Sinkholes observed at Vesturbunki, Surtsey

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ABSTRACT

We report observations and monitoring of sinkholes and tensional fissures occurring along the outer margin of the lava shield within Vesturbunki, one of Surtsey's two tuff cones. The features were first noted in summer 2015 and traced nearly continuously along roughly 500 m of the lava–tuff contact. In 2015, 49 sinkholes and fissures were observed; subsequent field work in 2017, 2019 and 2025 recorded approximately 20 features per visit, including some previously unrecorded openings. Field data includes GPS locations and photographs. To contextualize these observations, we compare them with geodetic and seismic data from the area and report maximum surface temperatures for the two tuff cones, Vesturbunki and Austurbunki, from surveys we conducted between 2008 and 2025. Earlier geodetic data on Surtsey indicates ongoing subsidence of the island, with a decaying rate since the eruption and Austurbunki is more stable than Vesturbunki. Seismicity near Surtsey during the years 2009–2024 was examined and was found to be low to moderate with five events ≥M 2.5. The seismic hypocentre locations are uncertain because of sparse station coverage. Surface temperature monitoring shows Vesturbunki is consistently hotter, up to 100°C, and fluctuates by up to 4.5°C between measurements, while Austurbunki is stabler and slightly cooler, up to 96°C, with only 2°C fluctuations. The sinkholes were likely produced and maintained by a combination of island-wide subsidence, local compaction of volcanogenic material, and possibly by seismicity that may trigger opening of fissures in the palagonite tuff cone that enhance upward heat flow locally and temporarily. Continued monitoring and mapping, as well as installation of a local seismic station on Surtsey, is recommended to better resolve the processes that produce these features.

INTRODUCTION

Jakobsson and Moore (1982) described how Vesturbunki was formed as a tephra cone during a phreatomagmatic eruption that began on February 1st, 1964. On April 4th, the character of the eruption changed to Hawaiian-style lava effusion when the sea no longer reached the vent, and lava erupted from the crater Surtungur. The eruption at Surtungur ended on May 17th, 1965, by which time a relatively flat lava shield had formed within the tephra cone. Geodetic surveys on August 24th, 1964, showed that Vesturbunki reached its highest elevation in the western part of the cone, 169 m above sea level (Þórarinsson 1966), but is today 140 m above sea level (Óskarsson *et al.* 2021).

The tephra on Surtsey was rapidly altered to palagonite tuff, and by 1998 it was estimated that about 80–85% of the tephra had been converted to palagonite (Jakobsson *et al.* 2000). While the tephra remained unconsolidated, the westernmost part of Vesturbunki was subject to intense marine erosion. When the erosion reached the hardened palagonite core, it decreased substantially. Today the sea-facing part of Vesturbunki is characterized by steep palagonite cliffs.

