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Short-term evolution of tremor metrics during the final phase of the 2021 Geldingadalir eruption, Iceland

Maria R.P. Sudibyo [α], Eva P.S. Eibl * [α], Sebastian Hainzl [β,α], Matthias Ohrnberger[α], and Egill Árni Gudnason[γ]

[α] University of Potsdam, Institute for Geosciences, Karl-Liebknecht-Str.24/25, Potsdam-Golm.

[β] GFZ Helmholtz Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany.

[γ] ÍSOR, Iceland GeoSurvey, Kópavogur, Iceland.

Abstract

Changes in seismic parameters reflect the physical state of the volcanic system and its eruptive dynamics particularly during transitions between eruptive and repose periods. We analyzed a single vertical component seismic time series from the last three months of the 2021 Geldingadalir eruption, Iceland, featuring 1380 effusion episodes of either minutes or hours duration. The calculated seismic parameters root-mean-square amplitude (RMS), mean instantaneous frequency (MIF), and permutation entropy (PE), differ between eruption and repose periods. While all parameters are stable during hour-long episodes, we observed two classes of minute-long episodes. The initial minute-long episodes show increasing RMS and decreasing MIF and PE. Later episodes exhibit a main peak followed by a smaller, shorter second peak, which increases MIF and PE $23 - 310$ s before the tremor ends. During repose, the parameters vary depending on whether the next tremor occurs in minutes or hours. Our candidate precursory patterns warrant future testing.

Keywords: Effusive eruption., Volcanic tremor, Seismic characteristics, Entropy, Iceland

1 Introduction

Tremor is a persistent seismic signal that lasts from minutes to months, preceding and accompanying a volcanic eruption [Konstantinou and Schlindwein 2003]. Prior to an eruption, the interaction of magma and gas with the surrounding rock can generate tremor [Aki et al. 1977; Julian 1994a; Chouet 1996a]. In the later stage of volcanic unrest, shallow pre-eruptive tremor often occurs before magma reaches the surface [Eibl et al. 2017; White and McCausland 2019]. Hence, it is commonly used as a short-term eruption precursor. After the eruption starts, the volcano emitting magma and gas can also generate eruptive tremor. At many basaltic volcanoes, tremor is almost always recorded during an eruption [Battaglia et al. 2005] and can persist during the whole eruption [Falsaperla et al. 2005]. Changes of the eruption style can also be reflected in the properties of the eruptive tremor [Falsaperla et al. 2005], and typically eruptive tremor stops when the eruption ends. Thus, monitoring tremor is a key observable of the physical state of the volcanic system.

Seismic time series analysis using different quantitative methods can reveal the temporal changes of features caused by an ongoing eruption. Although these metrics do not directly measure the physical state of the conduit, they describe the recorded waveform by quantifying signal strength, coherence, and complexity. Therefore, they can provide information on the eruption dynamics. Seismic tremor amplitude has been found to correlate with the eruption intensity, e.g., the plume

* eva.eibl@uni-potsdam.de

height [Prejean and Brodsky 2011; Fee et al. 2017], the lava fountain height [Alparone et al. 2003; Sciotto and Cannata 2019], or magma discharge rate [Coppola et al. 2009; Ichihara 2016]. Furthermore, seismic waves with different frequency ranges are generated when magma moves through the rock at shallow depth to the surface. Changes in frequency over time can be monitored, e.g. using the Frequency Index [Buurman and West 2010; Power and Roman 2024] or the Instantaneous Frequency [Sudibyo et al. 2024]. Sudibyo et al. [2024] reported distinct temporal changes in the Mean Instantaneous Frequency (MIF) in the different stages of the dyke propagation prior to the Holuhraun eruption in Iceland in 2014-2015, as well as during the corresponding subaerial and the presumed subglacial eruptions. The evolution of the eruptive process generally also varies the complexity of the seismic ground motion, which can be quantified using Permutation Entropy [Glynn and Konstantinou 2016; Konstantinou et al. 2022b; Sudibyo et al. 2024], or Shannon Entropy [Rey-Devesa et al. 2024]. Permutation Entropy (PE) of seismic time series is shown to be sensitive to the different stages of the eruptive cycle at Strokkur geyser, Iceland [Sudibyo et al. 2022], and correlates with the lava discharge rate at the Holuhraun eruption in 2014-2015, Iceland [Sudibyo et al. 2024].

