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Advancing the Onset-Delay-Method for Resonance Seismometry

Rolf Häfner, Manfred Joswig and Marco Walter

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INTRODUCTION AND MAIN RESULTS

Resonance Seismometry is one of the allowed techniques that the Inspection team may apply during the continuation period of an On-Site Inspection (OSI). The intent is to analyze seismic signals (earthquakes, active sources and noise) to detect wavefield disturbances indicative of a cavity or rubble zone caused by an underground nuclear explosion (UNE).

We present the Onset-Delay Method (ODM) to analyze data from local regional and teleseismic events. We utilize data from the 2022 Field Test near Rotmoos in the Austrian Alps.

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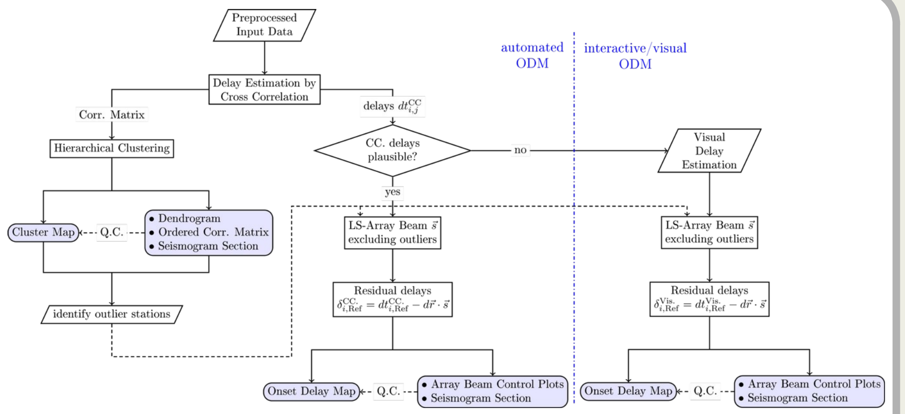
The Onset Delay Method

We present a Toolbox map subsurface anomalies utilizing seismic event waveform data from a small seismic array. Due to the short duration of an OSI Resonance Seismometry experiment, the number of suitable seismic events is limited. To ensure robust results under this constraint, we utilize multiple observables from each events:

- Waveform similarity clustering
- Seismic phase onset delays
- Spectral power variation

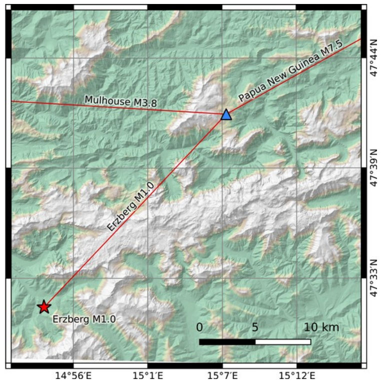


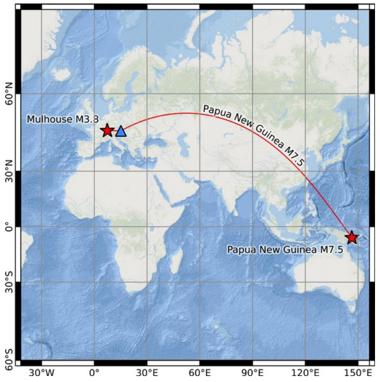
Processing flowchart for the onset delay method

