



Event couple spectral ratio Q method for earthquake clusters: application to North-West Bohemia

Marius Kriegerowski¹, Simone Cesca², Matthias Ohrnberger¹, Torsten Dahm^{1,2}, and Frank Krüger¹

¹University of Potsdam, Institute of Earth and Environmental Science, Karl-Liebknecht-Str. 24-25, 14476 Potsdam-Golm

²Helmholtz Centre Potsdam German Research Centre for Geosciences - GFZ, Telegrafenberg, 14473 Potsdam

Correspondence: Marius Kriegerowski (marius.kriegerowski@uni-potsdam.de)

Abstract. We develop an amplitude spectral ratio method for event couples from clustered earthquakes to estimate seismic wave attenuation (Q^{-1}) in the source volume. The method allows to study attenuation within the source region of earthquake swarms or aftershocks at depth, independent of wave path and attenuation between source region and surface station. We exploit the high frequency slope of phase spectra using multitaper spectral estimates. The method is tested using simulated full wavefield seismograms affected by recorded noise and finite source rupture. The synthetic tests verify the approach and show that solutions are independent of focal mechanisms, but also show that seismic noise may broaden the scatter of results. We apply the event couple spectral ratio method to North-West Bohemia, Czech Republic, a region characterized by the persistent occurrence of earthquake swarms in a confined source region at mid-crustal depth. Our method indicates a strong anomaly of high attenuation in the source region of the swarm with an averaged attenuation factor of $Q_p < 100$. The application to S phases fails due to scattered P phase energy interfering with S phases. The Q_p anomaly supports the common hypothesis of highly fractured and fluid saturated rocks in the source region of the swarms in North-West Bohemia. However, high temperatures in a small volume around the swarms cannot be excluded to explain our observations.

Copyright statement.

1 Introduction

The intrinsic and scattering attenuation of the amplitudes of seismic waves is described by the dimensionless factor Q . The mapping of spatio-temporal changes of Q is an important step in seismology, since Q is controlled by temperature, rock porosity, fluid saturation and rock composition (Toksöz et al., 1981). Hence, this factor may help to unravel the possible causes of fluid-induced earthquakes, or thermal anomalies in crustal regions affected by magmatic intrusions. For instance, North-West Bohemia is regularly affected by earthquake swarms lasting several days or weeks with thousands of recorded events with largest magnitudes up to M_l 4.4 (Fischer et al., 2014). The causes of the repeated earthquake swarms which occur in narrow focal zones remain under debate. Relative earthquake localizations are very precise because of the high waveform quality recorded with a dense local permanent network (Bouchaala et al., 2013). Different tomography studies revealed consistent fig-



ures of the 3D velocity structures (Alexandrakis et al., 2014). The attenuation structure in the source region of the earthquake swarms is scarcely discussed. Some previous studies on whole raypath Q exist and can be used for verification and benchmarking. However, the main aim of this study is to test whether the here developed method can enhance the resolution of near source Q and therefore enable more robust conclusions on source dynamics and the role of fluids in the swarm cycle.

5 Several studies investigated the regional attenuation of North-West Bohemia by integrating along the full path from sources to receivers. Gaebler et al. (2015) estimated intrinsic and scattering attenuation of S waves (Q_s) by means of 14 selected events. Their frequency dependent results indicate mean \bar{Q}_s of approximately 1000. A study by Michálek and Fischer (2013) investigated source parameters and inferred a station dependent, regional Q_p from P phase spectra. They estimated mean Q_p ranging between 100 and 450. They also discuss effects of directivity on Q concluding that the directivity has little influence due to the

10 position of stations with respect to radiation patterns.

A tomographic study of North-West Bohemia done by Mousavi et al. (2017) indicated a regional average attenuation of approximately $Q_p \approx 100$ to $Q_p \approx 300$ and a pronounced highly attenuative source region where $Q_p < 100$.

Bachura and Fischer (2016) employed two different methods to resolve the regional coda Q_c from the source volume to receivers. They used 13 selected events of the 2011 swarm and found a variation of Q_c between 100 and 2500 within the exploited

15 frequency range of 1-18 Hz.

A recent work by Wcisło et al. (2018) used a newly developed differential attenuation estimation technique focused on the source region. The authors employed the peak frequency method which relates the half-period of P pulses to attenuation. They also used a differential approach to map the inter-event attenuation using a single station (NKC) and found $Q_p \approx 120$ and $Q_p \approx 80$ in the source region.

20 Most previous Q studies focusing on NW Bohemia were inherently of low spatial resolution. Firstly, either because Q was estimated for the integral ray path between sources and stations (except for the work by Wcisło et al. (2018)) or secondly, because they focused on low frequencies, or both. E.g. Mousavi et al. (2017) used frequencies between 1 to 30 Hz and Gaebler et al. (2015) up to 32 Hz.

In this study, we aim to increase the spatial resolution and to resolve Q for waves traveling only within the small source region

25 of the earthquake swarms. The developed event couple spectral ratio method is based on the assumption of an exponentially decreasing spectral slope at high frequencies ω above the corner frequency of the earthquake, often referred to as the ω^2 model (Aki, 1980). From the ratio of the spectral slopes of two events one can estimate the attenuation of P and S phases for the ray path between the two events, given the differential travel time of both events.

The spatially compact seismic clusters in NW Bohemia provide us with a favorable case study scenario due to the high similarity of source characteristics (Michálek and Fischer, 2013). We test our method on data recorded from October 6 until

30 October 13, 2008 and a double-difference relocated event catalog of 3841 events with local magnitudes between -0.9 and 3.5 (Fischer and Michálek, 2008). The high density of events during earthquake swarms clustering within a small and confined region allows to infer the local attenuation from event couples, by applying the spectral ratio method (Aki, 1980) to their high frequency amplitude spectra as we will explain in the following section. One major issue when calculating spectral content of

35 very few data samples is spectral leakage, as a result of the finiteness of the time window under study. In order overcome this



problem Thomson (1982) proposed the multitaper method, which we employ using *mtspec* (Prieto et al., 2009; Krischer, 2016).

