Reviewed research article

Volcanic tremor associated with the Surtsey eruption of 1963–1967

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Abstract — *The formation of the island of Surtsey over 3.5 years, remains one of the best-documented volcanic, island-forming eruptions to date. The basaltic submarine volcanic activity was detected on November 14, 1963, where ocean depth was 130 m prior to the eruption at the southern end of the Vestmannaeyjar archipelago. The eruptions occurred in several phases involving explosive and effusive activity, including the initial submarine phase on November 12–13, 1963. Separate phases of subaerial volcanic activity occurred during November 14, 1963–January 1964, January–April 1964, April 1964–May 1965, May–October 1965, December 1965–August 1966, and August 1966–June 1967. Seismic data quality from this period is inferior compared to that of modern monitoring systems. Four permanent seismic stations were operated in Iceland at the time, whereof only two, located at 115 and 140 km distance, had the sensitivity to record tremor from Surtsey. Nevertheless, the scanned analog seismograms (http://seismis.hi.is/) show that the eruptive activity was accompanied by considerable seismic activity, both earthquakes, and volcanic tremor. Earthquakes were primarily associated with changes in vent location. Both spasmodic and harmonic tremor was identified, both with low (<3 Hz) and higher (3–5 Hz) characteristic frequencies. The results indicate a complicated relationship between tremor and magma flow rate or style of activity. During the explosive eruption, the highest magma flow rates occurred in the first 10–20 days, a period with little observed tremor. The highest tremor is observed in December 1963–March 1964, after the discharge rates had dropped substantially, and on a timescale of hours-to-days, no clear relationship between tremor and eruption style is observed. The same applies to the effusive activity, where no seismic tremor was observed during most of the effusive eruption of Surtungur, despite the fact that magma flow rates were ∼3 times higher than during later phases where some tremor was observed.*

Keywords: Submarine volcanism, eruption precursors, volcanic tremor, precursory tremor, continuous uprush eruptions

INTRODUCTION

Magmatic events, both intrusions and eruptions, are accompanied by characteristic seismic patterns (e.g., Brandsdóttir and Einarsson 1992; McNutt and Roman 2015). Recent studies confirm that all eruptions in Iceland in the last decades have been preceded by swarms of microearthquakes and short-term seismic precursors (Einarsson, 2018). The characteristics of such activity vary and are not the same for all volcanoes. Moreover, individual volcanoes may not always behave in the same way, calling for studies of multiple eruptive cycles to characterize the seismic precursors to an eruption, which may not be feasible where eruptions happen only infrequently (Unglert and Jellinek, 2015). High precision digital records of seismicity, including earthquakes and tremor, exist for various events over the last few decades and great advances have been made in analysis of such phenomena at volcanoes (e.g., McNutt and Roman, 2015 and references therein). However, seismic data collected during some notable events from the early days of seismic analog recordings, although of inferior quality compared to modern-day seismographs, may also provide useful insight. One such eruption of distinct character, where analog seismic data exist, is the 3.5-year long Surtsey eruption in 1963–1967. The eruption occurred off the south coast of Iceland at the southern end of the Vestmannaeyjar archipelago of Iceland's Eastern Volcanic Zone (Figure 1). Approximately 1.1–1.2 km^3 bulk volume of lava and tephra were erupted (Thorarinsson, 1968; Ólafsson, 2021). The eruption had several eruption episodes at different vents and included shallow to emergent Surtseyan explosive activity and long periods of effusive activity of varying magnitude that was well documented (e.g., Thorarinsson *et al.*, 1964; Thorarinsson, 1968).

There was no seismograph in Vestmannaeyjar at the time of the eruption onset. The four permanent stations operated in Iceland at that time were located at a considerable distance from the eruption site (80–291 km, see below). The network was operated by the Icelandic Meteorological Office, where the seismic records were analyzed, and the results published (Icelandic Meteorological Office 1970,1978,1979a,1979b,1980). Sigtryggsson and Sigurdsson (1966) noted the occurrence of tremor and earthquakes in November and December of 1963. An array of short-period seismograph was installed in Surtsey in the summer of 1966. This array recorded earthquake swarms associated with the cessation of the last explosive phase of the Surtsey eruptions (Jólnir) and the beginning of the final lava effusion on the island (Einarsson, 1974).

In 2017 a drilling program was carried out on Surtsey with multiple aims of detailed studies of the island's structure and evolution under the umbrella of the SUSTAIN project (Jackson *et al.*, 2019; Weisenberger *et al.*, 2019). This work has provided new insight into various aspects of the formation and evolution of Surtsey, including the structure and existence of a diatreme under the main crater (Jackson *et al.*, 2019), the progressive alteration of the volcanic rocks within the edifice (Prause *et al.*, 2020), the geothermal system (Kleine *et al.*, 2020; Perez Romero, 2019) and subsurface microbiology (Bergsten *et al.*, 2021). In this context, analyses of previously poorly studied aspects of the formation of Surtsey and associated volcanic activity can provide useful insight.

Seismicity related to volcanic activity is conventionally divided into earthquakes, i.e., sudden events with clear beginning and end, and volcanic tremor, characterized by sustained vibrations of the ground for minutes, hours or days or longer, without a sharp onset. The seismic activity preceding visible eruption and the earthquakes detected during the Surtsey eruption in 1963–1967 were analyzed and interpreted by Sayyadi *et al.* (2021). The analysis suggests that the eruption was preceded by earthquakes $\geq$M2.5, a week before the beginning of the eruption. Subsequent earthquake swarms were primarily associated with shifts in the eruption sites. The present paper is complimentary to Sayyadi *et al.* (2021) and focusses on the observations of volcanic tremor during the eruption. We explore the relationship between seismic tremor and a few well-constrained cases of the style of eruptive activity, notably continuous uprush, periods of cockscomb explosions, and gaps in visible eruption during the main explosive phase in November-December 1963. This re-analysis of the seismic records is greatly facilitated by the Seismis project, where historic analog seismograms of the Icelandic seismograph station have been scanned and made available through a webpage: seismis.hi.is (Einarsson and Jakobsson, 2021).

