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A new test for the analysis of volcanic activity over time

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Data and modeling

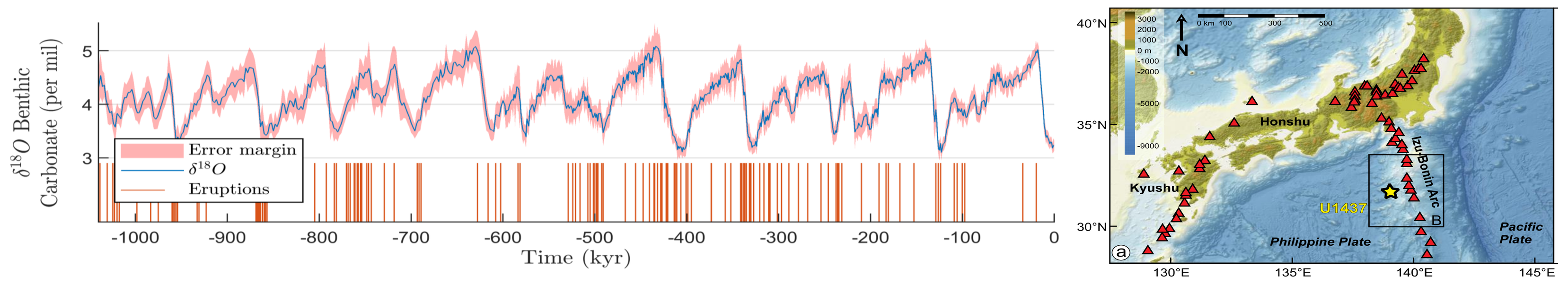

Fig 1. **Left -** Eruption and δ18O records for the last 1.1 Myr. **Right** – The star marks the location of IODP hole 350-U1437B

Eruptions record

- Identification and dating of ash layers from IODP hole 350-U1437B[4].
- 162 explosive eruption dates from the last 1 million years.

Climate proxy

- δ18O LR04 global reference stack[5].
- Proxy for global ice coverage.

Point processes

Point processes are commonly used in the literature for modeling onset times of eruptions[6]. It assumes that eruptions occur randomly, with eruption rate (possibly) changing over time. Given some observed data, it is possible to estimate the eruption rate, and given a time series for the eruption rate, it is possible to simulate data.

- Events $(t_1, t_2, t_3, \dots)$ happen randomly over some interval of time.
- Conditional Intensity Function (CIF) – Eruption rate at each point in time.

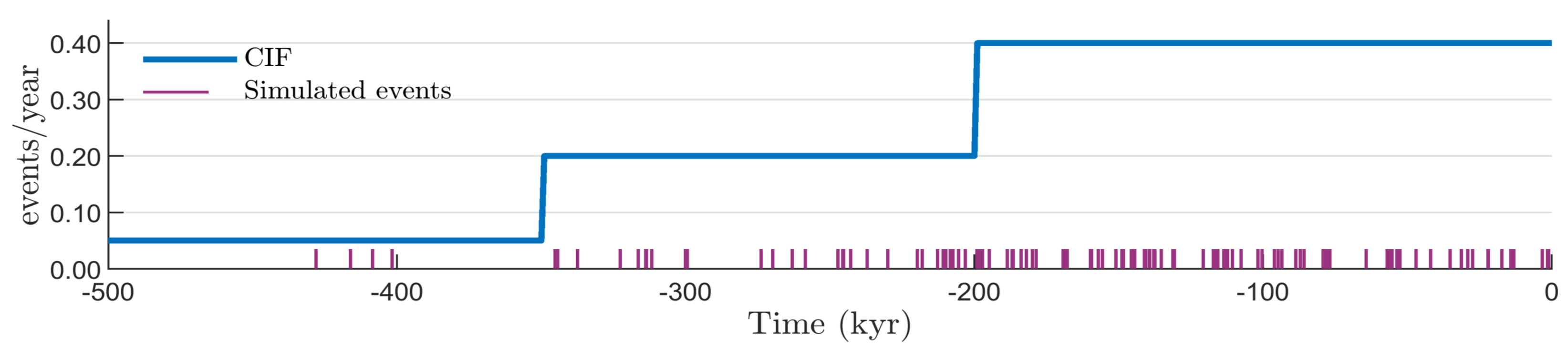

Fig 2. Simulation of an eruption record over 500 kyr from an arbitrary CIF. The larger the CIF, the more events tend to occur in that period of time.