Data

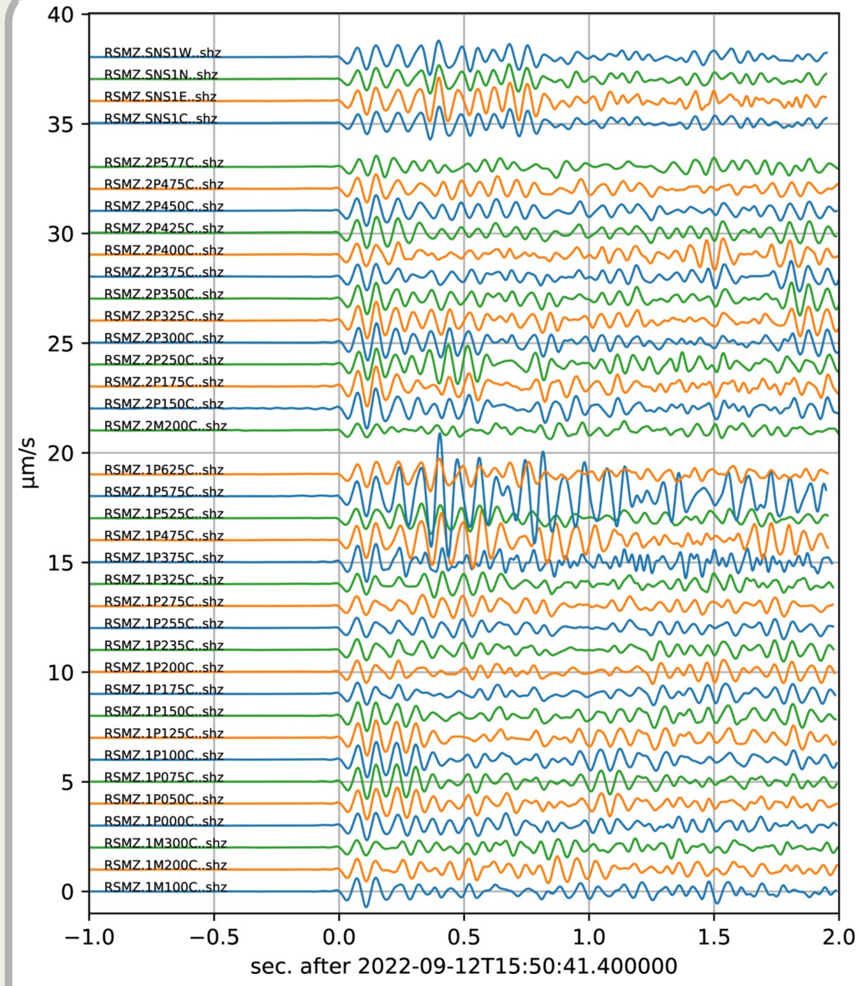
To demonstrate the capabilities of this method, we use seismic data from the 2022 OSI Field Test in Austria (see P3.3-556 for further details).

The data was recorded on the OSI-section's PSM equipment (Lennartz LE-3Dlite seismometers and Reftek 130 data recorder)s at 500Hz sampling rate. Global and regional bulletins showed 2 suitable events for processing. In addition, a local event was found using manual screening, and could be identified as a M_l 1.0 blast at the Erzberg iron ore mine ~30km southwest of the survey area.





Source Time	Lat..	Lon..	Mag..	Region
2022-09-10 15:58:12	47.7	7.4	3.8 M_w	Mulhouse
2022-09-10 23:46:59	-6.2	146.4	7.5 M_w	P.N. Guinea
2022-09-12 15:50:36	47.5	14.8	1.0 M_l	Erzberg



Data for the local M1.0 Erzberg event (1-20 Hz bandpass)

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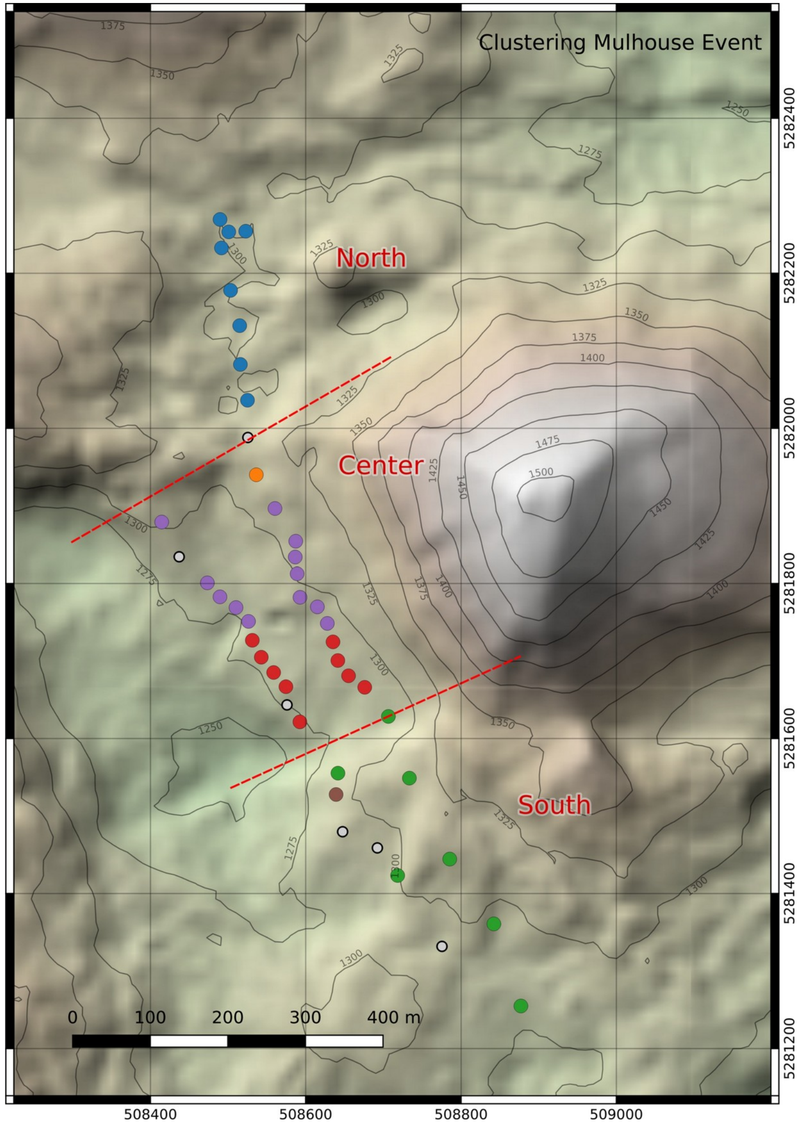
Waveform similarity mapping: Hierarchical Clustering

