity broke the sea surface on November 14, 1963. During this phreatomagmatic explosive phase of the eruption, tephra of alkali olivine-basalt composition was produced. The crater that formed during the first phreatomagmatic phase from November 14, 1963 - April 4, 1964, located on the eastern side of the island, was eventually called and will be referred to in this study as Surtur. The second crater was formed during the second phreatomagmatic phase in February 1, 1964 – April 4, 1964, when the eruptive activity shifted to a new vent about 500 m to the west of Surtur, was eventually called and will be referred to as Surtungur (Figure 1.2) (Jakobsson and Moore, 1982). Originally, these two vents were called Surtur I and Surtur II. A change in eruption style occurred when seawater could no longer access the Surtungur vent in April 1964. Basalt lava began to form lava fields during the effusive phase (Jakobsson and Moore, 1982). 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).

In later years the tephra cones have been called Vesturbunki (Surtungur tephra cone) and Austurbunki (Surtur tephra cone). For simplicity, in this work only the names Surtur and Surtungur are used, with the terms lava and tephra used to distinguish between the two types of craters.

Along with Surtsey, three other sea floor eruptions occurred at three different sites within a radius of 3 km from the original vent (Surtur). On December 28, 1963, submarine activity became visible 2.5 km ENE of the Surtur vent. Surtla, a 100 m high submarine tephra ridge that did not reach the sea surface, was built up during the submarine activity that ceased on January 6, 1964. Today, Surtla has a length of 0.9 km, a width of 0.6 km and only rises 70 m above the sea floor (Normann & Erlingsson, 1992).

The islet of Syrtlingur began forming with submarine activity considered to have begun around May 11, 1965, 0.6 km ENE of Surtur, when the volcanic activity in Surtsey shifted from Surtungur to a new submarine vent. Even though Syrtlingur reached its maximum height of 70 m above sea level on the 15th of September of the same year, its explosions were never as continuous, nor was the activity as intensive as on Surtsey. After its explosive activity ceased on October 17, wave activity began eroding the 2 million cubic meters of tephra above sea level at the start of a week of bad weather. By October 24, 1966, Syrtlingur was completely
washed away and today, only a 70-80 m high submarine platform remains (Jakobsson et al., 2009).

Another explosive submarine event began on December 26, 1965, 1 km SW of Surtsey. Two days later, Jólínir emerged from the sea and the island eventually reached its maximum height of 70 m and an area of 0.28 km², before the eruption died out on August 10, 1966. Due to rapid wave erosion, Jólínir island, as did Syrtlingur the year before, was rapidly eroded and had disappeared in late October of the same year. Recent bathymetric measurements place the now considered seamount at only 60 – 70 m in elevation above the sea floor (Jakobsson et al. 2009).

The island of Surtsey has also 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 and Moore, 1982). In 1968, Pórarísson estimated that by the end of the eruption in 1967, Surtsey had reached a size of 2.65 km² and that the total production of eruptives during the eruption was 1.1 km³, about 60 - 70 % of which was tephra (Pórarísson, 1969). The most recent air photos taken in summer 2018 and estimates by IES at the University of Iceland give a current surface area of 1.23 km².

2.3 The formation of the Surtsey tephra

The Surtsey tephra formed during the explosive submarine phase of the Surtsey eruption in the period between November 14, 1963 and April 4, 1964. The tephra formation was the result of approximately 1150° - 1160° C magma coming into contact with seawater and instantly quenching. The quenching resulted in phreatomagmatic explosions where two types of phreatic explosive activity dominated, intermittent “cocks-tail” explosions and continuous uprush of tephra (Figure 2.2) (Pórarísson, 1965). The deposition of the tephra resulted in the formation of the two crescent-shaped cones of Surtur (Austurbunki) and Surtungur (Vesturbunki), each with a diameter of about 400 m and a height of 150 – 170 m above sea level. The tephra was deposited as bedded air fall and as base surge flows (Jakobsson and Moore, 1982).
2.4 The formation of the lava field

When the island was large enough to isolate the western crater’s vent (Surtungur) from inflowing seawater, the eruption at Surtsey switched from explosive to effusive in April 4, 1964. From this point on and until June of 1967, lava was emitted from two main craters and five minor fissures at different times on Surtsey: A lava shield that reached 100 m above sea level with a volume of 0.3 km$^3$ was produced during this first major effusive phase from April 4, 1964 until May 17, 1965; while the second phase that lasted from August 19, 1966 until June 5, 1967, produced a 70 m high lava shield with a volume of 0.1 km$^3$ when a fissure approximately 220 m long opened up on the floor of Surtur.

The first of the minor fissures opened on the western side wall of Surtur between December 12 – 17, 1966 producing a small lava flow, followed by more effusion of lava between January 1 – 8, 1967 through the eastern tephra ring at four additional sites on the slopes of Surtur. The lavas from these minor fissures are very small and minuscule in volume compared to the two main lava shields (Jakobsson & Moore, 1982).
Chapter 3: Previous studies

The island of Surtsey is probably one of the best-studied volcanoes in Iceland and is considered to be one of the world’s best-preserved submarine tuyas. Aside from tephra and lava, the two primary geological units formed during the Surtsey eruption, three other secondary geological units have been mapped in detail: palagonite tuff, aeolian and talus sediments, and coastal sediments (Normann et al., 1974, Normann, 1978).

Figure 3.1: Geological map of Surtsey (Jakobsson, 2006).

3.1 Consolidation and palagonitization of the Surtsey tephra

Petrographic analysis performed during the summer of 1964, shortly after the deposition of the tephra, characterized the Surtsey tephra as alkali olivine basalt (Steinþórsson, 1965, 1966). The microscopic investigation showed that 82-88% of
the volume was made up of unaltered and unpalagonitized basaltic glass (sideromelane), while the rest were fragments of authigenic hyalobasalt and phenocrysts of olivine, plagioclase and Cr-spinel (Jakobsson and Moore, 1982). The tephra is poorly sorted and varies in grain size from silt to boulders, although some 60 – 70% is made up of fine glass shard less than 2 mm in diameter along with mineral phenocrysts and small rock fragments. The tephra deposited above sea level forms finely-bedded and poorly sorted layers, in contrast to the tephra below sea level, which is more chaotic in structure and whose grains sometimes demonstrate considerable size sorting. The porosity of the tephra layers above sea level must rate as very high, or 45 – 50% by volume (Oddsson, 1982) (Jakobsson et al., 2000).

One of the main objectives of the initial studies at Surtsey was to follow closely the processes of consolidation and palagonitization of basaltic tephra to describe how these processes take place under the local physical conditions (Jakobsson and Moore, 1982). Palagonitization is the alteration process during which the original glass shards in the tephra are chemically modified, devitrified and hydrated to produce palagonite (Bonatti, 1965). During the palagonitization process, 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 at the same time cements its particles together and forms palagonite tuff (Jakobsson and Moore, 1986). Since its formation, Sveinn P. Jakobsson visited the island almost every year, with the exception of 1965 and 1968, frequently inspecting the area of primary tephra and sampled various localities in order to determine the start and the conditions of the expected process of consolidation and palagonitization of the tephra (Jakobsson and 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 and it was proposed that the initial consolidation depended on the frequent oscillations in temperature and moisture on the surface since the exposures face SE, the main direction for precipitation and sun exposure (Jakobsson and Moore, 1982).
In April of 1968, Prof. Sigurður Þórarinsson discovered heating of tephra with emanations of steam at the surface of Surtur, close to the newest lava craters that erupted during January 1 – 8, 1967 (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 in 1969, a monitoring 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; 1978). The program consisted in 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. Data for eleven localities that presented roughly constant temperatures during this eight year period were collected and 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).

### 3.2 Surface measurements of the thermal area on Surtsey

The thermal field on Surtsey has on average been monitored and mapped, in accordance with the plan set up in 1969, for most of this period every third year but more frequently since 2011 (see Table 3.1). 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. Landmælingar Islands provided air photo stereo sets flown at a low altitude to aid the mapping of the tephra and the lava as well as the secondary geological units (palagonite tuff and sediments) that are still changing and expanding as the island undergoes erosion. In later years, these flights have been performed by the Loftmyndir ehf.

