GEOTHERMICA

COntrol **SEIS**micity and **M**anage **I**nduced earth**Q**uakes (**COSEISMIQ**)

Deliverable 2

Deliverable 2 (Month 17): Implementation of advanced microseismic imaging tools in workflows optimized for geothermal plays

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Introduction & rationale

A key desire during geothermal injection operations is to image fluid injection from the source region into the surrounding rock. One approach is to attempt to track pore pressure variations using induced microseismic events. This requires a good microseismicity database and the ability to track & quantify microseismic source evolution, and to determine near source geomechanical properties.

Since November 2018, within the framework of the COSEISMIQ project, the number of seismic stations deployed in the Hengill geothermal field has been increased from 16 to 40. Such a dense seismic network allows us to better monitor and analyze the micro-seismicity in this area, as one of the selected demonstration sites in this project. Over the past year this high resolution database has been growing, and initial results from it are used in this deliverable. Before we can consider source imaging, it is important to describe and characterize the available microseismicity database. To characterize the micro-seismicity in the Hengill geothermal site, we combined the seismic data acquired by the dense seismic network, consisting of short-period and broadband seismometers, with advanced and robust methods for seismicity location, spatial clustering and moment tensor inversion.

Data Set

The seismic network consists of combined permanent and temporary short-period (5 and 1 s) and broad-band (120 and 60 s) sensors, installed by the COSEISMIQ team, with overall local 40 stations within an area of about 15x15 square kilometers. Broadband and short-period seismometers continuously record the seismic data with sampling rate of 200 and 100 Hz, respectively.

The dataset considered here consists of about 367 events with local magnitude (M_L) range of 0.8-4.7 occurred between 2018-12-18 and 30-01-2019. The dataset includes a seismic sequence that occurred at the end of December, with the 'mainshock' M_L=4.7, that took place on 30th December 2018. Events spanned from a few days before this largest event, and lasted approximately one month. The dataset is characterized by a substantial number of low magnitude high frequency events, with strong noise contamination affecting the magnitude estimated process.

Seismicity Clustering

In order to obtain reliable results and meaningful interpretation from micro-seismicity imaging, we conducted spatial clustering of the seismic events for improving the solution of source information. By performing seismicity clustering for multiplet (a group of similar events) identification and analysis, we are able to assess the reliability of micro-seismic source properties (hypocenter location, seismic moment tensor etc.) and medium properties such as seismic-wave velocity and attenuation. Thus, clustering analysis can be a robust quality control tool on key parameters in micro-seismicity imaging.

A strategy for hypocentral and waveform clustering procedure has been developed by the GFZ Helmholtz Centre, Potsdam and implemented as software package called *SeisCloud*. It is an

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easy-to-use command-line tool that is configured with a plain text file in a human-readable structured data format. The seismicity clustering algorithm implemented in this module is based on Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm (Ester et al., 1996). DBSCAN is a density-based clustering non-parametric algorithm based on the location of high-density regions that are separated from one another by regions of low density; points that are closely packed together (points with many nearby neighbours) are grouped together, whereas points lying alone in low-density regions (whose nearest neighbours are far away) are marked as noise (outliers) (Figure 1). DBSCAN is one of the most common and powerful clustering algorithms used in data mining and machine learning and its application in micro-seismicity imaging can increase our confidence in using the data set for interpretation and monitoring.

