Application of Permutation Entropy (PE) to characterize the precursory phase of a volcanic eruption

Maria Sudibyo[1], Eva P.S. Eibl[1] and Sebastian Hainzl[2]
[1] Institute of Geosciences, University of Potsdam, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany,
[2] GFZ German Research Center for Geosciences sec. 2.1., Helmholtzstraße 6/7, 14476 Potsdam, Germany

Summary

- Forecasting an eruption is a challenge for geoscientists. It is crucial to answer questions about: "When will an eruption occur? What will be its style, and will it switch during the course of the eruption? How long will the eruption last?" It is vital for the scenario of hazard mitigation (Caudron et al., 2020).
- Permutation Entropy (PE) offers a simple yet robust method to contribute to eruption forecasting.
- We performed several synthetic tests to understand on how this method works and how to choose the optimum input parameters.
- PE is tested on two different types of eruptions, the recurrent eruptions of Strokkur Geyser, Iceland in 2018 and the Holuhraun eruption 2014 with the aim to find eruption precursors.
- The temporal variation of PE at the Strokkur Geyser on the 10th June 2018 exhibits repeating patterns between eruptions.
- Before the eruption of Holuhraun in 2014, high PE is observed during the period of the dyke propagation, and it drops at the start of the eruption.

Introduction

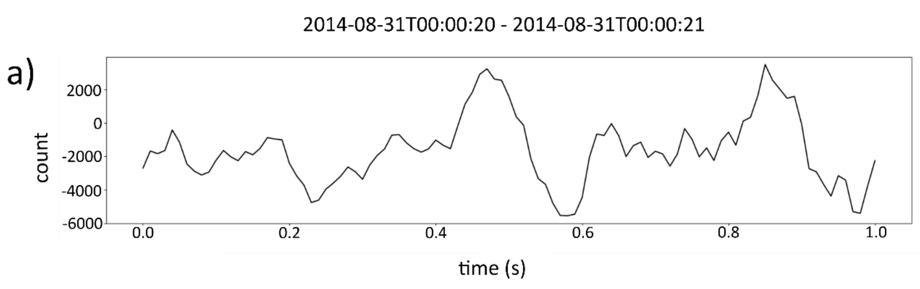
- Permutation Entropy (PE) is a simple yet robust method to quantify the complexity of a time series.
- The time series of a seismic noise wavefield that is propagating through a volcano carrying information of internal processes inside the volcano. By analyzing the temporal variation of its complexity, we aim to find features useful for eruption forecasting.
- PE has been applied to find features of eruption precursors in Gjalp 1996 (Glynn and Konstantinou, 2016) and to identify volcanic tremor (Melchor et al., 2020).
- The eruption of Strokkur Geyser in 2018, Iceland, repeats on a minute scale. It allows us to check if the result of PE exhibits similar pattern for multiple eruptions.
- We calculated PE during the Holuhraun eruption 2014, Iceland, as a study case of a magmatic eruption.

Method

PE calculation is based on the occurrence or absence of certain permutation patterns in a time series. The steps of the PE computation are the following.

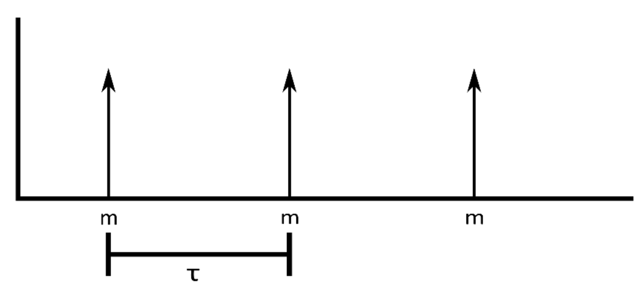
a) Example of a sequence of a seismic time series.

a)