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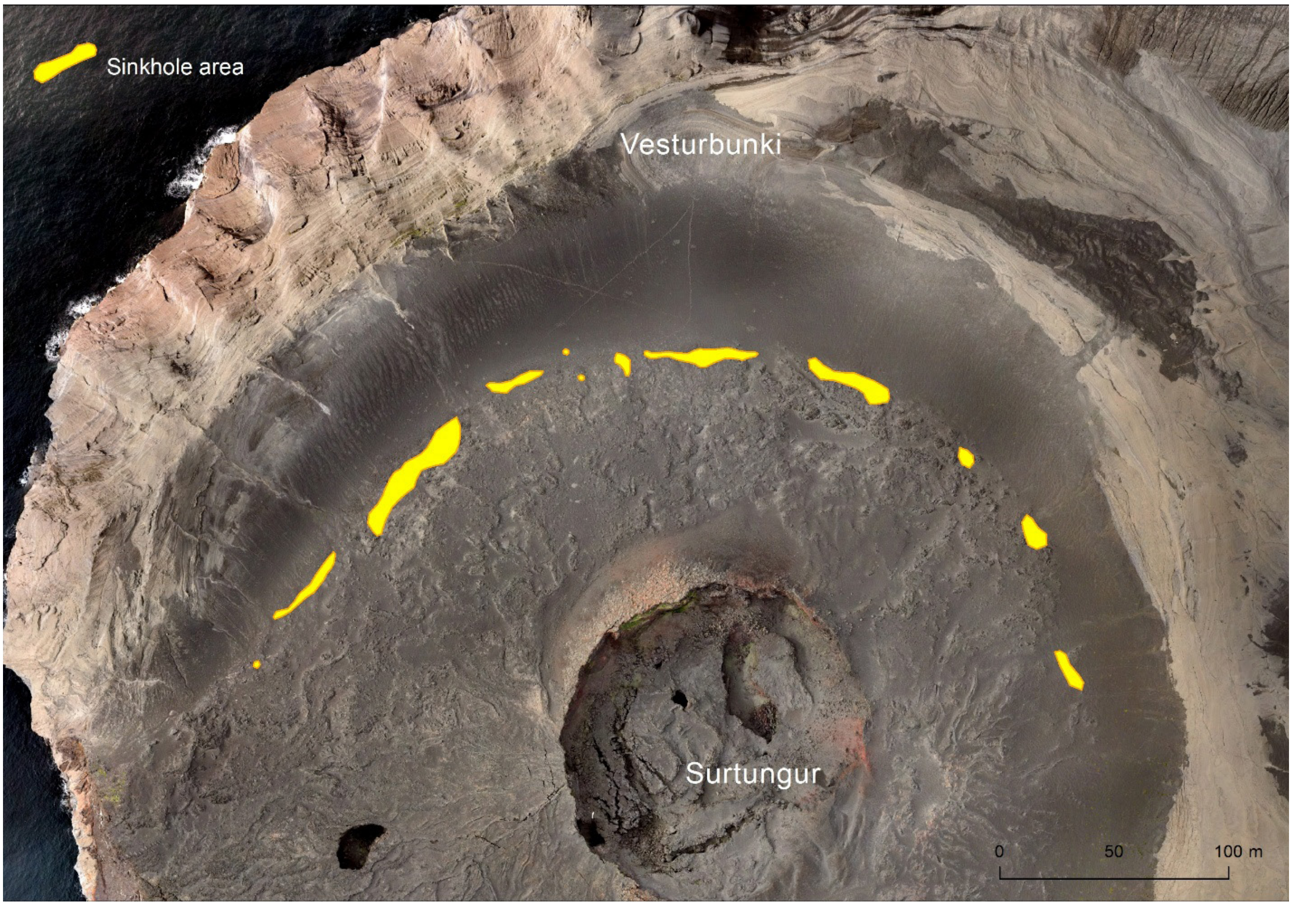

Figure 1. Distribution of sinkholes and tensional fissures along the lava margin within Vesturbunki. Orthoimage from 2023 (Natural Science Institute of Iceland, 2023. Unpublished data).

METHODS

In summer 2015 the authors noticed sinkholes and tensional fissures along the lava margin within Vesturbunki that could be traced almost continuously for about 500 m within the palagonite tuff cone (Fig. 1). Time did not allow detailed inspection on that expedition, but visible features were photographed and recorded with Garmin and Trimble Yuma GPS units. During geological field expeditions in summers 2017, 2019, and 2025, the features were examined further, and sinkholes and fissures were measured and photographed (Fig. 2).

The authors have also conducted regular surveys of surface temperatures in fissures on the palagonite tuff cones Austurbunki and Vesturbunki. The measurements are conducted with electronic thermometer that can be used either with an infrared sensor with a laser pointer or with an attached temperature-sensor thermocouple. For further discussion of the employment of these methods in Surtsey, see Perez et al. (2022).

Two further datasets were examined in search of potential explanations for localized sinkhole formation on the lava shield margin in Vesturbunki:

1. Results of regular geodetic surveys in Surtsey since 1967 to monitor island subsidence (Sturkell et al. 2009, 2025)
2. Seismic activity near Surtsey back to 2009, from the Icelandic Meteorological Office earthquake web viewer, Skjálfta-Lísa (Icelandic Meteorological Office 2025)

The seismic activity is considered in conjunction with temperature measurements from fissures on Surtsey's surface (see also Perez et al. 2022) to explore potential seismic influence on Surtsey's surface features.

Figure 2. The diversity of sinkholes and tensional fissures along the lava margin within Vesturbunki on Surtsey. Photos: Lovísa Ásbjörnsdóttir, Kristján Jónasson.

RESULTS AND DISCUSSION

Sinkholes

A total of 49 sinkholes and fissures were recorded in Vesturbunki in 2015; subsequent expeditions recorded fewer features (around 20 per campaign), and several new sinkholes were noted. Most of the prominent features are on the western and northern margin of the lava and generally remain visible between expeditions; a map of the sinkhole areas is shown in Fig. 1. In 2017 the opening width of fissures in the lava margin was measured, most being in the range of 10–12 cm wide. In addition to clear fissures in the lava, disrupted lava is visible within several sinkholes.

