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# Coda-Q in the 2.5 s - 20 s period band from seismic noise - Application to the greater Alpine area

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Short title: Coda-Q from seismic noise in the alpine area

## Abstract

Coda-Q is used to estimate the attenuation and scattering properties of the Earth (Aki & Chouet 1975). So far focus has been on earthquake data at frequencies above 1 Hz, as the high noise level in the first and second microseismic peak, and possibly lower scattering coefficient, hinder stable measurements at lower frequencies. In this work, we measure and map coda-Q in the period bands 2.5 s - 5 s, 5 s - 10 s and 10 s - 20 s in the greater Alpine region using noise cross-correlations between station pairs, based on data from permanent seismic stations and from the temporary AlpArray experiment. The observed coda-Q for short interstation distances is independent of azimuth so there is no indication of influence of the directivity of the incoming noise field on our measurements. In the 2.5 s - 5 s and 5 s - 10 s period bands, our measurements are self-consistent, and we observe stable geographic patterns of low and high coda-Q in the period bands 2.5 s - 5 s and 5 s - 10 s. In the period band 10 s - 20 s, the dispersion of our measurements increases and geographic patterns become speculative. The coda-Q maps show that major features are observed with high resolution, with a very good geographical resolution of for example low coda-Q in the Po Plain. There is a sharp contrast between the Po Plain and the Alps and Apennines where coda-Q is high, with the exception a small area in the Swiss Alps which may be contaminated by the low coda-Q of the Po Plain. The coda of the correlations is too short to make independent measurements at different times within the coda, so we cannot distinguish between intrinsic and scattering Q.

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2 Measurements on more severely selected datasets and longer timeseries result in identical  
3 geographical patterns but lower numerical values. Therefore, high coda-Q values may be  
4 overestimated, but the geographic distribution between high and low coda-Q areas is respected. Our  
5 results demonstrate that noise correlations are a promising tool for extending coda-Q measurements  
6 to frequencies lower than those analysed with earthquake data.  
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11 Keywords: Coda waves, seismic noise, surface waves and free oscillations, seismic attenuation, wave  
12 scattering and diffraction, Europe  
13

## 14 15 1 Introduction

16  
17 Since its inception by Aki & Chouet (1975), the coda quality factor  $Q_c$  has arguably become one if not  
18 the most employed measure of seismic attenuation around the world (see Herraiz & Espinosa 1987;  
19 Fehler *et al.* 1992; Mikesell *et al.* 2012 for reviews). In their seminal publication, Aki & Chouet (1975)  
20 demonstrate conclusively that, at sufficiently long lapse-time  $t$  after the energy release at the source,  
21 the energy envelope  $E(f,t)$  of late seismic arrivals (known as coda waves) observed in a narrow  
22 frequency band  $f \pm \Delta f$  follows an algebro-exponential decay of the form:  
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$$29 \quad E(f, t) = S(f) e^{-\frac{2\pi t f}{Q(f)} t^{-\alpha}} \quad (1)$$

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31 where the exponent  $\alpha$  typically varies between 1 and 2 depending on the type of waves (surface  
32 waves or body waves) and scattering model (single-scattering or diffusion). The coda wavefield itself  
33 can be shown to obey Gaussian statistics with very good accuracy (Anache-Menier *et al.* 2009;  
34 Obermann *et al.* 2014). This statistical property follows logically from the physical interpretation of  
35 the coda as a superposition of a large number of scattered waves with random phase, by application  
36 of the central limit theorem. Using the Gaussian hypothesis, it is straightforward to demonstrate that  
37 the energy envelope obeys an exponential distribution, which explains quantitatively the large  
38 fluctuations of the coda intensity observed in the data. A practical implication of these fluctuations is  
39 that the parameter  $\alpha$  cannot be determined unambiguously from the data alone, but has to be fixed  
40 in advance based on a physical model. Aki & Chouet (1975) proposed several simple scattering  
41 scenarios underpinning formula (1). In the single scattering model,  $\alpha$  equals 1 or 2 depending on the  
42 type of waves that dominate the coda: surface waves for the former, body waves for the latter.  
43 Single scattering also implies the relation:  
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$$55 \quad \frac{1}{Q_c} = \frac{1}{Q_i} + \frac{1}{Q_{sc}}$$

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2 suggesting that  $Q_c$  is a measure of total attenuation. In sharp contrast with single scattering, formula  
3 (1) may also be explained by a diffusion model where a large number of scattering events occur  
4 between source and detection. In the diffusion regime,  $\alpha$  depends on the dimensionality of the  
5 medium. In half-space geometry,  $\alpha=3/2$  whereas in waveguide geometry  $\alpha=1$ . Furthermore the  
6 diffusion model implies:  
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$$\frac{1}{Q_c} = \frac{1}{Q_i}$$

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15 suggesting that in this regime  $Q_c$  is a measure of absorption in the medium.  
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18 After Aki and Chouet's discovery, it has long been considered that single scattering was the most  
19 appropriate model for the coda on Earth. This situation changed radically in the mid-nineties with the  
20 introduction of quantitative methods of measurement of scattering and absorption properties in the  
21 framework of radiative transfer theory (Wu & Aki 1988; Fehler *et al.* 1992). It became clear that  
22 multiple scattering plays a fundamental role in the generation of coda waves and also that the  
23 interpretation of  $Q_c$  is not univocal. On the one hand extensive data analyses in Japan by Carcole &  
24 Sato (2010) show very good coincidence between  $Q_c$  and  $Q_i$  in agreement with the predictions of the  
25 diffusion model. On the other hand, Calvet & Margerin (2013) show on a data set from the Pyrenees  
26 that  $Q_c$  agrees well with  $Q_i$  only when scattering is not too strongly anisotropic and the coda window  
27 is chosen at sufficiently long lapse time. Independently of its physical interpretation,  $Q_c$  remains an  
28 interesting proxy for the mapping of spatial variations of attenuation.  
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37 In earthquake seismology,  $Q_c$  is generally observed in the 1 – 20 Hz frequency band, but imaging  
38 attenuation at longer periods is of crucial importance for seismic hazard calculations, as the  
39 resonance frequencies of tall buildings can lie below 1 Hz. It also gives important insights on the  
40 attenuating and scattering properties of rocks. The detection of the coda at longer period is  
41 hampered by the fact that the scattering coefficient decreases rapidly with  $T$  (as shown by theoretical  
42 studies in random media, e. g. Stanke & Kino 1984) and by the strong permanent excitation of  
43 ambient noise by swell and oceanic wave interactions between 5 s and 15 s period. In fact, this  
44 period band represents an observational gap for the seismic  $Q$ , which makes it difficult to pinpoint  
45 the dominant physical mechanisms at the origin of seismic attenuation. Seismic interferometry  
46 (Campillo & Paul 2003, Shapiro & Campillo 2004) offers an attractive alternative to study the  
47 attenuation of seismic waves, particularly in the period band of ocean-generated microseismic noise.  
48 While most efforts so far have focused on the determination of attenuation based on the  
49 propagation properties of ballistic waves (e. g. Prieto & Beroza 2008, Cupillard & Capdeville 2010,  
50 Denolle *et al.* 2013, Liu *et al.* 2015, Stehly & Boue 2017), it is clear that cross and auto-correlations of  
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2 the ambient noise wavefields also possess a coda that could fruitfully complement the standard  
3 analyses. This coda has in fact been exploited for more than a decade in monitoring techniques such  
4 as passive image interferometry (Sens-Schönfelder & Wegler 2006). In spite of the success of seismic  
5 interferometry and passive image interferometry, not much attention has been paid to the decay  
6 properties of the coda of ambient noise correlograms. It is the purpose of this paper to bridge this  
7 gap and to demonstrate that spatially coherent variations of coda attenuation may be extracted from  
8 ambient noise data thanks to appropriate data selection and processing procedures.  
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## 15 2 Data and data processing

### 16 2.1 Data

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18 We use continuous data (vertical component) recorded over twelve months, between July 2016 and  
19 June 2017. During this period, a large part of the AlpArray temporary seismic experiment was  
20 installed and running, hence the high station density in the Alpine region. A total of 736 stations,  
21 located in the area ( $2^{\circ}\text{E}$ - $20^{\circ}\text{E}$ ,  $35^{\circ}\text{N}$ - $55^{\circ}\text{N}$ ), are used, with 542 permanent and 194 temporary  
22 AlpArray stations. The AlpArray seismic network is the combination of  $\sim 350$  permanent broadband  
23 stations and  $\sim 280$  temporary broadband stations that span over the greater alpine area from Massif  
24 Central in the west to Pannonian Basin in the east, and Corsica in the south to north of the Czech  
25 Republic (Hetenyi *et al.*, 2018). The temporary array was designed to obtain a homogeneous  
26 coverage with station spacing 52 km. Because of its homogeneous distribution, regular spacing and  
27 long residence time (2 to 3 years) the AlpArray seismic network is well suited for seismic noise  
28 interferometry. Note that a larger number of stations is processed, but the 736 stations are those for  
29 which we can extract signal from correlations. We additionally use four years of data from a subset of  
30 permanent seismic stations to study convergence of observed coda-Q (see Section 4.2). The data are  
31 distributed by EIDA (European Integrated Data Archive), a service of ORFEUS ([www.orfeus-eu.org](http://www.orfeus-eu.org)).  
32 Figure 1 shows the station distribution.  
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### 46 2.2 Preprocessing and noise correlations

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48 Before computing the correlations, we preprocess the noise recorded by each station in two main  
49 steps. First, each daily record is detrended, low-pass filtered (0.45 Hz corner frequency), decimated  
50 to 1 Hz and corrected for instrument response. This reduced data set is stored to disk.  
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55 One specific difficulty of noise correlations is that they require handling of transient high amplitude  
56 signals such as earthquakes or storms. After tests, we choose a preprocessing that we will refer to as  
57 '*comb filter preprocessing*': the signal is filtered into several period bands (3 - 5, 5 - 10, 10 - 20, 20 -  
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2 40, 40 - 80 and 80 - 200 seconds), each of the filtered signals is normalized by its envelope, and the  
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4 six filtered and normalized signals are finally stacked. This preprocessing was chosen specifically since  
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6 it achieves broadband signals that do not have dominating transients, therefore well adapted to  
7  
8 obtain broadband correlations for Green's function estimation.  
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10 It has been demonstrated that convergence of the correlations is faster in shorter time windows as  
11  
12 compared to daily time windows (e.g. Poli *et al.* 2012). The window length must remain large as  
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14 compared to the maximum lag time used, in our case we use lag times of up to  $\pm 3000$  s. We  
15  
16 therefore calculate cross-correlations between each pair of stations using 4h windows, normalize and  
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18 stack them, to obtain one correlation trace for each station pair. We thus obtain  $\sim 500\,000$   
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20 correlations, where for each one we keep track of the total number of days stacked.

21 Figure 2 shows the seismic section of correlations in the three frequency bands we use in this study.  
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23 It is known that the Rayleigh wave component of the seismic noise in northern Europe is dominated  
24  
25 by waves emitted by sources in the North Atlantic Ocean during the winter season, and more widely  
26  
27 distributed if the whole year is considered (e. g. Friedrich *et al.* 1998, L. Stehly *et al.* 2006, Pedersen  
28  
29 *et al.* 2007, Kedar *et al.* 2008, Landès *et al.* 2010, Hillers *et al.* 2012, Retailleau *et al.* 2017). The  
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31 correlations are therefore oriented so that the causal signal (positive times) corresponds to seismic  
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33 waves propagating away from  $300^\circ$  azimuth, i.e. from the half space which contains the main noise  
34  
35 source area. As expected, the Rayleigh wave emerges very clearly in the causal part and less so in the  
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37 anticausal part, especially at longer interstation distances.

### 38 2.3 Coda-Q measurements

39 The coda-Q measurement is carried out independently in three period bands within the first (10 s –  
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41 20 s) and second (2.5 s -5 s, 5 s – 10 s) microseismic peaks. The processing and our observations are  
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43 exemplified for the 5 s – 10 s frequency band, where the measurement of coda-Q is of highest  
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45 quality. We analyze the correlations independently for the positive and negative times, so in the  
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47 following, the term 'trace' refers to either the positive or the time-reversed negative correlation.  
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49 Unless otherwise stated, we present examples and results on traces that are bandpass filtered  
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51 between 5 s and 10 s period. We have a total of  $\sim 1\,000\,000$  such traces. Figure 3 shows the different  
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53 steps of the coda-Q measurement for a single trace.