The first approach to identify stations influenced by subsurface anomalies is to map the similarity of an event's waveform.

To map similarities, we perform a Hierarchical Clustering algorithm, which divides the full set of waveforms into similar clusters. Similarity is determined by cross correlation of the P onset as visualized in the cross correlation matrix. We start with one cluster per waveform, and start merging the most similar clusters iteratively. Similarity between clusters is defined by the least similar pair of waveforms from each cluster to ensure maximal similarity.
If a chosen similarity threshold is reached, the algorithm stops, a color is the assigned to each cluster and the results are presented as a map.

The clustering process can be visualized in the form of a dendrogram. Ideally, reordering the stations in the correlation matrix should reveal a strong block structure with individual, anomalous, stations being separated consistently for multiple events.

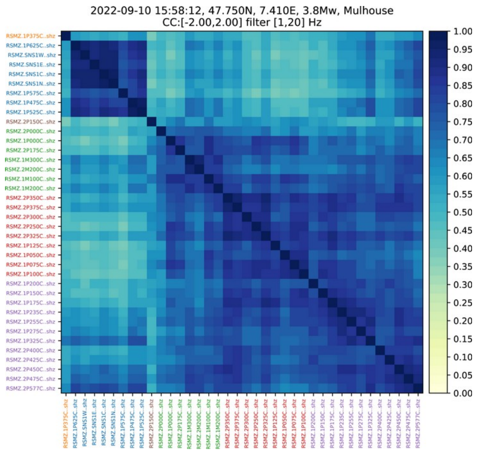
For this dataset, these clusters divide the survey area in North, Center and South sections.

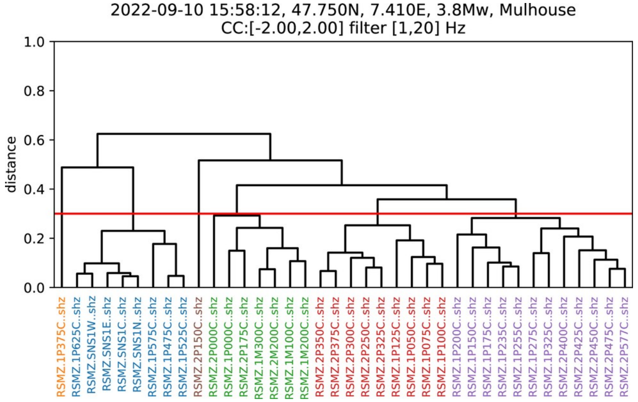


Similarity cluster map of P onsets, Mulhouse event

The reordered correlation matrix shows strong block structure, revealing a discrepancy between the northernmost stations (blue labels) and the rest of the array.

The station label colors match the cluster colors in the similarity cluster map.





Read from bottom to top, the dendrogram visualize the clustering process. the threshold of 0.3 (red line) corresponds to a minimum wave form cross correlation coefficient of 0.7 in each cluster.