The inside slopes of Vesturbunki are steep and largely covered by aeolian deposits. Substantial aeolian sediment has also accumulated on the lava below the slopes. It is therefore likely that many sinkholes are obscured by sediment. During the 2025 expedition, the authors observed sinkholes that were hidden beneath aeolian deposits but had voids underneath, making walking across the area potentially hazardous. No sinkholes have been observed along the lava margin within the eastern cone, Austurbunki.

Temperature Measurements

Table 1 presents a summary of maximum surface temperature measurements made in Vesturbunki and Austurbunki on research expeditions by the Natural Science Institute of Iceland (before 2024, the Icelandic Institute of Natural History) and the Surtsey Research Society. The number of points and fissures measured near this maximum temperature in each of the two areas varies from survey to survey, but the maxima give a good indication of the overall state of the geothermal system. Maximum temperatures at Austurbunki have been more stable than those of Vesturbunki, fluctuating between 93,1°C and 94,4°C from 2013 to 2021 and declining slightly since then, to 91,3°C in 2025. Vesturbunki, on the other hand, shows larger temperature oscillations, ranging between 93°C and 100°C over the entire period from 2008 to 2021 and fluctuating from measurement to measurement by up to 4.5°C.

Table 1. Maximum temperature measurements from Vesturbunki and Austurbunki, 2008–2025. Dates refer to the start date of each expedition. Initials of participants in the monitoring: SPJ: Sveinn P. Jakobsson, LÁ: Lovísa Ásbjörnsdóttir, KJ: Kristján Jónasson, MHG: María Helga Guðmundsdóttir.

Date	Vesturbunki T_{max} (°C)	Austurbunki T_{max} (°C)	Measured by
11.4.2008	100	94	SPJ, LÁ
18.7.2011	98	96	LÁ, KJ
19.7.2013	93	94	LÁ, KJ
14.7.2015	99.6	93.9	LÁ, KJ
17.7.2017	95.7	94.4	LÁ, KJ
18.7.2019	99.3	93.1	LÁ, KJ
15.07.2021	94.8	94.3	LÁ, KJ
14.07.2023	98.5	92.1	KJ, MHG
15.07.2025	97.7	91.3	LÁ, MHG

Deformation

Sturkell et al. (2009, 2025) describe how geodetic measurements show continuing subsidence across the island whose rate has decreased with time. Surtsey subsided rapidly during the first 10–15 years after formation, since which time the subsidence rate has decayed. In the period 1992–2000 the average subsidence rate was approximately 10 mm/yr, and for 2000–2023 approximately 3.8 mm/yr. One GPS station, SURG, is located on Vesturbunki; it shows linear vertical displacement and total subsidence of 78 mm since the year 2002. The measured horizontal displacements indicate constant horizontal velocities, unlike the vertical time series.

It has been suggested that the deformation processes currently active on Surtsey include compaction of volcanogenic material, slumping of the island flanks, lithospheric sagging due to the load of erupted material, and possible compaction of seabed sediments (Sturkell *et al.* 2009). Differential movement between the lava shield and the surrounding tuff cone rim, resulting in the observed sinkholes, might be a consequence of this subsidence.

The fastest-subsiding areas in Surtsey are at the edge of the island due to marine erosion, but the slowest-subsiding GPS station (512) is within the eastern cone, Austurbunki (Sturkell *et al.* 2025). Sinkholes have not been observed within Austurbunki, a fact that corresponds well with the observation that Austurbunki is subsiding less than any other part of the island.

Seismicity and Geothermal Activity

The authors examined whether seismic activity near Surtsey could have influenced movements at the lava margin, as the sinkholes were first observed

Table 2. Earthquakes ≥ M 2.5 recorded near Surtsey, 2009–2024 (Icelandic Meteorological Office 2025).