54 For each trace, the arrival time of the direct Rayleigh wave is estimated, within a window  
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56 corresponding to a propagation velocity of 1.5 to 5 km/s, as the time where the envelope of the trace  
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58 is maximum (green dashed line in Figure 3b). The energy as a function of time (grey line in Figure 3b)  
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60 is calculated as the square of the trace, normalized by the average energy in the last quarter (2250 -

3000 s) which is stable over this interval. After normalization, the average energy in the last quarter of the signal is 1 (dashed red line in Figure 3b). The normalized energy is then smoothed (blue line in Figure 3b) with a time window which has a length of 16 times the dominant period (after filtering, as stated above). In the following the signal-to-noise ratio (SNR) is defined as the value of the smoothed energy at the arrival time of the direct Rayleigh wave, after normalization.

Figure 4 shows plots of trace density of correlations in the Gräfenberg area (11°E-12°E, 49°N-50°N) for different frequency bands, using only correlations with station distances between 50 and 200 km which passed all selection criteria detailed later in this paragraph. We observe three different regimes of the smoothed energy, as already pointed out in Sens-Schönfelder & Wegler (2006): the main arrival (the ~200 s duration of this peak is created by the smoothing), followed by a gentle slope, corresponding to the coda, over a few hundred seconds, and finally followed by a smooth transition into the background noise.

To estimate coda-Q, we define the beginning of the coda window as 120 s (vertical green line in Figure 3b) after the main arrival. This choice, checked by visual inspection on a large number of traces and trace density plots such as those shown in Figure 4, is motivated by the need of avoiding strong influence of the main peak. It also corresponds to 16 times the central period of the 5 s – 10 s period band (which is the smoothing length). The window length is 400 s (600 seconds for 10 s - 20 s period band), chosen as the longest possible window length while staying above the noise level. These window lengths correspond to a lower limit of 40 periods in the 5 s – 10 s band and of 30 periods in the 10 s – 20 s band. In comparison, Mayor *et al.* (2016), who used earthquake data, used an observation window of 50 s in a frequency band between 1 Hz and 32 Hz that corresponds to 50 and 1600 periods.

Within the defined coda window, we measure coda-Q following the classical procedure of Aki & Chouet (1975). It models the coda energy decay with the equation  $E(f, t) = S(f)e^{-\frac{2\pi f}{Q(f)}t^{-\alpha}}$  (Equation 1) where  $E$  here is the normalized energy,  $S(f)$  is a constant which depends on source magnitude, site effects and frequency,  $t$  is the time since the event,  $f$  is the frequency of the signal,  $Q$  is coda-Q and  $\alpha$  is an algebraic coefficient (Aki & Chouet 1975) that depends on the type of waves (surface waves or body waves) and scattering model (single-scattering or diffusion). Since we are using noise cross-correlations instead of earthquake measurements, the time since the event is replaced by the correlation time. Coda-Q for the trace is obtained by least-squares fit of the logarithm of  $E(f, t) t^\alpha$ . We use  $\alpha=1$  (corresponding to single-scattering of surface waves) since we

1  
2 expect surface waves to be dominant and since our coda window is close to the Rayleigh-wave  
3 arrival.  
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6 At this stage, we exclude from further analysis a subset of correlations, using three criteria. First, as  
7 we will only use short interstation distances in the mapping we exclude traces that correspond to  
8 distances of more than 3000 km. Second, we exclude traces for which the coda energy (smoothed  
9 over a 40 period long window), falls below the noise level within the analysis window. Third, we also  
10 reject all coda-Q measurements with coda-Q values smaller than 10 or bigger than 2000 (4000 in the  
11 2.5 s – 5 s period band). This selection reduces the original dataset of ~1 000 000 traces by ~87% (2.5  
12 s – 5 s), 56% (5 s – 10 s) and 51% (10 s – 20 s). These rejection rates can be compared with those of  
13 Mayor *et al.* (2016) who chose a subset of 50% of their earthquake coda dataset for the mapping of  
14 coda-Q, decreasing the number of coda measurements from ~40 000 to ~20 000. The seismic  
15 sections after this selection are shown in Supplementary material S1.  
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24 As the fit to the energy depends both on the term  $t^{-\alpha}$  and on coda-Q, it is at this stage relevant to  
25 discuss the choice of  $\alpha=1$ . Figure 5 shows the equivalent to Figure 4 (5 s – 10 s periods) within the  
26 400 s long coda window, but this time corrected for the term  $t^{-1}$ . The remaining decay shows a clear  
27 linear decrease with time, which validates our choice for  $\alpha$ . However, the spread of the data means  
28 that  $\alpha$  cannot be constrained very strictly. Choice of for example  $\alpha=1.5$  (diffusion regime) implies an  
29 overall increase of the estimated coda-Q for all traces and an increase of the curvature upwards on  
30 Figure 5, which does not seem appropriate.  
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37 Figure 6 (left) shows the distribution of coda-Q (5 s – 10 s period) after data selection. In contrast  
38 with earthquake studies, we need to verify that coda-Q is independent of azimuth, due to the  
39 systematic directional dependence of incoming energy. Considering the 50 km – 200 km distance  
40 range (in blue), coda-Q is indeed independent of azimuth as shown in Figure 6 (center). This  
41 demonstrates that secondary observables such as coda-Q can be independent of azimuth even  
42 though the main arrival is not. At longer distances, there is a visible dependence of coda-Q with  
43 azimuth. This dependence corresponds to the distribution of noise sources: at longer distances, there  
44 is a bias towards lower coda-Q for azimuths corresponding to the main noise sources, and a bias  
45 towards higher coda-Q in the opposite direction. For short distances, the azimuthal coverage is very  
46 homogeneous over the whole area, whereas for longer distances the station distribution leads to  
47 uneven azimuthal coverage. For example, there are no long SW-NE oriented profiles that sample  
48 large parts of the Italian peninsula while many NW-SE profiles sample that same area. In addition,  
49 the azimuth distribution is poor for stations close to the edge of the array, and this effect increases if  
50 we use longer interstation distances. Therefore, the azimuth dependence at distances longer than  
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2 200 km may reflect that different azimuths do not sample exactly the same regions. The  
3 independence of coda-Q with azimuth in the 50 km – 200 km distance range demonstrates that, at  
4 least in our case, the distribution of noise sources does not influence the value of coda-Q. Based on  
5 these observations, we restrict ourselves to interstation distances of 50 km – 200 km for analyzing  
6 geographical variations in coda-Q; this selection corresponds to 18 433 coda-Q measurements in the  
7 2.5 s – 5 s period band, 40 699 in the 5 s – 10 s period band and 31 524 in the 10 s – 20 s period band.  
8 The observed independence of coda-Q with azimuth is in agreement with Colombi *et al.* (2014) who  
9 used both numerical simulations and field data to show that the coda of correlations is very stable in  
10 terms of waveforms with respect to source distribution. Figure 6 (right) shows that for short  
11 interstation distances, used for mapping (50 km - 200 km, shown with green lines), coda-Q (average  
12 in red, standard deviation in blue) is slightly increasing with distance. Consequently, we will have a  
13 (small) systematic bias in regions with long interstation distances towards higher coda-Q values.  
14 However, our station distribution is dense enough to avoid this problem, except on the edges of the  
15 array. As the coda is composed mainly of surface waves at the periods we are considering, leakage of  
16 coda into the mantle as described in Margerin *et al.* (1999) should not be a significant factor. Indeed,  
17 the depth penetration of the surface waves is much smaller than Moho depth.  
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### 30 3 Mapping of Coda-Q

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32 The main difficulty for transforming coda-Q measurements into a geographic distribution is that the  
33 area sampled by the coda is dependent on scattering regime. The additional propagation distance  
34 with respect to the great circle distance corresponds at the beginning of the coda wave window (120  
35 s after the main arrival) to ~ 360 km and at the end of the coda window (520 s after the main arrival)  
36 to ~1560 km. It can therefore be expected that the beginning and the end of the coda are not in the  
37 same scattering regime.  
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44 Additionally, we know that the typical estimation of the mean free time in the crust is of the order of  
45 tens of seconds at 1 s period. Although the scattering coefficient decreases at longer periods, we do  
46 not expect single scattering (e.g. Xie & Mitchell 1990) to be the dominant mechanism at long lapse  
47 time in our data. Furthermore, we know from the work of Mayor *et al.* (2014) that the slope of  
48 intensity decay (hence coda-Q) is more sensitive to absorption than scattering, if scattering is  
49 isotropic. Usually scattering anisotropy manifests itself in the data at much shorter periods, hence  
50 the assumption of at least partial dominance of absorption over scattering appears a fortiori valid for  
51 the ambient noise coda. The pattern of spatial sensitivity to absorption shown by Mayor *et al.* (2014)  
52 is dominated by singularities located at the source and receiver and local maxima located on the  
53 direct ray connecting the source to the station. Although our measurements are very likely  
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1 influenced by the scattering properties, it is not unreasonable to expect a single coda-Q ( $Q_c$ )  
2 measurement to be more sensitive to the attenuation structure in a (broad) region encompassing the  
3 source and the receiver. In any event, we know that the sensitivity is not uniform in the single-  
4 scattering ellipse but rather concentrated around specific locations.  
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10 However, before mapping, we made sure that there are discernible geographic patterns of the  
11 individual coda-Q measurements. This is illustrated by Figure 7 which shows the geographic  
12 distribution of observed coda-Q. We plot the rays joining each couple of stations, colouring them  
13 according to the corresponding coda-Q value. For this figure, as for all the following, we use only  
14 correlations over distances between 50 and 200 km. In the 2.5 s – 5 s and 5 s – 10 s period bands, in  
15 spite of some scatter, we clearly identify regions of high and low coda-Q values. On the contrary, the  
16 scatter in the 10 s – 20 s period band is too high to reveal geographic tendencies with this type of  
17 plot.  
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24 An alternative visualization, shown in Figure 8, is to plot the mean coda-Q per station: to each station  
25 we attribute the geometric mean of coda-Q ( $10^{\frac{\sum \log(\text{coda-Q})}{N}}$ , i.e. averaging over the logarithm of coda-  
26 Q) of all correlations that involve this station. We choose this mean because of its lower sensitivity to  
27 outliers and because of the exponential nature of coda-Q. We plot results only for stations with more  
28 than 5 coda-Q measurements. As expected, the pattern is very similar to that of Figure 7, but  
29 geographic patterns are more easily identified. A first result is that the contrasts in coda-Q decrease  
30 with period. This is expected if the coda is dominated by surface waves, as both lateral variations in  
31 intrinsic Q and variations in seismic velocities, leading to scattering, are relatively high within the  
32 uppermost part of the crust. We also observe that at long period (10 s – 20 s) there is less geographic  
33 coherency between neighbouring stations, coherent with Figure 7. This means that poor  
34 measurement quality (resulting in large uncertainty of coda-Q values) results in geographic  
35 dispersion of results which will not map into coherent geographic patterns.  
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46 On the contrary, in the 2.5 s – 5 s and 5 s – 10 s period bands, we observe clear geographic patterns,  
47 which are relatively similar. In both period bands, we observe the lowest coda-Q in northern Italy (Po  
48 Plain). We also observe areas of high coda-Q in the eastern Alps and in the south-westernmost part  
49 of the study area. There are also some differences between the two period bands. The most striking  
50 part is that the northwestern part of the study area is dominated by low coda-Q between 5 s and 10  
51 s, but less so between 2.5 s and 5 s.  
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57 To perform mapping, we choose the approach by Mayor *et al.* (2016), who map coda-Q onto the rays  
58 between the stations. In this method, the study area is divided into cells and to each cell we attribute  
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2 the mean value (geometric mean) of the coda-Q of the rays crossing the cell. In each cell, values  
3 higher or lower than three times the standard deviation (calculated independently for each cell) are  
4 excluded.  
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8 We implemented an adaptive grid based on Schaefer *et al.* (2011). Rather than merging cells, we  
9 start with a single cell. At each iteration, we subdivide any cell into four if it a) is crossed by at least  
10 ten rays and b) has at least three rays in at least three of the azimuth intervals 0°-45°, 45°-90°, 90°-  
11 135° and 135°-180°. If three of the four resulting subcells satisfy the same criteria, we keep this finer  
12 grid. The process is iterated for each cell until no subdivision is possible using the above criteria, or if  
13 the sub-cells become smaller than one wavelength. With this approach we ensure a good azimuthal  
14 coverage within each cell, to avoid any potential bias. This is a conservative procedure, as we already  
15 check for the absence of coda-Q dependency on azimuth (see Figure 6).  
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23 The results of the mapping are shown in Figure 9. As standard deviations in each cell are calculated  
24 using the logarithm of coda-Q, we cannot map the standard deviations in a meaningful way. The map  
25 of  $\log_{10}(\text{coda-Q})$  and associated standard deviations are shown in Supplementary Material S2. Note  
26 that the standard deviations show that in the frequency bands 2.5 s – 5 s and 5 s – 10 s, the  
27 geographic pattern of high and low coda-Q is resolved but interpretation of small-scale variations of  
28 coda-Q needs to be associated with stability tests. For 10 s – 20 s the standard deviations are such  
29 that the apparent geographic patterns in Figure 9 are barely resolved, but our results hint that it may  
30 be possible to obtain coda-Q information also in this period interval.  
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38 Figure 9 confirms the previous observation that the amplitude of the variations is larger at short  
39 period than at long periods. This observation is coherent with the strong heterogeneities in the  
40 uppermost crust, notably the deep sedimentary basins.  
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43  
44 To understand the geographic pattern of the coda-Q observations, Figure 10 shows the map of coda-  
45 Q between 2.5 s and 5 s period overlaying the topographic map and the map of sedimentary basins  
46 (see Figure 1). The maps shows an excellent definition of the Po Plain as a low coda-Q area (~400-  
47 600) while the Alps and the Apennines are characterized by high coda-Q (>800). This is in overall  
48 agreement with Mayor *et al.* (2016), but with our data providing a better resolution. Note that the  
49 area of Lg blockage in the Western Alps (Campillo *et al.*, 1993) is known to be very small so can not  
50 be resolved. There is a small part of the Swiss Alps, NW of the Po Plain, where coda-Q is of the order  
51 of 700. In the Swiss Alps it is likely that the combination of narrow lateral extension, nearby low  
52 coda-Q and orientation in the direction of the dominant noise source direction is the cause of the  
53 artificially low coda-Q. We tentatively estimated the severity of potential smearing from the Po Plain  
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2 in a  $1^\circ$  longitude x  $0.5^\circ$  latitude grid, where in each grid point we estimated the variations of coda-Q  
3 with azimuth. This analysis showed that smearing may be a problem in this area, and along the  
4 northern edge of the Po Plain. Similar problems occur in isolated spots along the edge of the array.  
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8 Other observations are moderately low coda-Q in the wider part of the Molasse Basin, while the  
9 narrowest part (SW part) does not have particularly low coda-Q. We infer from this pattern that this  
10 part of the basin is too narrow to be resolved. The same is the case for the Rhine Graben and the  
11 Rhone Valley. The Pannonian Basin, on the edge of the resolved area, is characterized by low coda-Q  
12 in the 2.5 s – 5 s period band, less so in the 5 s – 10 s period band. Two observations are surprising:  
13 the first one is that the Bohemian Massif shows low coda-Q, in contradiction to Gäbler *et al.* (2015).  
14 However, as can be seen in Figure 1, the station density in this area is lower than the rest of the  
15 study area, and as a consequence the ray coverage is relatively poor, as can be seen on the ray  
16 density (Figure 7) and plotting grid (Figure 9). Second, we observe, in contrast with the results of  
17 Mayor *et al.* (2016), that the South East French Basin, shown as a sedimentary basin in the south  
18 westernmost part of the resolved area, has high coda-Q. The equivalent map for 5 s – 10 s period  
19 (Supplementary material S3) overall has the same features as Figure 10.  
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## 29 4 Impact of data quality and time series length