2 Method

A velocity spectrum $A(\omega)$ of a direct body wave phase originating from a source j recorded at a station i can be described as
 5 (Sanders, 1993):

$$A_{i,j}(\omega) = S_j(\omega)I_i(\omega)R_i(\omega)G_{i,j} \cdot e^{-\frac{\omega t^*}{2}} \quad (1)$$

where ω is the angular frequency. $S_j(\omega)$ describes the source spectrum and $I_i(\omega)$ the instrument response. $R_i(\omega)$ is the receiver site effect. $G_{i,j}$ is the frequency independent geometric loss. The exponential term depends on the angular frequency ω and t^* , the path integrated attenuation from the source to the receiver:

$$10 \quad t^* = \int Q^{-1}/v ds \quad (2)$$

with Q as the dimensionless quality factor, velocity v of the medium and ds a segment along the ray path from the source to the receiver. Attenuation is considered here as a combination of intrinsic and scattering losses. Instead of estimating a total t^* describing the full ray path's attenuation we estimate a local t^* from velocity spectra of two earthquakes sharing the greater part of their ray paths from the seismogenic zone to a receiver. Site effects as well as the receivers response functions cancel
 15 out when two spectra recorded at the same site are analyzed by means of amplitude ratios. Let A_0 and A_1 be two velocity amplitude spectra of events E_0 and E_1 (in the following referred to as *first* and *second* event of a couple) recorded at a station j (Figure 1). Assuming that their source spectra $S_0(\omega)$ and $S_1(\omega)$ are similar, taking the natural logarithm of the spectral ratio of $A_{i,0}$ and $A_{i,1}$ yields:

$$\ln(A_{i,0}(\omega)/A_{i,1}(\omega)) = \frac{G_{i,0}}{G_{i,1}} - \omega t^*/2 \quad (3)$$

20 This equation describes a linear relation with frequency independent geometrical losses to the left of the negative sign. The slope k of a line fitted to equation 3 can be used to derive the attenuation time t^* in between the two sources from which Q^{-1} can easily be inferred using equation 2.

The far field amplitude spectrum $A(\omega)$ of P and S phases can be parameterized as follows: a seismic moment dependent low frequency plateau, the corner frequency f_c and the high-frequency spectral decay approximately proportional to ω^2 resulting
 25 from finiteness of particle rise time and the rupture duration (Aki and Richards, 2002). To remove the dependence on seismic moment we investigate the high-frequency spectral decay, only. Furthermore, exploiting spectral content above the corner frequency also reduces source directivity effects on attenuation estimates (Cormier, 1982).

We infer the corner frequency based on previous studies on NW Bohemia seismic swarms. We use a relation proposed by Michálek and Fischer (2013) to calculate source radii r based on the moment M_0 of an event:

$$30 \quad r = 0.155 \cdot M_0^{0.206} \quad (4)$$

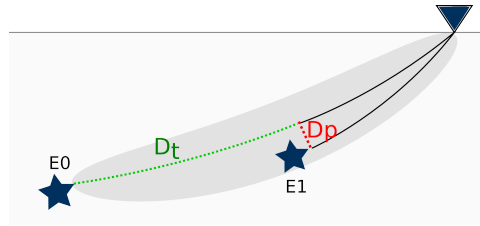


Figure 1. Schematic illustration of the geometrical constraints and the employed parameters. The triangle represents a recording station at the surface. Attenuation is estimated for the traversing distance ray path segment (D_t , Green dashed line). Geometrical constraints respect the passing distance (D_p). Grey shaded area illustrates the Fresnel volume of the first event.

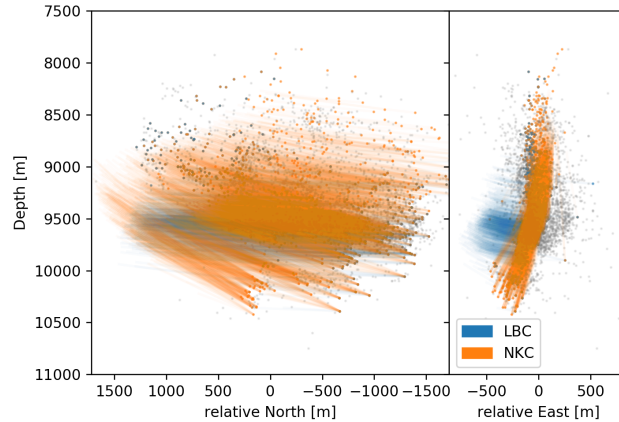


Figure 2. Ray segments. Left: Plane view of source slab. Right: side view. The colors indicate the station at which the displayed segment arrived. Grey points show hypocenters which occurred during the investigated time interval but where not attributed to an event couple.

where $M_0 = 1.38M_L + 10.3$. The resulting source radii r are then converted to f_c using

$$f_c = k\beta/r \quad (5)$$

with $k = 0.32$ (Madariaga, 1976), and $\beta = 3.5$ km/s, which is a reasonable assumption for the source region (Michálek and Fischer, 2013). We increase the lower frequency limit (f_{min}) used for our spectral analysis by additional 5 Hz with respect to f_c to account for uncertainties in M_0 and to ensure linearity of the high frequency decay. This approach allows frequency bands being wide enough for employing a stable linear regression. The upper frequency limit f_{max} was chosen dependent on the Fresnel volume of a couple's first event (Figure 1) and the upper corner frequency of the anti-alias filter of the recording equipment which is approximately 85 Hz. We calculate the power spectral density using the multitaper spectral analysis method (MTM) (Thomson, 1982; Park et al., 1987). With this method the time series is multiplied with several orthogonal slepian
 5
 10
 15
 20
 25
 30
 35
 40
 45
 50
 55
 60
 65
 70
 75
 80
 85
 90
 95
 100
 105
 110
 115
 120
 125
 130
 135
 140
 145
 150
 155
 160
 165
 170
 175
 180
 185
 190
 195
 200
 205
 210
 215
 220
 225
 230
 235
 240
 245
 250
 255
 260
 265
 270
 275
 280
 285
 290
 295
 300
 305
 310
 315
 320
 325
 330
 335
 340
 345
 350
 355
 360
 365
 370
 375
 380
 385
 390
 395
 400
 405
 410
 415
 420
 425
 430
 435
 440
 445
 450
 455
 460
 465
 470
 475
 480
 485
 490
 495
 500
 505
 510
 515
 520
 525
 530
 535
 540
 545
 550
 555
 560
 565
 570
 575
 580
 585
 590
 595
 600
 605
 610
 615
 620
 625
 630
 635
 640
 645
 650
 655
 660
 665
 670
 675
 680
 685
 690
 695
 700
 705
 710
 715
 720
 725
 730
 735
 740
 745
 750
 755
 760
 765
 770
 775
 780
 785
 790
 795
 800
 805
 810
 815
 820
 825
 830
 835
 840
 845
 850
 855
 860
 865
 870
 875
 880
 885
 890
 895
 900
 905
 910
 915
 920
 925
 930
 935
 940
 945
 950
 955
 960
 965
 970
 975
 980
 985
 990
 995



achieves stable spectral estimates also for very short time windows. A critical parameter of the *MTM* is the number of Slepian tapers as it balances the smoothness and precision of spectral estimates. We use the implemented default, which is

$$N_{\text{tapers}} = \text{int}(bw \cdot 2) - 1 \quad (6)$$

where *bw* is the *bandwidth_factor* which we set to $bw = 4$. Lower values prove to increase the number of outliers due to increased spectral leakage. Higher values did not change the results significantly but are more expensive to compute.