**Work of Ævar Jóhannesson 1970 – 1975**

Ævar Jóhannesson, at the Science Institute of the University of Iceland contributed significantly to the mapping of the thermal area in two expeditions, in 1970 and 1975 (Jóhannesson, 1972; 1978). He made temperature measurements on the tuff, the lava as well as localities near the craters, both for Surtur and Surtungur. The measurements in the tuff were performed by plunging a metal bar down to a certain depth, inserting a mercury thermometer down to the bottom through the hole and obtaining temperature readings after a three-minute time lapse. While in the low-consolidation areas, measurements were performed down to a depth of 140 cm, the highly consolidated tuff areas allowed for temperature measurements of only up to a few tens of centimeters. Temperatures in the lava were measured by inserting a thermometer into an up-flow vent, from which hot air or steam was rising. For temperatures below 250 °C, mercury thermometers were used; “Rototherm”-type thermometers (thermocouples) were used for higher temperatures (Jóhannesson, 1972).
Work of Sveinn Jakobsson and coworkers since 1969

Along with the mapping and sampling, temperature measurements at the surface have been carried out to monitor the surface temperatures, and in that way, map the extent of the thermal field. Even though the first temperature measurements were performed in September 1969 by Sveinn P. Jakobsson using a conventional mercury thermometer at approximately 5 cm depth in the hottest areas, the thermal field was not mapped in detail until August 1970 (Jakobsson, 1972).

Sveinn P. Jakobsson’s first detailed thermal survey was also completed in 1970 using a conventional mercury thermometer. Parallel to Jóhannesson’s study, Jakobsson reports encountering a complication while performing the temperature measurements in the tuff area where he attempted to measure the temperature gradient by hammering down an iron bar. It was usually not possible to get farther down than about 40 – 60 cm within the thermal field as the tephra gradually became harder. During his surveys, temperature measurements were
performed using mercury thermometers until 1979 when these conventional thermometers were replaced by electronic thermocouples.

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, with their first survey conducted in 2011 (See Chapter 4 on methods).

**Surface measurements in 2018**

The 2018 survey was conducted by the present author as a part of this MS-project. As a consequence of the highly consolidated state of the palagonite tuff, fifty-eight temperature measurements were taken along a network of fissures that are located throughout the two tephra/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, some of these active fissures also present condensation and emanation of steam.

![Figure 3.4: A) Measurement taken along an open fissure that stands out from the surrounding topography. B) Measurement taken along a small opening along a closed fissure at ground level.](image)

The maximum temperature value that was measured during the 2018 thermal survey reaches 103 °C. Since this temperature was taken within a fissure where up-flow steam is being released, and taking into account that the boiling point of water at sea level is 100 °C, it has to be noted that there is a 3 °C discrepancy within this value. The measurement was taken within the Surtungur palagonite tuff cone, along a fissure located at the top of the rim. In contrast, the highest temperature value recorded on Surtur only reaches as high as 88.9 °C. This value
was recorded on top of Surtur’s rim and at a point along the north-facing slope. No thermal anomalies were found within the lava field (Figure 3.5).

The current extent of the palagonite has also been mapped with the aid of an aerial photograph taken at the end of September 2018. Most of the Surtur tephra cone has been palagonitized except for the eastern and the north-facing slopes where the tephra still presents a low degree of consolidation (Figure 3.2). Palagonitization has also altered the Surtungur tephra cone and a full coverage at the surface can be expected in the following years at the north-facing slope if geothermal activity continues.

**Figure 3.5:** Thermal survey performed on July 2018. Most of the geothermal manifestations are concentrated along the top of the palagonite tuff cones. Maximum temperature measurement within the entire thermal area is located in Surtungur’s tephra/tuff thermal area.
Table 3.1: List of thermal surveys made on Surtsey since 1969 until present. The surveyor as well as the instrument used is also shown. Digital thermometer refers to an infrared sensor with a laser pointer and a temperature-sensor thermocouple stick attachment.

<table>
<thead>
<tr>
<th>Year</th>
<th>Date</th>
<th>Surveyor</th>
<th>Instrument used</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1969</td>
<td>November 22</td>
<td>Sveinn P. Jakobsson</td>
<td>Mercury Thermometer</td>
<td>Original paper map (Jakobsson)</td>
</tr>
<tr>
<td>1970</td>
<td>August 3</td>
<td>Sveinn P. Jakobsson &amp; Ævar Jóhannesson</td>
<td>Mercury Thermometer</td>
<td>Original paper map (Jakobsson) &amp; Literature (Jóhannesson 1972)</td>
</tr>
<tr>
<td>1971</td>
<td>October 12-13</td>
<td>Sveinn P. Jakobsson</td>
<td>Mercury Thermometer</td>
<td>Original paper map (Jakobsson)</td>
</tr>
<tr>
<td>1972</td>
<td>June 13</td>
<td>Sveinn P. Jakobsson</td>
<td>Mercury Thermometer-Thermocouple</td>
<td>Original paper map (Jakobsson)</td>
</tr>
<tr>
<td>1973</td>
<td>September 13</td>
<td>Sveinn P. Jakobsson</td>
<td>Mercury Thermometer</td>
<td>Original paper map (Jakobsson)</td>
</tr>
<tr>
<td>1974</td>
<td>August 10</td>
<td>Sveinn P. Jakobsson</td>
<td>Mercury Thermometer</td>
<td>Original paper map (Jakobsson)</td>
</tr>
<tr>
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<td>14</td>
<td>Sveinn P. Jakobsson &amp; Lovísa Ásbjörnsdóttir</td>
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<td>2011</td>
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<td>Velveth Perez</td>
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The 1979 Surtsey drilling project

Research on the formation of palagonite rocks in Surtsey continued for several years. Shortly after the eruption ceased, the idea of a scientific drilling program was originated because of the exceptional opportunity to study the development of a historic, well-studied, oceanic volcano from its inception on the seafloor, though the formation of a volcanic island, to the modification of the volcanic edifice by geothermal processes (Jakobsson and Moore, 1982). The aim of the drilling project was to provide constrains on the following: the nature of basaltic submarine volcanic activity from vents in the depth range from about 130 m to sea level, and the composition of rocks erupted during the course of the submarine eruption; geothermal processes, including the nature of palagonitization of the basaltic hyaloclastites and formation of secondary minerals; and lastly, the thermal history both above and below sea level as indicated by thermal logging and character of alteration (Jakobsson and Moore, 1982).

The drilling was a joint project of the Icelandic Museum of Natural History and the United States Geological Survey and was performed at the southeast corner of Surtur by the Icelandic State Drilling Contractors from June 29, 1979 to August 22, 1979, with 34 days of active drilling. The drill hole is located at an elevation of 58.39 ± 0.15 m above sea level, just inside the eastern tephra crater (Surtur), approximately 100 m southeast of the center of the vent that was active from November 1963 – February 1964. The area of the drill site location has been above sea level since November 22, 1963. A blanket of tephra of about 10-15 m thick from Surtungur that formed during the phreatic activity in February 1 - April 3, 1964 was deposited on Surtur but eolian erosion later removed a substantial part of this blanket from the drill site area. The drill site may have subsided about 4 m from 1964 to the time of drilling in 1979 (Moore, 1982) but no major disturbances of the tephra layers occurred at the drill hole site (Jakobsson and Moore, 1982).
The drill hole reached a depth of 181 m, at 123 m below sea level and within a few meters of the pre-eruption sea floor. The cored material that was obtained from this drilling project explored the subsurface structure and eruptive processes at Surtsey volcano (Jakobsson & Moore, 1982). Analyses of the core have given insights into the volcanic structures that lay above and below sea level, as well as the thermal system and the composition and alteration of basaltic tephra. The monitoring of the drill hole throughout the last 40 years has provided the unparalleled opportunity of observing the evolution of a post-eruptional mild geothermal system over time (Axelsson et al., 1982; Stefánsson et al., 1985).

Jakobsson and Moore (1982) suggested that the heat source which caused the elevated temperatures in the surface tephra originated from shallow intrusions. These intrusions happened at Surtungur in 1965 - 1966 and in December 1966 - January 1967 at Surtur. However, this idea is not considered definitive.

Using the available data on the well-documented sequence of eruption events along with the information that the drill hole has provided, it appears that the dykes apparently intruded upwards along concentric faults that formed during the construction of the tuff rings and fed the minor lava flows created in this period. An intrusion considered to be one of these dykes was found in the 1979
drill hole at depths of 14-27 m below sea level. The primary material that was cored throughout the 181 m deep drill hole was glassy basalt tuff. For the upper part of the pile, reaching at least down to 14 m below sea level, Jakobsson and Moore (1982) suggested that this was evidence of subaerial deposition.

The drill hole made it possible to study the thermal conditions within the island. During 1979 and 1980, the temperature logging was performed by the Icelandic National Energy Authority. On September 26, 1979 two temperature measurements were attempted but the first attempt was disregarded due to technical difficulties during the measurement which was done with a thermistor mounted on an electrical cable. The second attempt was successful and temperature measurements were taken every 4 m below 90 m depth while using a Kuster temperature gauge (Axelsson et al., 1982). The temperature measurements performed on September 9, 1980, a year after the 1979 drilling, are considered to represent the equilibrium conditions in the island at this time. They were taken using a platinum sensor mounted on a logging cable with a TEFZEL insulation. The accuracy of the measurement is within ± 0.5 °C, and the calibration uncertainty is less than 0.02 °C.