### 30 4.1 Effect of further data selection

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32 One specific concern about coda-Q obtained from noise correlations is the influence of data quality  
33 on the coda-Q values and maps. To evaluate the impact of data selection on observed coda-Q, we  
34 compare our results to those of a further reduced data set obtained by applying additional selection  
35 criteria. The thresholds for data rejection are adapted in each period band to ensure sufficient data  
36 for the mapping. The following selection criteria and associated thresholds are applied:  
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- 43 1. Reject all traces with SNR below 500 (300 for period band 2.5 s - 5 s).
- 44 2. Reject all unstable coda-Q measurements. To estimate the stability of observed coda-Q, we  
45 perform a second measurement with a different coda window length (300 s instead of 400 s  
46 for period bands 2.5 s – 5 s and 5 s – 10 s; 400 s instead of 600 s for period band 10 s – 20 s)  
47 and compare it to the initial measurement. If  $Q_{400\text{ s}}/Q_{300\text{ s}}$  ( $Q_{600\text{ s}}/Q_{400\text{ s}}$  for the period band 10 s  
48 – 20 s) is outside a defined range  $[1/R; R]$ , the measurement is rejected. R had to be adapted  
49 as the threshold for rejecting almost all measurements is different in the three period bands.  
50 We choose it as  $R=3$  (2.5 s – 5 s),  $R=2$  (5 s – 10 s) and  $R=1.25$  (10 s – 20 s).  
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57 3. Reject all correlations that are stacked over less than 200 days. This criteria is related to the  
58 convergence rate of coda-Q, specifically discussed in Section 4.2.  
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2 After application of these criteria, the remaining number of traces is 6 572 (2.5 s – 5 s), 8 466 (5 s –  
3 10 s) and 3 314 (10 s – 20 s) which represent approximately 0.5% of the initial dataset. On this  
4 reduced dataset coda-Q is independent of azimuth and distance in the 50 km – 200 km distance  
5 range, as opposed to the bias towards higher coda-Q on longer distances on the initial dataset. The  
6 map based on this reduced dataset is shown in Figure 11. This map has a significantly poorer lateral  
7 resolution (increased cell size) than the one of Figure 9, but overall the geographic pattern remains  
8 identical and the standard deviation on  $\log(\text{coda-Q})$  is significantly smaller. The stricter data selection  
9 does however show one systematic difference: coda-Q has overall decreased, mostly in areas with  
10 high coda-Q. Therefore, care should be taken on the absolute values of coda-Q measured on noise  
11 correlations.  
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#### 20 4.2 Convergence of Coda-Q

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22 It is generally agreed that correlating one year (or sometimes much less) of ambient-noise data is  
23 sufficient to obtain a stable main arrival (e. g. Sabra *et al.* 2005) but the convergence of coda-Q  
24 observed on noise correlations is not well known. Figure 12 shows the density distribution of  $Q(t)/Q_4$   
25 and  $Q(t)/Q_1$  for selected station pairs.  $Q_4$  and  $Q_1$  are coda-Q measured for four years of data (January  
26 2014 – October 2018, Figure 12a) and for one year of data (July 2016 to June 2017, Figure 12b). The  
27 selected station pairs are those of permanent stations, for which the correlations are accepted in the  
28 hyper-reduced dataset used in Figure 11.  $Q(t)$  is coda-Q made on stacks of  $t$  days of data. Note that  
29 when a station pair does not have four (or one) year of data,  $Q_4$  and  $Q_1$  use the maximum number of  
30 days available, and the station pair is not counted beyond the last day.  
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39 Figure 12 shows two main phenomena. The first one is that convergence is slow, and that at least  
40 200 days are necessary for convergence. We verified that convergence is independent of both  
41 azimuth and distance. The second observation is that convergence is systematically from higher  
42 coda-Q towards lower coda-Q. This means that coda-Q will decrease over time until convergence is  
43 reached and bias will be systematically towards higher coda-Q. This is expected as noise (in the sense  
44 of true noise) has stable amplitude with time, hence a poor coda/noise level should lead to higher  
45 coda-Q. The faster convergence of coda-Q for lower coda-Q values is a natural consequence of the  
46 measurement stability of a steep slope.  
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52 Figure 13a shows the distribution of  $Q_1/Q_4$ . By plotting  $Q_1/Q_4$  separately for  $100 < Q_1 < 150$  and  $400 <$   
53  $Q_1 < 1000$ , we confirm that the bias is stronger for high coda-Q values. It is possible to map this bias by  
54 plotting  $Q_1$  as a function of  $Q_4$ , using the median value of  $Q_1$  and  $Q_4$  for data in different intervals of  
55  $Q_1$  (Figure 13c, see caption for details). We confirm that high coda-Q values are likely to be  
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2 overestimated when we use the AlpArray dataset, for which we use one year of data. On the other  
3  
4 hand, geographic distribution of high and low coda-Q regions is not affected.  
5

## 6 7 5 Discussion and conclusions 8

9  
10 In the present article, we use the correlations of ambient noise to extract coda-Q in the period range  
11 2.5 s – 20 s. No such measures have been made in this period band previously because of the high  
12  
13 amplitude of the seismic noise that makes measures on earthquake coda very difficult. This difficulty  
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15 transforms into a strength in the case of noise correlations, due to a particular high signal to noise  
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17 ratio of the correlations in this period band. We are able to obtain a stable geographic pattern of high  
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19 and low coda-Q across the greater Alpine region, independently of whether we apply data selection  
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21 criteria where 15% or 1% of the data are used for the mapping. This result is confirmed in the 2.5 – 5  
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23 s and 5 s – 10 s period bands while our results in the 10 s – 20 s period band remain speculative.

24  
25 Another strength of the noise correlations is that a dense seismic network will yield a high resolution  
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27 image of coda-Q. In our case, the high resolution is achieved by combining data from permanent  
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29 seismic broadband stations in the greater Alpine area with temporary AlpArray stations. One of the  
30  
31 potential difficulties that we had to consider was whether the strong heterogeneity of the incoming  
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33 noise field, and in particular the high energy influx from the north-west (Atlantic Ocean noise sources)  
34  
35 would bias the measurements. Our results demonstrate that at shorter distances (50 km – 200 km),  
36  
37 coda-Q is independent of azimuth while there were systematic variations of coda-Q with azimuth at  
38  
39 longer distances. This type of test should be systematically applied to all coda-Q measurements using  
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41 noise correlations. The influence of the Po Plain on coda-Q in the Swiss Alps, and the uncertainty on  
42  
43 the low coda-Q in the Bohemian Massif also shows that we need to develop further tools to better  
44  
45 understand the conditions under which coda-Q is well constrained.