Hypotheses

In this setting, given our eruption record, there are two main questions which we aim to answer:

- What is the true intensity (CIF) of the observed volcanic process?
- Is eruption rate related to sea level changes?

Four different hypotheses on how eruption rate changed during the last 1.1 Myr were developed. Each of them determine a general shape of the CIF, but the specific values must be estimated from the data.

(a) Intensity remained constant – Poisson process
(b) Intensity proportional to changes in sea level – Inhomogeneous Poisson process
(c) Events tend to cluster, but have no relation with the climate proxy – Hawkes process
(d) Events tend to cluster and are related to the climate proxy – Inhomogeneous Hawkes process

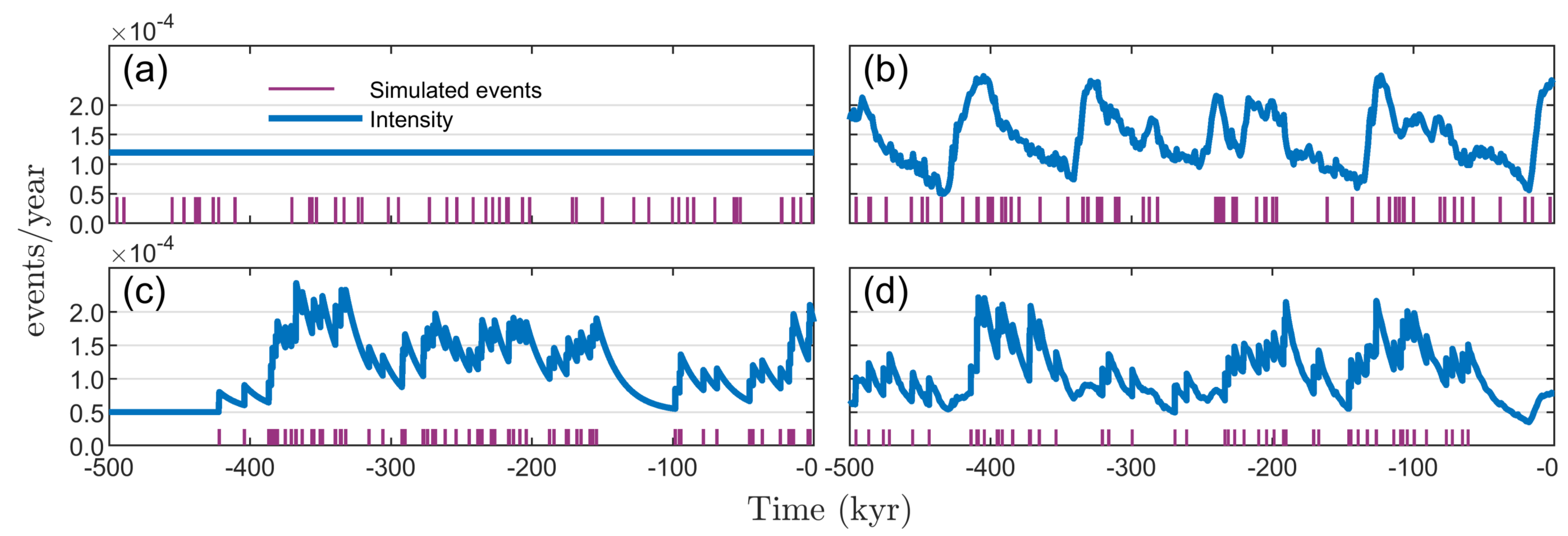

Fig 3. Point processes over 500 kyr simulated using conditional intensity functions corresponding to each of the four models.

Motivation

The impact of large volcanic eruptions on local and global climate is a well-established link in climate science. The reverse link, however, is less clear.
We hypothesize that periods following glacial ages exhibit increased volcanic activity, caused by the pressure change on the crust due to the melting of ice sheets. While evidence from the last deglaciation supports this hypothesis[1], an analysis comprising multiple glacial cycles is necessary for a robust correlation.
However, proper statistical methods for hypothesis testing on the change in eruption rate over time is missing in the literature, therefore, new techniques need to be developed.

Main contributions

- Sound statistical test for the influence of climate proxies on volcanic activity.
- General framework that can be applied to different areas.
- Openly available MATLAB® code implementing the procedures[2].
- Strengthen previous results[3] relating volcanic history of the Izu-Bonin volcanic arc with climate record.

Novel goodness-of-fit test

A sound goodness-of-fit test did not exist in the literature before, therefore, previous works[6] resorted to procedures that overestimated the model's fit.