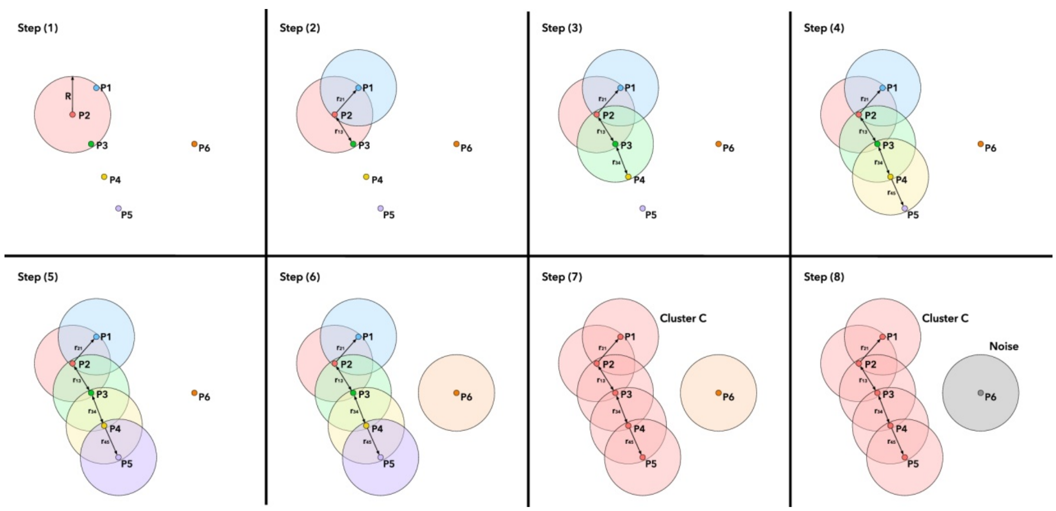

Figure 1. Sketch showing how the DBSCAN algorithm works.

Figure 2 depicts the hypocentral clustering results after running the *SeisCloud* computer programme package on a data set consisting of ~400 micro-seismic events in the Hengill area with magnitudes between M0.8 and M4.7. The clustering algorithm identified eight different clusters, where the biggest one (shown in red) is deeper and located further south of geothermal area with respect to most of other clusters. Following the hypocentral clustering, the *SeisCloud* module performs waveform clustering for each cluster to identify the similarities between events belonging to a specific cluster. Figure 3 demonstrates the waveform clustering results for the biggest cluster shown in Figure 2 and for one single station. The similarity matrices sorted after performing clustering show one single cluster for each component.
These results confirm and support the hypocentral clustering for the biggest cluster.

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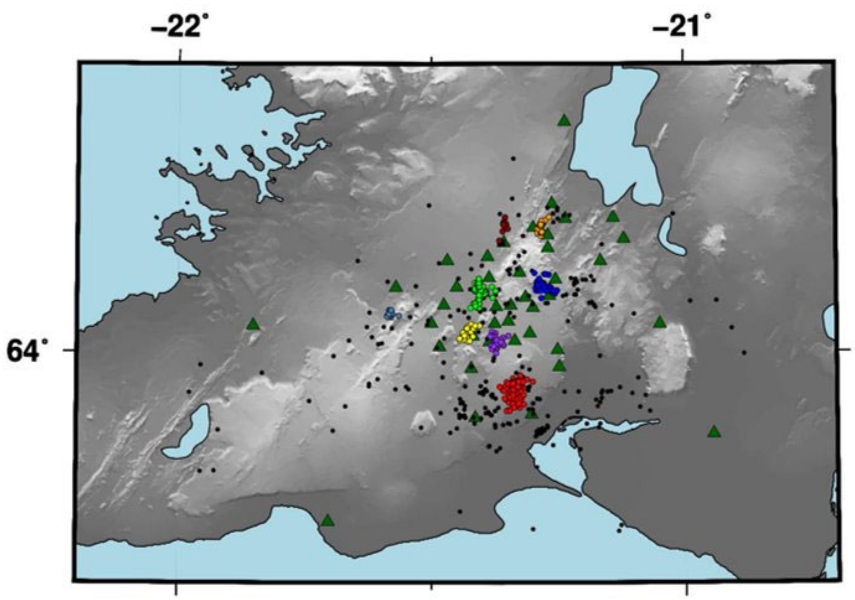

Figure 2. Map with the result of the hypocentral clustering.