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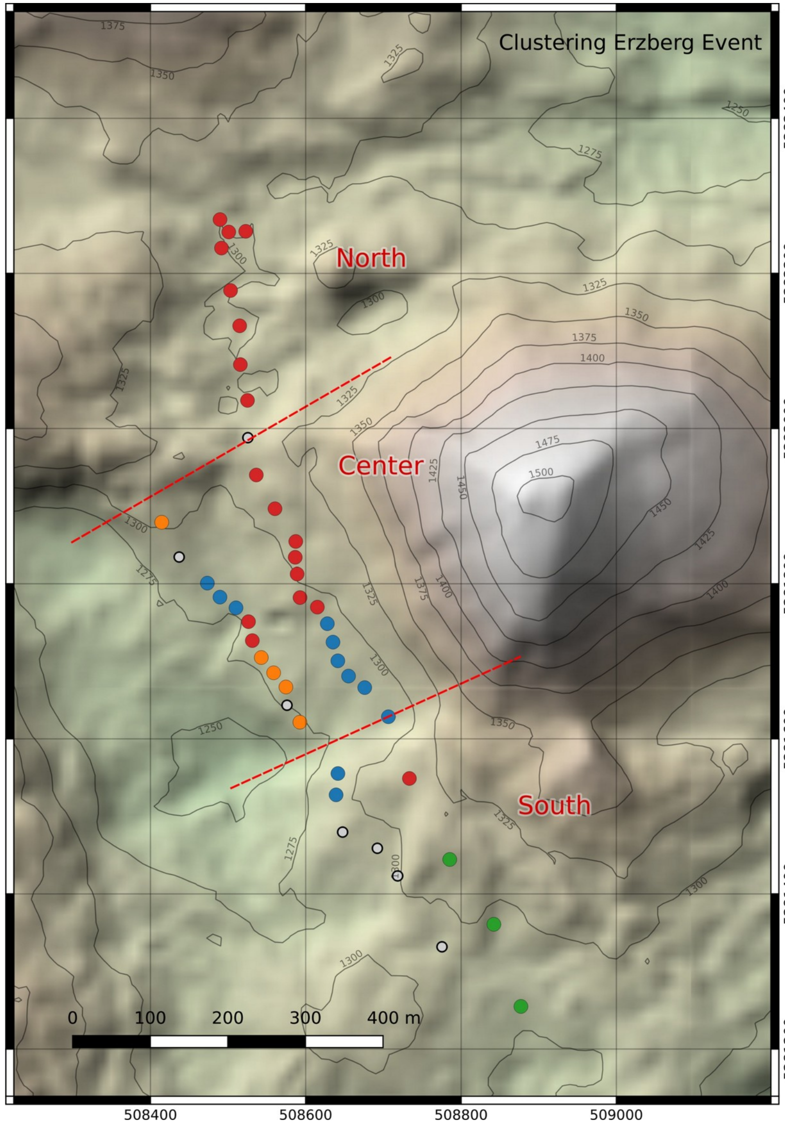
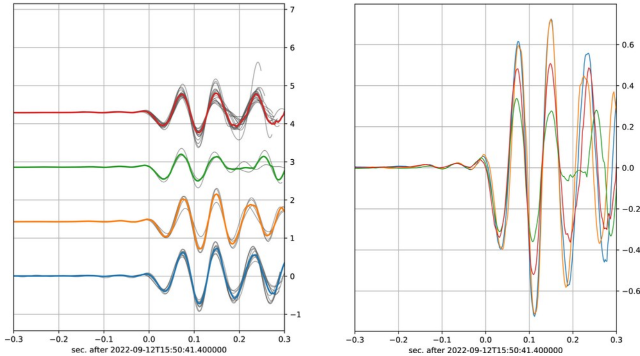
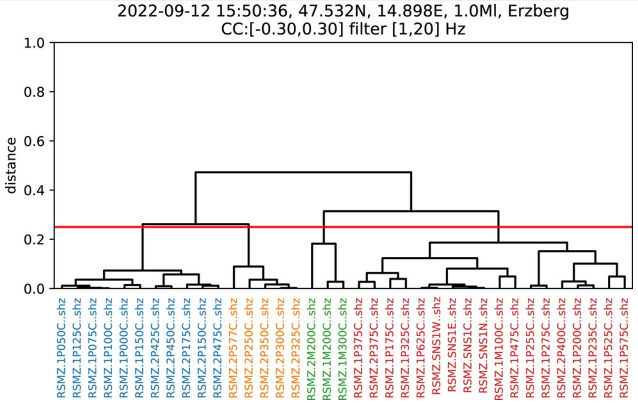
Mean seismograms for each cluster can be plotted, and the presence of specific waveform features may be interpreted.