We impose strong geometrical constraints to select event couples with respect to a station as sketched in Figure 1. Ray tracing is done based on a 1D velocity model suggested by Alexandrakis et al. (2014) for the seismogenic region combined with a regional crustal model proposed by Málek et al. (2000) (Fig. 4, left panel). The first geometrical constraint is the traversing distance (D_t , red dashed line, Fig 1) between an event E_0 with respect to perpendicular projections of other hypocenters onto that path. The second constraint is the passing distance (D_p , green dashed line in Fig 1) of that projection of E_1 onto the ray between E_0 and the station. We defined a minimum traversing distance of $D_t \geq 750$ m to ensure that the signal of the second event is attenuation sufficiently to be detectable in the couple's spectral ratio.

Subsequent to geometrical preselection upper frequency limits of the analyzed bandwidth are potentially corrected to lower values dependent on the Fresnel volume in between event E_0 and a station. This guarantees that E_1 is located within the Fresnel volume for the entire analyzed frequency band (grey shaded area in Figure 1).

With this approach we get an estimate for the attenuation along the traversing distance (green dashed line in Figure 1) and when repeated for a large number of event couples can retrieve a median attenuation for the entire source region. Furthermore, we expect rupture dynamics causing random perturbations of the high frequency source spectra to average out. The described method is advantageous over other methods which require handcrafted features like onset duration picking as it can be automatized given that an onset catalog is at hand.

3 Synthetic Study

In order to evaluate the expected number of exploitable couples given the geometrical constraints we calculate the relative number of pairs at discrete surface points covering the region of North-West Bohemia. The size of blue points in Figure 3 represents relative number of pairs based on ray tracing through a 1D layered model (Fig. 4). Largest numbers of pairs are expected along a North-South striking patch which follows the striking direction of the main fault plane. However, in this case study we use only those stations which provide continuous recordings for the investigated time span. These are stations *KRC*, *LBC*, *NKC*, *SKC* and *VAC*. After geometrical filtering we expect stations *NKC* and *LBC* to produce the highest number of couples since they provide continuous recordings for the entire time period and are in a favorable lateral location. Most other stations are located where no or a negligible number of event pairs are expected. Figure 2 shows the rays which penetrate the source volume and fulfill the geometrical requirements described above. It shows that for events recorded at the most significant stations *NKC* and *LBC* the highest ray density and therefore sensitivity is in the lower half of the seismogenic zone. This bias is more pronounced for recordings at station *LBC*. Also, these ray segments sample the volume up to approximately 500 m to the West of the seismic swarm.

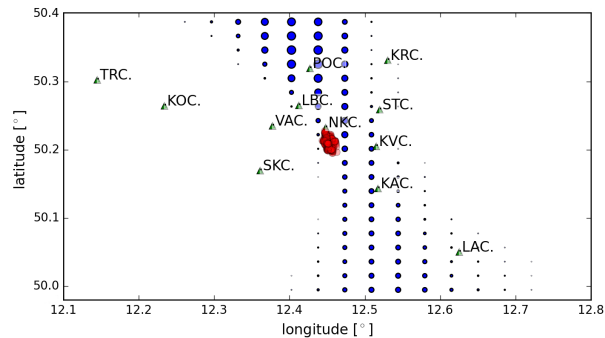


Figure 3. Relative number of event couples indicated by size of blue points. Red dots show the seismicity of the investigated swarm. Green triangles indicate locations of the WEBNET stations.

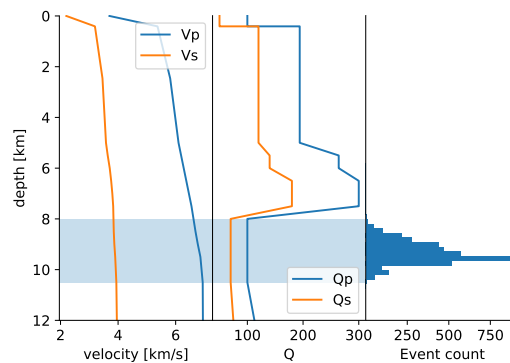


Figure 4. Synthetic velocity and attenuation model used for validation of the method. The seismogenic zone is marked by light blue. The attenuation in that zone is expected to be decreased with respect to the regional attenuation model.

We use synthetic waveforms calculated using reflectivity method (Wang, 1999) employing the same 1D velocity model as for ray tracing (Figure 4). Hypocentral locations and origin times are taken from the double difference relocated catalog of Fischer and Michálek (2008). All synthetic sources are double couple sources with mean strike, dip and rake set to 170 ± 10 , 80 ± 10 and -30 ± 10 degrees, respectively, uniformly distributed in all three domains. The mean strike, dip and rake values are the predominant source types stated by Fischer et al. (2014) which were retrieved based on polarity analysis of *P* phases. The seismogenic zone (depth 8500 m - 10500 m in Figure 4) has a Q_p of 100 and Q_s of 50. It is overlain by a more complex attenuation structure, characterized by higher Q values.

In order to mimic uncertainties in origin times, locations and velocity model travel times are perturbed by 10 ms, uniformly distributed. The uncertainties of the velocity model have an effect only in the source region since both rays of a couple traverse through the same overlaying velocity model.

The window length was 0.15 s for *P* and 0.3 s for *S* phases. The minimum allowed cross correlation of event couples in

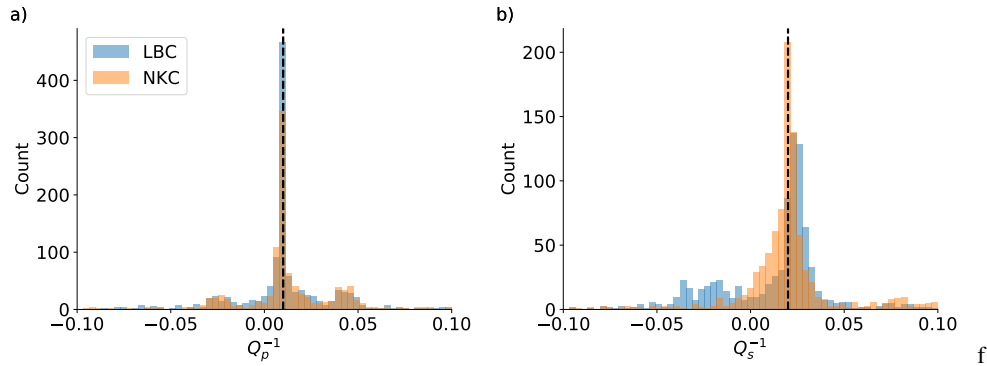


Figure 5. Synthetic tests targeting $Q_p = 100$ (a) and $Q_s = 50$ (b) with noise free data. The correct values for Q_p and Q_s are indicated by the vertical dashed lines. The station color coding as given in the legend is used consistently throughout all following images.