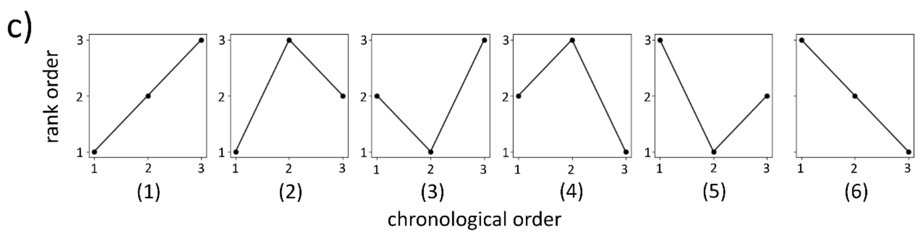
b) A comb function to illustrate embedding dimension(m) and delay time (τ). Here m = 3

b)



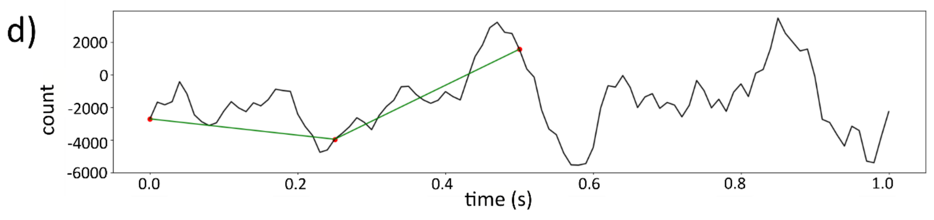
c) All permutation patterns that can be constructed by m = 3.

c)



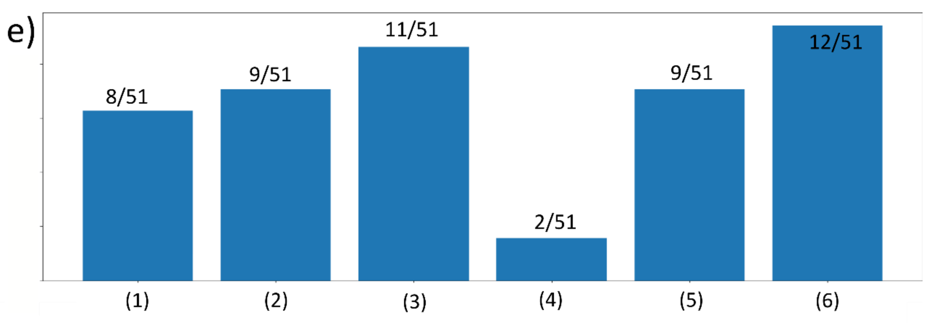
d) Example of the selected data points for m=3 and τ = 0.25 seconds, from seismic time series in figure (a), corresponding to permutation pattern (3) in c).

d)



e) Histogram of the number of each pattern in respect to total number of the shifting combs. This is defined as relative frequency (P_i). PE will be calculated as

e)

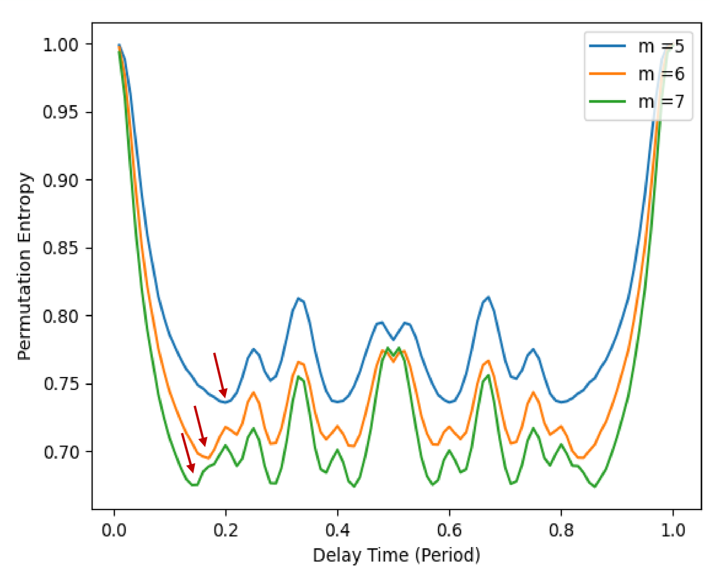


$$\mathrm{PE} = \frac{-\sum_{i=1}^{m!} P_i \log P_i}{\log m!}$$

How to choose the optimum delay time (τ)