PHASES OF THE ERUPTION

Seven episodes of activity for the Surtsey eruption may be identified, based on changes in phases and activities at the five active vents Surtur, Surtla, Surtungur, Syrtlingur, and Jólnir during the years 1963–1967 leading to the creation of the new island of Surtsey (Figure 1):

- Onset of the eruption. – Explosive eruption of Surtur crater, Nov. 1963–Jan. 1964.
- Submarine eruption of Surtla, Dec. 1963–Jan. 1964.
- Formation of the parasitic cone of Surtungur, Jan.–April 1964.
- Lava effusion from Surtungur, April 1964–May 1965.
- Formation of the temporary island of Syrtlingur, May–Oct. 1965.
- Formation of the temporary island of Jólnir, Dec. 1965–August 1966.
- Lava effusion from Surtur crater, August 1966–June 1967.

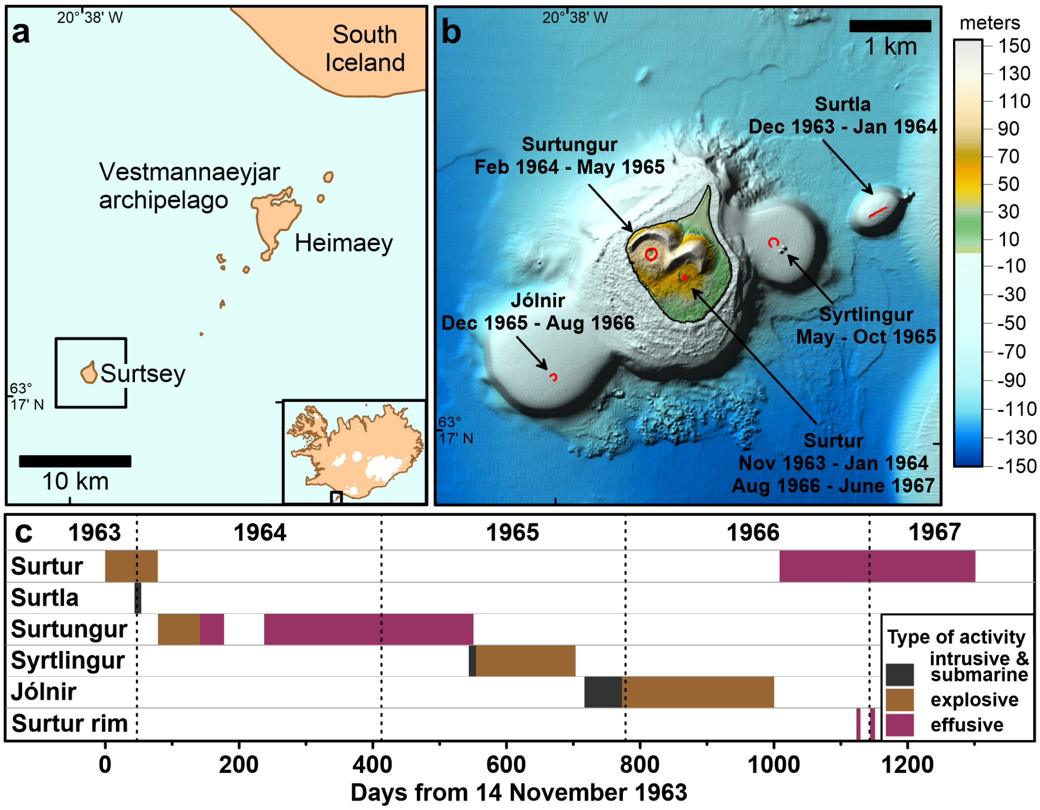

Figure 1. a) The Vestmannaeyjar archipelago off the south coast of Iceland. b) Map of the Surtsey volcano with its five different eruption sites that were active at different times during 1963–1967 (bathymetry: Jakobsson *et al.*, 2009). The two tuff cones (Surtur and Surtungur) and the later-formed effusive craters are indicated. c) The timeline and nature of different phases of the Surtsey eruptions in 1963–1967 (Thorarinsson *et al.*, 1964; and Thorarinsson 1965, 1966, 1967, 1968; Sayyadi *et al.*, 2021). – *a) Kort af Vestmannaeyjum. b) Kort af Surtsey og gosopunum sem voru virk á mismunandi tímum 1963–1967 (dýptarkort: Jakobsson og fl., 2009). Öskugígarnir tveir, Surtur og Surtungur eru sýndir, einnig hraungígarnir sem mynduðust síðar. c) Atburðarás gosanna í og við Surtsey á tímalínu (Thorarinsson og fl., 1964; og Thorarinsson 1965, 1966, 1967, 1968).*

TERMINOLOGY AND CLASSIFICATION OF VOLCANIC TREMOR SIGNALS

Magmatic activity is one of the natural processes that can generate continuous vibrations of the ground. Other processes include e.g., wind, water flow in a river, geothermal activity, waves on a shore, and swell on an open ocean. Magmatic or volcanic tremor has been described and classified by many authors (Brandsdóttir and Einarsson, 1992; Chouet, 1992; McNutt, 1992; Minakami, 1974). Some classification schemes refer to the appearance of the tremor on the seismograms, such as "harmonic tremor", with a narrow frequency band and one characteristic frequency in the range 1-10 Hz, dominating the record. The contrasting example would be "spasmodic tremor", with a broader frequency band and uneven amplitude. "Banded tremor" is characterized by regular temporal amplitude modulation of the tremor, making regular bands on the analog drum seismograms. Other schemes may use the volcanic process at work during the respective tremor episode as a basis for the classification, such as "eruption tremor" or "intrusion tremor". Various driving mechanisms have been suggested for the different types of volcanic tremor (Aki, 1984; Aki and Koyanagi, 1981; Dziak, 2002; Fehler, 1983; Fehler and Chouet, 1982; Koyanagi *et al.*, 1987; Sgattoni *et al.*, 2016; Zuccarello *et al.*, 2013) including gas emission, turbulent magma flow, boiling in a geothermal system, and water flow.