Similarity cluster map of P onsets, Erzberg event



Median seismograms for each cluster show subtile differences. As shown in the dendrogram, the red cluster has the strongest internal variance.



Read from bottom to top, the dendrogram visualize the clustering process. the threshold of 0.25 (red line) corresponds to a minimum wave form cross correlation coefficient of 0.75 in each cluster.

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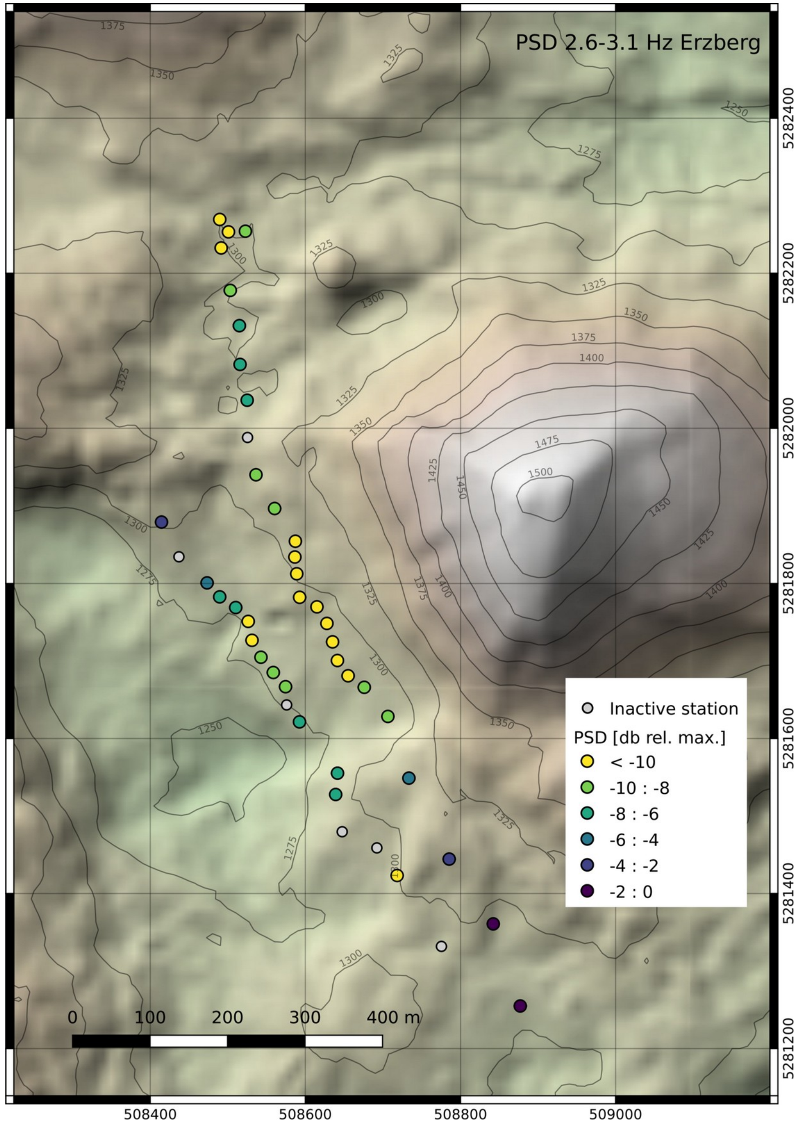
Spectral Power mapping