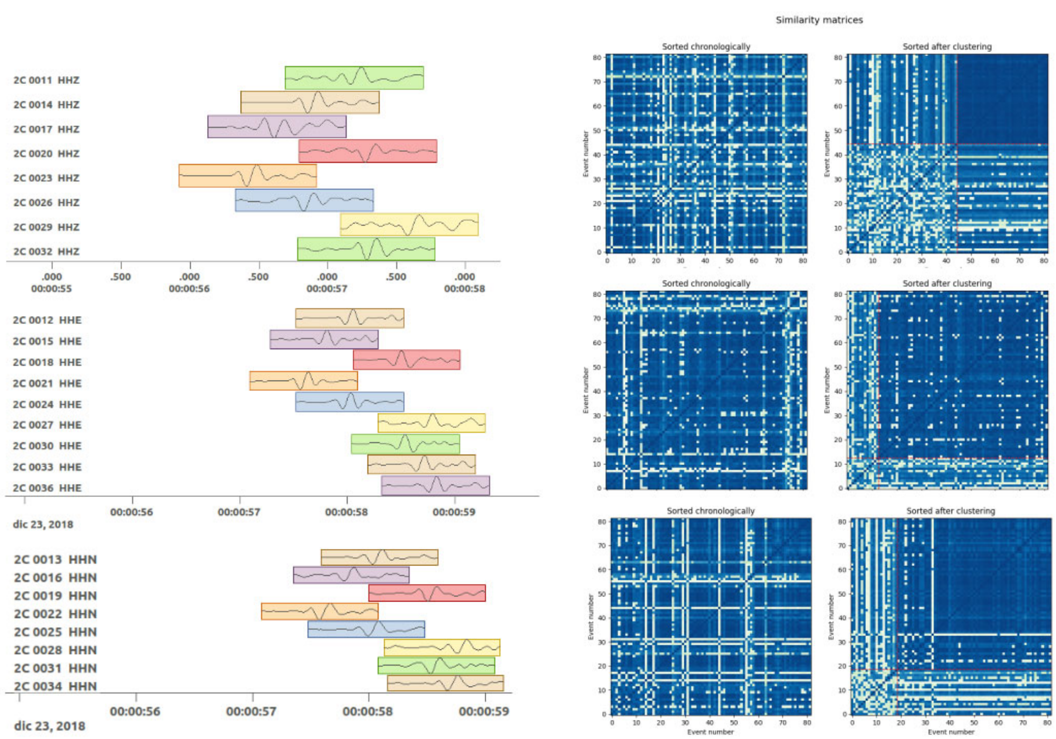

Figure 3. Waveform clustering for the largest cluster and for one station.

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Master-Event Identification

Once the clusters are identified, we select a subset of events in each cluster as so-called *master events*, that are events with “best” solutions. Events meeting the following criteria are selected as master events: (1) well-located with small location uncertainties, (2) high coherence value and (3) good quality of recorded seismic signal (large signal-to-noise ratio). These events are used to perform the moment tensor inversion. Later on, the moment tensor solutions for smaller events can be determined with respect to the master events. As a test implementation, we selected six and four master events in the first and second largest clusters, respectively. Figure 4 shows an example master event selected from the largest cluster. It can be seen that the location uncertainty for this event is low and it shows high spatial coherency in all dimensions. The signal-to-noise ratios of the recorded seismograms on all components are large and the filtered waveforms show clear seismic signals (Figure 5).