46  
47 While the geographic pattern is very stable, the numerical values of coda-Q strongly depend on data  
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49 selection and the duration of the timeseries used for the correlations. In particular, severe data  
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51 selection (e. g. in terms of SNR) results in a decrease of coda-Q. Further studies on longer timeseries  
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53 show that low coda-Q values tend to stabilize faster than high coda-Q values, but a minimum of 200  
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55 days of continuous recording is still required. Consequently, the numerical values of coda-Q in the  
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57 high coda-Q areas may be overestimated. Another consequence is that longer time series must be  
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59 used to test the possibility of stable measurements in the 10 s – 20 s period range, where there is an  
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observed coda in the correlations. At periods longer than 20 s, we did not observe any coda, but time  
series spanning over several years might achieve a sufficient signal to noise ratio to observe a stable

1 coda at longer periods (20 s – 40 s). At very long periods, it is known from earthquake studies that  
2 the Rayleigh wave coda is small.  
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6 Whilst caution should be taken as to the numerical values of coda-Q, we do observe that coda-Q  
7 decreases with period (~750 at 2.5 s – 5 s period, ~350 at 5 s - 10 s period, ~330 at 10 s to 20 s  
8 period). This decrease is coherent with observations from other studies (Aki & Chouet, 1975; Mayor  
9 *et al.*, 2016), but our observations do not extrapolate to meet those of Mayor *et al.* (2016) who  
10 observe earthquake data coda-Q of ~200 at 1 Hz - 2 Hz in the area. While the geographic distribution  
11 of high and low coda-Q is in overall agreement with Mayor *et al.* (2016), there are also differences for  
12 example in SE France basin. A possible explanation is the difference in the characteristics of the noise  
13 field (containing predominantly surface waves) compared to the short-period earthquake wavefield  
14 (containing predominantly body waves) so that the two studies may be sampling different depths in  
15 the medium. Additionally, the propagation regime of ambient noise coda is probably different from  
16 the one of earthquake coda as we expect scattering at longer period to be weaker than at high  
17 frequency.  
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27 More work remains to better characterize the physical meaning of the observations. Regardless of  
28 the avenues to further explore, this work demonstrates that noise cross-correlations can provide a  
29 new type of observation for seismic imaging.  
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## 37 6 Origin of Data

38  
39 Waveform data used in this paper belong to the permanent networks with codes AC, BE (Royal  
40 Observatory of Belgium 1985), BW (Department of Earth and Environmental Sciences, Geophysical  
41 Observatory, University of München 2001), CA (Institut Cartogràfic i Geològic de Catalunya-Institut  
42 d'Estudis Catalans 1996), CH [Swiss Seismological Service (SED) at ETH Zürich 1983], CR, CZ (Institute  
43 of Geophysics, Academy of Sciences of the Czech Republic 1973), ES (Instituto Geografico Nacional,  
44 Spain 1999), FR (RESIF 1995), G [Institut de Physique du Globe de Paris (IPGP) & Ecole et Observatoire  
45 des Sciences de la Terre de Strasbourg (EOST) 1982], GE (GEOFON Data Centre 1993), GR [Federal  
46 Institute For Geosciences And Natural Resources (BGR) 1976], GU (University of Genova 1967), HU  
47 (Kövesligethy Radó Seismological Observatory 1992), II (Scripps Institution of Oceanography 1986), IV  
48 (INGV Seismological Data Centre 2006), IX, MN (MedNet Project Partner Institutions, 1990), NI [OGS  
49 (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale) and University of Trieste 2002], NL  
50 (KNMI 1993), OE (ZAMG - Zentralanstalt für Meteorologie und Geodynamik 1987), OT (University of  
51 Bari "Aldo Moro" 2013), OX [OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale)  
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2 2016], RD (RESIF 2018), RF (University of Trieste 1993), SI, SJ, SK [ESI SAS (Earth Science Institute Of  
3 The Slovak Academy Of Sciences) 2004], SL (Slovenian Environment Agency 2001), ST (Geological  
4 Survey-Provincia Autonoma di Trento 1981), SX (Leipzig University 2001), TH (Friedrich Schiller  
5 University Jena and Thuringian Institute of Environment and Geology 2009), TT, WM [San Fernando  
6 Royal Naval Observatory (ROA), Universidad Complutense de Madrid (UCM), Helmholtz-Zentrum  
7 Potsdam Deutsches GeoForschungsZentrum (GFZ), Universidade de Evora (UEVORA, Portugal), &  
8 Institute Scientifique of RABAT (ISRABAT, Morocco) 1995]. We also used data of the temporary  
9 AlpArray network (network code Z3 2015; AlpArray Seismic Network 2015).

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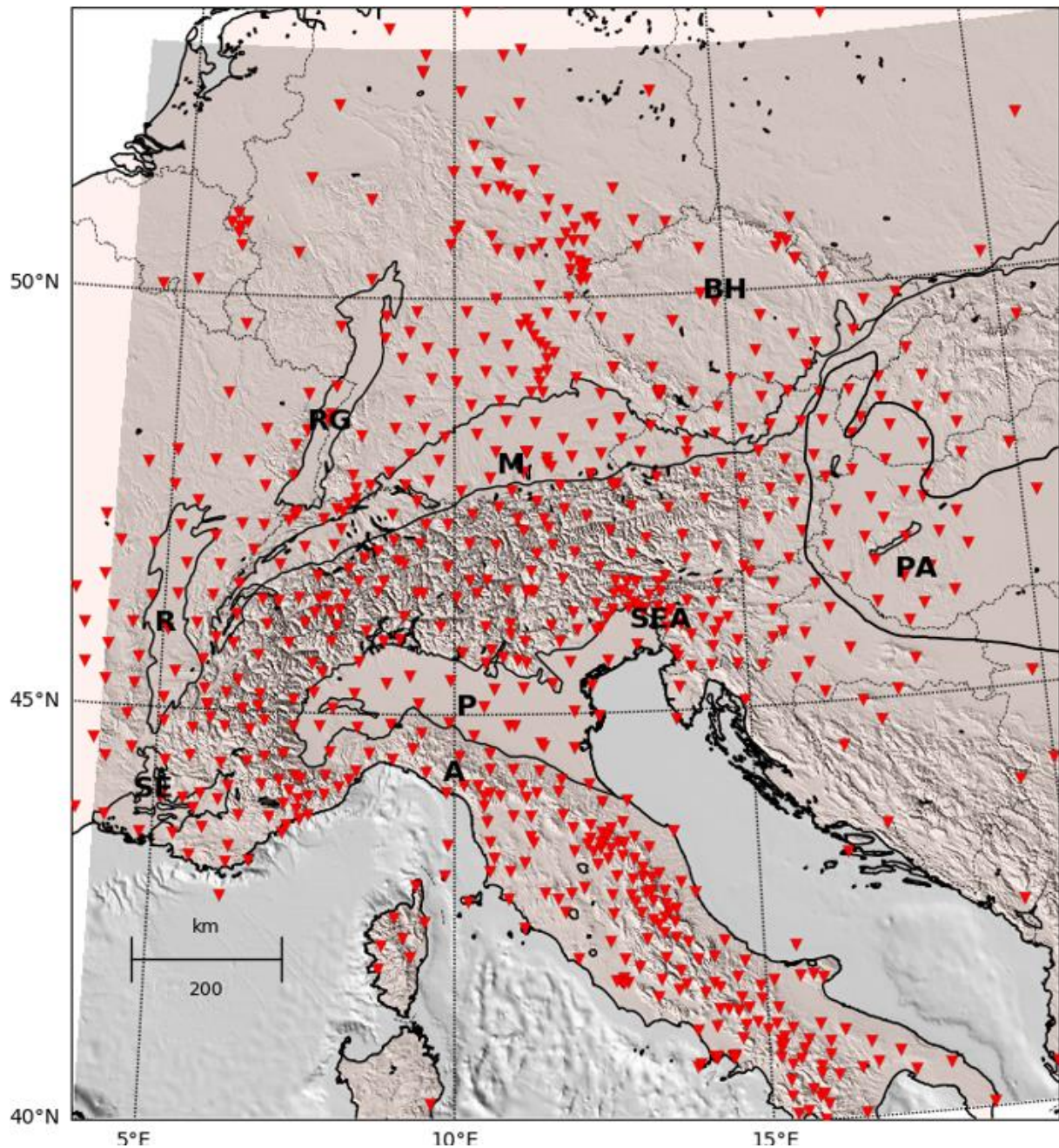


Figure 1: Map of stations used in this study. The network is composed of permanent stations as well as temporary stations of AlpArray (AlpArray Seismic Network 2015, Hetényi *et al.* 2018). The references to the datasets can be found in Section 6. Geographic locations mentioned in the text are: the Po Plain (P) and the South-Eastern Alps (SEA), the Bohemian Massif (BH), the South-East France Basin (SE), the Rhone Valley (R), the Rhine Graben (RG), the Molasse Basin (M), the Pannonian Basin (PA) and the Appenines (A). The outlines of the Bohemian Massif to the west and north correspond roughly to the frontiers of the Czech Republic (national boundaries shown as thin dotted lines).



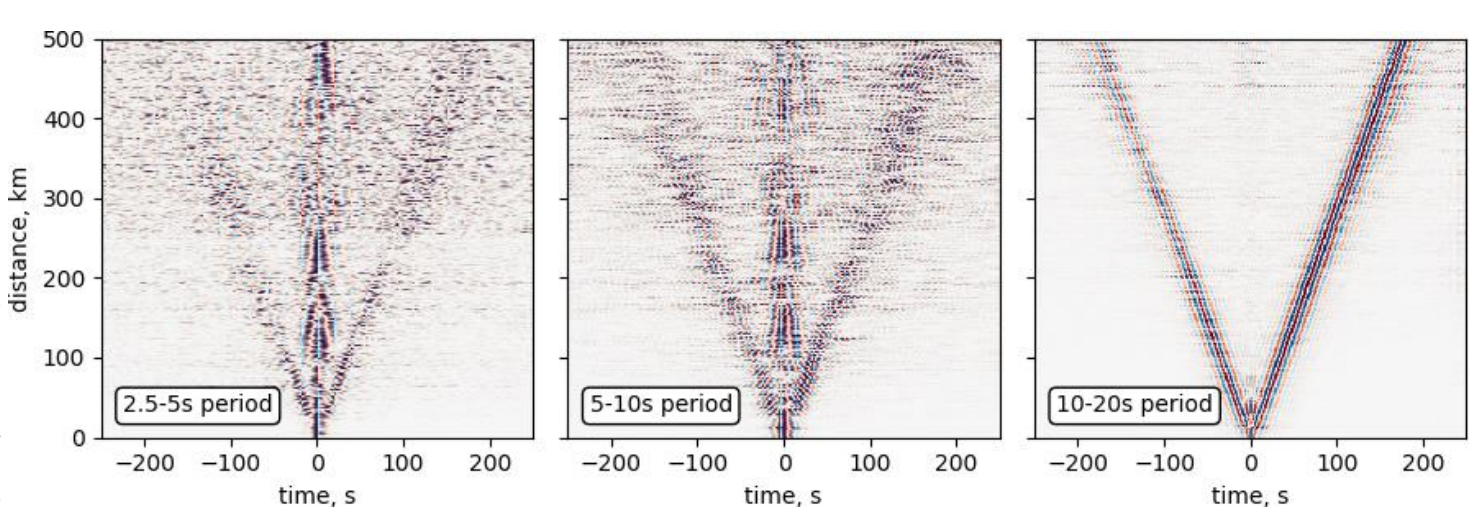


Figure 2: Seismic section of correlations in the 2.5 s – 5 s (left), 5 s – 10 s (center) and 10 s – 20 s (right) period bands. The traces are stacked in bins of 1 km and normalized by their maximum. All correlations have been oriented so that the causal part points away from 300° of azimuth; i.e. the direction which approximately corresponds to the dominant direction of the noise sources. We clearly see the dispersive Rayleigh waves. As expected, the amplitude of the causal part is higher than the anticausal part, especially for longer distances. The plot of seismic sections for the selected dataset (see Section 2.3) is shown as supplementary material S1.