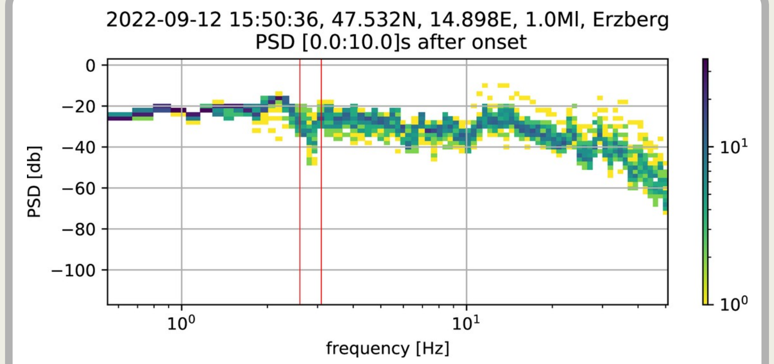
Identifying peaks in power spectra usually the first approach in approach to studying resonance phenomena. An events spectrum is formed by the convolution of the source function, the travel path and the recording instrument. As only the travel path deviates for small scale arrays, anomalous resonators should be identifiable as spectral peaks on nearby stations.
However, in all analyzed OSI Resonance Seismometry datasets to date, such well defined peaks are absent.

However, for each event, variations between the power spectra of different stations exist and are visible in a spectral histogram. One can identify narrow bands where these variations are strong, and plot the integrated spectral power on a map.

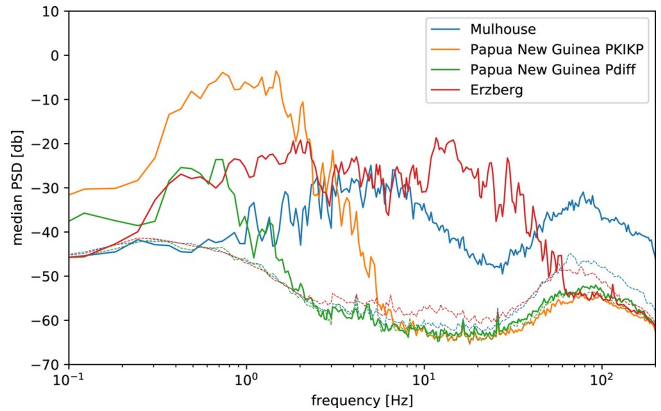
The resulting map shows dampening of the spectral power around the center area and near the northernmost stations, with a sharp 8-10 dB rise in spectral power between the center and the south.



Integrated Spectral Power (2.6-3.1 Hz) for the Erzberg event.



Spectral Histogram; color shows the number of individual station spectra passing each cell in the frequency / power plot.



Each event's spectrum at reference station 1P000 near the center of the array. No consistent structure is visible between events.

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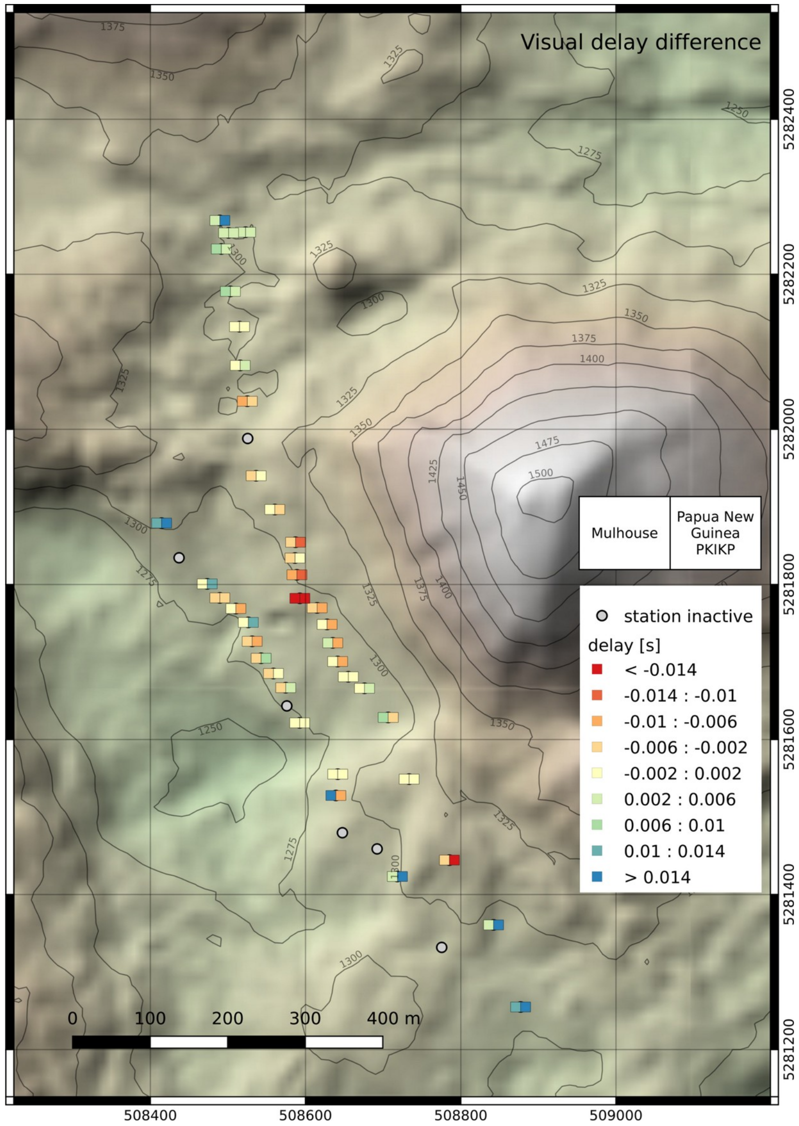
Phase Onset Delays