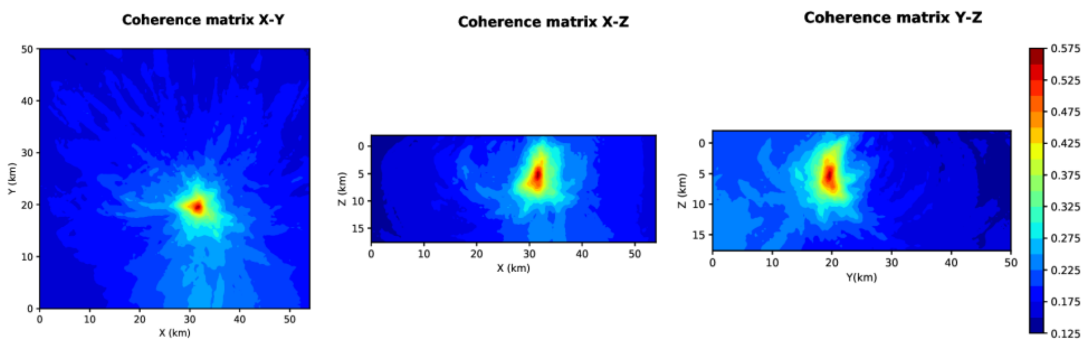

Figure 4. Coherence matrix related to a master event occurred on 30 December 2018. The coherence matrix XY is obtained by projecting, for each (X, Y) point, its maximum along Z direction (coherence matrices XZ and YZ are obtained in a similar way). Coherence values are represented in color scale.

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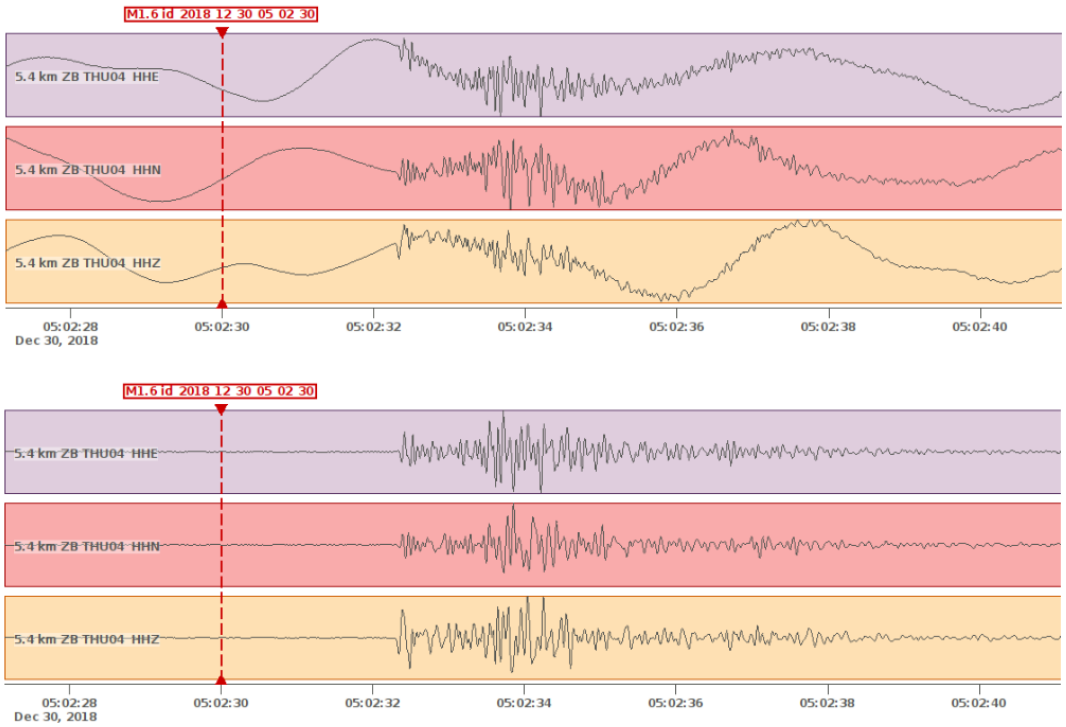

Figure 5. (top) raw and (bottom) filtered seismic waveforms for the master event mentioned in the previous figure.

Bayesian Moment Tensor Inversion

The seismic moment tensor inversion has been computed by using GROND software tool, a moment tensor inversion algorithm for robust characterization of earthquake sources. The inversion for one event can be performed using, at the same time, different data input, such as full waveform, first motion polarities and body wave amplitude ratios. Green's functions (GF) between all source points and receiver positions involved are pre-calculated by using QSEIS method for layered media (Wang et al., 1999). The optimization is based on the so-called Bayesian Bootstrap Optimization allowing for earthquake source optimization whilst providing the complete information for a fully Bayesian analysis. The algorithm is based on direct search, where random model parameters are drawn from a defined model space. These synthetic models are then calculated and compared with the target observed data, computing the objective function. The optimization algorithm implemented in the GROND software enables fully probabilistic bootstrapping of the optimization results that is realized in parallel with optimization chains to which bootstrapping weights are applied.