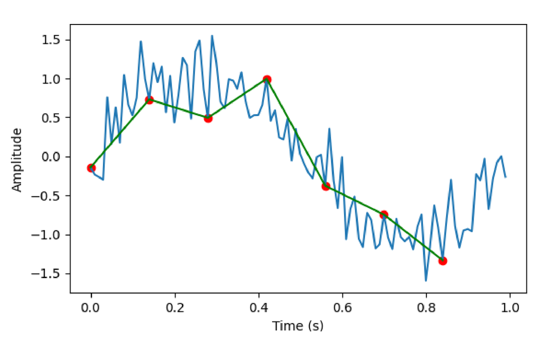
A synthetic signal is created to find out the optimum delay time.

- monochromatic signal + noise
- length of signal: 2000 seconds
- sampling frequency: 100 Hz
  embedding dimension: 5, 6, 7
  delay time: 0.01 -1 seconds
- Δ τ = 0.01 seconds



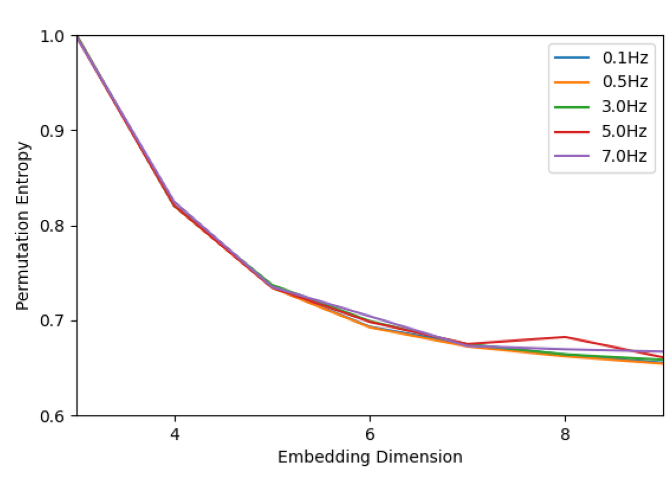
Optimum delay time = Period/ embedding dimension

Example of a permutation pattern constructed with optimum delay time, overlaid on the signal.



How to choose the optimum embedding dimension (m)

- 5 different monochromatic signals with noise, with f = 0.1 Hz, 0.5 Hz, 3 Hz, 5Hz, and 7 Hz
- Embedding dimension from 3 to 9
- Delay time = Period/embedding dimension