- **Goodness-of-fit tests -** Determine if a hypothetical model fits the observed data by computing p-values.
- **p-values -** Loosely speaking, the probability that the corresponding hypothesis would generate data compatible to what has been observed.
- **Test's reliability** – If applied to the correct hypothesis, a sound test should produce uniformly distributed p-values.

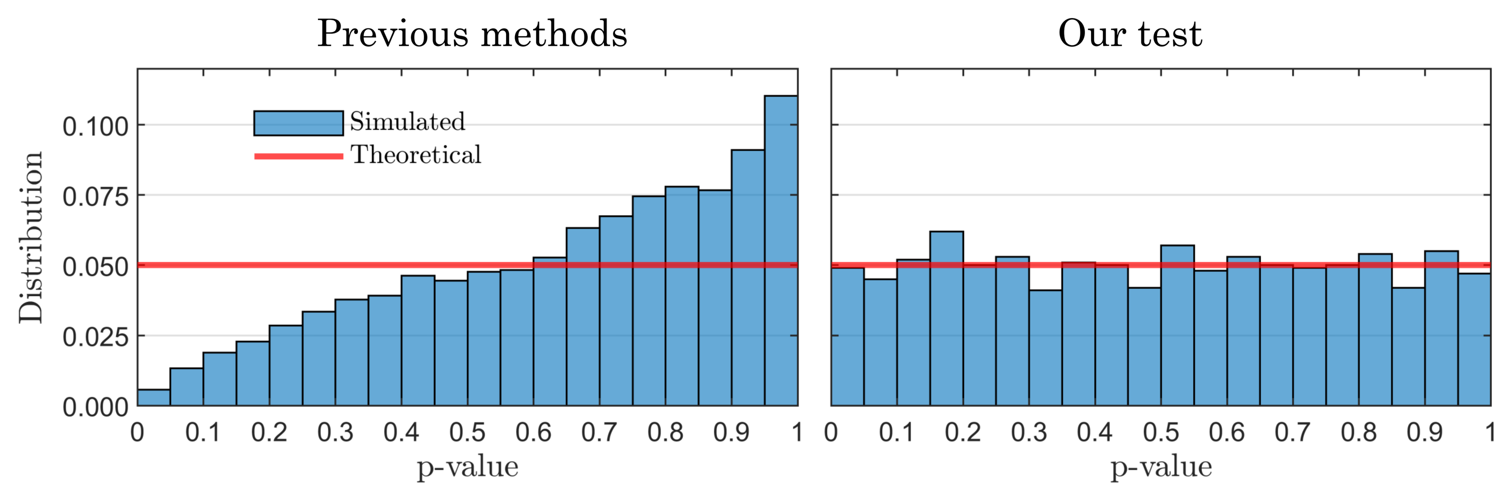

Fig 4. Distribution of 1000 p-values (histogram) when testing data stemming from the correct hypothesis. A sound statistical test should generate histogram with distribution close to the red line.

Example

The KS-plot is often used to assess how well a model fits the data, with rejection determined if the observed distribution is outside the 95% confidence bands.
These bands are calculated based on the test's p-value, which were greatly overestimated by the previous procedures.