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 general cooling rate of less than 1 °C per year (Jakobsson et al., 2000). 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 (Axelsson et al., 1982).
Figure 3.7: The results of the temperature measurements of September 1979 and of September 1980, along with a simplified representation of the core lithology based on Axelsson et al.’s study of the thermal conditions of Surtsey in 1982.

It is worth mentioning that in 2017, three new cored boreholes were drilled by the Surtsey Underwater volcanic System for Thermophiles, Alteration processes and Innovation (SUSTAIN) drilling project at Surtsey volcano. Two vertical core boreholes parallel the 181 m core drilled in 1979 and reach a depth of 152 m and 192 m respectively. The third cored borehole is inclined 35° from the vertical in a 264° azimuthal direction to 354 m measured depth. The time lapse drill cores precisely record the progression of geothermal alteration, the rapid evolution of magnetic properties, the driver processes of glass dissolution and alteration, and the cycling of authigenic mineral cements and their influences on the material and physical properties of young basalt (Jackson et al, 2019). Details and results from the new drill sites are not in the scope of this study.
Chapter 4: Methodology

Throughout four decades, Sveinn P. Jakobsson continued to perform thermal surveys and contribute to the logging of the geothermal’s surficial temperatures. His records show that conventional mapping (Table 3.4) was performed until 2006 when more modern techniques started to be implemented. During the following years after Jakobsson’s last visit to Surtsey in 2008, Icelandic Institute of Natural History (IINH) geologists Lovísa Ásbjörnsdóttir and Kristján Jónasson continued with the thermal monitoring program with surveys in 2011-2017 (Table 3.1) while the 2018 survey was carried out by the present author.

4.1 Field work – Surface temperature measurement survey

During the last scientific expedition to Surtsey that took place from July 18 – 22, 2018, the most current thermal survey was completed using an electronic thermometer that features an infrared sensor with a laser pointer and a temperature-sensor thermocouple stick attachment (Figure 4.1). In addition to a Trimble tablet with integrated GPS, the exact location of the temperature measurements was logged with the aid of a handheld GPS for better accuracy. This technology has improved the monitoring surveys by replacing the conventional mercury thermometers and the topographic paper maps that were used in the past. The temperature data obtained during this thermal survey forms the most recent addition to the thermal monitoring program records and will be further used in the spatial and temporal analysis of the thermal manifestations at Surtsey.

For better clarification of the analysis performed in this study, palagonite is used in this context as a synonym for an altered, hydrated, basaltic glass, of brown or yellow color. The term is related to the alteration process, called palagonitization. Palagonite tuff or Móberg is an Icelandic term for brownish, consolidated tephra, of basaltic or intermediate composition (Jakobsson, 1978; Stroncik & Schminke, 2002). Thermal field refers to the area at the surface of Surtsey that presents thermal anomalies including but not limited to the lava thermal region and the tephra/tuff thermal region and its geothermal subareas that will be discussed below.

Due to the highly consolidated nature of the palagonite tuff, the temperature measurements were performed along the open active fissures where the thermocouple temperature-sensor stick is introduced to take a temperature reading deeper into the ground while the thermal camera gun takes a reading of the exposed surface. These steaming fissures, through which vapor emissions are clearly visible, are located throughout the entire studied area that comprises both
Surtur and Surtungur palagonitized tephra mounds. 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 the infrared laser gun thermometer.

**Figure 4.1:** Images taken during the 2018 thermal survey: A) Photograph of a steaming fissure located at the top Surtungur. 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.
4.2 Digitization of map record

During this study, nineteen original paper maps that are part of the unpublished data by Sveinn P. Jakobsson on the surface manifestations of thermal activity were digitized using GIS software (Appendix A). Seven additional maps were created with the temperature data that is available in the digital record of the Icelandic Institute of Natural History (IINH).

The digitization process begins by scanning the paper maps that are also part of the IINH record, followed by the use of GIS ArcMap to create the digital maps of Surtsey and perform further spatial and temporal analysis. The IINH data set includes the air photographs that have been taken by Landmælingar Islands and later by Loftmyndir ehf in TIFF format and each scanned map is georeferenced to an air photograph taken in the same year or an air photograph taken around the same time. Since 1992, the aerial photograph record has improved when aerial photos of Surtsey were set to be taken every other year.

The different features of the thermal manifestations that Sveinn P. Jakobsson tracked during the thermal monitoring surveys include: the palagonite tuff, thermal area extension, steaming fissures and temperature measurements. These features are digitized by creating separate shapefiles which are then used to perform the spatial and temporal analysis.
Figure 4.2: Jakobsson’s original survey map from 1982 used for digitization. Palagonitized area is delineated with a dash line and shown in orange while the steaming fissures are shown in red. The numbers represent the measured temperature values and the palagonite tuff sample locations are circled and numbered with a SU-prefix.

4.3 Spatial and temporal analyses

During the spatial and temporal analysis of the thermal area at Surtsey, the maximum temperatures recorded, both for the lava and the tephra are recorded separately to monitor their course individually. For better comprehension and due to its volume and extent, the tephra/tuff thermal region is further subdivided into three separate areas: the Surtur tephra/tuff geothermal area, the Surtungur tephra/tuff geothermal area and the Intermediate tephra/tuff geothermal area.

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 also suitable since the interval is considerable enough to analyze the progression of the thermal area and its manifestations.
The extent of the thermal area and how it changes with time is an important parameter in describing the evolution of Surtsey. Here, the area at any given time is defined with three methods: when available, with the 20 °C isotherm line and the defined shaded area according to Jóhannesson (1972) and Jakobsson’s field data (as in the case of the estimated values for 1970 & 1979), and with thermal data extrapolation to 20 °C (as in the case of the estimated values for 1988 – 2018) (Table 5.3). The area values obtained are rounded to two significant digits reflecting an estimated 20 % uncertainty.
Figure 4.3: Partitioning of the thermal area according to spatial and temporal analyses (Loftmyndir ehf., 2018).
4.4 Surtsey 1979 drill hole analysis

The complete 1979 drill hole temperature record was provided to this study by Tobias B. Weisenberger, of the Iceland GeoSurvey (ÍSOR), for additional use in the analysis of the thermal manifestations of the geothermal system on Surtsey. The most recent thermal data included in the record was obtained on July 18, 2018, using a HOBO memory logging tool along with a StarrOddi memory tool.

The temperature down the drill hole has overall been monitored every two to five years for the past forty years. Since 1979, the record shows seventeen logs. However, only five of these will be used in this study to further analyze the evolution of the surface manifestations of the geothermal system: 1980, 1990, 2000, 2009, 2018. These surveys were strategically chosen to be about one decade apart in order to use only data that shows a distinctive trend with time in the temperature measurements at depth.
Chapter 5: Results

In this chapter, the spatial and temporal analysis of the thermal activity on Surtsey will be presented beginning with the evolution of the thermal anomalies in the lava fields (5.1), followed by the Surtur (5.2) and Surtungur (5.3) tephra/tuff geothermal area as well as the intermediate tephra/tuff zone that lies in between these two areas (5.4). This is followed by an analysis of the size of the area of elevated temperatures on the surface of Surtsey and how it has evolved with time (5.5). To conclude, analysis of the 1979 drillhole temperature records will also be presented (5.6). Maps for all surveys made since 1969 are presented in the Appendix.

5.1 Evolution of thermal anomalies in the lava fields

By analyzing Surtsey’s complete thermal record, the maximum surface temperatures for the lava fields have been compiled and graphed. By the time the first detailed thermal survey on the surface of Surtsey was performed in 1970, the effusive activity that produced the lava fields had been inactive for over three years. Lava effusion from Surtungur’s crater had ceased in May 1965 and the lava shield that reached 100 m above sea level had been cooling off for over five years before the first temperature measurements were recorded in the thermal survey.

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 (Jóhannesson, 1972) while the initial estimated magma temperature is 1150 °C. Compared to this value, the maximum temperature found within Surtur’s lava field was low, reaching only 63 °C at a location within the northern minor fissure that had been active in January 1967 (Figure 5.1). After the first temperature measurements were recorded in 1970, vapor emissions from Surtungur’s lava pile show a rapid decrease in temperatures to 160 °C in 1974. The temperature values taken within this period are shown in Figure 5.2 where the points in the graph clearly form a steep negative slope at the beginning, followed by a short period of constant values. A slow increase is observed between 1983 – 1985 and a slower and steady decrease in temperature values begins after that.
Figure 5.1: Thermal survey performed in 1970. The extent of the thermal area at this time is presented along with the maximum temperatures recorded in both thermal regions. The inset on the upper left corner shows an aerial photograph of the entire island and the extent of the study area lies within the red contour line.

A substantial gap in the thermal record of the entire lava thermal region is observed for most of the 1990’s and by the year 2000 (Table 3.1), the maximum temperature recorded is already reaching low values with a maximum of 16 ºC.