The Reykjanes Peninsula in southwest Iceland is a trans-tensional, oblique spreading boundary between the North American and Eurasian plates. It consists of several active volcanic systems due to the spreading activities. The volcano-tectonic cycle consists of a few hundred years of activity with 800-1000 years of repose [Saemundsson et al. 2020]. On 19 March 2021, the Geldingadalir eruption started at a 180 m long fissure in the Geldingadalir valley, at Mt. Fagradalsfjall on the Reykjanes Peninsula (Fig. 1a). The effusive eruption soon localized on two neighboring vents, 1a and 1b. On 5 April 2021, another vent (vent 2) opened northeast of the first vents, where effusion still continued. Later, more vents opened at different locations: Vent 3 opened on 7 April, vent 4 on 10 April, vents 5 and 6 on 13 April. By the end of April, the eruption stabilized at vent 5, while the other vents became inactive [Pedersen et al. 2022; Barsotti et al. 2023]. From 2 May to 28 June, the eruption style at vent 5 changed from continuous effusion to episodic lava fountaining periods [Lamb et al. 2022; Pedersen et al. 2022; Barsotti et al. 2023; Eibl et al. 2023]. From 28 June to 18 September, the eruption featured hours of repose between the eruption episodes [Barsotti et al. 2023]. Finally, the eruption end was declared on 18 September 2021.

The changing effusion styles of the 2021 Geldingadalir eruption were also reflected in the amplitude and duration of the recorded eruptive tremor. A comprehensive analysis of these tremor episodes based on the amplitude and duration led to a classification of six different phases [Eibl et al. 2023; 2024]. An overview of the eruptive phases is shown in Fig. 1b. The eruption started with phase I, covering the period of continuous effusion, recorded as continuous tremor from 19 March to 2 May. Phase II marked the change of the eruptive style to lava fountains, which were recorded as minute-long tremor episodes from 2 May to 13 June. Phase III occurred from 13 June to 5 July and included continuous tremor, followed by both minute- and hour-long tremor. Phase IV, which started on 5 July and ended on 19 July, consisted of five tremor sequences, where a sequence started as an episode of hour-long tremor followed by consecutive minute-long tremor episodes. From 19 July to 2 September, hour- and day-long tremor episodes dominated phase V. Phase VI started with a repose between 2 and 11 September, followed by a two-day-long tremor and minute-long episodes until the end of the eruption on 18 September 2021.

The complexity of the Geldingadalir eruption style, with almost 9000 tremor episodes, calls for an analysis of the tremor similarity, start, and ending behavior. It is possible to characterize the eruption dynamics using a small set of seismic parameters [Rey-Devesa et al. 2024]. Those characteristics can be utilized in seismic monitoring to improve the understanding of eruption duration and style, as well as the physical state of the volcanic system. Here, we further investigate the seismic time series during tremor episodes and repose using multiple seismic signal attributes: Root-Mean-Square (RMS) of the seismic amplitude, Mean Instantaneous Frequency (MIF), and Permutation Entropy (PE). Our aim is to extract their temporal patterns, assess their sensitivity in detecting the dynamics of the eruption, and understand how the eruption dynamics influence the behavior of these seismic parameters.

2 Methods

2.1 Pre-processing of seismic data

We use the high-quality data recorded by a Nanometrics Trillium Compact 120 s seismometer at station LHR from the 9F seismic network [Eibl et al. 2022], located about 1.8 km south of the main eruptive vent (Fig. 1a). We installed the seismometer at 90 cm depth and powered it using a permanent power generator at 1.5 km distance. Recording at LHR started on 24 June 2021 at a sampling rate of 200 Hz and data was saved on a Datacube [Eibl et al. 2024]. Due to a power outage, data from 2 to 6 July are missing. We analyze tremor episodes recorded from 7 July to 18 September 2021, covering the last three phases of the Geldingadalir eruption reported by Eibl et al. [2024], allowing us to assess different eruptive styles in one eruptive period. We use the vertical component of the seismometer. To reduce the noise from the oceanic microseisms and the wind, we filter the seismogram from 1 to 10 Hz using a Butterworth zero-phase filter with four corners. As the tremor episodes vary from minutes to hours, we choose a 10 s long time window without overlap for data processing. This provides a good temporal resolution of the RMS of the seismic amplitude, the mean instantaneous frequency (MIF), and the PE value.