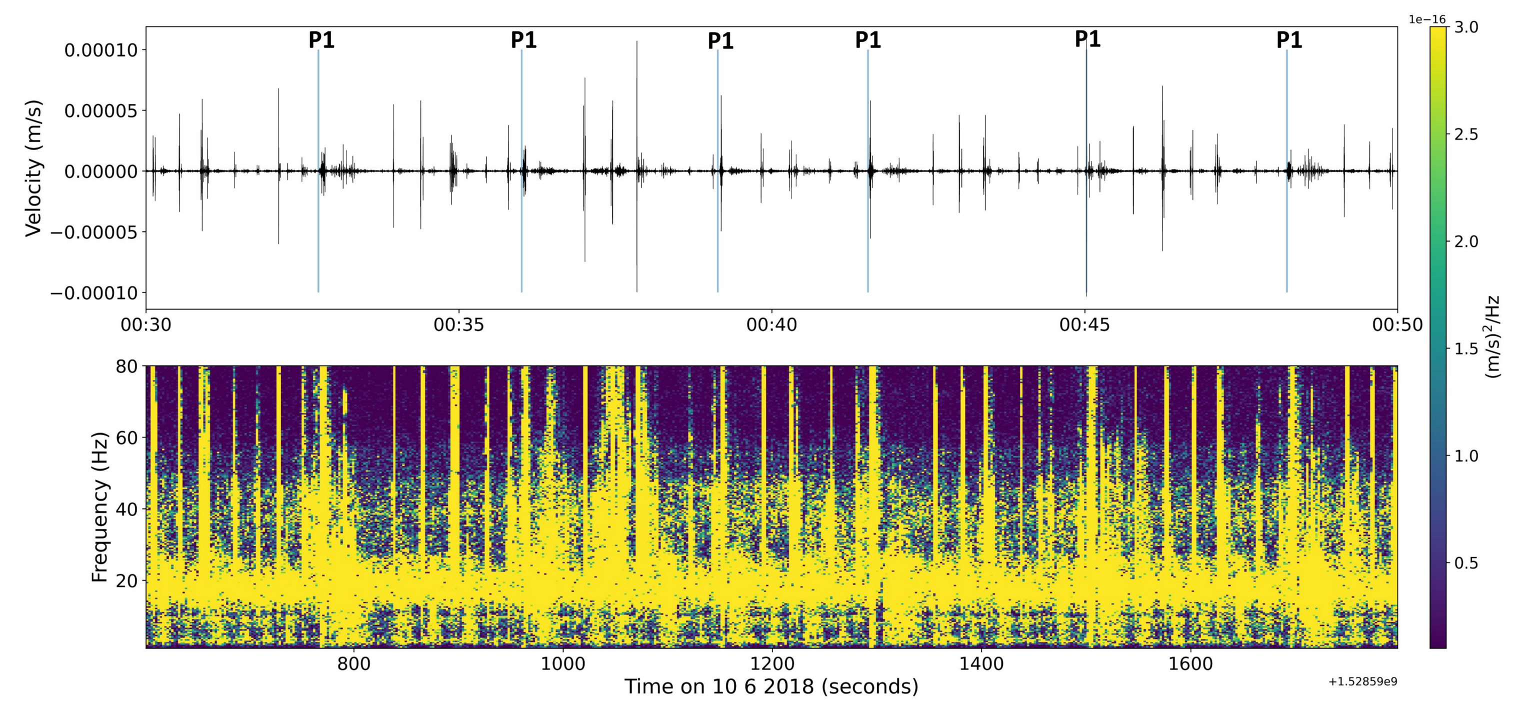


Optimum embedding dimension is m ≥ 6.

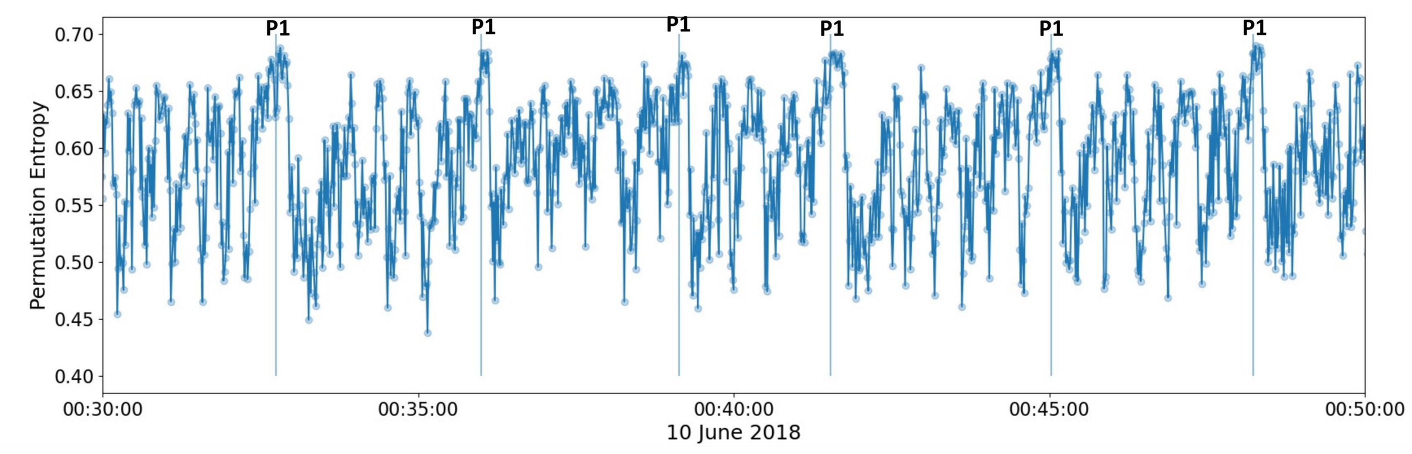
Application to the geyser eruptions at Strokkur, Iceland 2018