The final observable considered are delays of seismic phase arrival times. This is the most sensitive component of this data analysis toolbox, and enables the analyst to visual travel time anomalies with a resolution matching the sampling interval.

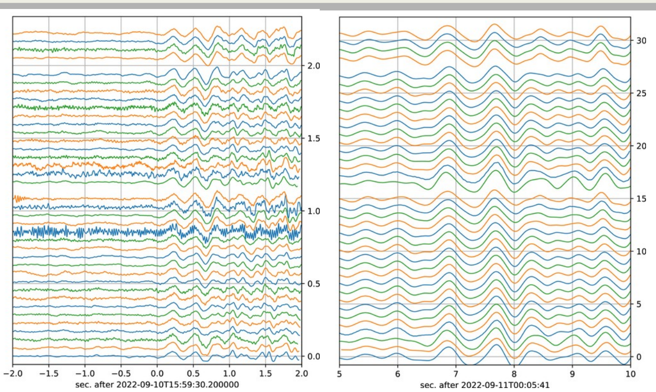
Arrival time differences can, for sharp phase onsets in low noise data, be determined automatically via cross correlation, or by using a small graphical software tool for quick visual alignment of nearby and reference traces.

The arrival time delays are then corrected for planar wave propagation using least-squares minimization. This, in addition yields an estimate of the apparent velocity and propagation, which can help identify events if external sources can't be accessed.

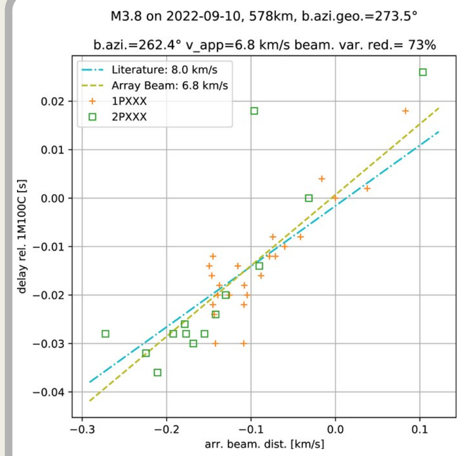
In this case, visual alignment was deemed necessary and revealed fast phase arrivals in the north and south sections of the array, with the slowest arrivals near the borders of the central section at the northeastern profile (Profile 1).



Onset Delays for manually aligned phase arrivals for Mulhouse and P.N.G. events.



Checking the seismograms shifted in time according to the estimated delays ensures the correctness of the chosen alignment procedure.



Least-squares beamforming results for the Mulhouse event's P onset; A plausible apparent velocity of 6.8 km/s fits the data best and results in a variance reduction of 74%. Note however the anomalous late arrivals at some stations. If consistent across multiple events, these may relate to subsurface anomalies.

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Interpretation

All methods showed a different behavior between the north, south and center of the survey area. The North and South consistently show higher Power Spectral Density in specific spectral bands, and later phase arrival times. The clustering algorithm showed the center region to have the highest internal variation in waveform features. Thus, while spatially clearly constrained anomalies could not be identified, subsurface variation is to be expected in the center area.