2.2 Root-Mean-Square (RMS) of Seismic Amplitude

The RMS value is commonly used in volcano monitoring to continuously estimate the average seismic energy. We calculate the RMS of the seismic amplitude using the formula:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2} \quad (1)$$

where x_i is the ground velocity amplitude of the i-th sample in the moving time window with total length of n samples.

2.3 Instantaneous Frequency (IF)

The IF value is calculated by means of the analytic signal $X(t) = x(t) + iy(t)$, where $x(t)$ is the recorded seismic signal and $y(t)$ its Hilbert transform [Gabor 1946; Taner et al. 1979]. The Python code *Scipy.signal.hilbert* implements the procedure defined by Gabor [1946] to compute the analytical signal, as follows: (i) Fourier transforming the real component, (ii) zeroing the amplitude for negative frequencies and doubling the amplitude for positive frequencies, (iii) inverting Fourier transform for the positive frequencies to obtain the analytical signal with real and imaginary components [Virtanen et al. 2020].

The degree of the $X(t)$ rotation is known as the instantaneous phase. The instantaneous phase $\theta(t)$ is calculated using

$$\theta(t) = \tan^{-1}\left(\frac{y(t)}{x(t)}\right). \quad (2)$$

figure/overview.jpg

Figure 1: (a) Overview of the lava flow field of the 2021 Geldingadalir eruption (brown), the eruptive vents 1-6 (red) and the seismic station LHR (black). The inset shows the location in Iceland. (b) Timeline of the 6 different eruptive phases according to Eibl et al. [2024].

The instantaneous frequency (IF(t)) is defined as the derivative of $\theta(t)$,

$$IF(t) = \frac{1}{2\pi}\frac{\mathrm{d}}{\mathrm{d}t}\theta(t) \tag{3}$$

For each sampling interval between subsequent samples we can obtain one estimate of the IF. We then calculate the Mean Instantaneous Frequency (MIF) value for every 10 s window, without overlapping, as the frequency representative of the window, enabling us to assess its temporal changes with the same resolution as RMS.

2.4 Permutation Entropy (PE)

PE quantifies the complexity of a time series based on the comparison of neighboring amplitudes [Bandt and Pompe 2002]. The relative order of these adjacent amplitudes is represented by an ordinal pattern, which is defined as the vector $[x_s, x_{s+\tau}, \ldots, x_{s+(m-1)\tau}]$, where the embedding dimension m defines the number of samples used to reconstruct the vector, and the delay time (τ) is the time interval between the successive samples. To extract all ordinal patterns in a short time window, we shift the first sample x_s one sample forward until the last ordinal pattern reaches the end of the window. We then calculate the probability or the relative frequency p_k of each ordinal pattern (indexed by k) in the window, and PE is then calculated by

$$PE = \frac{-1}{\log m!}\sum_{k=1}^{m!} p_k \log p_k \tag{4}$$

The synthetic test done by Sudibyo et al. 2022 shows that PE becomes stable when the window length is longer than $3T_0$, where T_0 is the dominant period of the targeted signal. Our interest lies in the frequency range from 1 to 10 Hz, meaning the longest period of the signal of interest is 1 s. The window length 10 s is therefore sufficient to calculate PE and to get the same resolution as RMS and MIF.

Amigó et al. [2008] suggested that in a noisy time series, the total samples in a window must be more than $5m!$. While each 10 s window contains 2000 samples, the highest m we can use is 5. Sudibyo et al. [2024] suggested that τ should be less than half of the shortest period of signals of interest. Our interest lies in the frequency range from 1 to 10 Hz, with a Nyquist period of 0.05 s, therefore we use τ =0.02 s. Suppl. Fig. S1 and S2 show that the choices of m and τ influence only the absolute value of PE rather than the PE trends, confirming that the trends observed are not artifacts from the parameter choices.

3 RESULTS

3.1 Overview of the temporal variation of RMS, MIF, and PE during the last three months of the Geldingadalir 2021 eruption

Fig. 2a shows the chronology of minute-, hour-, and day-long tremor episodes from 7 July to 30 September 2021, covering phases IV, V, and VI defined by Eibl et al. [2024]. The RMS amplitude, MIF, and PE show different temporal variations in the last three phases of the eruption (Fig. 2b-d). During tremor episodes, the RMS amplitude is higher, MIF is stable and PE is lower than during the repose (e.g., Fig. 2g-i, 2l-n, and 2q-s).