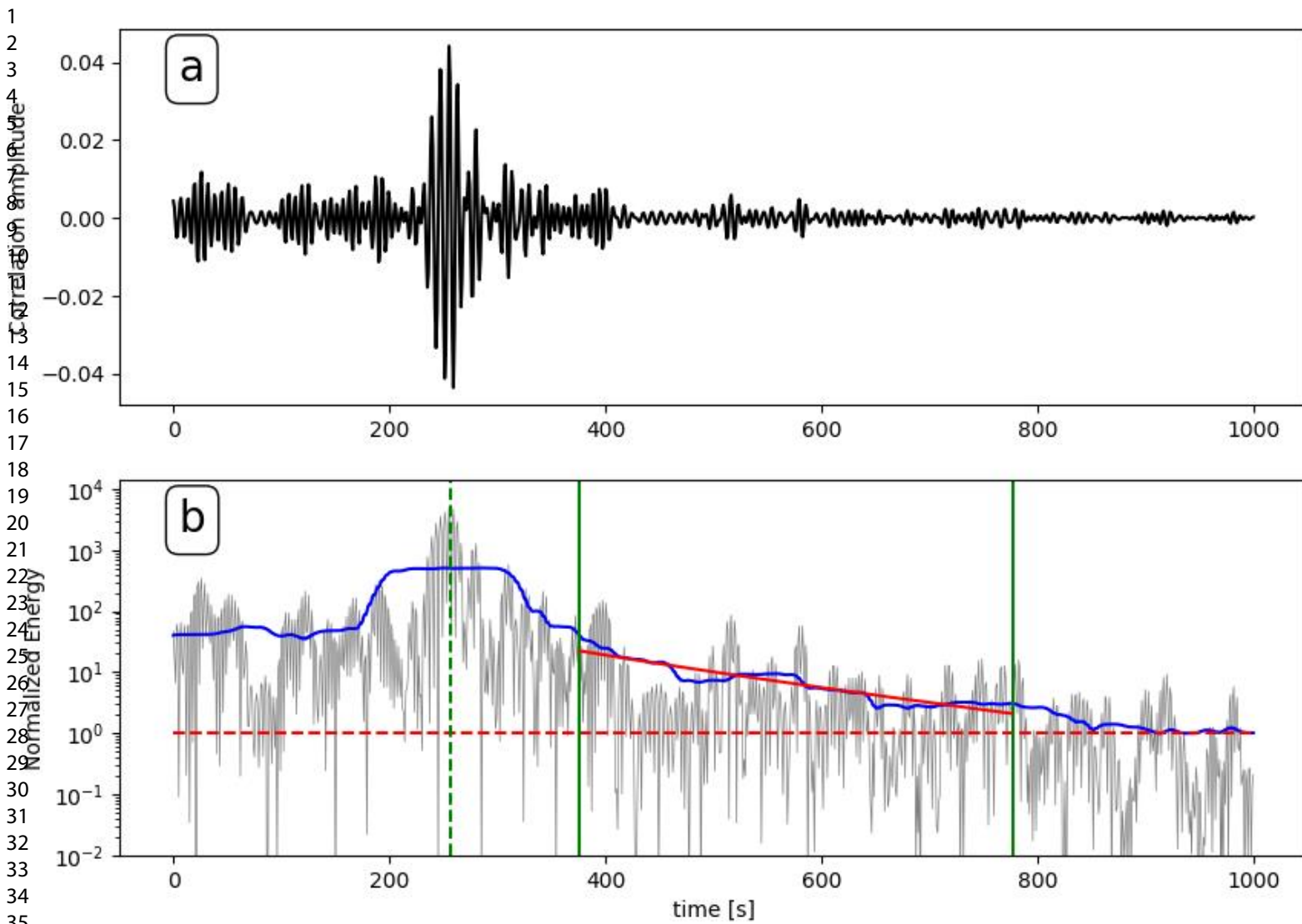


Figure 3: Example of processed trace (station couple CH.BERGE - Z3.A263A, interstation distance 703 km). a) Correlation filtered between 5 and 10 seconds. b) Same trace squared (grey) and smoothed (blue). The red line corresponds to the modeled coda decay after inversion for coda-Q. The green lines mark the borders of the interval in which the coda is fitted. Green dashed line : main arrival. Red dashed line: noise level (normalized to 1). Note the logarithmic vertical scale in the bottom plot.

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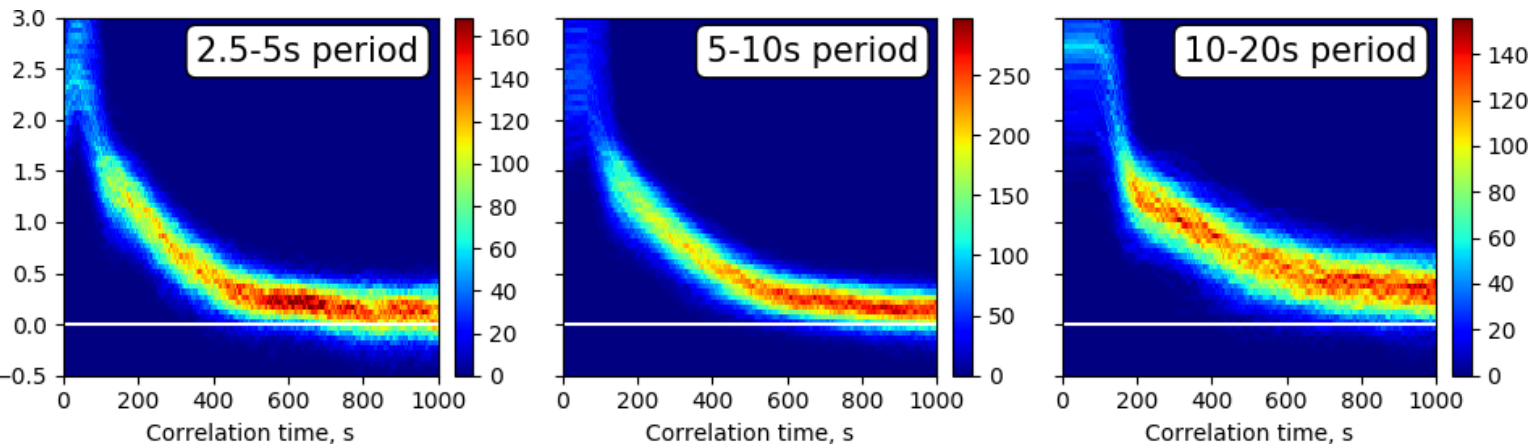


Figure 4: Smoothed energy (log scale) as a function of time (correlation time) for correlations for which one of the stations is located in the Gräfenberg area ( $11^{\circ}\text{E}$ - $12^{\circ}\text{E}$ ,  $49^{\circ}\text{N}$ - $50^{\circ}\text{N}$ ) and the interstation distance is between 50 km and 200 km. This plot uses only traces for which the trace is above the noise level in the coda window and where the measured coda-Q is in the acceptable coda-Q range. The traces are shown in the form of trace density where the colour of each pixel indicates the number of traces crossing it. The white line corresponds to the noise level.

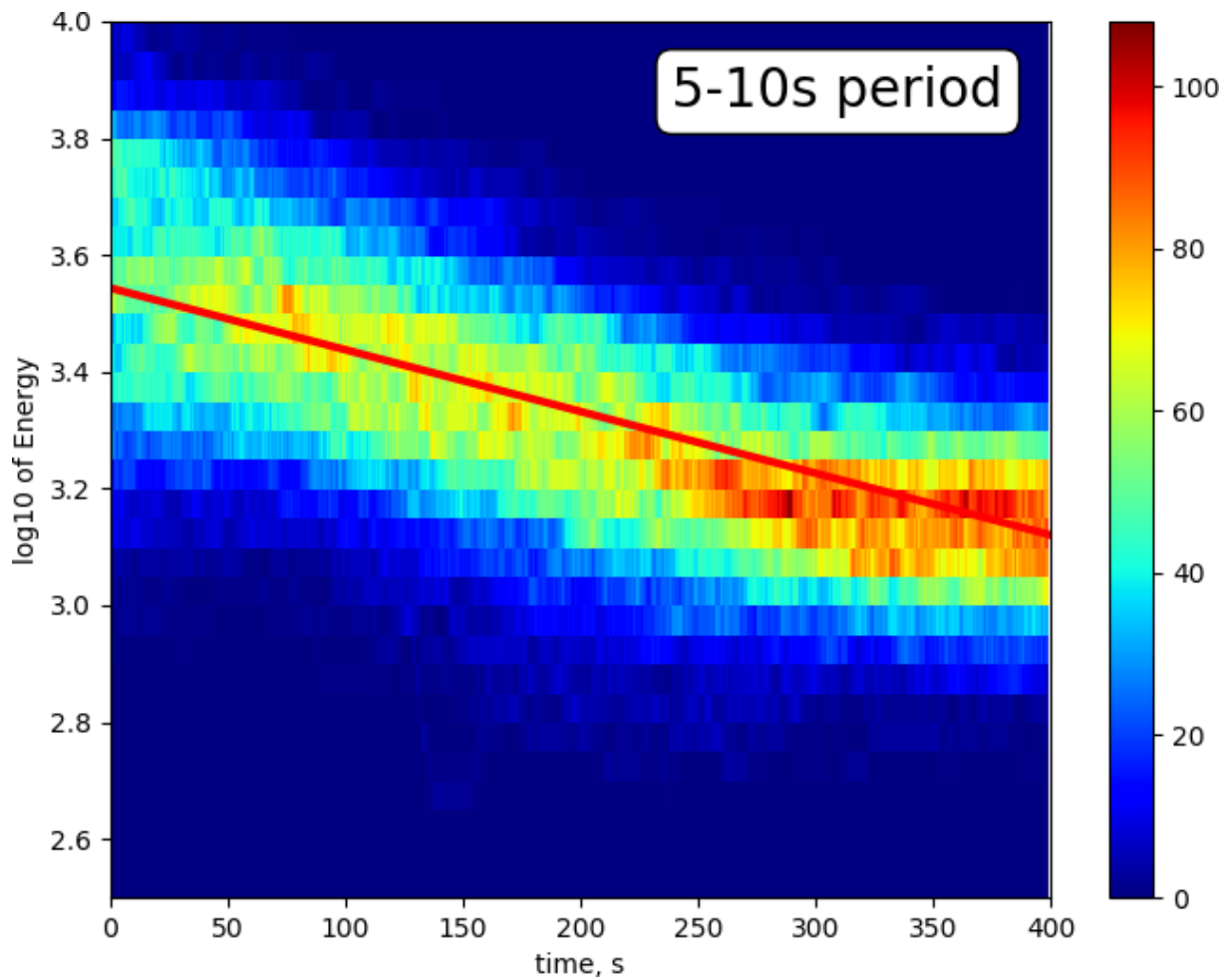


Figure 5: Smoothed energy (log scale) as a function of time (lag time after main arrival), after correction for the  $t^{-\alpha}$  term, for the same traces as in Figure 4, and for the 5 s – 10 s period band. The traces are shown in the form of trace density where the colour of each pixel indicates the number of traces crossing it. The red line corresponds to the (geometrical) average of coda-Q observed on the same traces.

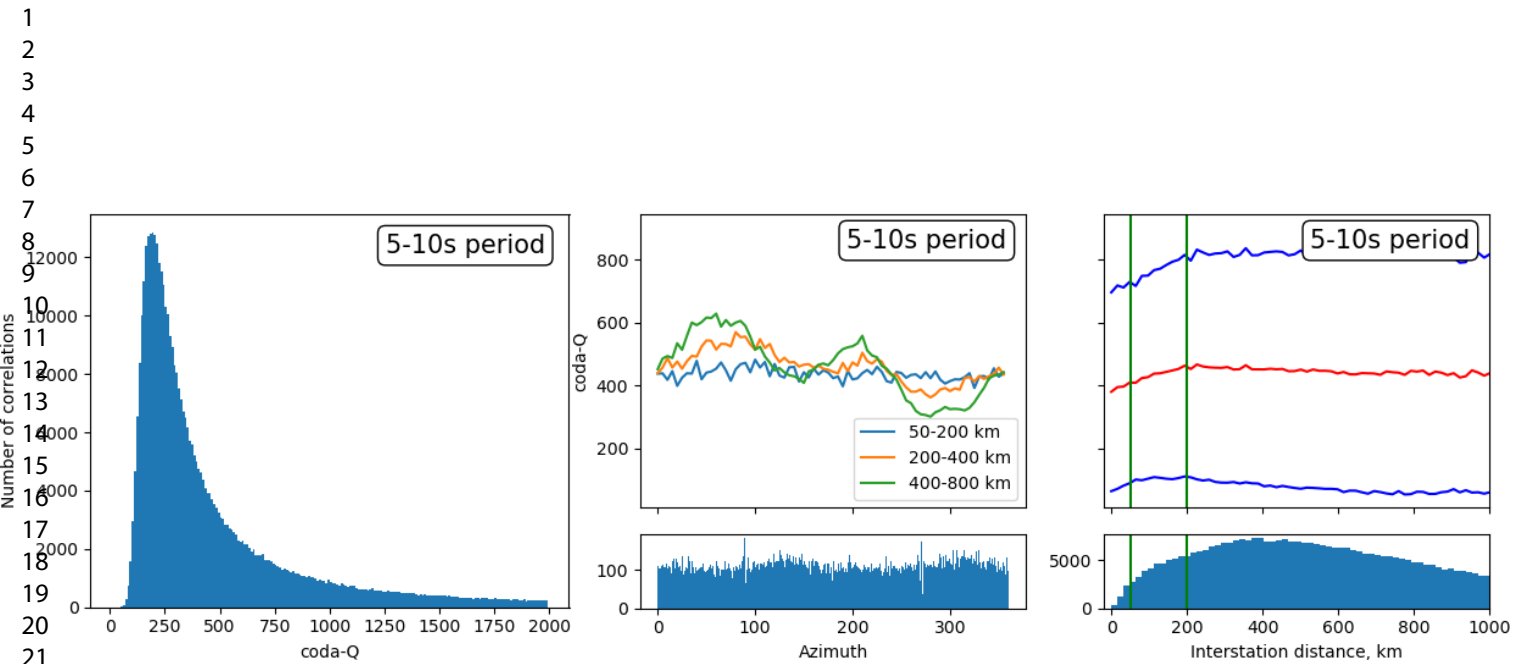


Figure 6: Left: Histogram of coda-Q. Center: coda-Q as a function of azimuth in the distance bands 50 km – 200 km, 200 km – 400 km and 400 km – 800 km, and histogram of azimuth (in the distance range 50 km – 200 km). For longer distances, azimuths corresponding to the main noise sources have lower coda-Q values, whereas azimuths opposed have higher ones. This is most likely due to the difference in signal-to-noise ratio, as if the coda window is dominated at least partly by noise the measured coda-Q will be higher. As compared to Figure 2, the anticausal part corresponds to the data for azimuth between 30° and 210° whereas the causal part corresponds to data for azimuths between 210° and 360° and between 0° and 30°. Right: coda-Q as a function of distance, and histogram of distances (green lines show the 50-200 km range). The red line corresponds to the average coda-Q and the blue lines corresponds to the average  $\pm$ one standard deviation.