Date	Latitude	Longitude	Depth (km)	Magnitude (M)
17.08.2009	63.33	-20.633	15	2.5
25.04.2015	63.309	-20.631	16	2.8
24.04.2018	63.342	-20.617	14	2.5
31.01.2019	63.319	-20.64	14	3.4
06.09.2020	63.343	-20.604	18	2.6
06.06.2023	63.321	-20.637	15	3.1

in July 2015, shortly after the M 2.8 earthquake of April 25th, 2015. The Icelandic Meteorological Office earthquake web viewer, Skjálfta-Lísa (Icelandic Meteorological Office), provides earthquake data back to 2009. Typically, about 5–10 earthquakes are recorded annually near Surtsey, most of them at depths of roughly 10–15 km. Magnitudes are generally in the range M 1–2, although several larger earthquakes (≥ M 2.5) have occurred (Table 2). The hypocentres appear about 1.2–2.3 km northwest of Surtsey. However, it has been pointed out that earthquake locations in the Vestmannaeyjar area should be treated with caution because there are few seismic stations in the region and the earthquakes are deep, which reduces location accuracy (Kristín Vogfjörð, pers. comm., 1 October 2025).

When maximum surface temperatures are plotted against the timing of these earthquakes (Fig. 3), it becomes apparent that the upward jumps in temperature in Vesturbunki (in 2015, 2019, and 2023) were all preceded by an earthquake in the six months preceding the measurement. No such correlation can be observed for the temperatures in Austurbunki, which, as previously mentioned, shows far less fluctuation in its maximum temperature. It is suggestive that both geodesy and thermal monitoring reveal Austurbunki to be more stable than Vesturbunki.

One possible interpretation of this correlation for Vesturbunki is that it relates to movement on fissures in the palagonite tuff, which could provide a more direct pathway for heat to reach the surface. These temperature changes are suggestive that larger earthquakes could have some effect on the geological features of Surtsey, and a seismic contribution to the formation of sinkholes cannot be ruled out. The temporal sparsity of temperature measurements does, however, demand a degree of caution when interpreting the data.

Conclusions

It is not well understood what caused these sinkholes along the lava margin within Vesturbunki, or what maintained them between field expeditions. A plausible explanation is that multiple interacting factors are involved, related to island subsidence and possibly seismicity. It is important to continue to monitor the sinkholes and fissures at the lava margin of Vesturbunki and it would be desirable to map these features in more detail and measure their extent and depth. The authors recommend that the Icelandic Meteorological Office, in cooperation with the Surtsey Research Society and research

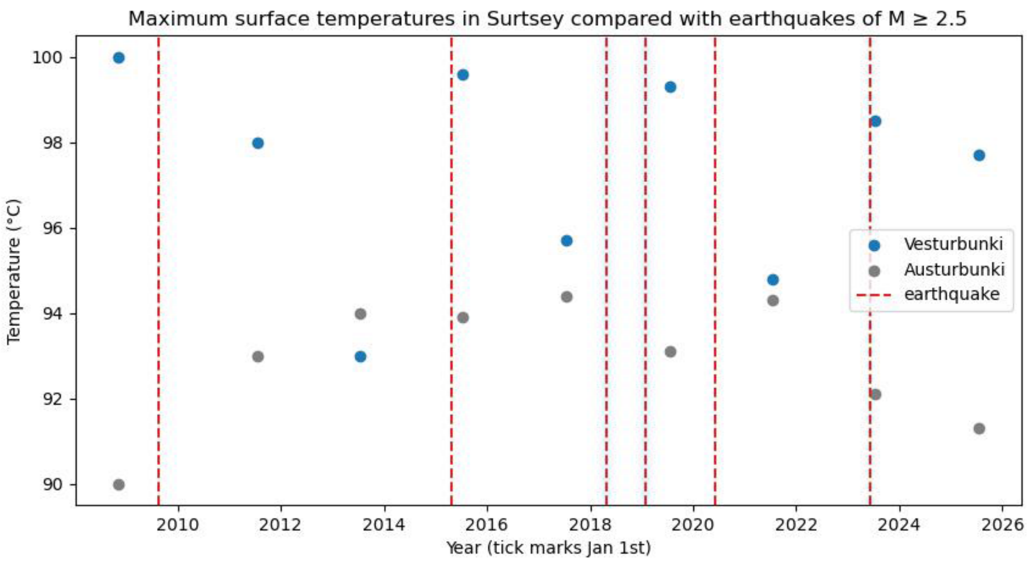

Figure 3. Time series of maximum temperatures measured in fissures in Austurbunki and Vesturbunki and earthquakes with ≥ M 2.5.

institutions associated with Surtsey, install a seismic station on Surtsey to obtain more accurate earthquake measurements, particularly hypocentre locations. A seismic station on Surtsey would also be crucial for monitoring the Vestmannaeyjar volcanic system.

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