Phase IV occurred on 7-19 July and consisted of five tremor sequences (Fig. 2b). Each sequence starts with an hour-long tremor and is followed by successive minute-long tremor episodes (see Fig. 2a for Phase IV). In the first sequence, on 7-8 July, the RMS amplitude of the tremor reaches 10^{-6} m/s, much smaller than in the other sequences. In the second sequence, on 9-15 July, the tremor episodes become ten times stronger, with the RMS gradually increasing to $1.2 \cdot 10^{-5}$ m/s before dropping during the last three sequences. Phase V occurred on 19 July-2 September, composed of episodes of hour- or day-long tremor separated by hour-long repose. The RMS amplitude in phase V is smaller compared to the tremor episodes in the sequences of phase IV, with a maximum RMS of up to $5 \cdot 10^{-6}$ m/s (Fig. 2b Phase V). Phase VI started with a 9-day-long repose. The first sequence started on 11 September with a 2-day-long tremor followed by minute-long tremor episodes and lasted until 18 September. Note the data gap on 15 September 2021. The RMS of the day-long tremor varies around $5 \cdot 10^{-6}$ m/s while that of the minute-long tremor episodes gradually increases to $8 \cdot 10^{-6}$ m/s (Fig. 2b Phase VI). The second sequence occurred 9 hours before the eruption ended on 18 September. The RMS during the last 9 hours is lower than before, varying around $3 \cdot 10^{-6}$ m/s during the hour-long tremor and about $6 \cdot 10^{-6}$ m/s during the minute-long tremor.

Throughout the last three phases, MIF and PE are stable in a fixed range during tremor episodes, between 2 and 4 Hz and 0.5 and 0.6, respectively (Fig. 2b-c). During repose, MIF varies between 7.5 Hz and 1 Hz (Fig. 2c). PE is always higher during repose than during tremor episodes, with values up to 0.7 (Fig. 2d). During the 9 days of repose in the beginning of phase VI, no tremor was present and merely noise and MIF and PE strongly fluctuated.

3.2 Changes of RMS, MIF and PE in minute-, hour-, and day-long episodes

In phases IV and VI, the eruptive tremor occurred in sequences separated by hour-long repose time. Each tremor sequence started with an episode of hour- or day-long tremor followed by a succession of minute-long tremor episodes. The succession of minute-long tremor episodes evolves from tremor containing a main pulse (blue dots in Fig. 2a) with high RMS, low MIF and PE (e.g., Fig. 2e-i) to tremor containing main and second pulses (pink dots in Fig. 2a), where the smaller second pulse increases MIF and PE before the tremor ends (e.g. Fig. 2j-n). Tremor pulses are tremor amplitude peaks separated by low tremor amplitude within a tremor episode. A tremor episode ends when the tremor ends. Exceptions are the sequence on 7-8 July when the hour-long tremor is only followed by a minute-long tremor main pulse (blue dots in Fig. 2a), two sequences on 18 July when the hour-long tremor is followed immediately by minute-long tremor episodes with the main pulse and the second pulse (only pink dots in Fig. 2a), and the last sequence on 18 September (same as on 7-8 July). In phase V, most episodes of hour- or day-long tremor are followed by one episode of minute-long tremor, this minute-long tremor displays figure/overview_seisparams_revised.jpg

Figure 2: Overview of the eruptive tremor during the last three months of the 2021 Geldingadalir eruption and their seismic parameters (a-d), and the example of three different tremor episodes (e-s). (a) Occurrence of minute-, hour-, and day-long episodes with time. (b) RMS, (c) MIF, and (d) PE during the last three phases, where phases IV, V, and VI are three different eruption phases defined by Eibl et al. [2024]. The eruption ended on 18 September 2021, when phase VI ended. Three arrows in (a) show the location of the tremor shown in (e-s). The gray vertical lines in (a-d) separate the three phases and the numbers in (b) mark the order of the sequences in phases IV and VI. Blue and pink dots represent minute-long tremor episodes with and without a second pulse, respectively. (e-i) A minute-long tremor episode on 16 July, representing tremor episodes marked by blue dots in subfigure (a), with the corresponding (e) seismogram in vertical component and filtered between 1 and 10 Hz, (f) amplitude spectrogram plotted using a window length of 1028 samples and no overlap, (g) RMS, (h) MIF, and (i) PE. (j-n) Same as (e-i) but on 18 July, representing tremor episodes marked by pink dots in (a), and (o-s) for the hour-long tremor followed by a minute-long tremor on 13 August. The blue vertical lines mark the tremor start times, while the orange lines mark the tremor end times.