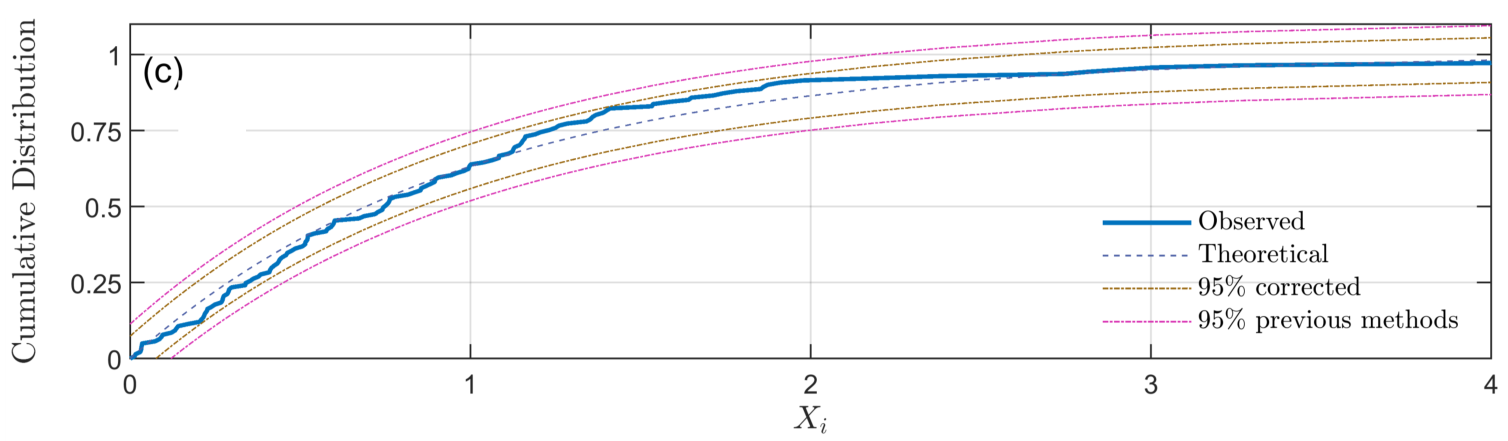

Fig 5. Comparison between corrected and previously used 95% confidence bands. In this example, previous methods would fail to reject an incorrect model.

Results

Complete eruption record

The p-values for each of the four hypotheses was calculated using our novel goodness-of-fit test.

- Hypotheses **(a)** and **(b)** returned p-values of 0, therefore, the hypothesis that eruption rate was constant or simply proportional to sea level change are rejected.
- Hypotheses **(c)** and **(d)** cannot be rejected at a 95% confidence level.
- Further investigation on possible clustering and relation to climate.

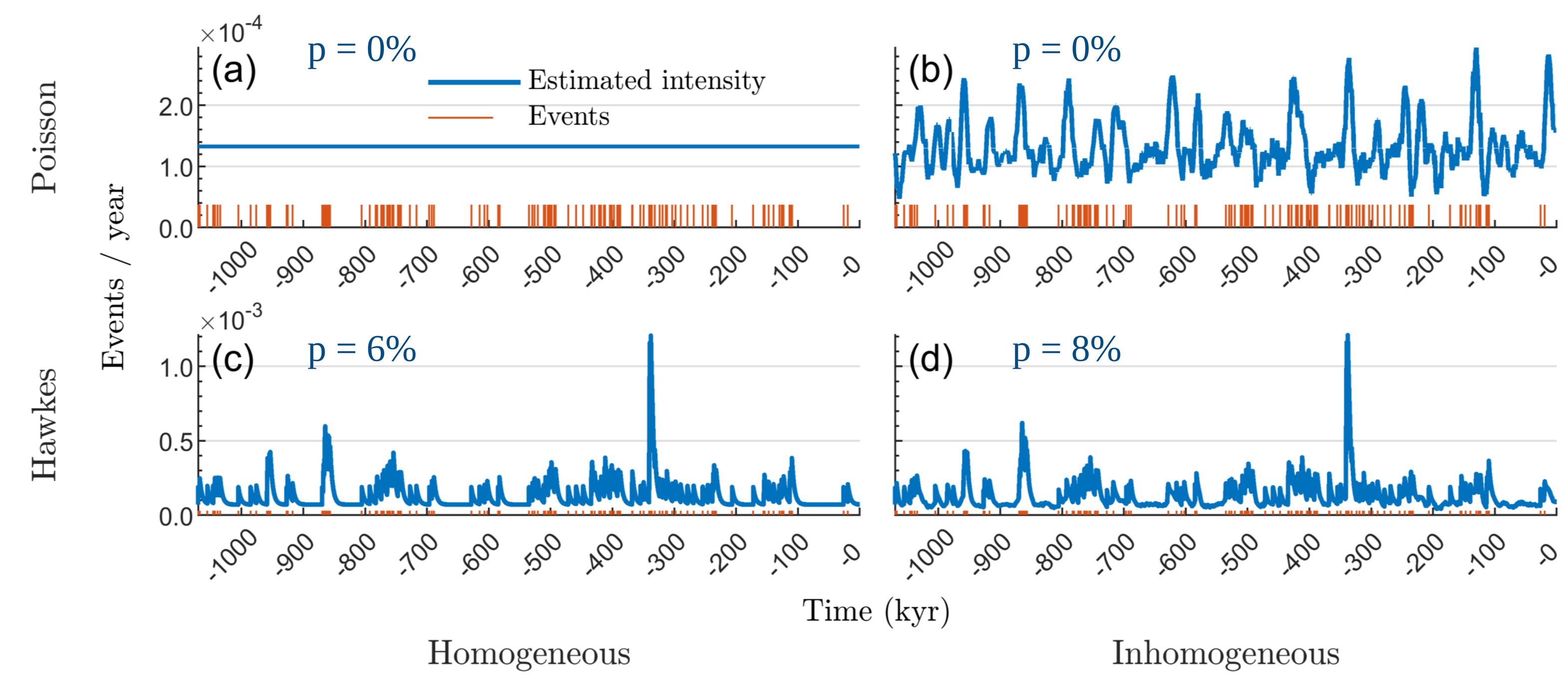

Fig 6. Estimated CIFs and test's p-values with respect to each of the four hypotheses.