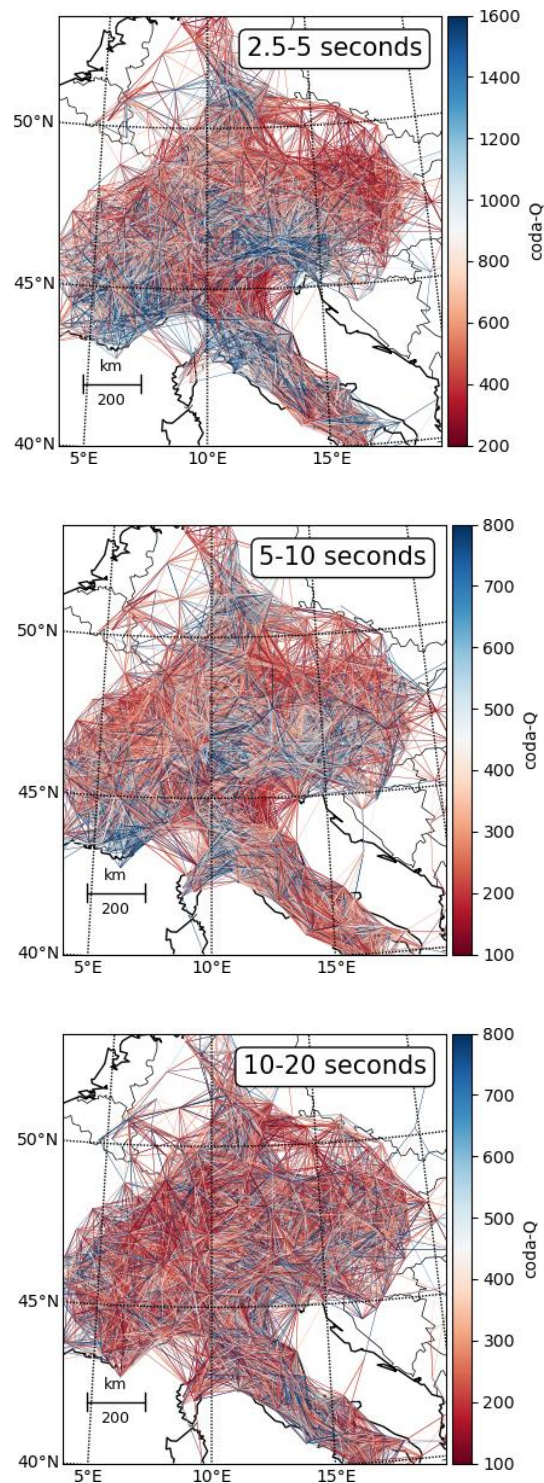


Figure 7: Maps of coda-Q measured for each station pair. Each path between pairs of stations is coloured according to the observed coda-Q (note the difference of colour scale in different period intervals). Only correlations with interstation distances comprised between 50 and 200 km are used. Note that between 25% and 40% of all correlation pass all selection criteria for both the causal and anticausal parts and will therefore not show on these kind of plots, as one covers the other. A geographic pattern clearly emerges in the two period bands 2.5 s – 5 s and 5 s – 10 s, whereas geographic patterns remain speculative in the 10-20 s period band.

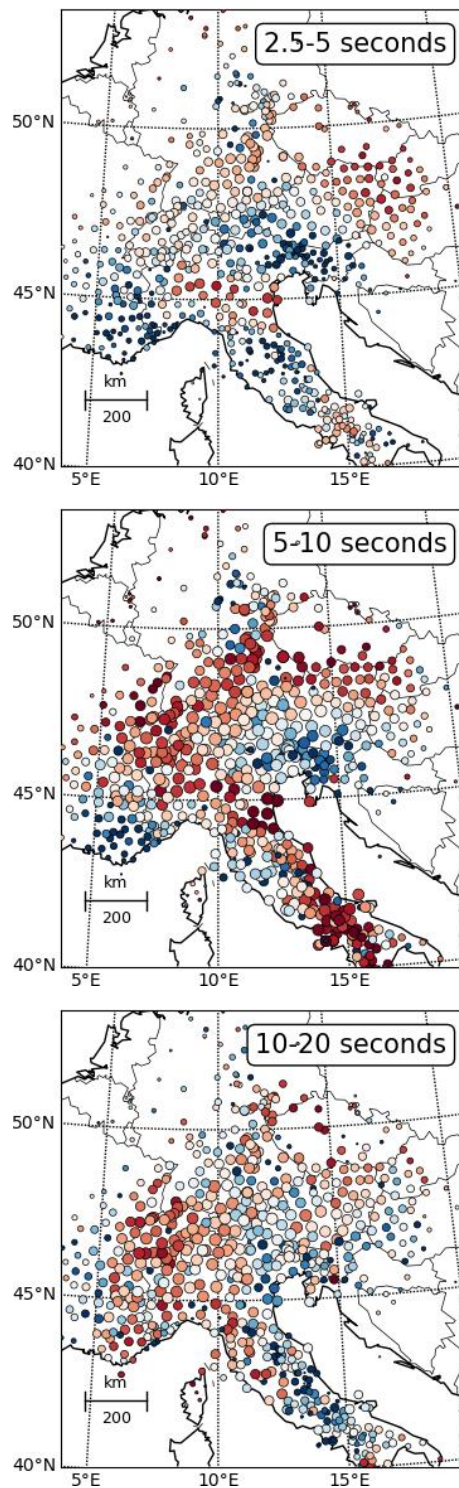


Figure 8: Average coda-Q (colour scale) per station (circles). For each station that has more than five measurements of coda-Q, the average has been calculated by calculating the mean of  $\log_{10}(\text{coda-Q})$  excluding all measurements further than 2 standard deviations away from the average and calculating the power of 10 of the resulting mean. The size of the circle indicates the number of correlations used in the average. Only pairs with interstation distances between 50 and 200 km are used. As in Figure 7, we see a clear pattern in the two first period bands, while the results in the 10 s – 20 s period band are more randomly distributed.

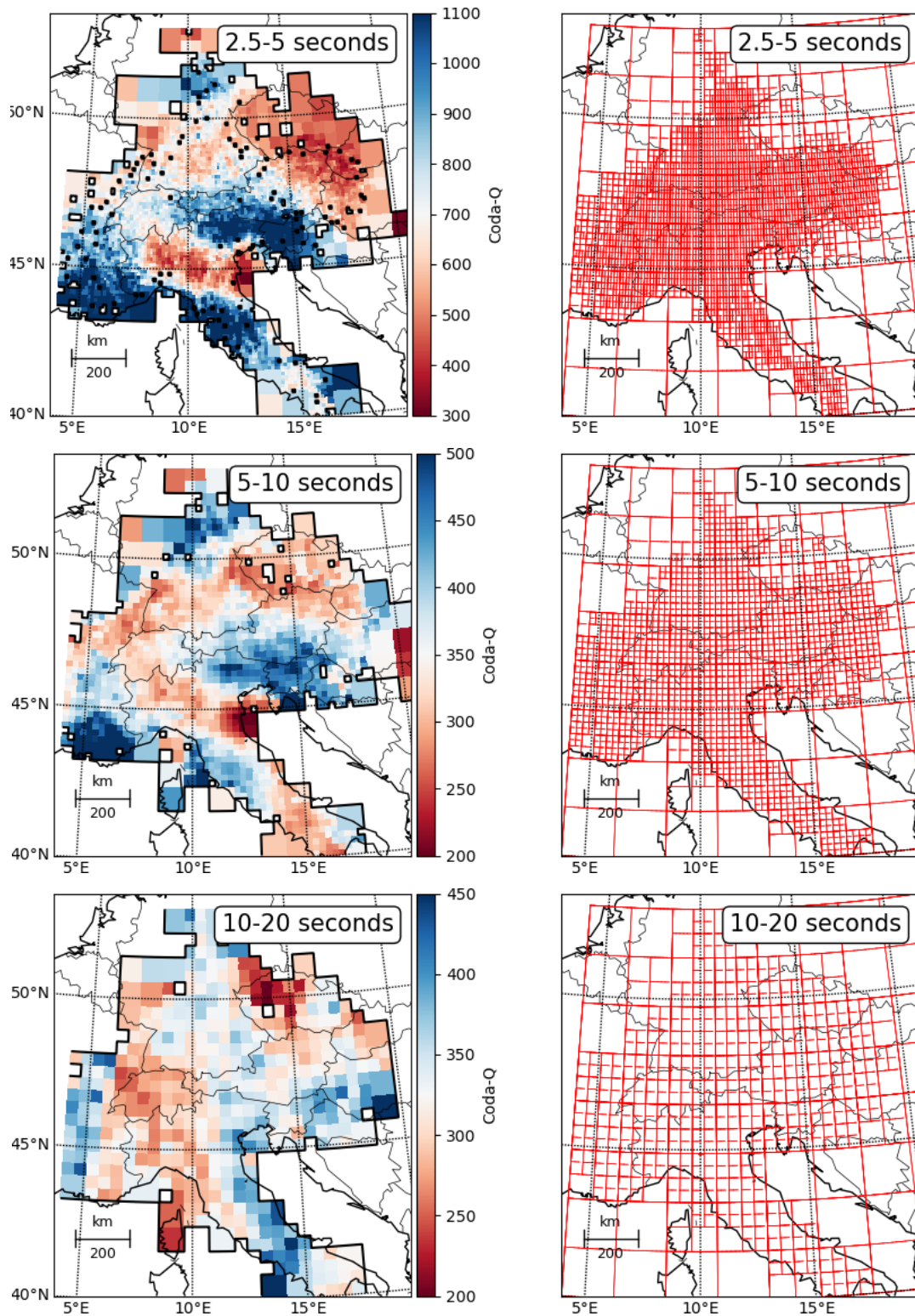


Figure 9: Left: Maps of coda-Q. Right: adaptive grid. Note that the colour scale is not the same in all period bands. Rays are not drawn in the adaptive grid because of the very high ray density in most of the region.