only a main pulse similar to Fig.2e-i. We summarize the time occurrence of the two types of minute-long tremor in Suppl. Table 1.

Fig. 2o-s shows the example of an hour-long tremor followed by an episode of a minute-long tremor on 13 August 2021 in phase V. The energy gradually increases at the beginning, reaches the maximum and stays high before dropping abruptly at the end (Fig. 2o-q). MIF and PE drop gradually in the first two hours and then stay low until the tremor ends (Fig. 2r-s). We observed the same variation for the hour- and day-long tremor episodes in phases IV and VI.

3.3 Stack of the seismic parameters on the normalized tremor duration

Based on the variation of the seismic parameters during the tremor episodes, we separated the tremor into three groups, consisting of two groups of minute-long tremor episodes (blue and pink dots in Fig. 2a) and one group of combined hour- and day-long tremor episodes. We normalized their duration into the range [0, 1], stacked their RMS, MIF, and PE, calculated the mean and the 68% confidence interval of each parameter for each window bin (Fig. 3).

The first group consists of 280 minute-long tremor episodes with only a main pulse and following directly the hour- and day-long tremor episodes in phases IV, V, and VI (blue dots in Fig. 2a, Fig. 3a-c). The stacked RMS forms two distinct groups (Fig. 3a), the lower amplitude one belongs to the sequence on 7-8 July and the minute-long tremor following the hour-long tremor in August, and the higher amplitude one belongs to the rest. Despite the differences in their RMS, these tremor episodes show coherency in the MIF and PE (Fig. 3b-c). Both MIF and PE gradually decrease to the minimum and then increase until the end of the tremor episode.

The second group consists of 1015 minute-long tremor episodes with a main and second pulse in phases IV and VI (pink dots in Fig. 2a, Fig. 3d-f). For the RMS attribute the 'two-pulse structure' of the minute long tremor is smeared in the length-normalized stacks but still discernible (Fig. 3d). However, both MIF and PE show a rather clear two phase appearance first decreasing to the minimum at about a quarter of the duration followed by an increase to the maximum at about three-quarters of the duration. PE and MIF then remain high until the end of the tremor (Fig. 3e-f).

The last group consists of the hour- and day-long tremor throughout phases IV, V, and VI (Fig. 3g-i). The hour- and day-long tremor episodes have similar RMS, MIF, and PE patterns. The RMS initially increases gradually but drops sharply at the end (Fig. 3g). MIF shows decreasing values at the beginning of the tremor followed by a flat trend until the end (Fig. 2h). PE also shows a decreasing trend at the beginning. Afterward, PE further decreases slightly until half the duration before increasing slightly until the end (Fig. 2i).

figure/stack_tremor_revised.jpg

Figure 3: The stack of seismic parameters for each tremor group on the normalised tremor duration between -0.1 and 1.1: (a) RMS, (b) MIF, and (c) PE for the 280 episodes of minute-long tremor marked as blue dots in Fig. 2a. (d-f) Same as (a-c) but for 1015 episodes of the minute-long tremor marked as pink dots in Fig. 2a. (g-h) Same as (a-c) but for the hour- and day-long tremor episodes. The red lines represent the mean and the 68% confidence interval and the vertical dashed lines represent the start and end of tremor episodes.

4 Discussion

4.1 Factors influencing the eruptive behaviour and their implication in the seismic parameters

Throughout the 2021 Geldingadalir eruption, tremor was recorded when effusion on the surface occurred [Eibl et al. 2023; 2024]. The eruptive tremor features a higher RMS amplitude and lower MIF and PE values than during the repose time. Previous studies have reported low PE values for tremor [Konstantinou et al. 2022a; b; Sudibyo et al. 2024]. The tremor signal is generally confined in a narrow low-frequency band and less chaotic than the environmental noise. The tremor hence manifests in low MIF and PE. The spectrogram shows the main energy between 1 and 10 Hz during tremor episodes, with most energy between 2 and 4 Hz (e.g., Fig. 2f, 2k, 2p). The dominant energy is in agreement with the MIF value. When no tremor episodes occur, the seismometer records mainly environmental noise. While the noise energy is low, it spreads over a broad frequency bandwidth and results in fluctuating MIF and higher PE values.