To obtain the high time precision, the picking for selected events has been performed. To distinguish *P* and *S* phases and to avoid the overlap of phases on the recorded seismogram, we inverted both full waveform and body waves for *P* and *S* phases, respectively, for stations near to the source area (epicentral distance less than 4.8 km) and far away from the source (epicentral distance larger than 4.8 km).

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Figure 6 shows the full moment tensor solutions and axis orientation of the "best" events belong to the first two clusters. Most of the solutions show a large component of CLVD (compensated linear vector dipole) and the orientation of the tension axis located in the same region.

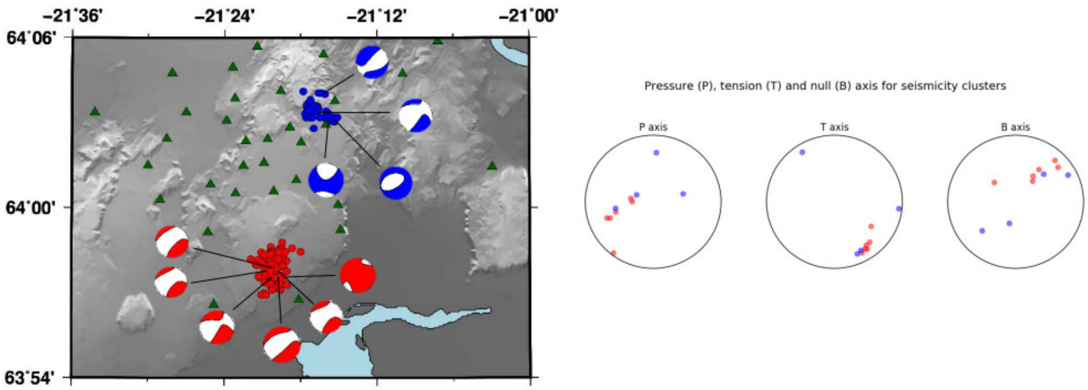

Figure 6. Map with the full moment tensor solutions and axis orientation of the "best" events of the first two clusters.

Discussion on the sources

Hypocentral distribution shows two class of depth: (1) shallower events occurred in the center of the geothermal site and (2) deeper events are located further south of geothermal site. Hypocentral clustering confirms earthquake location: the biggest cluster appears as a separate cluster located outside the geothermal area, on the neighboring SISZ, whereas, most of other clusters are shallower and located in the proximity of geothermal plants (Figure 7).

The Hengill site is a complex geodynamic area, where tectonic, volcanic & geothermal processes occur. Based on earthquake locations, it seems that shallower events are associated with natural geothermal process or to some extent geothermal energy exploitation operations in the area, whereas deeper events seems to be mostly associated to the transform tectonic zone.

The full moment tensor solutions show a large CLVD component in most of events (Figure 6), typical of volcanic and geothermal environments, where earthquakes can be caused not only by the activation of faults but also by fractures opening and closing due to other physical process, for instance the circulation/injection of hydrothermal fluid.

Forcing the moment tensor solutions to be DC (double-couple), we noticed that solutions of the first cluster show a nodal-plane oriented NNE-SSW and E-dipping (Figure 8). This solution reflects depth-trend/pattern of the first cluster E-dipping and it is in agreement with the tectonic trend of area (Figure 8). The second cluster shows two solutions with the same orientation of the first cluster, and the other two with a more E-W orientation that it is in agreement with the second tectonic trend of this area.