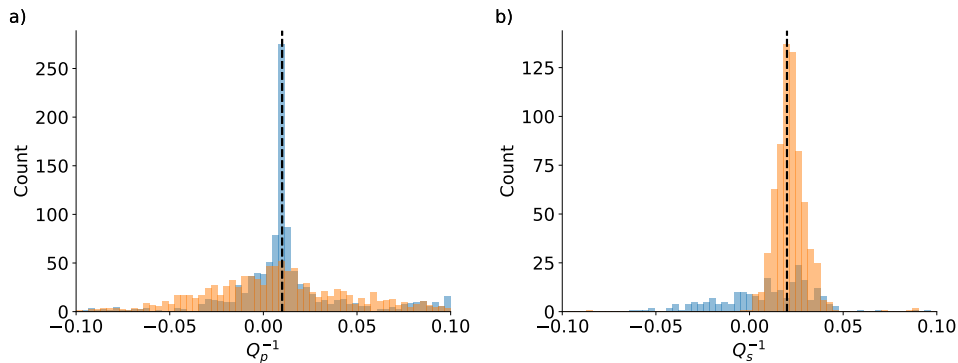


Figure 6. Synthetic tests with the same setup as in 5 but with additive real recorded noise from analyzed stations.

synthetic tests and later application to real data was set to 0.75. Signal-to-noise ratio (SNR) of a phase under consideration compared against a noise sample preceding the P phase has to be larger than 5 across the entire selected frequency band (after slight spectral smoothing to reduce effects of spectral notches). These three requirements efficiently reject outliers. The minimum allowed bandwidth is 10 Hz, which excludes all events with magnitudes of less than 0.5, given the magnitude
 5 dependent lower frequency limit ($f_{min} = f_c + 5.0Hz$, where f_c is calculated using equation 5). The bandwidth threshold stabilizes the linear fit to the spectral ratio as it limits the minimum number of data points. We evaluate Q_p from vertical channels and Q_s on North-South and East-West components and average results for each couple.

Data availability of the recorded dataset has been accounted for. Synthetic traces were only produced for an event if the recorded dataset contains data as well. All synthetic traces were convolved with the transfer functions of the WEBNET
 10 stations to generate realistic velocity traces.

Figure 5 shows distributions of retrieved Q^{-1} estimates from all event couples of the synthetic test using noise-free traces.

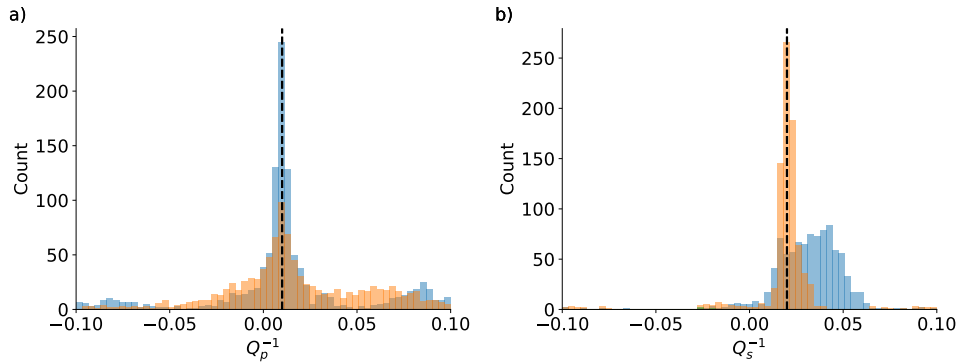


Figure 7. Synthetic tests with the same setup as in 6. Synthetic traces convolved with synthetic source time functions.

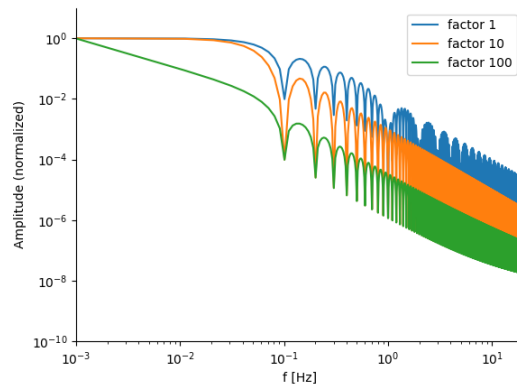


Figure 8. Normalized synthetic amplitude spectra of applied source time functions with different durations as a factor relative to the blue one (factor=1).

The distributions show some scattering solutions. A peak in both cases (Q_p and Q_s) resemble the targeted attenuation model (grey, vertical line).

The next test depicted in Fig. 6 includes additive recorded noise. Data windows without seismic events in the recorded data have been manually extracted and randomly added to synthetic traces to mimic realistic noise conditions. P phase results show a broadening of the distributions at all stations. While the distribution of station LBC still centers around the model value, the results of station NKC show only weak correlation with the correct model. This is a result of the location of station NKC close to the nodal plane of the dominant rupturing plane where smallest signal amplitudes are expected. S phase results match the model at NKC but show strong scattering at LBC .

In a next step (Fig. 7) we convolve synthetic Greens functions with realistic magnitude dependent source time functions. The applied source time function is half sine shaped where the slope of the high frequency spectral roll off is not dependent on

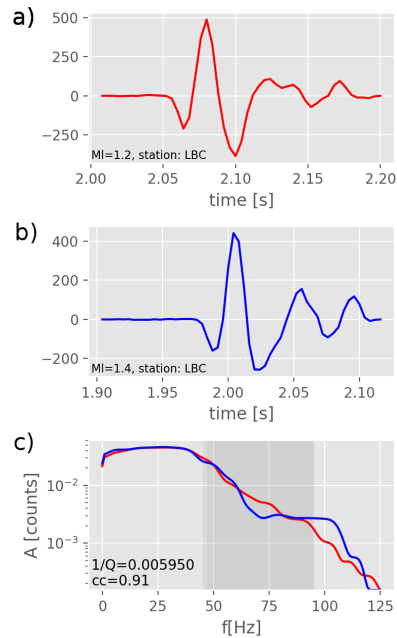


Figure 9. Two P phase wavelets recorded at station LBC and their spectra. First two panels show a) first and b) second event of the analyzed event couple. The grey shaded area in c) indicates the used frequency band. The cross-correlation coefficient is 0.91 and the attenuation (Q^{-1}) was in this case estimated as approximately 0.006

the width of the applied pulse as can be seen in Figure 8 where normalized synthetic source spectra are depicted for different relative pulse widths. The vertical position of the spectral envelope changes with changing duration but the slope remains the same for all depicted factorized pulse widths. Other than expected, this stabilizes results. This is a result of the pulse broadening which leads to a stabilization of MTM estimates as onsets become less transient.