Felsic and mafic/bimodal eruptions

The test was applied to two different subsets of the eruption record, the felsic events, and the mafic and bimodal events. The difference between them is the silica content of the magmas. Felsic magmas are richer in silica than mafic, making them more viscous and prone to explosive eruptions.

- **Felsic** – Very large p-value returned by hypothesis **(b)**. Indicates correlation with climate.
- **Mafic/bimodal** – Hypotheses **(a)** and **(b)** rejected. Strong clustering.
- Composition of magmas have a strong effect on volcanic activity.

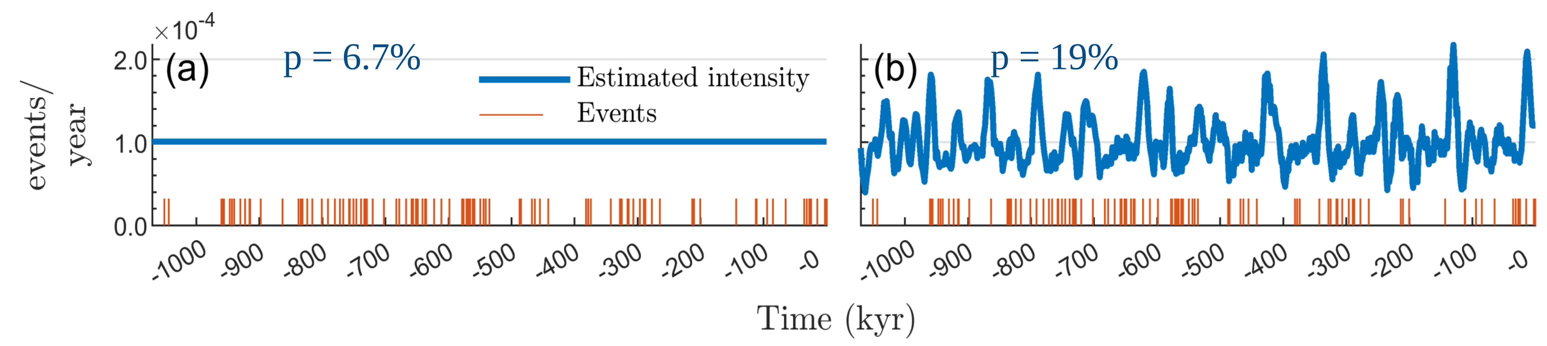

Fig 7. Goodness-of-fit test for hypotheses **(a)** and **(b)** applied to felsic events.

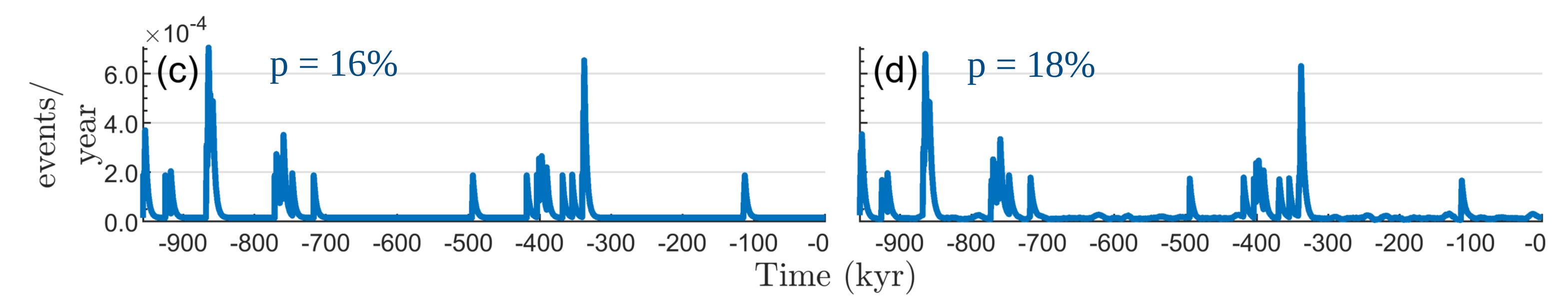

Fig 8. Goodness-of-fit test for hypotheses **(c)** and **(d)** applied to mafic/bimodal events.

References

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