Harmonic tremor, according to Zobin (2012), is often observed during eruptions before and during explosive phases and may be related to stress variations when magma rises in the earth's crust. Low-frequency earthquakes frequently accompany tremor at dominant frequencies of 1-5 Hz. Phreatomagmatic processes produce these in the crater of a volcano and by the movement of lava and pyroclastic flows on its slopes, as well as rockfalls (Zobin, 2012) . Most harmonic tremor looks like an irregular sinusoid with frequencies between 1 and 5 Hz.

Spasmodic tremor consists of pulses of higher frequency, usually 5–10 Hz or higher. It has only been recorded in relatively few volcanic areas, and no signals like these are known from non-volcanic regions (McNutt, 1992). During the Krafla volcano-tectonic episode in Iceland 1975–1984, spasmodic tremor was observed during intrusive activity when dikes propagated away from the central volcano's magma chamber (Einarsson and Brandsdóttir, 2021). It may be the expression of a very dense swarm of small earthquakes associated with the tip of a propagating dike. In contrast, harmonic tremor was observed at Krafla when the magma reached the surface in effusive eruptions (Brandsdóttir and Einarsson, 1992). At Krafla the amplitude of the eruption tremor reflected the intensity of the eruption. Several tremor signals recorded by seismic and acoustic networks during submarine eruptions suggest that other mechanisms may be responsible for its generation, for example, banded tremor in the Izu- Oshima eruption of 1986 (Hashimoto *et al.*, 1989) and harmonic tremor on the Volcano Islands arc south of Japan (Dziak, 2002).

Banded tremor is not observed in the records associated with the Surtsey eruption during 1963–1967 and is not considered further here.

DATA AND MONITORING SYSTEM

The four permanent seismic stations in Iceland during the eruption were in Reykjavík (REY), Kirkjubæjarklaustur (SID), Vík í Mýrdal (VIK), and Akureyri (AKU). The location of each station, distance from Surtsey, and the characteristics of the instruments used are summarized in Figure 2 (Icelandic Meteorological Office, 1970; Sigtryggsson and Sigurdsson, 1966).

Seismic station characteristics

The two stations in Reykjavík (REY) and Kirkjubæjarklaustur (SID) had a much higher magnification than the two older stations (Figure 2). The analysis presented here is based on information obtained from REY and SID. The older stations (AKU and VIK) with early 20th century Mainka seismographs (Sigtryggsson and Sigurdsson, 1966; Sayyadi *et al.*, 2021) of low magnification, do not contain signals useful for this project. The seismograms were written on paper sheets fastened on rotating drums, giving time resolution of 1 mm/second. The dynamic range of such records is low and for the observed tremor during first 150 days of eruption is estimated in the range 6 dB (low frequency) to 12 dB (high frequency and spasmodic). Moreover, resolving frequencies above 1 Hz is not possible. The waveforms at high frequencies of local earthquakes are therefore lost, even though arrival times of body waves and magnitude of the earthquakes can be determined with fair accuracy. For volcanic tremor only low-frequency (1–5 Hz) or harmonic tremor can be resolved on the seismograms. The high-frequency waveforms are already lost in the recording process, so they cannot be reconstructed from these records. The type of tremor and the dominant frequency can, however, be determined. Considering the passband of seismographs, the course of events and relative wave amplitude can be assessed. The Wilmore seismograph at SID station had a wide passband (4–25 Hz) compared to the Sprengnether sensors in Reykjavík, both N-S and Z components. For more details on the seismic network at this time see Sayyadi *et al.* (2021) and Einarsson and Jakobsson (2020).

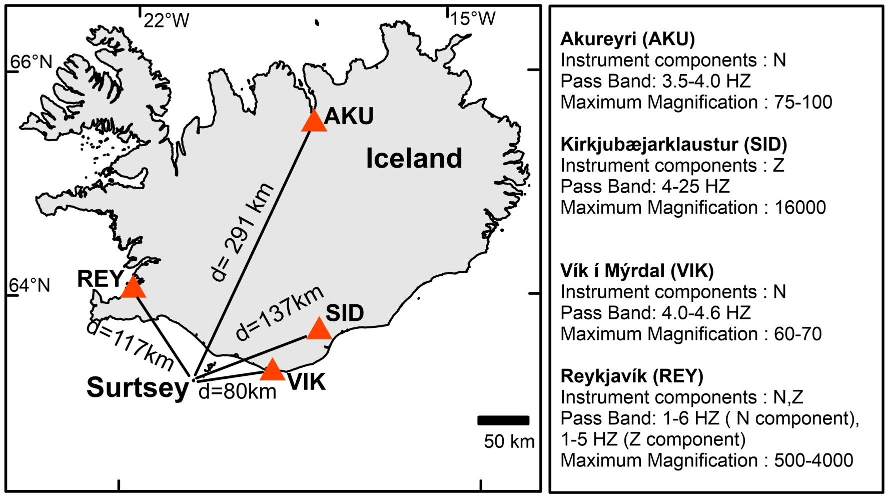

Figure 2. Seismic stations operating in 1963–1967, their characteristics, location, and distances from Surtsey (Icelandic Meteorological Office, 1970; Sigtryggsson and Sigurdsson, 1966). Modified from Sayyadi *et al.* (2021). – *Skjálftamælistöðvar á tímabilinu 1963–1967, eiginleikar mælanna, staðsetning og fjarlægð þeirra frá Surtsey (Sigtryggsson og Sigurdsson, 1966; Veðurstofa Íslands, 1970). Mynd frá Sayyadi og fl., (2021) með breytingum.*

THE RELATIONSHIP BETWEEN SEISMIC TREMOR AND EPISODES IN THE ERUPTION

Tremor was repeatedly recorded during the eruptions. The types of tremors observed, and their domain of frequencies are categorized in three groups (Table 1). The dominating tremor frequency changed during the eruptions and different types of tremors were observed (Figure 3), which can be related to different sources. Many cases are known where magma emplacement within conduits or formation of lava domes has produced volcanic tremor of medium to high amplitude that is strong enough to be observed at stations farther from source than the 137 km between Surtsey and the SID station (e.g., Arámbula-Mendoza *et al.*, 2016; Brandsdóttir and Einarsson 1992; Einarsson 2018).