The thermal record for Surtur’s lava field is not as consistent nor as complete as the monitoring of the thermal area on Surtungur. There are no temperature measurements recorded within Surtur’s main lava field. Jakobsson’s thermal records from this area focus on the temperatures along the minor fissures at the slopes of the tephra/tuff cone. The highest maximum temperature value recorded in lava in Surtur was in 1979-1980. This observation of 100 ºC is not from the lavafield; it was taken from vapor that was emitting from the western minor fissure that is located within Surtur’s cone inner wall. From then on, the maximum temperature values oscillate during the following years but the recorded temperature never reaches similar high values again. Regardless of these temperature fluctuations, an overall decrease in temperature is observed in the thermal record and the last surface temperature measurement is taken in 2008 at a value of 55 ºC (Table 5.1).
Table 5.1: Thermal record of Surtsey’s lava thermal region - maximum temperatures recorded along Surtur and Surtungur’s lava fields.

<table>
<thead>
<tr>
<th>Year</th>
<th>Surtur lava maximum temperature (°C)</th>
<th>Surtungur lava maximum temperature (°C)</th>
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<td>63</td>
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</tr>
<tr>
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The maximum temperature recorded at the surface of the entire lava field is graphed against time in Figure 5.2 to better understand the temporal evolution of the thermal activity.

**Figure 5.2:** The graph shows the maximum temperature recorded in both Surtur’s and Surtungur’s lava fields since the initial surface temperature measurements made on Surtsey were logged in the 1970 thermal survey. Temperatures taken within Surtungur’s lava field are shown in red while the temperature measurements made in Surtur’s lava field area are shown in blue.

### 5.2 Evolution of thermal activity in Surtur tephra/tuff cone

The first thermal survey made on the tephra formation was performed in November 1969 by Sveinn P. Jakobsson after the first signs of palagonitization were observed at the surface of Surtur’s tephra cone. At this time, the maximum temperature at the surface of Surtur’s tephra cone was 84 °C and by the following year, a report on thermal observations made by Ævar Jóhannesson (1972) placed the maximum temperature value at 98 °C at a location on the southeastern part of Surtur’s rim, near the location where the first signs of palagonitization were observed (Figure 5.3).
In contrast with this high value, the maximum temperature value for the tephra at Surtur in Sveinn P. Jakobsson’s records only reaches as high as 54 °C at a location along the inner rim. However, a temperature of 100 °C along the same location is noted in a study published in 1972 (Jakobsson, 1972) where five 40 – 100 cm deep holes were made to record the temperature of the Surtsey tephra. The extent of the thermal field within the tephra area as in August 1970 is shown in Figure 5.3 and is indicated by the 20 °C and 40 °C isotherms measured at 20 cm depth. At this point, only the inner wall of the Surtur tephra cone shows consolidation and within this consolidated area, an even smaller volume of tephra shows signs of palagonitization.

![Figure 5.3: Thermal survey performed in August 1970. The thermal area covers the craters and immediate surroundings of the effusive craters of Surtungur and Surtur as well as part of the Surtur tephra/tuff cone and the intermediate tephra part between Surtur and Surtungur. The consolidated area is shown in the inset along with the area covered by the palagonite. The inset on the upper left corner shows an aerial photograph of the entire island and the extent of the study area lies within the red contour line.](image-url)

The thermal records of the following years show an oscillation in the thermal values within Surtur’s tephra/tuff cone where the highest maximum temperature reached as high as 96°C in 1979 and as low as 30 °C in 1976 (Table 5.2). Surface temperature values gain stability in 1979 and the temperature record of the following decade shows values within the 90 – 98 °C range. A temperature measurement of 100 °C was recorded in 1992. From this year on and until 2008,
there is a consistent gap in the thermal data of Surtur’s tephra/tuff cone but a measurement made in the year 2000, places the maximum temperature value at 98.5 °C at the top of the rim. This data gap is followed by a period of stable temperatures that remain within the 90 – 100 °C range for the most part until 2016 when the maximum temperature measured drops down to 84.3 °C. The last surface temperature measurement made in 2018 places the present maximum temperature value at 88.9 °C.

Table 5.2: Thermal record of Surtsey’s tephra/tuff thermal region - maximum temperatures recorded along Surtur, Surtungur and the intermediate tephra/tuff zone geothermal areas.

<table>
<thead>
<tr>
<th>Year</th>
<th>Surtur tephra/tuff maximum temperature (°C)</th>
<th>Surtungur tephra/tuff maximum temperature (°C)</th>
<th>Intermediate tephra/tuff zone maximum temperature (°C)</th>
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<tr>
<td>2006</td>
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<td>2016</td>
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<td>2017</td>
<td>94</td>
<td>96</td>
<td>94</td>
</tr>
<tr>
<td>2018</td>
<td>89</td>
<td>103</td>
<td>80</td>
</tr>
</tbody>
</table>
The maximum temperatures recorded at the surface of Surtur’s tephra/tuff cone are graphed against time in Figure 5.4 and are shown in blue. The data for 1992 - 2008 is quite sparse. However, the period can be split into two parts: a period of substantial temperature fluctuation during the first decade after the onset of the thermal activity at the surface (1969 – 1979), and the period after 1979, where the record has been rather stable, possibly with a slight decrease in the maximum temperature observed in Surtur.

![Figure 5.4](image.png)

**Figure 5.4:** The graph shows the maximum temperature recorded in Surtur and Surtungur tuff cones since the start of surface temperature measurements in Surtsey. Temperatures taken within Surtungur’s tuff cone are shown in red while the temperature measurements made in Surtur’s tuff cone are shown in blue.

### 5.3 Evolution of thermal activity in Surtungur tephra/tuff geothermal area

While the maximum temperature values measured within the Surtur tephra cone reached 98 °C, the maximum temperature recorded along the tephra at Surtungur only went as high as 10 °C in 1970. Temperature values for the following years present an overall increase and by 1979, the thermal values within the Surtungur
tephra/tuff cone finally match the high value of 98 °C that was recorded in the Surtur tephra nine years earlier.

Unlike the temperature values at Surtur, the measurements made during the following thermal surveys show a period of stable values within the 90 – 99 °C range. These values have also been consistently higher than those measured within the Surtur tephra/tuff since 1979. The 100 °C mark is reached in 1992 and 2008 and a value of 103 °C is measured at the top of Surtungur’s rim during the last thermal survey performed in 2018 (Figure 3.5). As previously mentioned, there is a 3 °C discrepancy within this value and this will be attributed to improper calibration at the time the measurement was taken.

The maximum temperatures recorded at the surface of Surtungur’s tephra/tuff cone are graphed against time in Figure 5.4 and are shown in red. No obvious trend can be detected after 1979; the maximum temperatures stay similar.

5.4 Evolution of thermal activity in the intermediate tephra/tuff geothermal area

The thermal record for the zone where the Surtungur tuff cone overlaps the Surtur cone is referred to in this study as the intermediate tephra/tuff 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 (Table 5.2).

From this point forward, the thermal record of the intermediate tephra/tuff zone shows a substantial temperature fluctuation of 85 °C within the 15 – 100 °C range from 1969 – 1976. In 1979 the maximum temperature values present a marked stability with temperature values staying within the 90 – 100 °C range until 2000 when the maximum temperature value drops to 80 °C. The present period of temperature fluctuation began that year and temperatures have dropped as low as 79 °C in 2016 and reached as high as 94.3 °C in 2017 (Table 5.2).

These maximum temperatures recorded at the surface of the intermediate tephra/tuff area are graphed against time in Figure 5.5.
Figure 5.5: The graph shows the maximum temperature recorded in the intermediate tephra/tuff geothermal area since the initial temperature measurements were taken in 1969.

5.5 Changes in the extent of Surtsey’s thermal field

To better understand the significance of the surface temperature analysis, it is essential to analyse the different components of the thermal field by breaking it down even further into smaller units to be able to comprehend the overall evolution of Surtsey’s thermal manifestations for the past 50 years.

A visual evolution of the entire thermal field at the surface of Surtsey is presented in Figures 5.6 – 5.11, where the field has been divided into its two main thermal regions as well as the subareas discussed above. The temporal distribution presented in these figures aids a better visualization of the spatial evolution of the thermal activity on Surtsey given the fact that throughout the last fifty years, not only the island has significantly changed in volume and surface area, as it is being eroded away by ocean currents, but also the thermal field and its manifestations at the surface have also undergone a drastic change in size and location.
By 1970, most of the thermal heat anomaly is concentrated within the lava thermal region especially that of Surtungur’s lava field, with an estimated surface area cover of about 0.42 km². The largest extent of the surface thermal heat anomaly observed at this time within the tephra cones resides throughout Surtur’s tephra/tuff geothermal area at about 0.14 km² (Table 5.3) and only a fraction of this surface thermal heat is present in the intermediate tephra/tuff zone covering only 0.02 km². At this time, the temperatures recorded at the surface around the Surtungur tephra cone are around ambient, indicating that activity in this area had not picked up significantly at this time.