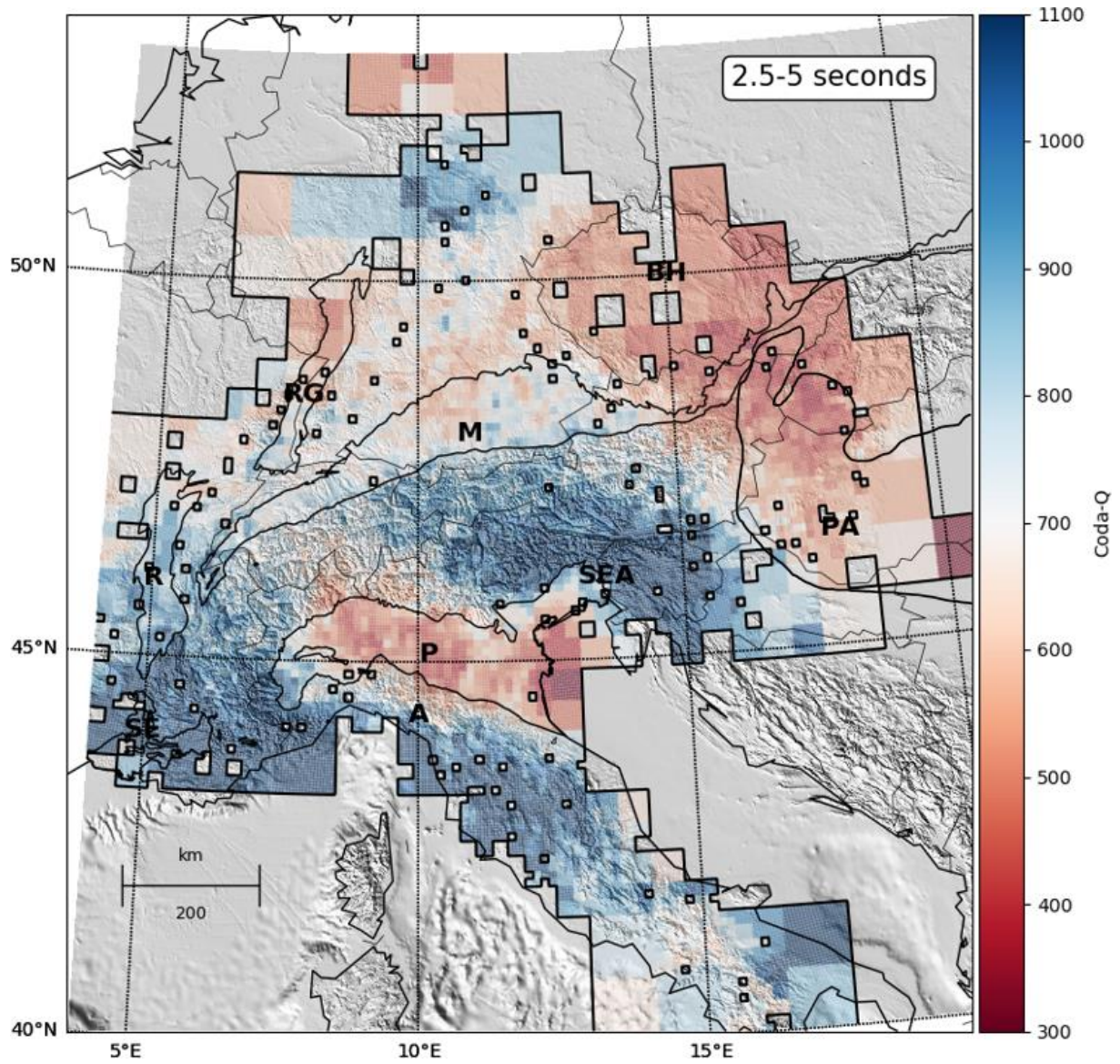


Figure 10: Map of coda-Q overlain onto the topography and main sedimentary basins (see Figure 1, and caption to Figure 1).

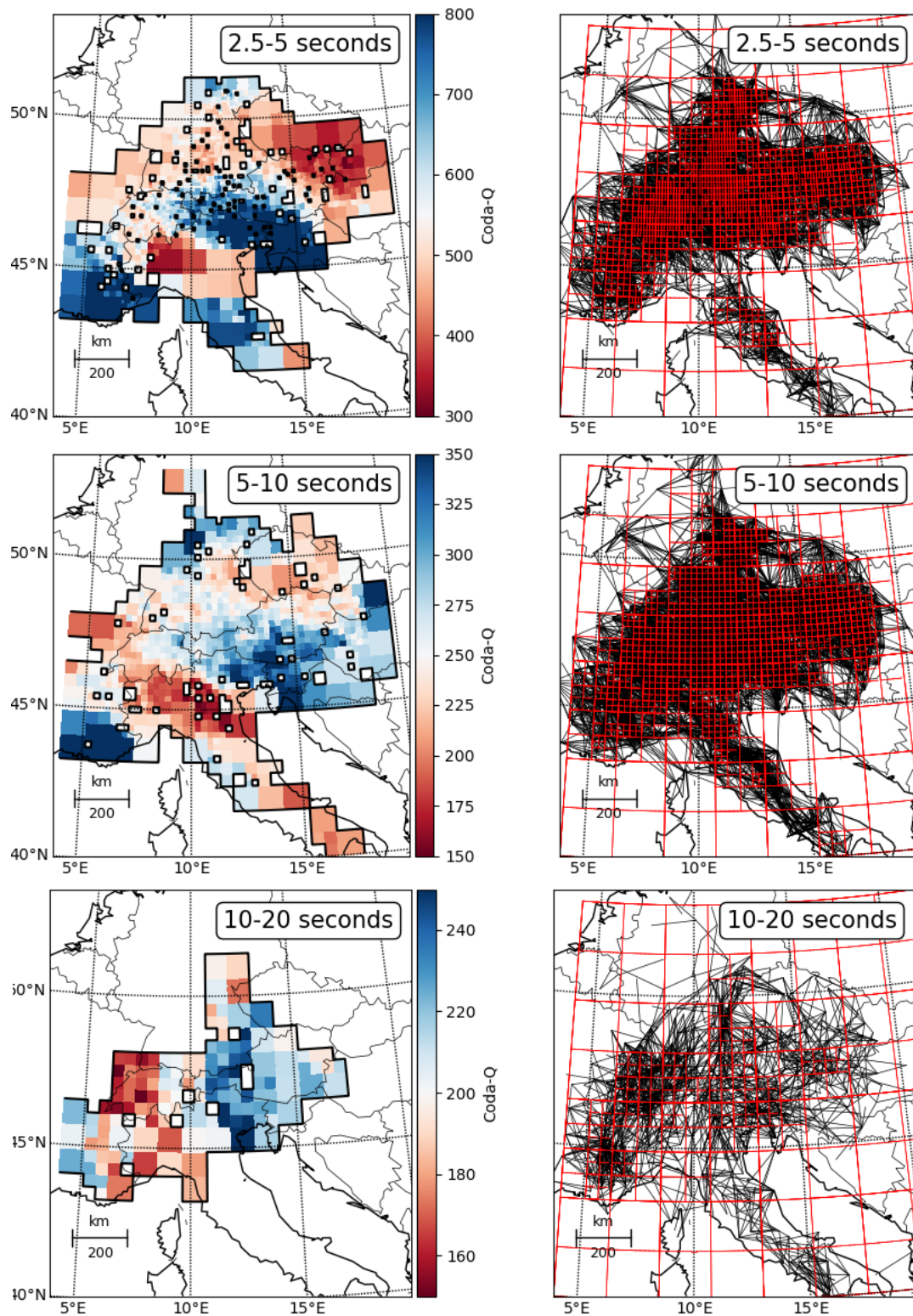


Figure 11: Left: Maps of coda-Q using the further reduced dataset (see section 4.1 for selection criteria). Right: path coverage and adaptive grid. Note that the colour scale is not the same in all period bands.

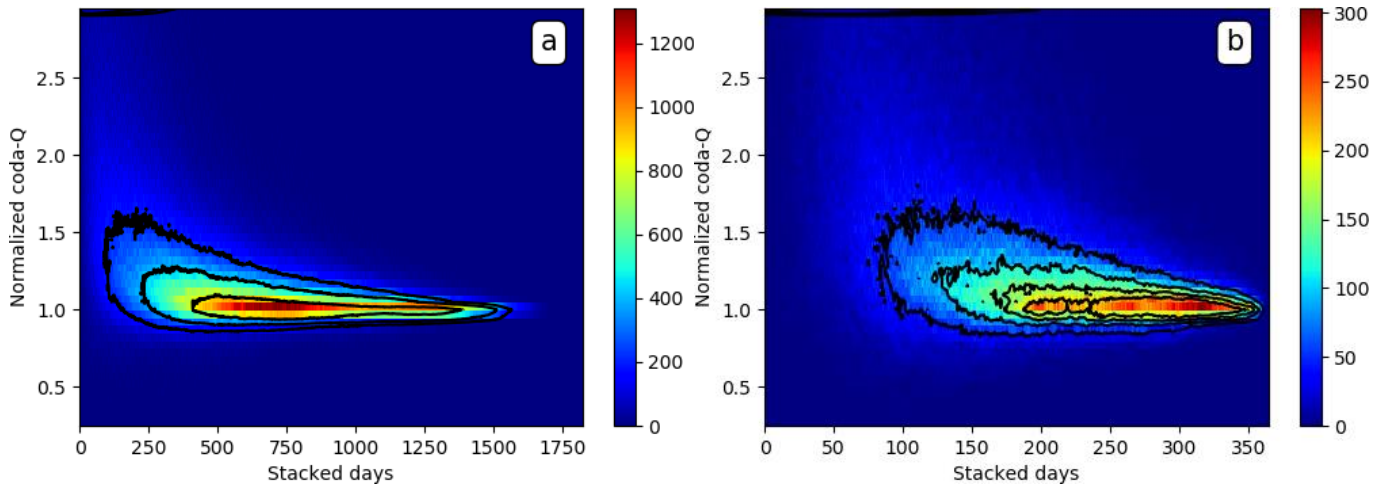


Figure 12: Coda-Q convergence as a function of the number of days stacked using a) the four-year dataset and b) the one-year dataset (station pairs for which less than 200 days are available are not shown) in the 5 s – 10 s period band. For each station pair we calculate coda-Q using an increasing number of days in the stack, and normalized with the coda-Q obtained using all days available for the station pair. Note that the four-year dataset has on average three years of daily correlations with coda-Q measurements for any given station pair. This Figure shows a systematic bias towards high coda-Q when averaging is insufficient.

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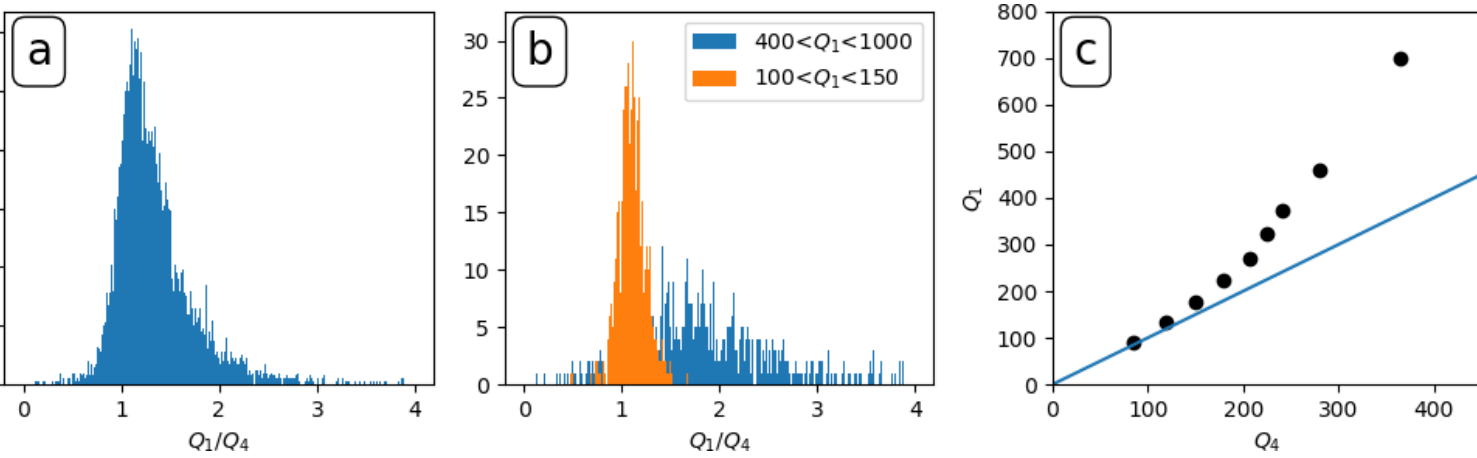


Figure 13: Coda-Q bias with time series length. a) Histograms of the ratio of coda-Q calculated with the one-year ( $Q_1$ ) and the four-year ( $Q_4$ ) dataset for identical station pairs. b) Same plot but using only data with low  $Q_1$  (orange) or high  $Q_1$  (blue). c) Based on separation into  $Q_1$  intervals (one year results, bins 0-100, 100-150, 150-200, 200-250, 300-350, 350-400, 400-600 and 600-1000), plot of the median of  $Q_1$  as a function of the median of  $Q_4$  using the same station pairs. The blue line corresponds equal  $Q_1$  and  $Q_4$ . With the simple increase as a function of  $Q_4$  we consider that high values of coda-Q may be overestimated, but that our results reflect contrasts between high coda-Q and low coda-Q.