- The performed synthetic tests cannot reproduce waveforms in its full natural complexity. Nevertheless, they prove that the concept is capable to estimate attenuation of the anticipated region.

4 Application to North West Bohemia

North-West Bohemia is a favorable case for testing our approach. Several focal mechanism studies on earthquake swarms in this region indicate dominant principle faults striking at 169° and 304° (Vavryčuk, 2011), which have been active in different seismic sequences. Events occurring during a swarm tend to rupture on the same fault. This observation in combination with compactness of seismic clusters (Figure 10) explains the high similarity of waveforms observed for each swarm. We therefore also assume that source characteristics including rupture directivity effects are similar throughout each swarm cycle.

By the time of the 2008 swarm the WEBNET stations were equipped with three component short period seismometers, except for station NKC located in the epicentral area which is a broad band station. All waveforms are sampled at 250 Hz. A manual

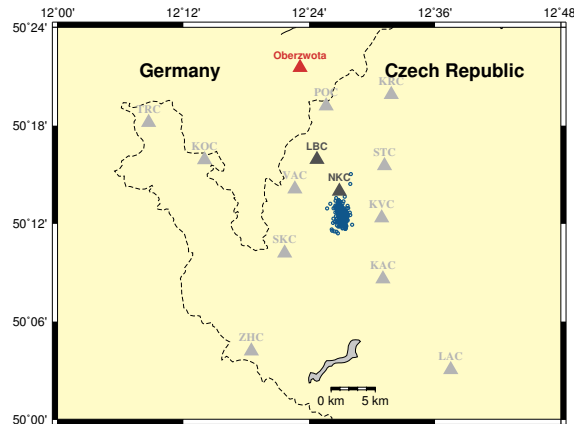


Figure 10. WEBNET stations (triangles) and seismicity (blue circles) which occurred in North-West Bohemia during the investigated time period. Red triangle: temporary station installed by University of Potsdam in October, 2017. Stations in Nový Kostel (*NKC*) and Luby (*LBC*) are highlighted. All other stations produce no or insignificant number of data points.

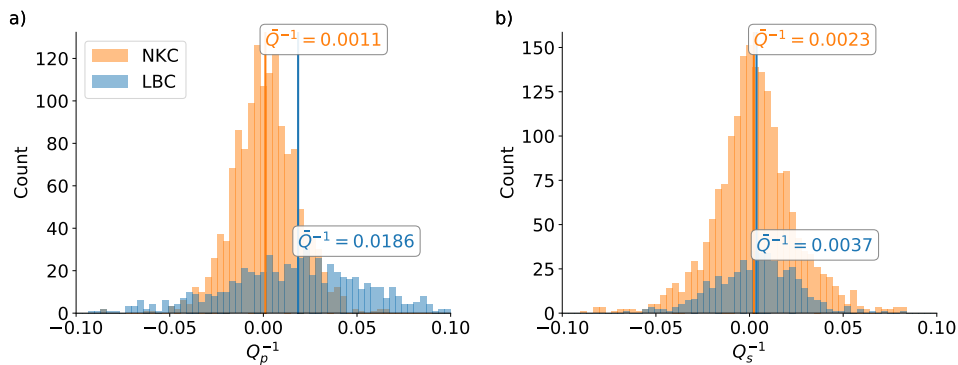


Figure 11. Attenuation results at stations *LBC* and *NKC* for Q_p (a) and Q_s (b). Median values are indicated by the overlined Q .

revision of all event waveforms has been done to remove those which show indications of event doublets happening shortly after each other but not being indicated as such in the catalog. Spurious signal leftovers of a preceding event not necessarily cause high distortion of the fundamental P phase waveform and may thus not be removed by setting a cross correlation threshold. However, their effect lead to distortion at high frequencies of phase spectra and significantly increase the number of outliers during the analysis. The catalog of *HypoDD* (Waldhauser and Ellsworth, 2000) relocated events is comprised of 3841 events and their associated P and S phase picks. When applied to station *LBC*, a total of 641 couples were used which fulfill the requirements in terms of SNR, cross-correlation and geometrical constraints. Results of P phases evaluated at station *LBC* (Fig. 11, left) have a median $\bar{Q}_p^{-1} = 0.019$, equivalent to $\bar{Q}_p = 53$. The distribution shows some negative results which do not have a physical meaning and are related to noise in spectral estimates. Results retrieved based on data from station *NKC* are significantly more unstable, as Figure 11 (right) indicates. The distribution shows a large number of negative results. The

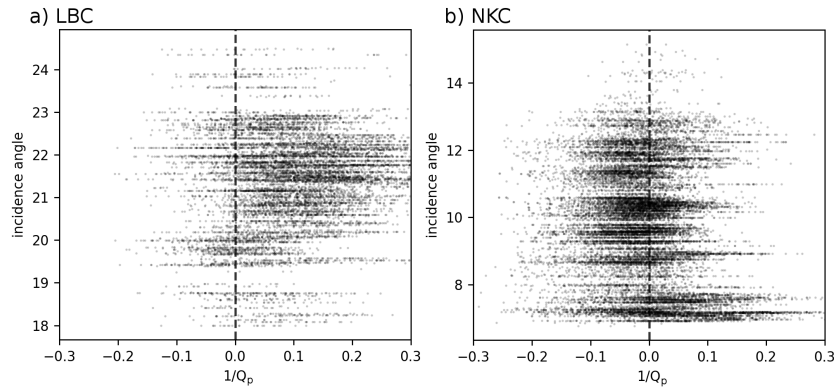


Figure 12. Incidence angles plotted against Q_p^{-1} of rays originating from event couples recorded at station *LBC* (left) and *NKC* (right). $Q_p^{-1} = 0$ is highlighted with a dashed line.

median attenuation is $\bar{Q}_p^{-1} = 0.001$, equivalent to $\bar{Q}_p = 1000$. 1404 couples were used in this case.

Attenuation evaluated for *S* phases show almost zero centered distributions at both stations *NKC* and *LBC* which in turn means significant number of negative and therefore unphysical measures. Median attenuation values are $\bar{Q}_s^{-1} = 0.0023$ ($\bar{Q}_s = 435$) at station *NKC* and $\bar{Q}_s^{-1} = 0.0037$ ($\bar{Q}_s = 270$) at stations *LBC*, respectively. Both values are comparably large compared to Q_p estimates from station *LBC*. A bias of these *S* phase attenuation measures is introduced by the *P* phase coda energy interfering with *S* phases and therefore distorting the anticipated high frequency content.