In 1979, the surface manifestations of the thermal cover a surface area of about 0.39 km². Spatial analysis places the largest extent of the thermal anomalies within the entire tephra/tuff region. The Surtungur tephra/tuff geothermal area has a surface extent of 0.11 km² while Surtur’s value is at about 0.14 km² (Table 5.3). A decrease in surface area is observed in the following years, especially within the lava thermal region. By 1988, the extent of the thermal heat only covers about 0.01 km² within the lava region and the entire thermal field has been reduced to 0.33 km². Surtur’s geothermal area is expanding to the eastern side of the tephra/tuff cone and is the only zone within the thermal field that has increased its surface area value.

The lava thermal region presents temperatures around ambient by 2000 and its surface area has been reduced to a small area outside the Surtungur lava crater and to the minor fissures located along the slopes of Surtur’s tephra/tuff cone. Most of the thermal activity is still localized on the surface of Surtur’s tephra/tuff cone with a spatial extent of about 0.13 km² while Surtungur’s extent only reaches about 0.05 km². The intermediate tephra/tuff zone is the smallest geothermal area at the time with a value just below Surtungur’s at 0.04 km².

A considerable change in the extent of the thermal field can be observed in 2011. The entire thermal field is confined within 0.04 km² and the thermal anomaly within the lava field region has completely disappeared. At this point, most of the thermal activity resides along the top of the tephra/tuff cone rims and the extent of the thermal area in the intermediate tephra/tuff zone reaches 0.02 km². Surtungur’s geothermal area extents 0.010 km² and closely behind, Surtur’s geothermal area extents 0.09 km².

The 2018 spatial and temporal analysis of the field observations and temperature measurements have placed the current thermal field extent at about 0.021 km². Where Surtungur’s and the intermediate tephra/tuff zone expands to about 0.008 km² and Surtur tephra/tuff geothermal area is as low as 0.06 km². The thermal heat is now mostly concentrated along the top of the tephra/tuff rings. This concentration of thermal activity at topographic highs can be explained by a
chimney effect that forms by buoyancy caused by the density difference between the hot fluid in the up-flow zone and the surrounding colder fluid, in this case air (Stefánsson, 1983).

Table 5.3: The surface extent of the different zones within Surtsey’s thermal field. Results on area are rounded to two significant digits reflecting the estimated 20% uncertainty.

<table>
<thead>
<tr>
<th>Year</th>
<th>Zone</th>
<th>Area (km²)</th>
<th>Area definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>Thermal field</td>
<td>0.42</td>
<td>Defined area in map &amp; 20 °C isotherm (Jakobsson’s field data; Jóhannesson, 1972)</td>
</tr>
<tr>
<td></td>
<td>Lava</td>
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<td>Defined area in map (Jakobsson’s field data; Jóhannesson, 1972)</td>
</tr>
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<td></td>
<td>Surtur tephra</td>
<td>0.14</td>
<td>Defined area in map - 20 °C isotherm (Jakobsson’s field data; Jóhannesson, 1972)</td>
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<tr>
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<td>Intermediate tephra</td>
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<td></td>
<td>Surtungur tephra</td>
<td>Not Active</td>
<td>Defined area in map - 20 °C isotherm (Jakobsson’s field data; Jóhannesson, 1972)</td>
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<tr>
<td>1979</td>
<td>Thermal field</td>
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<tr>
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<td>Surtur tephra</td>
<td>0.14</td>
<td>Defined area in map - 20 °C isotherm (Jakobsson’s field data; Jakobsson, 1982)</td>
</tr>
<tr>
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<td>0.06</td>
<td>Defined area in map - 20 °C isotherm (Jakobsson’s field data; Jakobsson, 1982)</td>
</tr>
<tr>
<td></td>
<td>Surtungur tephra</td>
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</tr>
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<td>Thermal data extrapolation</td>
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<td>Intermediate tephra</td>
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<td>Surtungur tephra</td>
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<td>Thermal data extrapolation</td>
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<td>Surtungur tephra</td>
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</tr>
<tr>
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<td>Lava</td>
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<td>Surtungur tephra</td>
<td>0.008</td>
<td>Thermal data extrapolation</td>
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</table>
Figure 5.6: Extent of thermal field in 1970 according to Jakobsson’s map records and Jóhannesson’s thermal survey (1972). The maximum temperature value recorded in the lava thermal region reaches 460 °C, while the maximum temperature value in the tephra/tuff thermal region is 98 °C near the location where the first signs of palagonitization at the surface were discovered in 1969.
Figure 5.7 Extent of thermal field in 1979. The maximum temperature value recorded in the lava thermal region is 153 °C south of Surtungur’s lava crater and the maximum temperature value in the tephra/tuff thermal region is 98 °C, measured along a fissure on the inner wall of the western side of Surtungur tephra/tuff cone.
Figure 5.8: Extent of thermal field in 1988. The maximum temperature value recorded in the lava thermal region is 188 °C outside of Surtungur’s lava crater and the maximum temperature value in the tephra/tuff thermal region is 98 °C, measured along a fissure located in the intermediate tephra/tuff zone.
Figure 5.9: Extent of thermal field in 2000. While the maximum temperature value recorded in the lava thermal region is now 16 °C outside of Surtungur’s lava crater, the maximum temperature value in the tephra/tuff thermal region is 98 °C, measured along a fissure located at the top of Surtur’s tephra/tuff cone.
Figure 5.10: Extent of thermal field in 2011. The lava thermal region has dissappeared by now and the maximum temperature value in the tephra/tuff thermal region is 99.6 °C, measured along a fissure located at the top of Surtungur’s tephra/tuff cone.
Figure 5.11: Extent of thermal field in 2018. The maximum temperature value in the tephra/tuff thermal region reaches 103 °C, measured along a fissure located at the top of Surtungur’s tephra/tuff cone. The maximum temperature recorded in Surtur’s tephra/tuff geothermal area is 88.9 °C and a lower value of 80 °C corresponds to the intermediate tephra/tuff zone.
The data on the surface extent of the different zones within Surtsey’s thermal field, collected in Table 5.3, is combined (Table 5.4) and further analysed with a series of graphs that summarize the temporal evolution of the field’s extent.

**Table 5.4: Surface area values for six different years calculated using Jakobsson’s map records combined with Jóhannesson (1972) and present author’s thermal data.**

<table>
<thead>
<tr>
<th>Year</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>0.42</td>
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<td>1979</td>
<td>0.39</td>
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<td>0.33</td>
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<tr>
<td>2011</td>
<td>0.03</td>
</tr>
<tr>
<td>2018</td>
<td>0.02</td>
</tr>
</tbody>
</table>

**Figure 5.12: 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 extent of the thermal anomalies at the surface of the lava fields are reaching critical numbers before they disappear.
Figure 5.13: Thermal evolution of Surtur’s tephra/tuff geothermal area from 1969 until present. A gradual decrease in surface area is observed since 1969 with a markedly decrease in the period from 1988 – 2011.

Figure 5.14: Thermal evolution of Surtungur’s tephra/tuff geothermal area from 1969 until present. 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 only extent as far as 0.008 km² within Surtungur’s tephra/tuff cone.
Figure 5.15: Thermal evolution of the intermediate tephra/tuff zone geothermal area from 1969 until present. 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 extent as far as 0.008 km$^2$ within the intermediate tephra/tuff zone.

Figure 5.16: The graph shows the surface evolution of the extent of the entire thermal field on Surtsey (Table 5.4). Maximum surface area value is 0.42 km$^2$ in 1970 and gradual decreased values follow shortly after. Based on the thermal survey performed in 2018, the current extent of the thermal field is about 0.02 km$^2$. 
5.6 Surtsey 1979 drill hole analysis

When individual records are analyzed in Figure 5.16, the temperature profiles from 1980, 1990, 2000, 2009, and 2018 show a couple of trends: they all show a common trend by reaching their maximum temperature zone at about 100 m depth, as well as a decrease of temperature from that depth to the bottom of the hole, where the temperature is about 40 °C. These profiles also show various differences: the zero-temperature gradient that can be observed in the temperature profile from 1980, in which a constant temperature of 100 °C between 12m depth in the hole and mean sea level at 58 m is observed, shows a decrease in range throughout the temperature profiles from the following years; while in 1990, the zero-temperature gradient at 100 °C begins at about 35 m depth, this gradient is not observed in the temperature profiles from 2000, 2009 and 2018; and the zero-temperature gradient observed in 1980 between 142 m and 159 m is not observed in the profiles from the following years.
Figure 5.17: Temperature profiles from 1980, 1990, 2000, 2009 and 2018. The overall trend shows a decrease in temperature since 1980.
Further analysis shows a clear decrease in the maximum temperature value that has been measured in the drill hole since 1979. This decrease is shown by the negative slope of the trend in the graph of the maximum temperature measured by year (Figure 5.17). The maximum temperature in 1980 was 141.3 °C while the maximum temperature recorded in 2018 was only as high as 123.4 °C. 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. However, two distinctive maximum temperature measurements deviate from the trend. The first one corresponds to the 145.6 °C measurement in 1985 and the second one to the 143.1 °C in 2004. These two surveys, in particular the one in 2004 appear to be outliers and may be due to poorly calibrated or faulty instruments. They will not be considered further here.