The onset of seismic disturbance with the characteristics of low frequency volcanic tremor, detected on November 12 at SID between 12:00 and 14:00, is considered to mark the onset of submarine volcanic activity, about 40 hours before the eruption was first observed at the surface (Sayyadi *et al.*, 2021). During the submarine eruption on November 13, low frequency (<3 Hz) harmonic tremor was observed, but only minor indications of tremor were detected from the seismogram of the following day despite the onset of explosive subaerial activity (Figure 4).

Table 1. Types of tremor and their domains of frequency. – *Tegund óróa og tíðnisvið.*

Type of tremor		Frequency domain	Amplitude
Harmonic	Low frequency	$\leq$3 Hz	Slowly varying
	High frequency	3–5 Hz	
Spasmodic (Broad band)		5–15 Hz pulses of high frequency, 5–10 Hz periodic bursts separated by quiescence of uniform duration $\geq$10 Hz	Rapidly varying

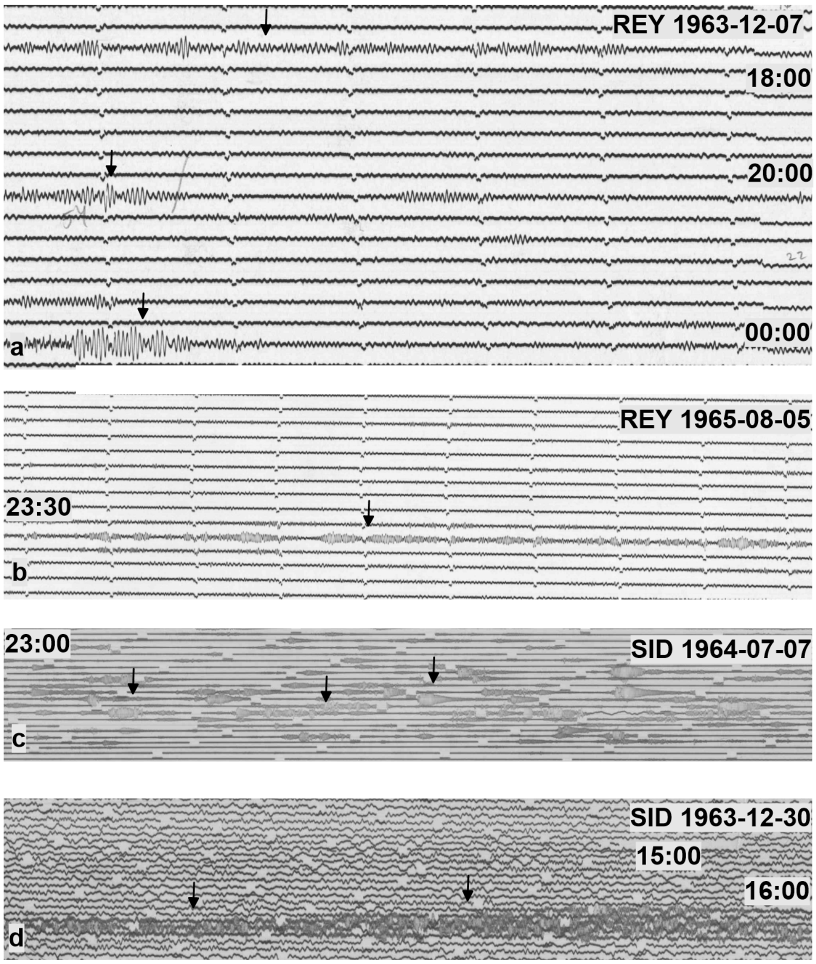

Figure 3. Types of observed tremor. a) Harmonic low frequency tremor at REY station. b) Harmonic high frequency volcanic tremor at REY station. c) Spasmodic tremor at SID station. d) Burst of mixture of harmonic high frequency with spasmodic tremor at SID station. – *Tegundir óróa. a) Hreintónaórói með lágri megintíðni á skjálftariti frá Reykjavík. b) Hreintónaórói af hárri tíðni á skjálftariti frá Reykjavík. c) Krampaórói á skjálftariti frá Kirkjubæjarklaustri. d) Blandaður órói, bæði krampa- og hreintóna á skjálftariti frá Kirkjubæjarklaustri.*

The next burst of low-frequency tremor after the eruption broke through the ocean surface on November 14 was recorded some hours before and after the time of continuous uprush at the vent at 15:00 on November 23 (day 9). A few days later, on December 1 (day 17), high-frequency tremor appeared on the SID records while an explosive eruption at Surtur was going on. Tremor continued throughout the period of activity at Surtla in December 1963.

As the active vent switched to Surtungur on February 1, 1964 (day 79), low-frequency tremor disappeared, and spasmodic tremor was first observed. During the period April 29–July 9, 1964, no surface flow of lava was observed in Surtungur although a lava pond with some activity remained in the crater (Thorarinsson 1967a). Spasmodic tremor continued through this period of no surface flow but disappeared on July 9, 1964 (day 238), when the surface effusive eruption began again from Surtungur (Figure 5).