During the last three eruptive phases, the eruption is recorded as tremor sequences and cycles of hour- or day-long tremor episodes. The system works as a semi-closed vent recharged by magma [Eibl et al. 2024; Soubestre et al. 2025], where the process of magma flow and cooling in the shallow vent governs the cyclic hour- or day-long tremor episodes [Soubestre et al. 2025]. Long hours of repose are always followed by an episode of hour- or day-long tremor classified as a ramp-shaped tremor by Eibl et al. [2024], which is characterized by a gradual increase of amplitude in the beginning and a sharp drop of amplitude at the end (Fig. 3g). Eibl et al. [2024] interpreted the gradual increase in amplitude at the beginning of tremor as the result of magma opening the vent, which is semi-closed by the cooling plug formed by the previous eruption episodes. We observed a decrease in MIF and PE at the beginning of the hour- and day-long tremor episodes (Fig. 3h-i). The decrease in MIF reflects a more narrow-band behavior observed in many systems when fluid flow becomes more organized or when tremor sources migrate or reorganize (e.g., Chouet [1996b] and Fee and Matoza [2013]). These changes could reflect the emergence of more organized magma–gas flow during the onset of fountaining, but they could equally arise from processes such as shifts in degassing style, variations in the proportion of bubble bursts to continuous flow, or changes in the dominant tremor source region (e.g., Julian [1994b], Hellweg [2000], and Fee and Matoza [2013]). During the Geldingadalir eruption, Soubestre et al. [2025] also observed a progressive energy in the lower frequency range decreasing at the beginning of the hour-long tremor and interpreted it as magma reaching the shallow conduit and melting the solidified dyke, lengthening the oscillating magma volume in the vent. Another possibility is that when magma passes through a constricted conduit and actively widens the conduit, this process could generate a tremor with a decreasing frequency in its early part [Lees et al. 2008]. While the decrease in PE at the beginning of a tremor episode may also be related to the magma movement underground, large values of both MIF and PE are observed for small RMS of less than 10^{-6} m/s. This drop in PE and MIF may hence also represent the gradual dominance of narrow-banded tremor over broadband noise. While the signal to noise ratio increases, the PE and MIF drop and stabilize once tremor is dominant.

The laboratory models of Jaupart and Vergniolle [1988] and Vergniolle and Jaupart [1990] showed that constant magma degassing can lead to continuous effusion or intermittent eruptions. When the rising gases are trapped below the roof of the magma compartment connected to a narrower conduit, forming a foam layer with a critical thickness, they could collapse into a larger gas slug. The gas slug then flows through the conduit and creates an explosion on the surface. The cycle of foam accumulation and collapse results in periodic explosions. However, Vergniolle and Jaupart [1990] observed that the critical foam thickness could only be obtained if the gas influx exceeds a threshold that depends on the magma's viscosity, surface tension, bubble size, as well as the geometry and the size of the roof area. When the gas influx is below the threshold, the foam bubbles will not coalesce and hence continuously flow through the conduit, generating a continuous effusion on the surface. With the assumption that magma outflux is proportional to the magma influx, increase in the time-averaged discharge rate of magma (TADR) from 5 – 8 m^3/s in 5-27 April to 9 – 13 m^3/s in 27 April-29 June [Pedersen et al. 2022] could trigger the transition from an effusive eruption to lava fountains, as the influx of gas-saturated magma exceeds the threshold [Soubestre et al. 2025].