In order to achieve a better understanding of the method's breakdown for *P* phase recordings of station *NKC* we disable the cross correlation threshold and scrutinize Q^{-1} against a multitude of parameters for station *NKC* and *LBC*. Figure 12 shows incidence angles of rays of event couples on the y- and Q^{-1} on the x-axis. By definition the incidence angle is almost identical for both events of a couple. It becomes evident that larger incidence angles (> 8 degrees) show a tendency to produce negative Q^{-1} while results from events with steep incidence angles produce positive Q^{-1} values. When compared to the same kind of plots for station *LBC* no such trend is evident.

Station *NKC* is located at the northern edge of the swarm's epicentral region. Hence, incidence angle approximately correlates with latitude, indicating a location dependent problem. When plotting latitude of both events of a couple and color coding Q^{-1} (Figure 13) the results for station *LBC* show, in accordance with Figure 11 mostly positive results and few negative outliers. Results of station *NKC* show a transition from positive Q^{-1} values in the North to negative ones in the South, separated by a gap of event pairs between $lat = 50.211$ and $lat = 50.212$. This trend is mostly dependent on first events (x-axis) of each couple. This implies a systematic change in frequency content from two separated segments of the swarm occurring along raypaths from the source region to station *NKC*.

Figure 14 shows *P* phase waveforms of first events of couples at station *NKC* and *LBC*, filtered between 1 and 30 Hz for northern (Fig. 14, left panels) and southern (Fig. 14, right panels) events, separated at $lat = 50.2115$. While the used filter frequencies are actually below the exploited frequency band used in the analysis they highlight that the waveform complexity

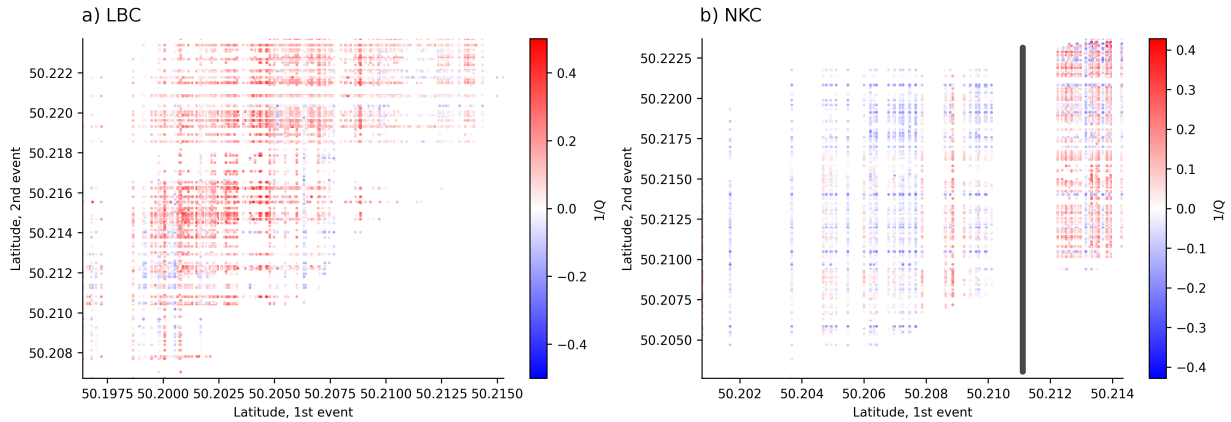


Figure 13. Latitudes of both events of each couple on x- and y-axis and color coded attenuation. a) *LBC*, b) *NKC*. A clear separation of negative (blue) from positive (red) attenuation at a latitude of 50.211 degrees becomes evident (vertical bar) with reference to the 1st event (x-axis). Attenuation at station *LBC* is mostly positive.

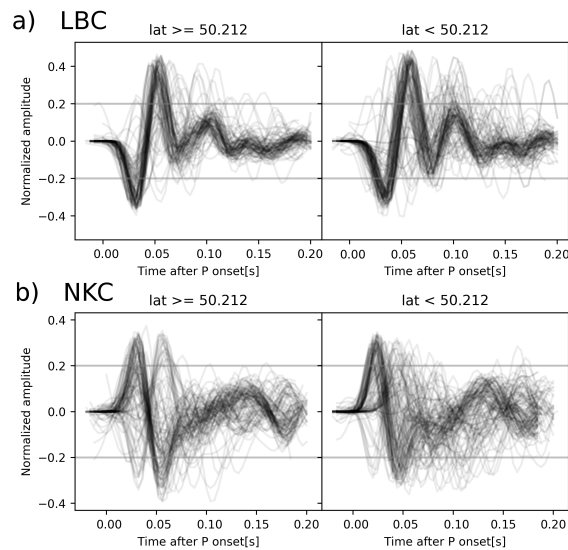


Figure 14. *P* phase onsets of couples' first events in the northern ($lat > 50.212$) and the southern part of the swarm area. a) show recordings at station *LBC*, b) recordings at station *NKC*.

is significantly higher for events at station *NKC* than for those at station *LBC* indicating that scattering plays a major role along the ray paths to station *NKC*. Furthermore, there are *P* phases with flipped polarities which indicates that the station was situated close to the nodal plane. This aspect is in accordance with synthetic tests in chapter III which show worse performance of station *NKC* than station *LBC* for *P* phase measures.



5 Interpretation and Discussion

We present a newly developed method to estimate attenuation from spectral ratios of event couples. The short analyzed time windows are prone to spectral leakage which we mitigate by applying the multitaper approach. However, this method can only suppress leakage caused by windowing effects. Leakage from source effects such as finiteness of the slip and the rupture are not smoothed as they are expected source characteristics and not filter artifacts.

The given geometry and available data limit the perceptible field of the applied method mostly to the lower half of the seismic swarm (Fig. 2).

Synthetic tests show that the method is capable to reproduce average source volume attenuation of $Q_p = 100$ and $Q_s = 50$ given the 2008 earthquake swarm hypocentral locations. In noise free condition a precise result can be achieved for both, P and S phases at both significant stations NKC and LBC . With additive recorded noise, the distribution of Q_p results broadens but still resembles the true attenuation with high precision at station LBC . Synthetic waveforms at station NKC suffer from weaker SNR at high frequencies indicating that the applied SNR -threshold of 5 is too optimistic. However, reducing this value would also reduce the number of data points and therefore have a negative impact on the statistical significance of results. Q_s results at station NKC are more robust than at station LBC . Both measures, Q_s and Q_p , improve when convolving synthetic waveforms with synthetic source time functions as this stabilizes the multitaper spectral estimates.