**Figure 5.18:** Graph showing the maximum temperatures measured in the 1979 drill hole during forty years of thermal monitoring.

Based on the first observations made in 1980 where the zone of maximum temperature measured in the hole was located at 104 m depth (Axelsson et al., 1982), the maximum temperature value from every surveyed year was analyzed. By studying the complete temperature record from the 1979 drill hole, it can be observed that the zone at the temperature maximum – where the same temperature value is recorded, can be up to 6 meters thick, with lower temperatures both above and below. The depth value used (Figure 5.18) here and shown in Table 5.5, is the depth to the top of this zone of maximum temperature.
When the depth of maximum temperature zone is plotted against the surveyed year, a clear trend emerges where a positive linear correlation is observed, with progressive shallowing to the temperature maximum with time. The deepest value at which the highest temperature zone has been reached is 104 m in 1979 – 1980, but has been reduced to 95 m in 2018.

**Figure 5.19:** Graph showing the depth at which the maximum temperature zone is reached during forty years of thermal monitoring.
Table 5.5: List shows the highest temperature value reached at depth for each thermal survey performed.

<table>
<thead>
<tr>
<th>Date</th>
<th>Maximum Temperature (°C)</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
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<td>September 26, 1979</td>
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</tr>
<tr>
<td>September 9, 1980</td>
<td>141.3</td>
<td>104.0</td>
</tr>
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<td>September 8, 1982</td>
<td>139.5</td>
<td>102.8</td>
</tr>
<tr>
<td>August 5, 1985</td>
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<td>102.8</td>
</tr>
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<td>July 16, 1986</td>
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</tr>
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<td>August 7, 1988</td>
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</tr>
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<td>September 24, 1990</td>
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<td>August 8, 1991</td>
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<td>August 10, 1992</td>
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<td>101.0</td>
</tr>
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<td>August 15, 1993</td>
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</tr>
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<td>August 22, 1998</td>
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<td>July 13, 2000</td>
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<td>98.0</td>
</tr>
<tr>
<td>August 16, 2002</td>
<td>131.5</td>
<td>98.0</td>
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<tr>
<td>September 13, 2004</td>
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</tr>
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<td>July 15, 2009</td>
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<td>100.0</td>
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<td>No data</td>
</tr>
<tr>
<td>July 19, 2018</td>
<td>123.4</td>
<td>95.0</td>
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</tbody>
</table>
Chapter 6: Discussion

During the last fifty years, 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 process of consolidation and palagonitization of basaltic tephra to be able to describe how they take place under the local physical conditions. This chapter will begin by shortly discussing the process of palagonitization based on the observations of Sveinn P. Jakobsson, followed by a detailed discussion on the thermal areas that constitute the entire surface manifestations of Surtsey’s thermal field.

6.1 The palagonitization of the Surtsey tephra

Jakobsson and Moore hypothesized that the geothermal system was developed as a consequence of intrusive activity in the eastern tephra crater during December 1966 – January 1967 (Jakobsson and Moore, 1986). 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 takes 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 and 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 and the palagonitized area in 1970 had substantially increased in only year after the first signs of palagonitization appeared on the surface in 1969.

6.2 The thermal areas on Surtsey

At the onset of the thermal manifestations at the surface of the tephra in 1968, the output of thermal heat was substantial and widespread along the lava field and the tephra cones. 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 sub-areas.
The lava field thermal region

The thermal area in the lava fields of Surtur and Surtungur was mostly confined within the large crater depressions of the two tephra cones and was active and vigorous during and immediately after the eruption, before the first anomalous temperatures were detected at the surface of Surtur’s tephra cone in April 1968. The main source of thermal heat in the crater areas was the remnant heat of the lava as it solidified and cooled down from its estimated erupting temperature of 1150 – 1160 °C. Due to the volumetric and emplacement time differences between the lava fields, it is convenient to discuss separately the thermal areas in the Surtur lava and the Surtungur lava.

The thermal anomaly at Surtungur’s lava field

The Surtungur lava field formed during the effusive eruptive activity in April 1964 - May 1965. This lava field rises to about 100 m above sea level and contained a total volume of 0.3 km³ by the end of its eruptive period. The thermal area comprising the Surtungur lava was characterized by the emission of steam/gas at specific localities but the maximum temperatures that were recorded during the thermal surveys, dropped fast with time. The highest surface temperature recorded in Surtsey, 460 °C in 1970 (Jóhannesson, 1972), greatly exceeds the maximum temperature of 63 °C measured at the surface of the Surtur lava during the survey period (Figure 5.1 & 5.6).

The rapid decrease in maximum temperature in 1970 – 1974, from 460 °C to 160 °C (Figure 5.2), recorded in the thermal surveys reflects a rapid cooling rate during this specific period. This cooling most likely began during emplacement as the lava experienced greater loss of heat due to the larger difference between its original high temperatures and the ambient temperatures of the island. Additionally, the lava pile contained a greater volume of heat that could easily be mined by precipitation seeping into the permeable rock and releasing superheated steam at the surface as it heats up above boiling point deeper into ground. In 1974, the thermal record shows the beginning of a slower cooling rate, specifically around the crater depression of Surtungur that Sveinn P. Jakobsson prioritized on measuring throughout the different thermal monitoring surveys.

From this point forward the lava begins to cool down slower and by 1982, the maximum temperature recorded at the surface has only decreased about 30 °C (Figure 5.2). The unexpected continuous rise in surface temperature that is observed at Surtungur’s lava crater starting in 1983 when the maximum temperature value rises from 127 °C in 1982 to 155 °C is attributed to a series of E-W fissures in the
surface lava that widened about 10 – 20 cm between September 1983 and August 1985 (Jakobsson et al., 2000). Subsidence of the southern part of the 100 m thick lava shield, opening of these fissures, and conduction of hot gases from below account for the temperature increase that ends in 1985 with a value of 190 °C. This temperature rise is short lived and another decrease in the temperature values at the surface of Surtungur´s lava is observed. A substantial gap in the thermal record of the entire lava thermal region is observed for most of the 1990’s and by the year 2000, the maximum temperature recorded is already reaching near ambient atmospheric values at 16 °C. The monitoring at Surtungur’s lava pile stops after that and a surface temperature value taken in 2011 indicates that the thermal anomaly in the Surtungur lava cooled down to near ambient and completely disappeared in certain localities within 30 – 35 years.

The thermal anomaly at Surtur’s lava field

The Surtur lava field formed during the effusive eruptive activity that took place from August 1966 – June 1967. This effusive activity formed a lava shield that was originally 70 m high with a volume of 0.1 km³. In addition, five small lava flows from five different fissures on the slopes of Austurbunki erupted from December 1966 – January 1967. The Surtur lava thermal area comprises both eruption zones and is worth mentioning that the thermal monitoring emphasized temperature measurements at locations within the fissures located on the slopes of Surtur’s tephra cone. The thermal record does not include temperature measurements from or around the Surtur crater depression.

The data from the Surtur lava thermal area presents an initial maximum temperature of 63 °C in 1970 (Figure 5.1 & 5.6). While the temperature data for the following years fluctuates between periods of decreasing values and sporadic increases in temperature, a period of stable high values that reach 98 – 100 °C is observed from 1975 – 1982 at locations along the west side fissure of Austurbunki’s inner wall. Even though the last thermal monitoring within the Surtur lava thermal area was made in 2008, and the maximum temperature value reaches as high as 55 °C at the same fissure previously mentioned, the maximum temperature value for the eastern side fissure located a few meters apart, only reaches up to 27 °C. With this inference, it can be concluded that the thermal anomaly in the Surtur lava field cooled down to near ambient and eventually disappeared within 40 – 45 years.
The evolution of the thermal anomaly within the lava region

Since the thermal heat present in the lava is not directly attributed to the hypothesized intrusions that caused the onset of the thermal manifestations at the surface of the tephra, an overall decrease in the extent of the thermal anomalies within the lava region is expected. The thermal data recorded in Sveinn P. Jakobsson’s thermal surveys clearly shows this decrease in surface area as the thermal manifestations extend to 0.26 km² in 1970 and gradually decrease to ambient temperatures by 2000 (Table 5.3) (Figure 5.6 – 5.9). 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 heat transfer by water. The last thermal measurement recorded of the maximum temperature value of 55 °C, taken along Surtur’s minor fissures, was still high enough to conclude that the thermal activity ended around 2008. This temporal uncertainty could have been resolved by performing a few more thermal surveys along the minor fissures in the years after.