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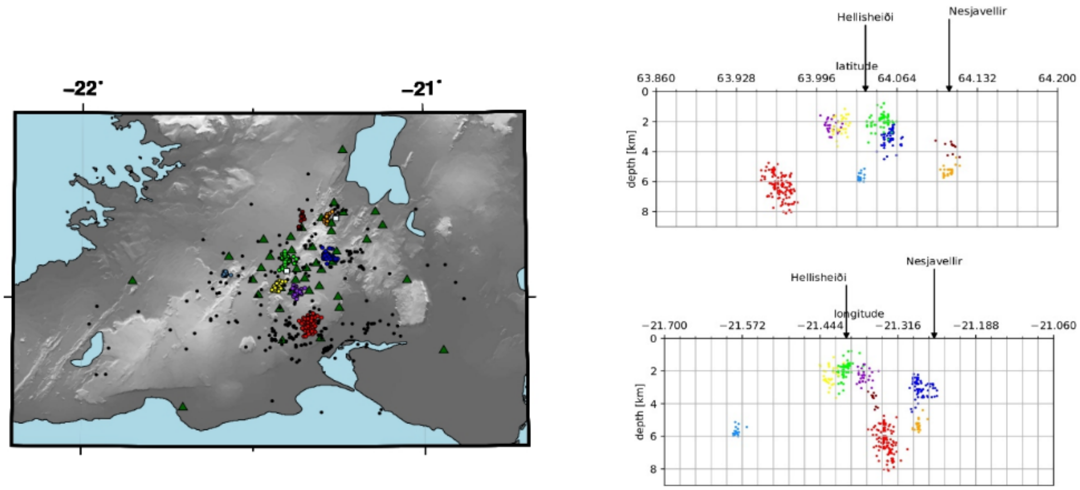

Figure 7. Map and cross sections with the results earthquake locations and hypocentral clustering.

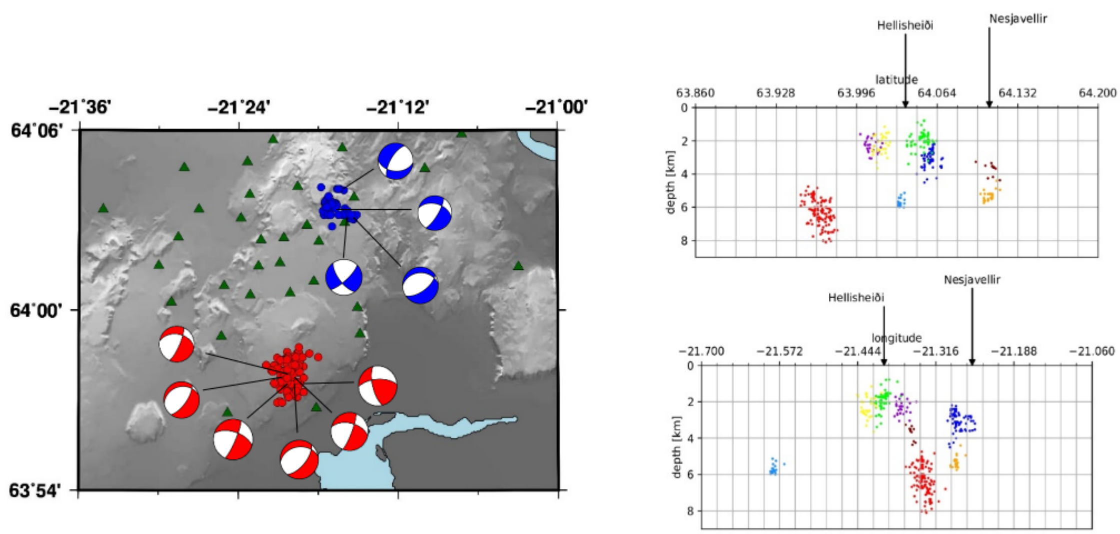

Figure 8. DC solutions of the first two clusters and cross sections of all clusters.

Near source imagery: Vp/Vs ratios

Local anomalies of the rheological parameters controlled by injection operations can be investigated by imaging near-source Vp/Vs ratios, potentially providing estimations of pore pressure variation and helping to track fluids in the subsurface.