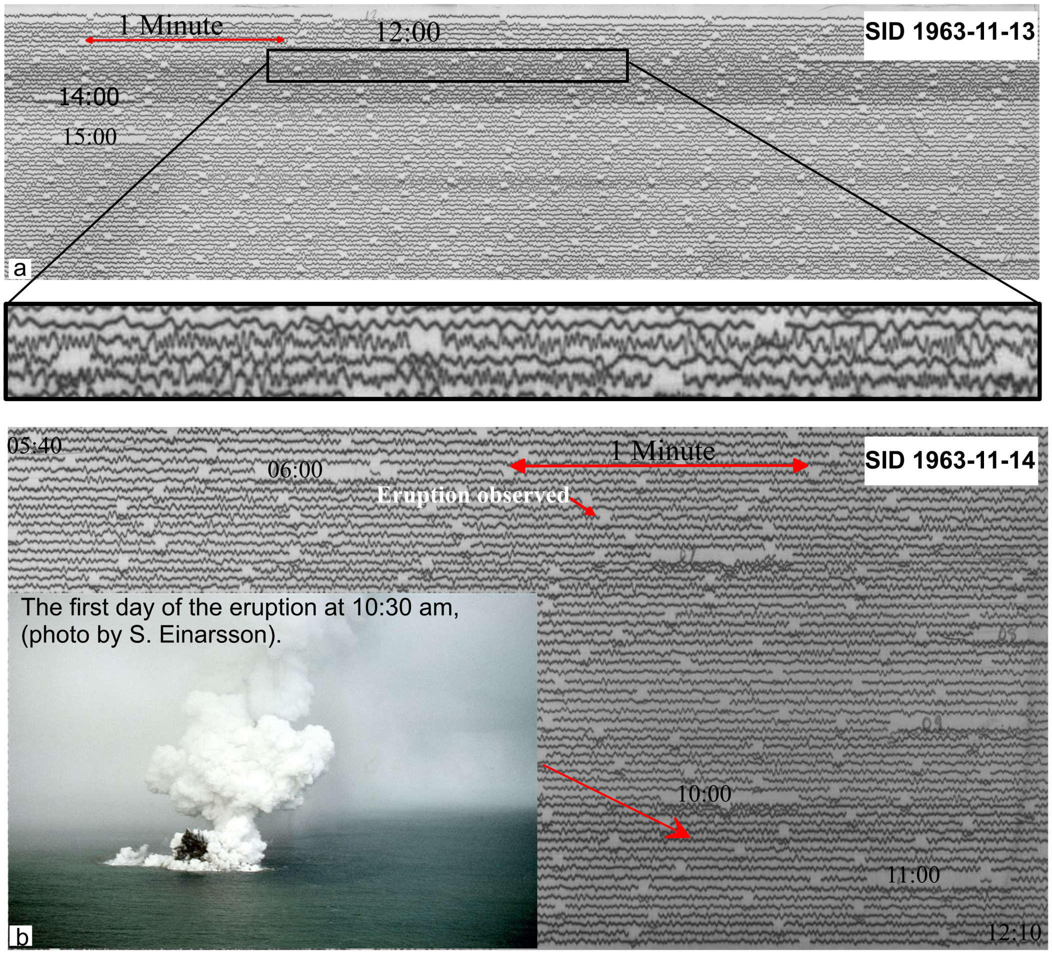

Figure 4. a) Bursts of low frequency harmonic tremor at SID on November 13, 1963, between 13:20 and 16:10 UTC, around 17 hours before the first observation of eruption in the sea and about 22–23 hours after tremor was first detected in the early afternoon of November 12, considered to mark the start of submarine eruption (Sayyadi *et al*., 2021). b) Seismic records on the first day of the eruption at SID station. The inset shows the eruption at 10:30 AM on November 14. – *a) Hviður af hreintónaóróa af lágri tíðni sjást á skjálftariti frá Kirkjubæjarklaustri 13. nóvember 1963, milli klukkan 13:20 og 16:10, um það bil 17 klukkustundum áður en gosið sást á yfirborði sjávar (Sayyadi og fl. 2021). Nokkuð samfelldur órói hófst þó fyrr, eða stuttu eftir hádegi 12. nóvember og markar hann að líkindum byrjun neðansjávargossins. b) Skjálftarit frá Kirkjubæjarklaustri fyrsta gosdaginn. Ljósmynd S. Einarssonar er tekin klukkan 10:30, 14. nóvember.*

Effusive activity at Surtungur continued until May 10, 1965 (day 543). This 10-month long phase was one of seismic tranquility; there is no record of any seismic activity between the end of July 1964 and May 10, 1965 (day 543), when lava effusion ended at Surtungur.

The intrusive phase of the Syrtlingur eruption was characterized by spasmodic tremor, first observed on May 17, 1965 (day 550). However, the explosive activity during the Syrtlingur eruption, was mainly accompanied by high-frequency tremor (Figure 5). Eruptive activity in Syrtlingur ended on October 18,

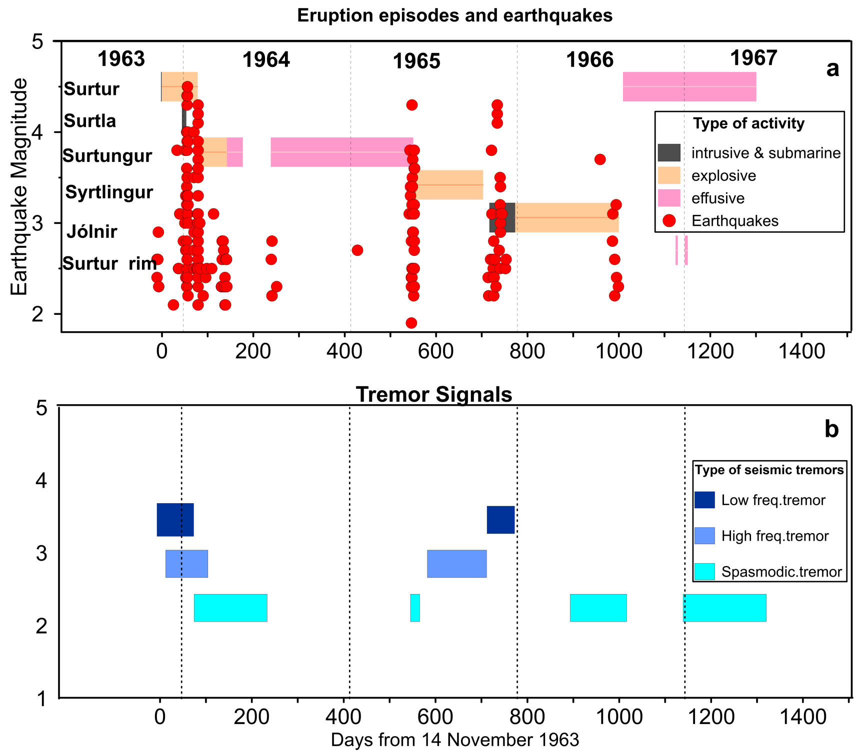

Figure 5. Timeline of earthquakes (a) and tremor signals (b) during the 3.5 years of eruptions. The colored areas in (b) mark periods where the tremor of the type indicated occurred. Within each period episodes of tremor alternated with intervals of no visible seismic activity. Earthquake data from Sayyadi *et al.* (2021). – *Tímalína jarðskjálfta (a) og óróa (b) meðan á gosum stóð 1963–1967. Lituðu reitirnir í (b) sýna hvers konar órói mældist. Jarðskjálftagögnin eru samkvæmt Sayyadi og fl. (2021).*

1965 (day 704) and the island soon disappeared. In the 70 days that followed (days 703–773) no volcanic activity was observed on the surface. During this period earthquakes were detected, considered to mark the intrusive and/or submarine volcanic activity preceding the visible eruption at Jólnir that reached the ocean surface around December 26, 1965 (Thorarinsson, 1966; Sayyadi *et al.*, 2021). Moreover, low-frequency tremor was seen during the intrusive and submarine eruption (days 713–772). Spasmodic tremor was occasionally observed during the explosive eruption that followed at Jólnir and in the days after cessation of explosive activity on August 10 (day 1000). Compared to the Syrtlingur activity, seismic signals during the Jólnir eruption were of slightly lower intensity.