We found that the changes in TADR in July-September by Pedersen et al. [2022] coincide with the changes in the tremor during the last three phases. During the sequences of hour- and minute-long tremor in July, the TADR was stable at 11 ± 0.8 m^3/s. The TADR then dropped between 8.5 ± 0.8 and 9.4 ± 1.0 m^3/s on 19 July- 2 September, when the tremor changed from sequences into cycles of hour- and day-long tremor. During the last 8 days, the TADR increased to 12.2 ± 0.8 m^3/s and the eruption returned to tremor sequences. While the TADR changes are minor, a modification of the shallow magma compartment on 2 and 11 July could also play a role in changing the eruptive behavior [Eibl et al. 2024]. The change in reservoir geometry could increase the threshold required to change the eruption from continuous to intermittent. We speculate that the episodes of hour-long tremor, which started the tremor sequences, are generated when the magma starts getting trapped in the shallow magma compartment. It takes a longer time to reach the critical thickness of foam, before the bubble foam could collapse and form a bigger bubble slug. Once the critical thickness is reached, the eruption switches to intermittent minute-long eruptions and generates minute-long tremor episodes.

4.2 The occurrence of the second pulse before the end of the minute-long tremor episodes

1015 tremor episodes contain a second pulse with higher MIF and PE (see Suppl. Table 1 for the occurrence time). This second pulse is a possible signature of the end of the tremor episode. The stack of these 1015 tremor episodes (Fig. 3d-f) shows the increase of MIF and PE of around 0.7 of the tremor length. We fitted the sigmoid function using `scipy.optimize.least_squares` [Virtanen et al. 2020] to obtain the length of the second pulse (Suppl. Fig. S4). Suppl. Fig. S5a shows a linear correlation between the main pulse and the tremor durations (Suppl. Fig. S5a). Suppl. Fig. S5b also shows a positive correlation between the duration of the second pulse and that of the tremor, where the length of the second pulse increases systematically with the tremor duration. Converting the normalized length of the second pulse to seconds, we obtained the length of the second pulse as 23 s to 310 s.

The second pulse occurred before the end of the minute-long tremor episodes, and is characterized by a higher frequency band, more chaotic motion, less energy, and shorter duration than the main pulse. This second pulse is visible in the tremor amplitude of raw seismic data and is not a processing artifact. We rather interpret it as consequence of the evolution of the shallow fluid-dynamic processes. The increase in PE and MIF in combination with the amplitude drop might reflect a cyclic degassing for minute-long episodes. We hypothesize that at the beginning of an episode the pressure due to degassing is high therefore causing a widening of the conduit reflected by large seismic amplitudes, lower instantaneous frequencies and small PE values being in accordance with the link between amplitude and conduit width suggested by Eibl et al. [2023]. Towards the end of the episode the degassing rate and pressure drops, the conduit closes slightly and tremor amplitude drops and frequency increases. During hour-long episodes the degassing may stop quickly leading to a quick drop in tremor amplitude and sharp increase in MIF and PE, while the system transitions to noise-dominated repose.

Scott et al. [2023] observed bubble bursts and lava spattering that last over ~60 s at the end of each lava fountaining in May, which was interpreted as the transition to repose. These events were recorded as seismic coda [Lamb et al. 2022]. We speculate that this similar transition process in shallow conduit behavior during the waning phase of fountaining, possibly related to changes in degassing style or the collapse of gas-rich foam in the cavity could also still occur at the end of minute-long tremor episodes in July and September, generating a second pulse lasting from 23 s to 310 s (Suppl. Fig. S5b). Other explanations such as several overlapping tremor sources are unlikely due to the similar shape of the episodes and no evidence for several tremor source from a network based tremor location [Soubestre et al. 2025].

4.3 Changes of the seismic parameters during the minute- and hour-/day- long repose time

During some repose times between lava fountains in May, a gentle spattering of magma and many small bubbles on the lake were often observed [Scott et al. 2023], while at other repose times, magma was withdrawn revealing the conduit and the lake drained [Eibl et al. 2023; Scott et al. 2023]. From July to September, during the repose in the early part of the tremor sequences, MIF and PE (e.g. Fig. 2h-i between orange and blue lines) increase less than in the late part of the tremor sequences (e.g. Fig. 2m-n between orange and blue lines) and even higher between hour-long tremor episodes (e.g. Fig. 2r-s after orange line). The stack of the seismic parameters during the minute-long repose between 280 tremor episodes without a second pulse (Suppl. Fig. S6a-c), between 1015 tremor episodes with a second pulse (Suppl. Fig. S6d-f), and during the hour-/day-long repose during phases IV-VI (Suppl. Fig. S6g-i) confirmed the consistency of this behavior. During the repose in the early part of tremor sequences, the RMS is slightly higher than the RMS in the later part, while dropping to the lowest value during the hour- or day-long repose. During the minute-long repose, MIF and PE are more coherent, suggesting the presence of magma on the lake or in the shallow conduit. During the hour-long repose, MIF and PE are heavily influenced by noise, suggesting no magma in the conduit.