## Supplementary material

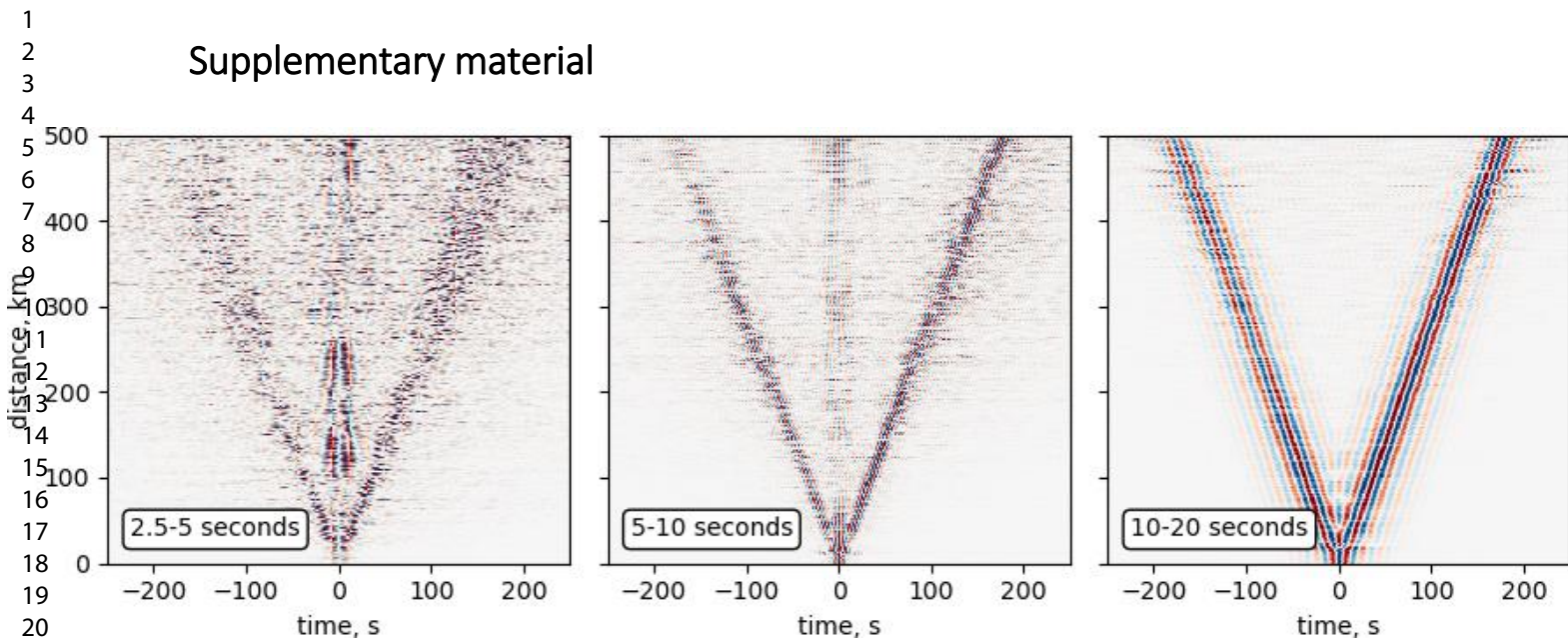


Figure S1: Seismic section of correlations in the 2.5 s – 5 s (left), 5 s – 10 s (center) and 10 s – 20 s (right) period bands, for the selected dataset (see Section 2.3). The traces are stacked in bins of 1 km and normalized by their maximum. All correlations have been oriented so that the causal part points away from 300° of azimuth; i.e. the direction which approximately corresponds to the dominant direction of the noise sources.

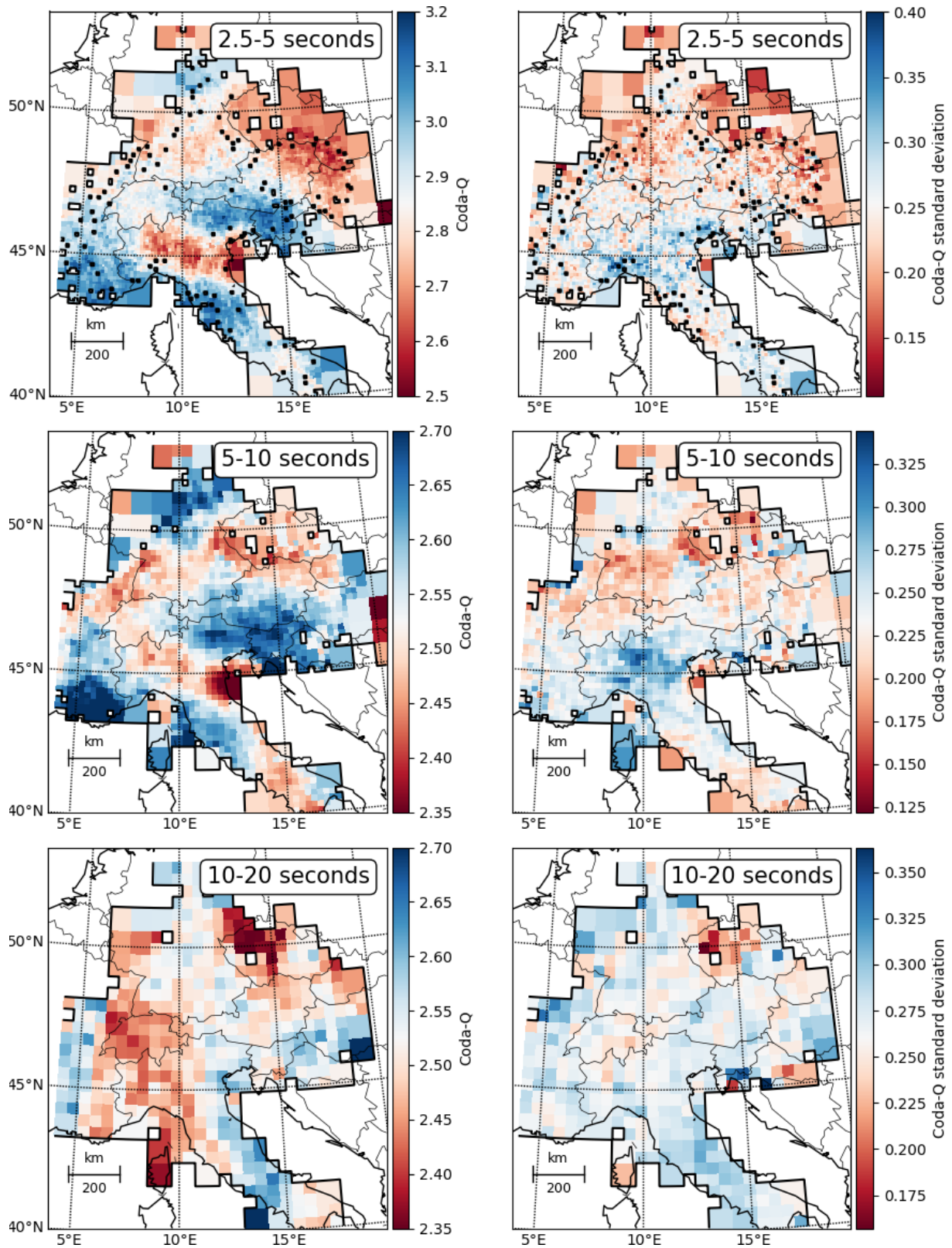


Figure S2: Map of log<sub>10</sub> of coda-Q (left) and its standard deviation in each cell (right). As the distribution of log(coda-Q) is not Gaussian in the cells, the standard deviation only has indicative value.

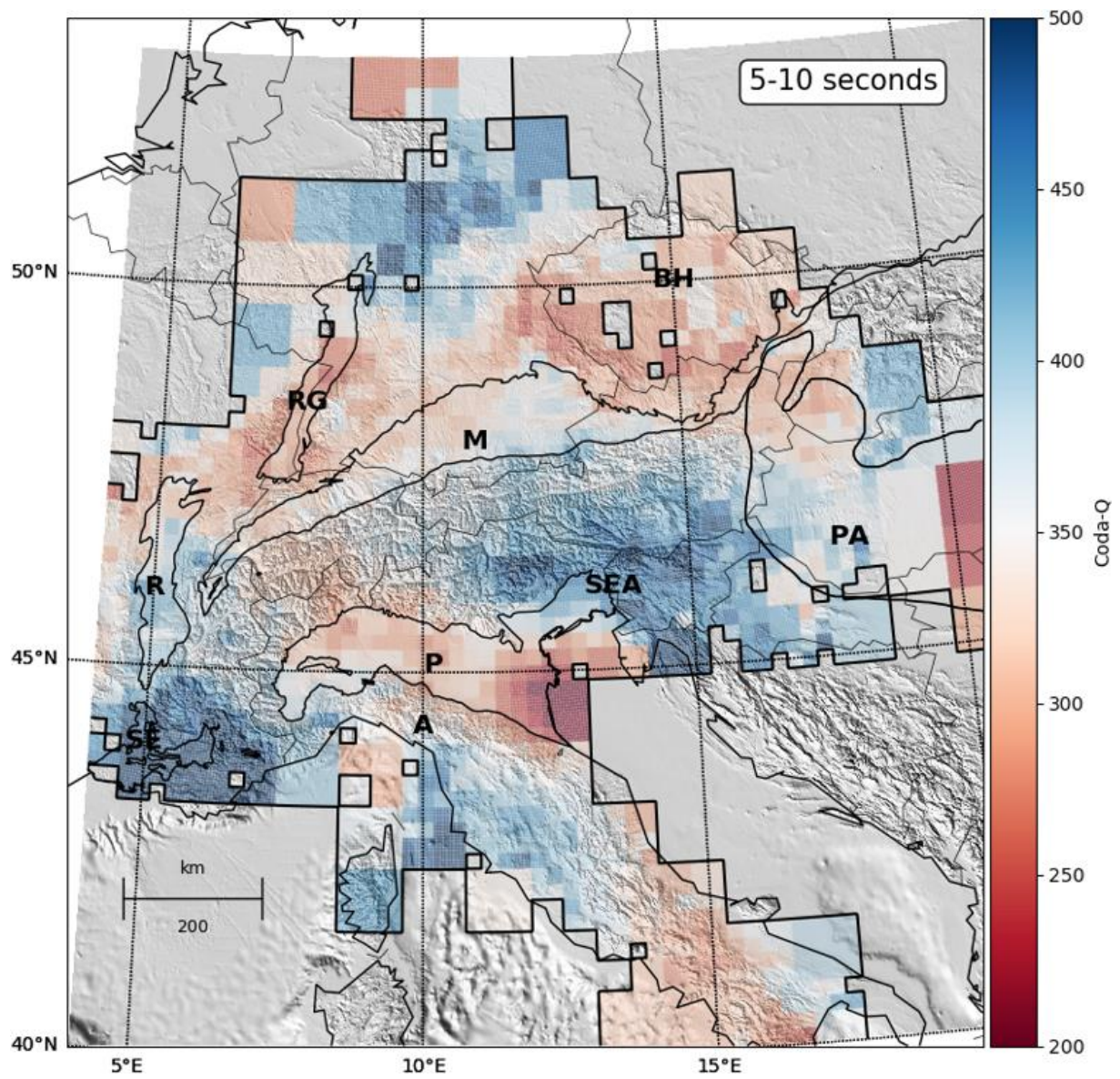


Figure S3: Map of coda-Q superposed to topography and main sedimentary basins.