Large scale Vp/Vs velocity ratios are typcially imaged using local earthquake tomography of noise tomography applications. However, these approaches retrieve average ratios and are not suited to resolve variations at the sub-kilometer scale, which may be present in the geothermal reservoir. Small scale anomalies can be accurately resolved, and their values tracked in time, based on the processing of Wadati diagrams (Lin and Shearer, 2009; Dahm and Fischer, 2014). Beside technical differences in their implementation, both methods of Lin

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and Shearer (2009) and Dahm and Fischer (2014) can be used to estimate pore pressure variation and track fluids into the subsurface during injection operations, thus providing an important input for reservoir development and operations. These methods have been successfully applied to study the focal region of natural, fluid induced seismic swarms in the Czech Republic (Dahm and Fischer, 2014).

The modified Wadati method by Dahm and Fischer (2014) has been recently applied to three swarms in NW Bohemia. This approach was successful at resolving near-source Vp/Vs ratio variations at the swarm focal region, as shown for an example for the 2000 seismic swarm in NW Bohemia in Figure 9), suggesting strongly reduced Vp/Vs ratios in short time intervals at the beginning of intensive swarms.

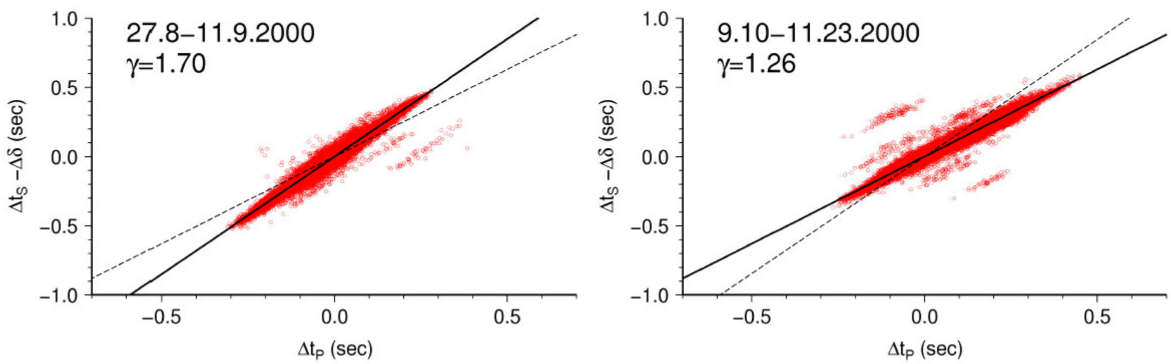

Figure 9. Fit of double-difference traveltimes for the time interval 27 August to 11 September 2000 (day 240-255, left panel) and 9 to 23 October 2000 (day 283-297, right panel) of the 2000 swarm (after Dahm and Fischer, 2014). The solid lines indicates the retrieved slope, γ where γ = Vp/Vs. The dashed lines represent theoretical slopes for Vp/Vs = 1.69, Vp/Vs = 1.26. Station LAC has been excluded from the plot because of higher scatter.

Within the COSEISMIQ project, a significant attempt was dedicated to the implementation of a Python-based tool to process data from the Hengill geothermal region and to track the temporal evolution of Vp/Vs. The algorithm is currently implemented, and offers the flexibility to use any of the two proposed approaches, by Lin and Shearer (2009) and/or by Dahm and Fischer (2014), but it is still in beta version. It requires some further testing before being applied to real data. We are currently testing the implementation with synthetic datasets, which have been created including localized velocity anomalies. One example of the software automated output is shown in Figure 10.