5 Conclusions and implications

We used several seismic parameters, namely RMS amplitude, mean instantaneous frequency, and permutation entropy to monitor the temporal changes in the eruption style during the last three phases of the 2021 Geldingadalir eruption in Iceland. These three parameters are fast to calculate and can characterize and analyze the changes in the eruption with high sensitivity, capable of detecting tremor transition within a sequence. The tremor episodes exhibit consistently higher RMS, lower MIF and PE than during repose. 78% of minute-long tremor episodes feature a second pulse, lasting between 23 s and 310 s, with smaller RMS, higher MIF and PE, possibly marking evolving shallow processes associated with the transition to the repose. During the repose time, RMS, MIF and PE vary in different ranges. The minute-long repose periods feature higher RMS values and more constrained variation of MIF and PE compared to during hour-long repose. This could imply that, when MIF and PE do not change significantly from tremor to repose, the eruption cycle may still resume. When MIF and PE change significantly during repose, it could imply that the system goes into 'resting mode', requiring more time to restart another effusion. It is important to note that the behavior of RMS, MIF, and PE described here is specific to the Geldingadalir eruption and requires testing on different episodic eruptions. Nevertheless, the results may contribute to improve the eruption monitoring framework. Our findings are candidate precursory patterns that warrant future testing.

Author Contributions

E.E. and E.Á.G. organised the field work and collected the data. E.E. initiated the study. M.S. analysed, visualised and interpreted the seismic data. E.E., S.H. and M.O. supported the data analysis. M.S. led the writing of the manuscript with contributions from all authors. E.E. led the revision of the manuscript with contribution from all authors.

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Data Availability

Seismic data from station LHR are available via GEOFON [Eibl et al. 2022].

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6 Appendix

Table 1: Minute-long tremor without and with second pulse

	Date and Time
Tremor without a second pulse	7 July, 14:37:05 - 8 July, 17:37:41
	10 July, 05:13:24 - 12:58:14
	16 July, 22:35:15 - 17 July, 06:42:03
	20 July 15:45:52, - 30 August, 16:25:23
	13 September, 16:21:41 - 19:29:42
	18 September, 09:14:07-17:40:34
Tremor with a second pulse	10 July, 12:59:30 - 15 July, 04:55:36
	17 July, 06:59:17 - 16:45:33
	18 July, 03:30:29 - 08:38:57
	18 July, 18:53:45 - 19 July, 17:37:27
	13 September 19:34:39 - 18 September 09:07:29

figure/PE_LHR_20210710_compared_m.jpg

Figure S1: Comparison of PE calculated with different m and $\tau = 0.02\ s$.

figure/PE_LHR_20210710_compared_delay.jpg

Figure S2: Comparison of PE calculated with $m = 5$ and different delay times.

figure/tremor_spectrum.jpg

Figure S3: Power spectral density for tremor episodes on (a) 16 July 2021 at 23:02:07, (b) 18 July 2021 at 22:30:15, and (c) 13 August 2021 at 00:17:50.

figure/fitted_example.jpg

Figure S4: Example of overlay of MIF and its sigmoid function for tremor with duration shorter than 4 minutes (a), between 4 and 8 minutes (b), longer than 8 minutes. The vertical blue line marks the points where the sigmoid function and IF overlap, or in other words, when the second pulse begins.

figure/main_second_pulses_reglin_try.jpg

Figure S5: Comparison of the length of the main pulse of tremor (a) and the length of the second pulse (b), with the respective tremor episode duration. Note the different y-scales of the two figures.

figure/repose_stack.jpg

Figure S6: The stack of seismic parameters for the repose before tremor in each tremor group defined in subsection 3.3. (a) The stacked RMS, (b) MIF, and (c) PE for the minute-long repose before tremor with only a main pulse. (d-f) Same as (a-c) but for the minute-long repose before tremor containing a main and a second pulses. (g-h) Same as (a-c) but for the repose before tremor sequences, and hour- and day-long episodes.