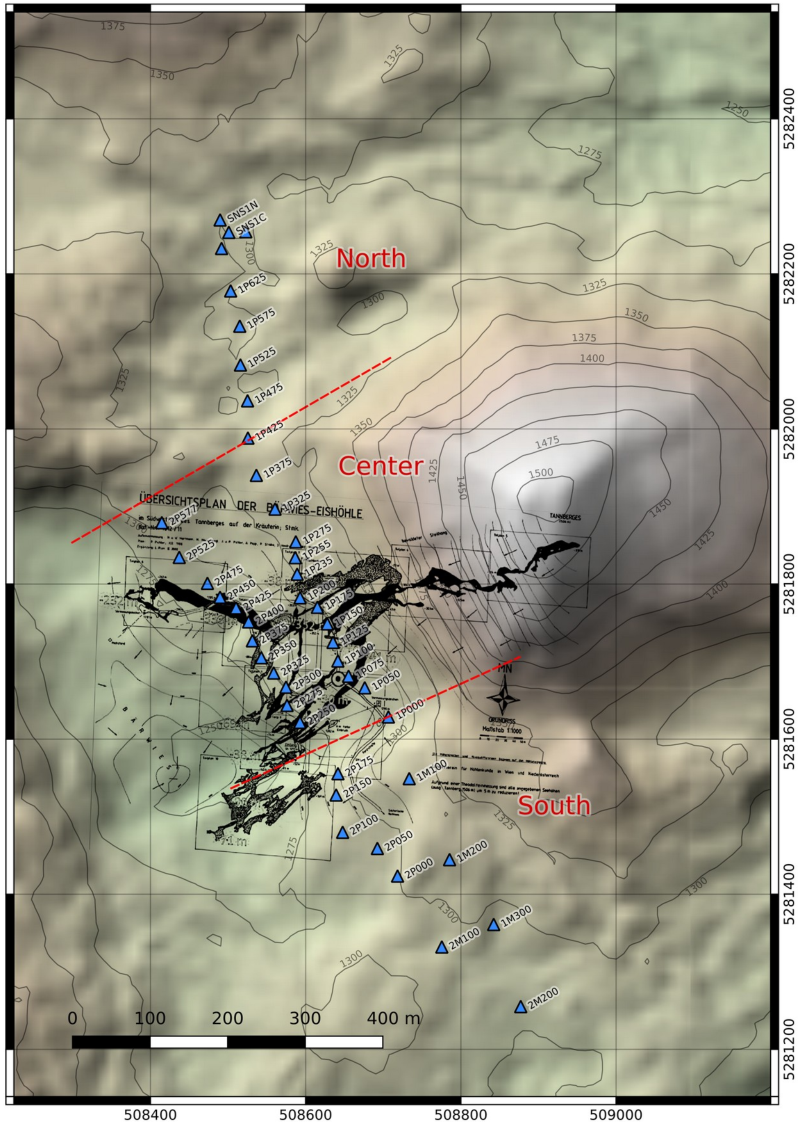
This is consistent with the known geometry of the Bärwies Eishöle (Pichler 1987).

References

- *Häfner, R., Walter, M. & Joswig, M. Testing the Onset Delay Method for Resonance Seismometry: The Underground Nuclear Explosion "Tiny Tot" Case Study. Pure Appl. Geophys. (2025). https://doi.org/10.1007/s00024-025-03746-7*
- *Häfner, R., Walter, M. & Joswig, M. Report for Purchase Order No.: 2022-1359 "Analysis of seismic ambient noise and earthquake recordings (Task 2)", available through the CTBTO*
- Pichler, P., 1987. Baerwies-Eishoehle (1812/11) Die Ergebnisse der Forschungen in den Jahren 1985 und 1986,Hoehlenkundl. Mitt. (Wien) , 43 (4), 8492.

Funding & Disclaimer

This study was financed by the CTBTO under Purchase Order No: 2022-1359. The application of each method described to each of the events was omitted in this presentation for brevity and is described in full detail in the Report available through the CTBTO.



Map of the Bärwies Eishöle Pichler 1987

Conclusion

The Onset Delay Method (ODM) method ...

- implements Resonance Seismometry using earthquake data as defined by the 'Protocol to the Comprehensive Nuclear-Test-Ban Treaty' Part II
- requires the recording of ideally multiple teleseismic, regional or local earthquakes.
- requires no active sources.
- maps the horizontal extent of subsurface anomalies using the joint interpretation of multiple observable quantities.

However, because of the lack of short period signal power the earthquake signals and data quality, a true inversion of an anomalies depth and shape is not feasible. Therefore, once the horizontal extent of a suspected anomaly is constrained, other geophysical methods must complement the ODM method to accurately identify such anomalies.

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