On August 19, 1966 (day 1009), the third phase of effusive activity started at the eastern crater, Surtur, forming lava. Bursts of spasmodic tremor were observed and continued until August 31 (day 1021). From January 1 to 8, 1967 (day 1144–1151), the effusive eruption was briefly intensified by the opening of new minor fissures at the rims of the Surtur tuff cone. On January 27 (day 1170), two minor vents opened along short concentric fissures on the inner wall of the Surtur tuff cone. These rim-fissures were short-lived and produced minor amounts of lava. Finally, June 7, 1967 (day 1301) was the last day when molten lava was observed on the island. Occasional bursts of spasmodic tremor were detected from January 1 until June 31, 1967 (day 1144 to 1325).

Tremor signals and style of explosive activity

During the 4.5 months of explosive activity 1963–64, no instruments could be deployed on the island and direct observations could only be made from ships or aircraft. Visual observations were as a result not continuous and depended on weather. This limits the possibility of comprehensive analysis. However, the main characteristics of activity could be identified and some periods exist where timing and styles of activity were recorded (Thorarinsson *et al.*, 1964).

Two types of volcanic activity were frequently observed during the explosive phases: tephra-finger (cock's tail) explosions and "continuous uprush" explosive eruptions (Thorarinsson *et al.*, 1964). Tephra finger explosions occurred when there was easy access for water to vents. Sometimes when the access of the sea to the vent was restricted with the formation of a thick tephra wall, continuous uprush eruptions appeared. They could go on continuously for several hours. Apparently, as the uprush eruption progressed, the pressure exerted on the conduit walls from the magma decreased, increasing the risk of the conduit collapsing inwards (Moore, 1985).

Continuous uprush eruptions were sometimes followed by gaps in activity lasting several minutes to hours. Thorarinsson *et al.* (1964) gave some timings of the abrupt end of uprush, the length of time which the following inactivity lasted and the gradual onset of explosive activity following such a gap. Moore (1985) also indicates some of the continuous uprush events based on available photos.

Characteristic maximum amplitude of SID records was analyzed for three periods in Nov.–Dec. 1963 (Figure 6), during the explosive phase of Surtur. On 16–18 December, at 772–776 hours (time since visible start of the eruption on November 14), a continuous uprush event with a duration of 3–4 hours occurred (Figure 6c). This was followed by 17 hours of no visible activity. As the graph shows, there does not appear to be any correlation between the uprush activity and the seismic wave amplitude at SID over the period studied. The tremor bursts were observed at 766 hours and during the quiet period at 783–790 hours, showing no apparent correlation with the explosive eruption style. The same lack of correlation is apparent for the other two episodes, 23–28 November, and 1–3 December 1963 (Figures 6a and 6b).

Seismic tremor and eruption rate

Although the observation of tremor was not continuous, when observed, the highest amplitudes occurred in the first 150 days, with all of the three types of tremor bursts detected at Surtsey observed in this period (low frequency, high frequency and spasmodic). After July 9, 1964 (day 238), a significant gap occurred with no observed tremor. The tremor was observed again on May 17, 1965 (day 550), by the end of effusive eruption at Surtungur and the onset of the Syrtlingur eruption. By this time the occurrence of detected tremors had decreased, and for long periods it was hardly observed continuously. Thorarinsson *et al.* (1964) and Thorarinsson (1966, 1967b, 1968) estimated the average eruption rates for different periods of the eruption, noting a slow decline with time. By using lava bulk density of 2500 kg/m^3 and the bulk density of the piles of pyroclasts formed during the explosive phases of 1500 kg/m^3, Thorarinsson's estimates can be converted to approximate time-averaged discharge rates (TADR) using a dense rock equivalent (DRE) of 2700 kg/m^3. Values obtained for TADR (Figure 7a) being 65 m^3/s for 12–24 Nov. 1963, 25 m^3/s for 24 Nov. 1963-1 February 1964, 13 m^3/s for 1 Feb.–4 April 1964, 7–8 m^3/s for April 1964-May 1965, and varying between 2 and 3 m^3/s for the period May 1965-June 1967 (Syrtlingur, Jólnir, Surtur). Note that the TADR values for the first 15–20 days are only displaying a part of the total eruption rate, as they do not include the airborne tephra fallout outside the island which was quite significant in November-December 1963 (Thorarinsson *et al.*, 1964; Ólafsson, 2021).

Duration and approximate amplitude plots of the tremor in the first 150 days (Figures 7 b and c) show discontinuous appearance of tremor in these first several weeks which indicates that magma flow rate and tremor relationship is not simple. Little tremor is detected during the most vigorous activity in the first 20 days of the eruption (Figure 7). In contrast, the strongest tremor is detected in December and at times in January to March 1964. This indicates that it is not primarily the magma flow rate that determines the