The tephra/tuff thermal region

The thermal area of Surtsey is now confined to the tephra/tuff region of Surtur (Austurbunki) and Surtungur (Vesturbunki) and its thermal emission is characteristically steam issuing from fissures that formed in the tephra once it consolidated. The main source of thermal heat within the Surtur tephra/tuff cone is still up for debate but it has been hypothesized to be the intrusive activity in Surtur, during December 1966 – January 1967 (Jakobsson and Moore, 1986). It can also be argued that due to the high porosity of the Surtsey formations, any water at sea level inside Surtsey is presumed to be boiling, which leads to vapor dominating the hydrothermal system above sea level and to temperatures of around 100° C prevailing in the porous tephra pile (Friedman et al. 1976).

The Surtur tephra/tuff geothermal area

The Surtur tephra cone, also known as Austurbunki, formed during Surtsey’s explosive phase that lasted from November 14, 1963 – January 31, 1964. The edifice originally had a crest-width of 0.43 km and an elevation of 155 m above sea level with a true height of 285 m if the sea depth prior to the eruption at 130 m is taken into account.

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 and is still
active with thermal manifestations concentrating along the top of the palagonite tuff rim. Regardless of the present thermal activity in the area, these thermal values also show that the temperature at the surface of Austurbunki is declining slowly 50 years after its onset. The thermal activity on Surtur’s tephra/tuff geothermal area is expected to weaken and the thermal manifestations to eventually disappear in a distant future.

The Surtungur tephra/tuff geothermal area

The Surtungur tephra cone, also known as Vesturbunki, formed during Surtsey’s explosive phase that lasted from February 1, 1964 – April 4, 1965. The edifice originally had a crest-width of 0.52 km and an elevation of 141 m above sea level. The first thermal measurement was made and recorded in 1970 as the thermal field had not yet expanded to this area, and the initial thermal value only reached as high as 10 °C.

Thermal values show a slow increase in the surface temperatures around Vesturbunki and temperatures near 100 °C are finally reached in 1979 when a maximum temperature value of 98 °C is recorded at a location within the inner rim’s west side. The surface extent of the thermal area into the western side of Vesturbunki is observed in the map record of 1975 and this surface expansion of the thermal field on Surtsey can be attributed partly to vapor being forced to the sides of the highly consolidated core of palagonite tuff, that by now had been established in the Austurbunki, but more importantly due to the removal of loose tephra from the surface by wind and water erosion affecting this side of the island.

The thermal values recorded in the monitoring surveys indicate that even though the establishment of the thermal anomaly on Surtungur tephra/tuff 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. Thermal heat is expected to remain strong somewhat longer within this thermal area compared to the other two areas, Surtur and the intermediate zone, which both 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 intermediate tephra/tuff zone cone area

Overall, the intermediate zone between the well-defined Surtur (Austurbunki) and Surtungur (Vesturbunki) tephra/tuff cones has shown relatively high temperatures
since the first thermal survey was performed 1969. The initial maximum temperature recorded within this area is 80 °C, which falls shortly below the maximum temperature value of 84 °C recorded at Austurbungi in 1969. Temperature values begin to surpass the Surtur tephra/tephra thermal area in 1972 when the maximum temperature recorded value reaches 100 °C, with a temperature difference of almost 30 °C, at a location near the established limits of Surtur’s tephra/tuff thermal area.

From this point forward, a short period of temperature fluctuation is observed within the intermediate zone before a period of high-temperature stability sets in 1979 when, for the most part, the thermal values recorded within this area duel within the 90 – 100 °C range. The location of these maximum temperature values also changes in 1979, when the area of stronger thermal activity migrates south and begins to concentrate along the thinner rim area.

The thermal data from 1990 begins to show values that are slightly lower than those measured at Vesturbungi, indicating that the thermal activity within this area has not only weakened since then but also strengthened further west. Temperature measurements taken in 2013 have also started to show a gradual decrease in thermal heat but the latest thermal survey performed in 2018, still places the maximum temperature value at 80 °C which suggests that the thermal activity at the intermediate tephra/tuff zone is still very active and 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, covered with the Surtungur tephra.

**The evolution of the tephra/tuff thermal region**

The marked 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 likely much higher permeability of the lava that allows the groundwater, that accumulates as precipitation falls on the island, to easily seep through until the water reaches hot rock, evaporates and steam is emitted up through the lava pile. Therefore, the amount of steam emission and its variability is related to the weather condition on the island. In contrast, the permeability in the tephra decreases once consolidated and prevents the groundwater to seep through the tuff formation which 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 seeing 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 range up to 100 °C as the water at sea level inside of Surtsey boils and evaporates.

The hypothesis that intrusions account for the excess heat content of Surtsey has been previously favored as the 13 m thick discontinuous complex, observed in the drill core, is sufficient to explain the excess heat content in the vicinity of the 1979 borehole and the shape of the temperature profiles recorded (Friedman et al., 1976). However, the main source of thermal heat within the Surtur tephra/tuff cone is still up for debate and could potentially be a combination of the development of the geothermal system as the tephra edifice was been built by phreatomagmatic explosions, and the later intrusions that happened from December 1966 – January 1967 (Jakobsson and Moore, 1986).

Therefore, the onset of the thermal anomalies at the surface of the Surtur tephra cone could be the result of the time that it took for the water vapor to reach and heat up the entire tephra edifice before the first thermal manifestations were visible at the surface. The intrusions 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. This explains the extent of the thermal manifestations to the Surtungur tephra cone in the later years. 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, as well as the constant erosion of the island 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 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.
Chapter 7: Conclusions

The monitoring of the surface thermal manifestations in 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/tuff cones has followed markedly different paths.

- The thermal activity on the lava fields initially exhibits very high heat loss followed by gradual cooling. Temperatures of up to 460 °C are recorded in fumaroles 5 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/tuff exhibits a gradual onset of thermal activity. The behaviour between the two tephra/tuff cones is markedly different:
  - Surtur (Austurbunki): the onset of the geothermal activity at the surface of this area was detected in 1968. High temperatures still prevail at the surface where temperatures have only declined from 100 to 80 – 90 °C in 50 years. However, the size of the thermal area is now clearly declining and has been doing so gradually with time.
  - Surtungur (Vesturbunki): the onset of the geothermal activity in this area 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.
  - Intermediate area where tephra cones of Surtur and Surtungur merge: the geothermal activity in this area has evolved broadly in the same way as Surtur. Maximum temperatures that remained within the 90 – 100 °C range from 1979 – 2000, are now clearly declining.

- Temperatures measured within the 1979 drill hole exhibit a decrease in the maximum temperature value since 1980. An 18 °C drop in the maximum temperature in a 38-year period has been estimated in this study as the maximum temperature value dropped to 123.4 °C in 2018.

- Overall, the time series demonstrate a slow but clear trend of cooling of Surtsey with time. The record also demonstrates a clear distinction between the
cooling and behaviour of a pile of lava, which can cool fast, being highly permeable, and palagonitizised tuff, which has much lower permeability, reducing the effectiveness of heat mining by convection and advection thus retaining heat much better than the lava.

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. Not only recent but also future submarine eruptions can benefit from the monitoring programs similar to the one initiated by Sveinn P. Jakobsson 50 years ago on Surtsey volcano.
References


Loftmyndir, ehf., 2018. Aerial photograph of Surtsey.


Appendix A – Thermal surveys

The following maps are digitized versions of Jakobsson’s field maps that were performed during the thermal surveys from 1969 – 2008. The rest of the maps are digital versions that include the thermal data, provided by the IINH, from 2008 – 2017. The 2018 thermal survey was performed by the present author.

Every map states the year of the survey, date, surveyor, instrument used as well as a short section of comments. The data shown in the maps vary with every thermal survey as the digitization was performed according to the original thermal records.
Year: 1969
Date: November 22
Surveyor: Sveinn P. Jakobsson

Instrument used: Mercury thermometer

Comments: First thermal survey performed on Surtsey. The maximum temperature recorded within the tephra is 84 °C. Palagonitization is observed at the surface at a small area at the inner east corner of Austurbunki.
Surtsey

Author: Velverth Perzei
Data source: Landmælingur Islands and Núpurulfströnd Islands
Coordinate System: WGS 1984, Lambert, Conformal, Conic
1:150,000

Year: 1970
Date: August 3
Surveyor: Sveinn P. Jakobsson and Ævar Johannesson

Instrument used: Mercury thermometer

Comments: First detailed thermal survey was performed this year. The thermal area covers the Surtungur crater and most of Surtur crater and tephra cone. The maximum temperature value measured in the lava is 460 °C in Surtungur, while the maximum temperature measured in the tephra is 98 °C in the inner wall of Austurbúklu. Consolidation extends along the inner wall of Surtur and palagonitization covers two thirds of this area.