The application to recorded P phase onsets shows fewer negative Q_p results at station LBC and than at station NKC which results in a distribution with a clearer offset with respect to $Q_p = 0$. Waveforms recorded at station LBC are significantly higher correlated than those at station NKC where changing waveform polarities and high waveform complexity can be observed. We hypothesize that rays arriving at NKC experienced relatively stronger scattering or that a nearby reflector creates multiples which interfere with signals recorded at NKC . In the latter case, the reflector would have to be situated in a location where interactions with signals arriving at LBC are weaker. Mousavi et al. (2017) assume a highly fractured medium in combination with accumulated free gas or fluids. Our findings support this hypothesis. A 3D V_p/V_s tomography by Alexandrakis et al. (2014) identified a low V_p/V_s ratio body directly overlaying the focal zone. The increased waveform complexity seen at station NKC can be a result of waveform interaction with that body. The effects do not necessarily have an influence on results at station LBC where rays have different paths and take off angles.

Another influence may be rooted in the different families of focal mechanisms. Vavryčuk et al. (2013) reported three different families of focal mechanisms for the 2008 swarm. While the slope of high frequency spectra should not directly be affected by the radiation pattern, there can be higher order effects like rupture propagation and rupture complexity. Dependent on the take off angle these rupture dynamics can affect the high frequency spectral roll off and therefore map into attenuation estimates (Kaneko and Shearer, 2015). P phase polarity changes at station NKC indicate that the station is located close to the nodal plane of the main rupturing fault. This circumstance can increase the effect of the aforementioned effects seen at station NKC . If they differ systematically in the lower and upper source region, this can lead to biases in attenuation analysis due to the heterogeneous sensitivity across the fault plane. Still, we do not see such effects at station LBC and therefore speculate, that the dominating effect is the differing raypaths or a combination of both, raypath scattering and rupture dynamics.



Previous studies by Michálek and Fischer (2013) investigated source characteristics in NW Bohemia and suggested station dependent whole path integrated mean Q_P values ranging between 100 and 450. We find lower values which can be a result of hydration of the seismogenic zone. Haberland and Rietbrock (2001) also report highly increased attenuation ($Q < 100$) within earthquake cluster regions and postulated that this could be related to hydration or partial melting. For instance, melt migration has been postulated from the size and migration pattern of earthquakes of the 2000 earthquake swarm (Dahm et al., 2009). On the other hand, Alexandrakakis et al. (2014) interpret their results on velocity variations by dehydration processes. Our results deduced from station *LBC* for average attenuation are in line with previous findings pointing to high attenuation in the source volume.

Frequency bandwidth is a critical parameter which is limited mostly by the corner frequency of the recording setup and signal to noise ratio at high frequencies. Future plans of the Intercontinental Drilling Project (ICDP) include the installation of up to 4 borehole seismometers in NW Bohemia. It can be expected that our method will benefit from these measurements. Improved signal to noise ratios allow to sample and exploit information at higher frequencies which will stabilize the spectral estimate. Furthermore, higher sampling rates allow a better temporal (and therefore spectral) resolution of *P* and *S* phases. This will, in turn, also allow to use even shorter time windows. For the method discussed here, it would be favorable if at least one of these borehole stations will be situated in a location where a high number of ray path sharing couples can be found. The most sensitive region follows the NNE - SSW striking of the fault and concentrates in the North of the earthquake swarm (Fig. 3). In late September 2017 the University of Potsdam installed a short period seismometer close to the Czech-German border in Oberzwota (red triangle, map 10) which is a favorable location. The station recorded 1000 samples per seconds for 62 days during a period of relative quiescence. Nevertheless, approximately 30 events were recorded in the swarm area with local magnitudes down to $M_l=0$. Despite the installation directly on top of the weathering layer the recordings showed signal to noise ratios larger than 5 at 120 Hz and above for smallest magnitudes. It becomes evident that even a surface mounted station would allow to harness spectral information above the corner frequency of the WEBNET stations also for smallest magnitudes and which indicates that this will improve the resolution and robustness of our method once the ICDP borehole installations are operating.

6 Conclusions

Applying the source couple amplitude spectral ratio method to differential phase measures is an alternative to methods which commonly exploit the lower frequency ranges. Theoretically, it is therefore able to achieve better resolution. Our synthetic study validates this. The geometrical constraints of this method require a high density of events as it is the case for natural earthquake swarms or seismic nests but also for hydrofracturing experiments.

The application to data from the 2008 North West Bohemia earthquake swarm indicates source region $Q_p < 100$ based on measures at station *LBC*. This is in accordance to previous findings by Weisło et al. (2018) who used station *NKC*. The sensitive region measures only approximately 2000 * 500 * 500 meters in North, East and West direction (Fig. 2). Results can therefore be considered of high spatial resolution. Nevertheless, the distribution of solutions significantly scatter and we see room for



improvement e.g. through high frequency borehole recordings. We are not able to retrieve stable estimates at station *NKC* but instead see negative attenuation in southern and positive attenuation in the northern section of the swarm. *P* phase waveforms of the two sections show systematic differences at both significant stations which indicates a North-South structural difference. Furthermore, this effect does not inflict on measures at station *LBC*. Given the fact that ray segments at *NKC* and *LBC* probe
5 two different but directly neighboring media leads us to the conclusion that the fractured medium is highly concentrated along the source patch and that the surrounding medium can be considered much more dense or intact.

Author contributions. MK: Implementation, testing, evaluation and application to synthetic and recorded data, as well as paper writing. SC: Scientific supervision, evaluation of tests and applications. MO: Scientific supervision, discussion, manuscript revision. TD: Scientific supervision, discussion, manuscript revision. FK: Scientific supervision, discussion, manuscript revision.

10 *Competing interests.* None

Acknowledgements. This work is part of the HISS project which is funded by the DFG ICDP. Project no.: CE 223/2-1