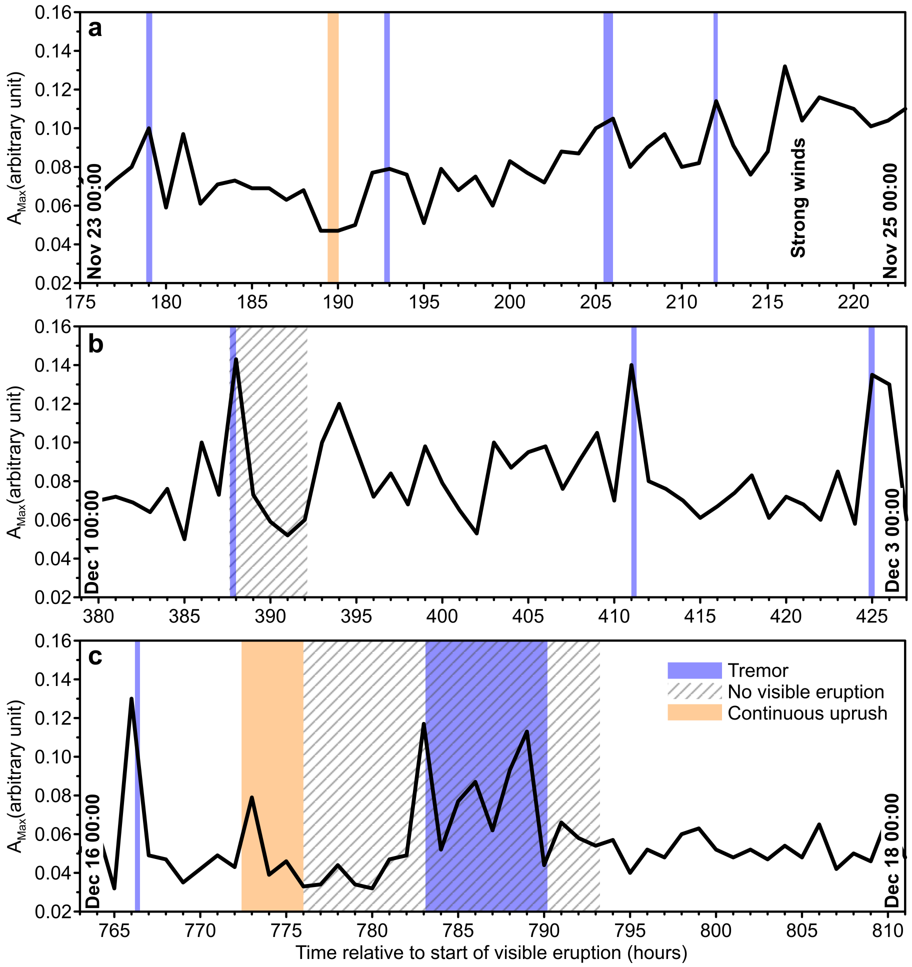

Figure 6. Variation of characteristic seismic maximum amplitude (the wave-amplitude observed on the seismograms excluding earthquakes) during selected periods in November–December 1963. a) 23–25 November. b) 1–3 December. c) 16–18 December; period with the occurrence of continuous uprush, 17 hours of no visible activity followed by gradually increasing explosive activity. – *a) Breytingar á mesta útslagi óróa 23.–25. nóvember, 1963. b) Breytingar á mesta útslagi óróa 1.–3. desember 1963. c) Breytingar á mesta útslagi óróa 16.–18. desember 1963. Á þessum tíma var first sígos, þá goshlé í 17 klukkustundir, og síðan hægt vaxandi sprengivirkni.*

tremor intensity in this explosive part of the eruption, possibly vent conditions (geometry, magma-water interaction, or the absence of it, etc.) are far more influential in determining the intensity of tremor activity than the magma flow rate.

The complicated relationship between eruption rate and tremor is further highlighted by the lack of observation of tremor during the effusive eruption between July 1964 and May 1965, when the TADR was 7–8 m^3/s, while it was observed in the final year of effusive eruption when the TADR was only 2–3 m^3/s.

In the short term (hours-days), apparently no correlation is observed as demonstrated above for the episodes of explosive activity in November-December 1963 (Figure 6). This lack of correlation for e.g., 16–18 December 1963 may indicate that during the ex-

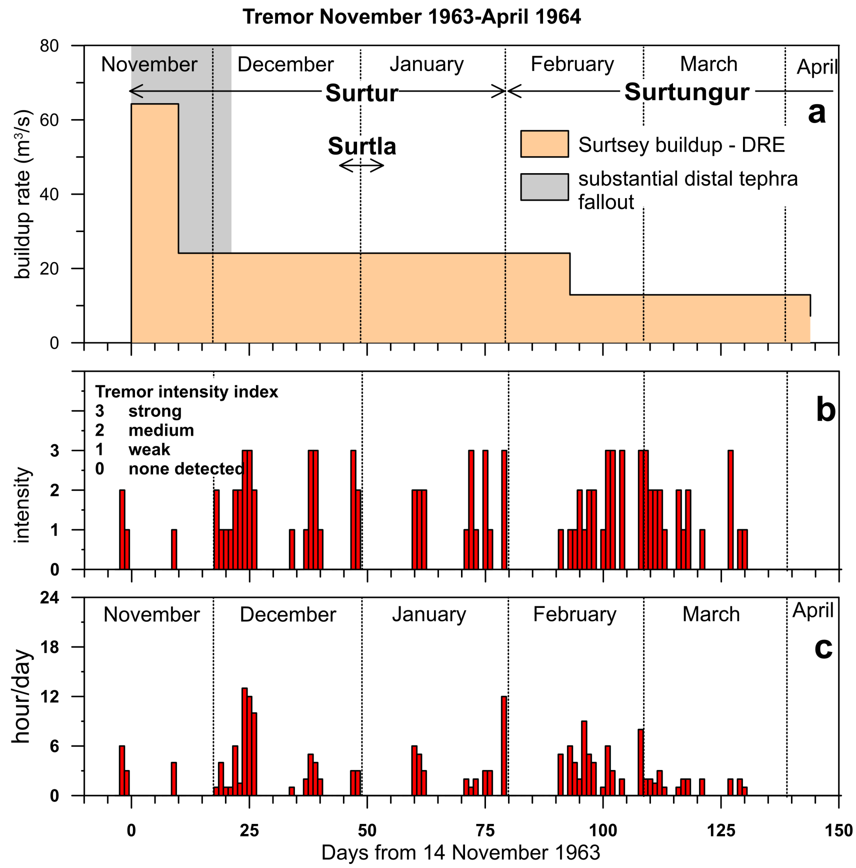

Figure 7. Eruption rate versus tremor intensity for the first 150 days of eruption, November1963–April 1964. a) Buildup rate for the first 150 days (Thorarinsson *et al.*, 1964; Ólafsson, 2021). A DRE-equivalent volume is used assuming loose tuff density of 1500 kg/m^3, lava density of 2500 kg/m^3 and DRE density of 2700 kg/m^3. b) Tremor intensity for the first 150 days of eruption. c) Daily tremor duration during first 150 days of eruption, in hours per 24 h. – *Framleiðni gosefna og óróinn fyrstu 150 daga gossins. a) Upphleðsluhraði, reiknaður út frá eðlismassa móbergstúffs 1500 kg/m^3, eðlismassa hrauns 2500 kg/m^3, og DRE 2700 kg/m^3. b) Styrkur óróa. c) Varandi óróa á sólarhring, í klukkustundum.*