- We used 5 hours of seismic data on the 10th June 2018. (how far the station from the eruption?)
- The seismic data were filtered by high pass filter with corner frequency 1Hz.
- The PE was calculated using m =7 and τ = 0.0048 second, and window =1 second.

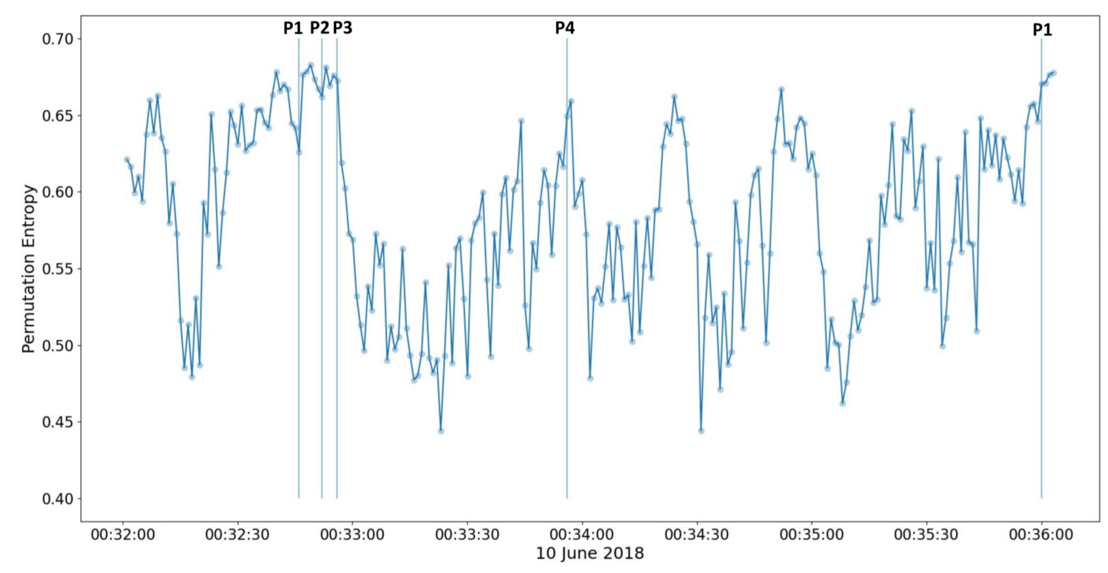
a)



b)