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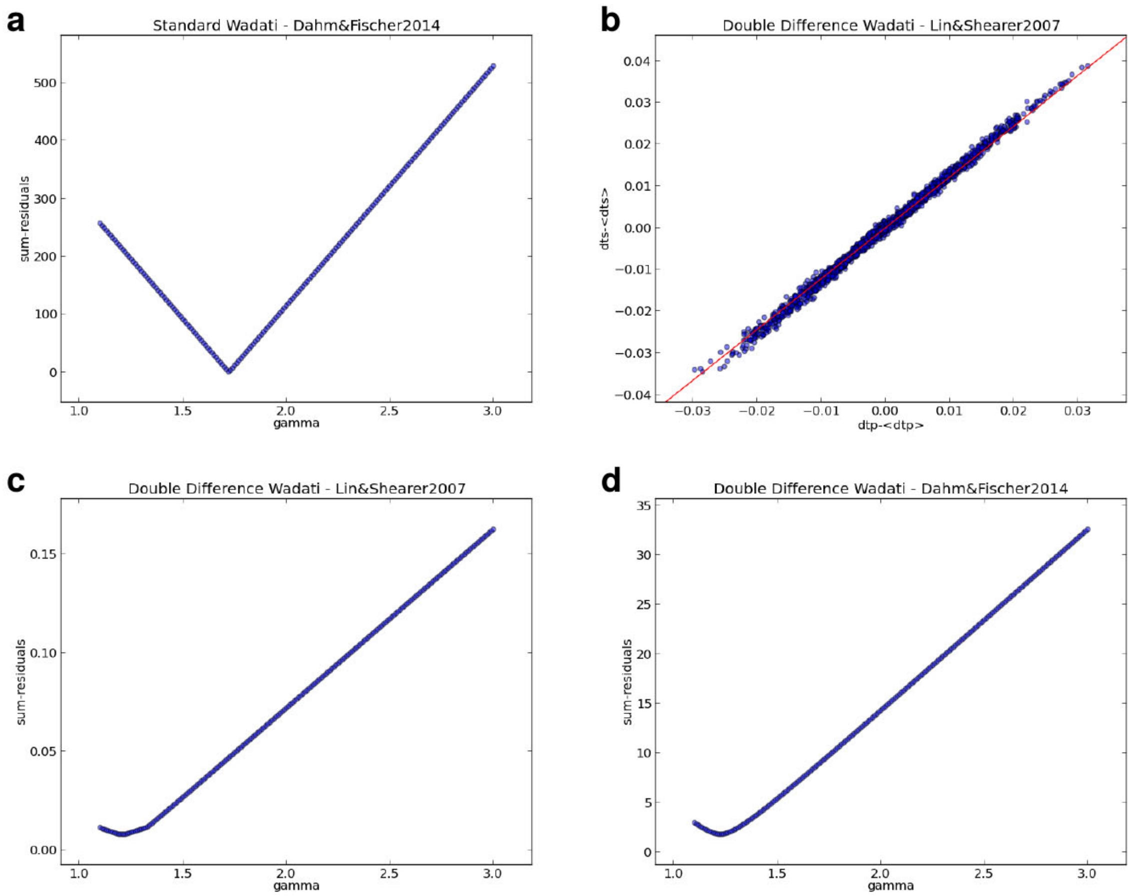

Figure 10. Example of output of the gammatracker Python algorithm to estimate Vp/Vs based on Wadati diagram. a, the average Vp/Vs (γ) is estimated by minimizing travel time residuals (the input value of γ=1.73 is correctly retrieved). b, intermediate step result, with plot of the deviation of differential S vs. differential P times, which is approximated by a straight line. (c) The local Vp/Vs (γp) in the focal region is estimated by minimizing travel time residuals using a double-difference Wadati approach, following the method by Lin and Shearer (2009) (the input value of γp=1.23 is correctly retrieved). (d) Same as (c), using the method by Dahm and Fischer (2014).

Similar to tomographic methods, which imaging potential depends on the geometry of sources and recordings, and the number of raypaths crossing each model cell, double difference Vp/Vs are also sensitive to the geometry of sources and receivers. Here, however, velocity ratios can be resolved only within compact regions with a high concentration of earthquake hypocenters in a compact volume. Preliminary location results and spatial clustering analysis, for a selected time span at the end of the year 2018, have revealed the presence of a number of seismic clusters in the initial high resolution Hengill dataset, and discussed above and seen in Figure 7 (left). These conditions are optimal for the application of the Vp/Vs at Hengill, and the future application of our tools to all detected clusters should allow the determination of local Vp/Vs values, track their temporal evolutions and compare them with the average Vp/Vs ratio in the study region.

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