plosive eruption magma was continuously rising in the conduit despite gaps in activity on the surface. Throughout the continuous uprush episodes, the conduit is apparently excavated to progressively deeper levels while there remains external water access to magma. This may suggest that the uprush activity eventually stops when either (1) the water in the conduit dries up, and therefore no longer has access to the magma, resulting in cessation of phreatomagmatic fragmentation, or (2) the conduit is flooded by water after a period of progressively deeper excavation of the magma, resulting in a sudden increase in confining pressure exerted on the magma-water interface from the overlying water column. Such a sudden increase in water pressure may inhibit magma-coolant interaction and therefore temporarily prevent energetic fragmentation (e.g., Zimanowski and Buttner, 2003). In this case, magma needs to rise in the conduit to near the surface before the hydrostatic pressure has become sufficiently small to allow for explosive phreatomagmatic fragmentation to begin again. Both of these processes (1 and 2) can be reconciled with continuous flow of magma from below. However, the second hypothesis seems more plausible, since, as pointed out by Moore (1985), it is difficult to see how a hundreds-of-meters deep conduit, dammed by a permeable pile of pyroclastic material, can remain water free for extended periods in this oceanic setting.

SUMMARY AND CONCLUSIONS

The inherent limitations of our observations of old analog data preclude a detailed interpretation of the tremor signal in terms of eruption dynamics. However, they provide useful lessons on the relationship between eruption behavior and tremor signals.

•The strongest tremor signals occur during the early periods of activity, when eruption rate was highest, indicating a broad correlation between tremor intensity and eruption rate. Due to the limited bandwidth and analog nature of the instruments, any connection between tremor amplitude and frequency content is difficult to assess.

•On shorter timescales of minutes to hours, correlations between eruption rate and style of eruption are not apparent.

•During the explosive phase of Surtur, comparisons between seismic tremor occurrence and visible activity indicate that magma flow from below was more or less continuous. Gaps in visible activity sometimes following episodes of continuous uprush may have been caused by seawater entering a partly excavated conduit, temporarily preventing powerful phreatomagmatic fragmentation.

Thus, the tremor was at least at times not correlated with shallow vent-processes. This illustrates the complicated nature of seismic tremor in volcanic eruptions.

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Eldvirkniórói í Surtseyjargosinu 1963–1967

Af þeim neðansjávargosum sem myndað hafa eyjar er Surtseyjargosið líklega einna mest rannsakað. Neðansjávargossins varð fyrst vart 14. nóvember 1963. Gosstaðurinn var á um 130 m hafdýpi sunnan Vestmannaeyja. Á þeim 3½ árum sem gosvirknin stóð mynduðust þrjár eyjar en tvær þeirra eyddust fljótt vegan sjávarrofs og eftir stóð Surtsey ein. Gosvirknin var kaflaskipt og skiptust á sprengigos og hraungos. Fyrsti kafli var neðansjávargosið en bæði óróinn og hitafrávik í sjónum (Sayyadi og fl., 2021) benda til þess að það hafi hafist 12. nóvember, þ.e., nokkru áður en gosið sást upp úr sjó. Aðrir kaflar stóðu frá 14. nóvember 1963 til janúar 1964, frá janúar til apríl 1964, frá apríl 1964 til maí 1965, frá maí til október 1965, desember 1965 til ágúst 1966, og ágúst 1966 til júní 1967. Gosunum fylgdi talsverð skjálftavirkni, bæði jarðskjálftar og eldvirkniórói. Rannsóknir á skjálftavirkninni eru nokkrum erfiðleikum bundnar af tvennum orsökum: Skjálftamælakerfi landsins var ennþá fremur frumstætt og atburðirnir gerðust utan mælanetsins. Fjórir skjálftamælar voru á landinu og einungis tveir þeirra voru nógu nálægt til þess að sýna virknina greinilega. Gögn frá þessum mælum eru nú aðgengileg á vefsíðunni http://seismis.hi.is/ og voru notuð til rannsóknar á skjálftavirkninni. Jarðskjálftar urðu flestir í tengslum við breytingar á gosinu, þegar virknin hætti á einum stað og tók sig upp á nýjum. Eldvirkniórói sást á mælunum í Reykjavík, í 140 km fjarlægð frá Surtsey og á Kirkjubæjarklaustri í 115 km fjarlægð. Órói af að minnsta kosti tveimur gerðum mældist, annars vegar svokallaður krampaórói (spasmodic tremor) sem gjarnan fylgir innskotavirkni, og hins vegar hreintónaórói (harmonic tremor) sem oft mælist þegar gos er uppi. Bæði mældist hreintónaórói með lágri megintíðni (< 3 Hz) og hærri (3–5 Hz). Ekki

var hægt að greina einfalt samband milli útslags óróans og virkninnar í gosinu, hvorki í sprengigosunum né hraungosunum. Í fyrsta sprengigosakaflanum var framleiðni gosefna mest fyrstu 10–20 dagana, en þá mældist lítill órói. Mestur órói mældist frá desember 1963 til mars 1964 en þá hafði talsvert dregið úr framleiðni gossins. Ekki var heldur hægt að sjá tengsl óróans við hegðun gossins frá degi til dags. Svipaða sögu er að segja af hraungosaköflum. Enginn órói mældist í tengslum við hraungos í Surtungi 1964-1965 þó framleiðni gossins þar væri þrisvar sinnum meiri en í síðari hraungosaköflum, þegar órói var greinilegur.

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