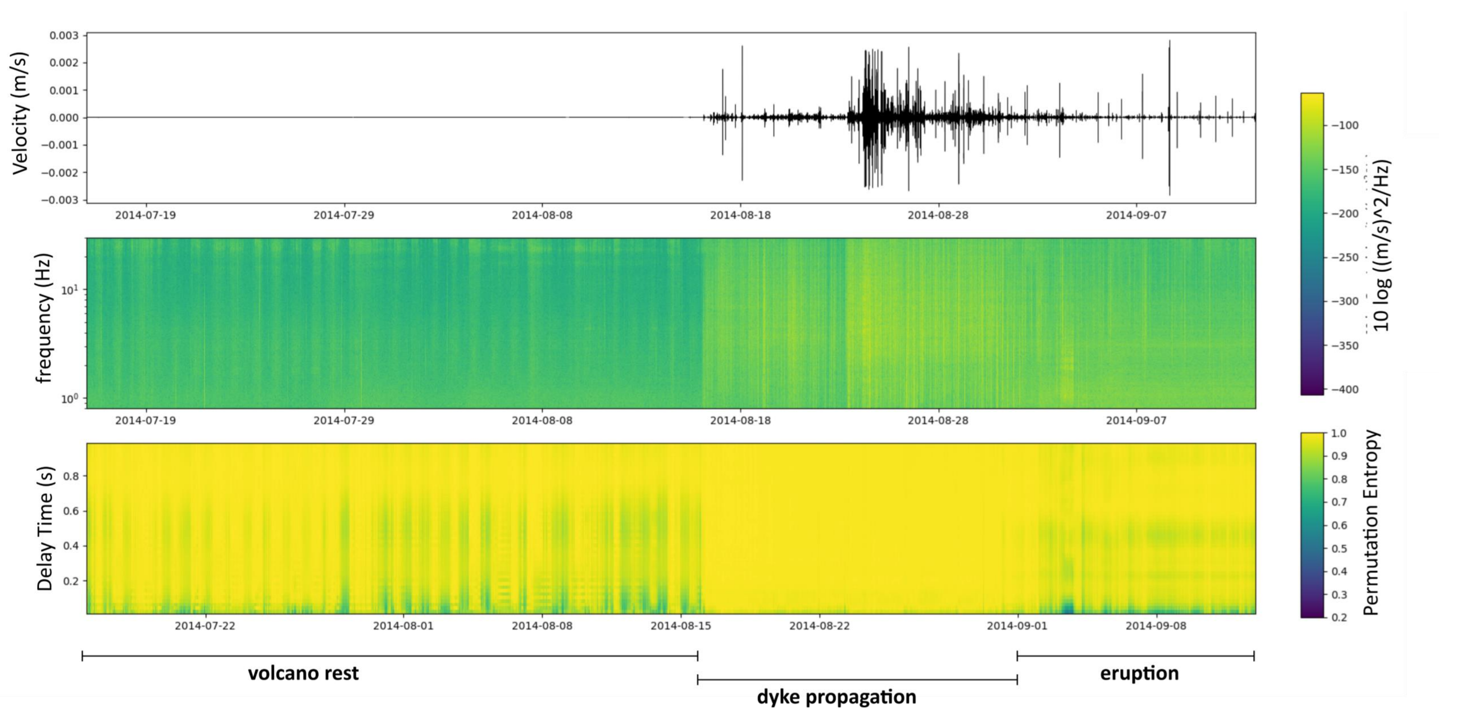


c)



- a) A 20 minutes seismogram and spectrogram on 10 June 2018, b) 20 minutes of PE showing the repetition of patterns between the eruptions, and c) the temporal variation of PE four minutes before the eruption at 00:36:01.
- P1 = eruption, P2 = end of the eruption (start of the conduit refill), P3 = start of bubble accumulation at depth, and P4 = bubble collapses at depth. These four phases composes the eruptive cycle according to Eibl et al.(2021)
- The PE is high during and after the eruption (P1 and P2), then drops at the phase 3 in which is associated with the process of gas filling of the bubble trap. Further, PE is increasing again towards phase 4. In the phase 4, several bubbles collapse at depth (Eibl et al., 2021), and we observed the repeating increasing and dropping PE during this phase. PE then continues to increase towards the next eruption. The PE values at the eruptions are slightly higher than the peaks of PE during the phase of bubble collapses.

Application to the Holuhraun 2014 eruption



Seismogram (top), spectrogram (middle), and PE (bottom) from mid of July to mid of September 2014. PE was calculated using m=7 and multiple delay times 0.01≤ τ ≤1. The seismicity increased on 16 August 2014, leading to a short eruption on 29 August 2014 and followed by a 6 months of eruption between 31 August 2014 and 27 February 2015 (Sigmundsson et al., 2015). Temporal variation of PE shows a jump of PE on 16 of August 2014. PE stays high during the increased seismicity which is associated with the dyke propagation (Sigmundsson et al., 2015). PE starts to drop when the eruption started.

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