References

- Aki, K.: Attenuation of shear-waves in the lithosphere for frequencies from 0.05 to 25 Hz, *Physics of the Earth and Planetary Interiors*, 21, 50–60, [https://doi.org/10.1016/0031-9201\(80\)90019-9](https://doi.org/10.1016/0031-9201(80)90019-9), 1980.
- Aki, K. and Richards, P. G.: *Quantitative seismology*, University Science Books, Sausalito, California, 2 edn., 2002.
- 5 Alexandrakakis, C., Calò, M., Bouchaala, F., and Vavryčuk, V.: Velocity structure and the role of fluids in the West Bohemia Seismic Zone, *Solid Earth Discussions*, 6, 511–534, <https://doi.org/10.5194/sed-6-511-2014>, <http://www.solid-earth-discuss.net/6/511/2014/>, 2014.
- Bachura, M. and Fischer, T.: Coda Attenuation Analysis in the West Bohemia/Vogtland Earthquake Swarm Area, *Pure and Applied Geophysics*, 173, 425–437, <https://doi.org/10.1007/s00024-015-1137-3>, <https://doi.org/10.1007/s00024-015-1137-3>, 2016.
- Bouchaala, F., Vavryčuk, V., and Fischer, T.: Accuracy of the master-event and double-difference locations: Synthetic tests and application
10 to seismicity in West Bohemia, Czech Republic, *Journal of Seismology*, 17, 841–859, <https://doi.org/10.1007/s10950-013-9357-4>, 2013.
- Cormier, V. F.: the Effect of Attenuation on Seismic Body Waves, *Bulletin of the Seismological Society of America*, 72, 169–200, 1982.
- Dahm, T., Fischer, T., and Hainzl, S.: Mechanical intrusion models and their implications for the possibility of magma-driven swarms in NW Bohemia Region, *Studia Geophysica et Geodaetica*, 52, 529, <https://doi.org/10.1007/s11200-008-0036-9>, <https://doi.org/10.1007/s11200-008-0036-9>, 2009.
- 15 Fischer, T. and Michálek, J.: Post 2000-swarm microearthquake activity in the principal focal zone of West Bohemia/Vogtland: Space-time distribution and waveform similarity analysis, *Studia Geophysica et Geodaetica*, 52, 493–511, <https://doi.org/10.1007/s11200-008-0034-y>, 2008.
- Fischer, T., Horálek, J., Hrubcová, P., Vavryčuk, V., Bräuer, K., and Kämpf, H.: Intra-continental earthquake swarms in West-Bohemia and Vogtland: A review, *Tectonophysics*, 611, 1–27, <https://doi.org/10.1016/j.tecto.2013.11.001>, 2014.
- 20 Gaebler, P. J., Eulenfeld, T., and Wegler, U.: Seismic scattering and absorption parameters in the W-Bohemia/Vogtland region from elastic and acoustic radiative transfer theory, *Geophysical Journal International*, 203, 1471–1481, <https://doi.org/10.1093/gji/ggv393>, 2015.
- Haberland, C. and Rietbrock, A.: Attenuation tomography in the western central Andes: A detailed insight into the structure of a magmatic arc, *Journal of Geophysical Research*, 106, 11 151, <https://doi.org/10.1029/2000JB900472>, 2001.
- Kaneko, Y. and Shearer, P. M.: Variability of seismic source spectra, estimated stress drop, and radiated energy, derived from cohesive-zone
25 models of symmetrical and asymmetrical circular and elliptical ruptures, *Journal of Geophysical Research: Solid Earth*, 120, 1053–1079, <https://doi.org/10.1002/2014JB011642>, 2015.
- Krischer, L.: *mtspec Python wrappers 0.3.2*, <https://doi.org/10.5281/zenodo.321789>, <http://krischer.github.io/mtspec/>, 2016.
- Madariaga, R.: Dynamics of an expanding circular fault, *Bulletin of the Seismological Society of America*, 66, 639–666, <http://bssa.geoscienceworld.org/content/66/3/639.abstract>, 1976.
- 30 Málek, J., Janský, J., and Horálek, J.: Layered Velocity Models of the Western Bohemia Region, *Studia Geophysica et Geodaetica*, 44, 475–490, <https://doi.org/10.1023/A:1021859516682>, <http://dx.doi.org/10.1023/A:1021859516682>, 2000.
- Michálek, J. and Fischer, T.: Source parameters of the swarm earthquakes in West Bohemia/Vogtland, *Geophysical Journal International*, 195, 1196–1210, <https://doi.org/10.1093/gji/ggt286>, 2013.
- Mousavi, S., Haberland, C., Bauer, K., Hejrani, B., and Korn, M.: Attenuation tomography in West Bohemia/Vogtland, *Tectonophysics*, 695,
35 64–75, <https://doi.org/https://doi.org/10.1016/j.tecto.2016.12.010>, <http://www.sciencedirect.com/science/article/pii/S0040195116306096>, 2017.



- Park, J., Craig, R. L., and Vernon III, F. L.: Multitaper spectral analysis of high-frequency seismograms, *J. Geophys. Res.*, 92, 12 675–12 684, <https://doi.org/10.1029/JB092iB12p12675>, <http://onlinelibrary.wiley.com/doi/10.1029/JB092iB12p12675/abstract>, 1987.
- Prieto, G., Parker, R., and Vernon III, F.: A Fortran 90 library for multitaper spectrum analysis, *Computers & Geosciences*, 35, 1701–1710, <https://doi.org/10.1016/j.cageo.2008.06.007>, <http://www.sciencedirect.com/science/article/pii/S00983300409000077>, 2009.
- 5 Sanders, C. O.: Local earthquake tomography: attenuation—theory and results, *Seismic Tomography: Theory and Practice*, pp. 676–694, 1993.
- Thomson, D. J.: Spectrum estimation and harmonic analysis, *Proceedings of the IEEE*, 70, 1055–1096, <https://doi.org/10.1109/PROC.1982.12433>, 1982.
- Toksöz, M. N., Johnston, D. H., and of Exploration Geophysicists, S.: Seismic wave attenuation, *Geophysics reprint series*, Society of
10 Exploration Geophysicists, <https://books.google.de/books?id=rjlnAQAAIAAJ>, 1981.
- Vavryčuk, V.: Principal earthquakes: Theory and observations from the 2008 West Bohemia swarm, *Earth and Planetary Science Letters*, 305, 290–296, <https://doi.org/https://doi.org/10.1016/j.epsl.2011.03.002>, <http://www.sciencedirect.com/science/article/pii/S0012821X11001373>, 2011.
- Vavryčuk, V., Bouchaala, F., and Fischer, T.: High-resolution fault image from accurate locations and focal mechanisms of the 2008 swarm
15 earthquakes in West Bohemia, Czech Republic, *Tectonophysics*, 590, 189–195, <https://doi.org/10.1016/j.tecto.2013.01.025>, 2013.
- Waldhauser, F. and Ellsworth, W. L.: A Double-difference Earthquake location algorithm: Method and application to the Northern Hayward Fault, California, *Bulletin of the Seismological Society of America*, 90, 1353–1368, 2000.
- Wang, R.: A simple orthonormalization method for stable and efficient computation of Green’s functions, *Bulletin of the Seismological Society of America*, 89, 733–741, <http://www.bssaonline.org/content/89/3/733.short>, 1999.
- 20 Wcisło, M., Eisner, L., Málek, J., Fischer, T., Vlček, J., and Kletetschka, G.: Attenuation in west bohemia: Evidence of high attenuation in the Nový Kostel focal zone and temporal change consistent with Co₂degassing, *Bulletin of the Seismological Society of America*, <https://doi.org/10.1785/0120170168>, 2018.