Legend:
- Lava centers
- Tephra
- Consolidated tephra
- Isotherm 20 °C
- Isotherm 40 °C
- Isotherm 60 °C
- Isotherm 80 °C
- Isotherm 100 °C
- Isotherm 120 °C

1970 Surface temperatures (°C)
- 9 - 20
- 21 - 40
- 41 - 60
- 61 - 80
- 81 - 100
- 101 - 120
**Year:** 1971

**Date:** October 12-13

**Surveyor:** Sveinn P. Jakobsson

**Instrument used:** Mercury thermometer

**Comments:** First thermal survey performed. A few temperature measurements were taken at the surface around Surtungur's lava crater. The maximum temperature value is 370 °C. No surface temperatures on the tephra cone were recorded. Consolidation covers most of the inner wall of Austurbunki and palagonization covers most of this area.

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Legend:
- Lava craters
- Consolidated tephra
- Isotherm 20 °C
- Thermal area
- Tephra
- Möberg

1971 Surface temperatures (°C)
- 100
- 159
- 200
- 260
- 300
- 340
- 370
Year: 1972
Date: June 13
Surveyor: Steinn P. Jakobsson
Instrument used: Mercury thermometer

Comments: The thermal area covers both lava craters as well as most of Surtur’s and part of the eastern side of Vesturbunki. The maximum surface temperature measured in the lava is 282 °C in Surtur’s north-western lava pile. The maximum tephra temperature is 100 °C located within the intermediate tephra/tuff zone. Palagonization is expanding along the north-facing tephra slope of Austurvulkan.
Year: 1973

Date: September 13

Surveyor: Svein P. Jakobsson

Instrument used: Mercury thermometer

Comments: The thermal area covers both lava craters as well as the inner walls of the tephra cones and parts of the north-facing slope of Austurbunki. The maximum temperature measured in the lava pile is 228 °C outside of Surtungur’s lava crater. The maximum temperature measured in the tephra is 75 °C in the intermediate tephra/tuff zone. Consolidation and palagonitization of the Surtsey tephra continues to expand along Austurbunki.
Year: 1974

Date: August 10

Surveyor: Sveinn P. Jakobsson

Instrument used: Mercury thermometer

Comments: The thermal area has expanded to the outer west side wall of Vesturbunki. The maximum recorded temperature in the lava pile is located outside of Surtangur's lava crater at 160 °C. The highest recorded temperature in the tephra is 64 °C in the outer west side wall of Vesturbunki. Palagonitization is expanding to the inner wall of Vesturbunki.
Year: 1975
Date: September 5
Surveyor: Steinn P. Jakobsson

Instrument used: Mercury thermometer

Comments: The thermal area has not changed much since last year. The maximum temperature recorded in the lava pile is 160 °C outside of Surtungur’s lava crater. The maximum temperature recorded in the tephra is 60 °C within the intermediate tephra/tuff zone. Palagonitization expands within the eastern side of Vesturbulurki’s inner wall.

Legend

- Lava centers
- Møberg
- Isotherm 20 °C
- Tephra
- Isotherm 40 °C
- Thermal area

1975 Surface temperatures (°C)
- 11 - 20
- 21 - 52
- 53 - 85
- 86 - 115
- 116 - 140
Year: 1976

Date: September 26

Surveyor: Steinn P. Jakobsson

Instrument used: Mercury thermometer

Comments: The thermal area has not changed much since last year. The maximum temperature recorded in the lava pile is 163 °C at Surtungur’s lavacrat. The maximum temperature recorded in the tephra is 31 °C within the Surtungur tephra/huff cone. Palagonitization expands within the eastern side of Vesturbunga’s inner wall.

Legend
- Lava craters
- Tephra
- Möberg
- Thermal area

1976 Surface temperatures (°C)
- 8 - 12
- 13 - 19
- 20 - 26
- 27 - 30
- 31 - 40
- 41 - 49
- 50 - 60
- 61 - 70
- 71 - 80
- 81 - 90
- 91 - 100
- 101 - 120
- 121 - 163
Year: 1979
Date: August 15-17
Surveyor: Sveinn P. Jakobsson
Instrument used: Electronic thermometer

Comments: The thermal area covers an extensive area within both craters as well as the tephra cones. The maximum temperature value measured in the lava pile is 153 °C south of Surtungur’s lava crater. The maximum temperature measured in the tephra is 98 °C at a location within Vesturbunki.
Year: 1988
Date: August 6
Surveyor: Sveinn P. Jakobsson
Instrument used: Electric thermometer
Comments: The maximum temperature value measured in the lava is 188 °C outside of Surtungur's lava crater. The maximum temperature measured in tephra is 98 °C within the intermediate tephra/tuff zone. Palagonitization expanded along the western side Vesturbunki.

Legend
- Drill hole site
- Tephra
- Lava craters
- Möberg
- Steaming fissures

1988 Surface temperatures (°C)
- 12 - 20
- 21 - 50
- 51 - 80
- 81 - 110
- 111 - 188
Year: 2000
Date: July 14
Surveyor: Sveinn P. Jakobsson
Instrument used: Electric thermometer
Comments: The maximum temperature recorded in the lava region is 72 °C. The maximum temperature recorded in the tephra region is 98.5 °C. Palagonitization expands along the north-facing slopes of the tephra/tuff cones.

Legend
- Drill hole site
- Tephra
- Lava craters
- Möberg
- Steaming fissures

2000 Surface temperatures (°C)
- 12 - 20
- 21 - 40
- 41 - 60
- 61 - 80
- 81 - 98
Year: 2006
Date: July 14
Surveyor: Svínu P. Jakobsson & Lovisa Ásbjörnsdóttir
Instrument used: Electric thermometer

Comments: The maximum temperature recorded in the tephra/tuff is 94 °C within Vesturbukla. Palagonitization expands along the north-facing slopes of the tephra/tuff cones.
Year: 2011
Date: July 18 – 21

Surveyor: Lovisa Ásbjörnsdóttir & Kristján Jónasson

Instrument used: Electric thermometer

Comments: The maximum temperature recorded in the tephra/tuff is 98 °C within Vesturbunki. Palagonitization expands along the north-facing slopes of Austurbunki.
Year: 2013
Date: July 19
Surveyor: Lovisa Ásgeirsdóttir & Kristján Jónasson

Instrument used: Electric thermometer

Comments: The maximum temperature recorded in the tephra/tuff is 94.2 °C within Austurbunklú. Palagonization expands along the north-facing slopes of both tephra/tuff cones.

Legend
- Drill hole site
- Tephra
- Lava craters
- Móberg
- Steaming fissures

2013 Surface temperatures (°C)
- 0 - 20
- 21 - 40
- 41 - 60
- 61 - 80
- 81 - 100
Year: 2015
Date: July 14

Surveyor: Lovísa Asbjörnsdóttir & Kristján Jónasson

Instrument used: Electric thermometer

Comments: The maximum temperature recorded in Austurbunki as well as in the intermediate tephra/buff zone is 93.9 °C. The maximum temperature recorded in Vesturbunki is 99.6 °C.

Legend:
- Drill hole site
- Tephra
- Lava craters
- Möberg
- Steaming fissures

2015 Surface temperatures (°C):
- 0 - 20
- 21 - 40
- 41 - 60
- 61 - 80
- 81 - 100
Year: 2016
Date: June 19

Surveyor: Lovisa Ásbjörnsdóttir & Kristján Jónasson

Instrument used: Electric thermometer

Comments: The maximum temperature recorded in Austurbunki is 84.3 °C. The maximum temperature recorded in the intermediate tephra/lava zone is 79 °C. The maximum temperature recorded in Vesturbunki is 91.9 °C.
**Year:** 2017

**Date:** July 17

**Surveyor:** Lovisa Ásbjönsdóttir & Kristjan Jónasson

**Instrument used:** Electric thermometer

**Comments:** The maximum temperature recorded in Austurbunki is 94.9 °C. The maximum temperature recorded in the intermediate tephra/tuff zone is 83.2 °C. The maximum temperature recorded in Vesturbunki is 95.7 °C.
Year: 2018
Date: July 18 - 22
Surveyor: Velveth Perez
Instrument used: Electric thermometer

Comments: The maximum temperature recorded in Austurbunki is 88.9 °C. The maximum temperature recorded in the intermediate tephra/hull zone is 80 °C. The maximum temperature recorded in Vesturbunki is 96 °C and 103 °C.