

Rayleigh wave attenuation tomography based on ambient noise interferometry: methods and an application to Northeast China

Hongrui Peng¹ and Jiangtao Li^{1,2}

¹*School of Geodesy and Geomatics, Wuhan University, Wuhan 430079, China. E-mail: jiangtaoli@whu.edu.cn*

²*Hubei Luojia Laboratory, 129 Luoyu Road, Wuhan 430079, China*

Accepted 2024 March 20. Received 2024 March 17; in original form 2023 August 10

SUMMARY

Although ambient noise interferometry has been extensively utilized for seismic velocity tomography, its application in retrieving attenuation remains limited. This study presents a comprehensive workflow for extracting Rayleigh wave amplitude and attenuation from ambient noise, which consists of three phases: (1) retrieval of empirical Green's functions (EGFs), (2) selection and correction of amplitude measurements and (3) inversion of attenuation, site amplification and noise intensity terms. Throughout these processes, an 'asynchronous' temporal flattening method is used to generate high-quality EGFs while preserving relative amplitudes between stations. Additionally, a novel 't-symmetry' criterion is proposed for data selection along with the signal-to-noise ratio. Furthermore, 2-D sensitivity kernels are utilized to estimate the focusing/defocusing effect, which is then corrected in amplitude measurements. These procedures are designed to deliver reliable attenuation measurements while maintaining flexibility and automation. To validate the effectiveness of the proposed noise-based attenuation tomography approach, we apply it to a linear array, NCISP-6, located in NE China. The obtained results correlate reasonably well with known geological structures. Specifically, at short periods, high attenuation anomalies delineate the location of major sedimentary basins and faults; while at longer periods, a notable rapid increase of attenuation is observed beneath the Moho discontinuity. Given that attenuation measurements are more sensitive to porosity, defect concentration, temperature, melt and volatile ratio than seismic velocities, noise-based attenuation tomography provides important additional constraints for exploring the crustal and upper mantle structures.

Key words: Continental crust; Seismic attenuation; Seismic interferometry; Seismic tomography; Surface waves and free oscillations.

1 INTRODUCTION

Seismic interferometry, utilizing cross-correlation (CC) to retrieve empirical Green's functions (EGFs) from ambient noise, has become a routine technique in seismology (Shapiro *et al.* 2005; Weaver 2005). This technique has been successfully used in various applications, including surface wave traveltime tomography (e.g. Yang *et al.* 2007; Lin *et al.* 2008; Xu *et al.* 2013; Bao *et al.* 2015; Li *et al.* 2022), monitoring seismic velocity changes (e.g. Xu & Song 2009; Brenguier *et al.* 2014; Li *et al.* 2021; Mao *et al.* 2022) and even extracting seismic core phases to investigate Earth's inner structure (e.g. Lin *et al.* 2013; Wang *et al.* 2015). Those studies have demonstrated the validity of EGFs in providing crucial traveltime information for characterizing the elastic properties of Earth. In addition to seismic velocity, seismic attenuation, which reflects the anelastic property of Earth's media, is another significant parameter. The inversion of attenuation typically relies on measurements

of seismic wave amplitudes. However, the ability of EGFs to retain reliable relative amplitudes remains a subject of debate, and there is a need for appropriate methods to preserve and extract such data.

Theoretical analysis and numerical simulations by Weaver (2011, 2013) suggested that attenuation can be recovered from EGF amplitudes, even for non-fully diffuse noise fields, as long as they vary smoothly with location and direction. However, in the real-Earth situation, ambient noise-based surface wave attenuation tomography faces two main challenges. First, in the preprocessing procedure from original seismic noise records to stacked EGFs, it is crucial to preserve the relative amplitudes between station pairs. Some conventional signal processing procedures in noise-based velocity tomography, including one-bit normalization, running average normalization and spectral whitening (Bensen *et al.* 2007), exhibit strong non-linearity. Although those techniques contribute to the reconstruction of EGF phases and enhance the signal-to-noise ratio (SNR), theoretical studies (Weaver 2011), numerical simulations

(Zhou *et al.* 2020a) and comparisons with real earthquake signals (Viens *et al.* 2017) have demonstrated their distortion of the apparent attenuation of EGFs. Consequently, these approaches are unsuitable for retrieving amplitudes from ambient noise. To produce high-quality EGFs while preserving undistorted relative amplitudes, several novel processing methods have been developed recently, including temporal balancing (Weaver & Yoritomo 2018), asynchronous temporal flattening (Zhou *et al.* 2020a) and optimal processing schemes (Fichtner *et al.* 2020). Nevertheless, the rapid achievement of accurate correlation waveform and amplitude information still requires further exploration of preprocessing and stacking strategies.

Secondly, apart from intrinsic attenuation, numerous other factors also contribute to noise CC amplitudes. These factors include the site amplification, focusing/defocusing effect, noise directionality and intensity variations, seismic wave scattering, waveform dispersion, finite stacking duration, etc. These factors are non-negligible and can introduce biases to attenuation measurements. Several studies have attempted to disentangle attenuation from these factors. Prieto *et al.* (2009) and Lawrence & Prieto (2011) claimed that biases caused by source directionality can be disregarded, once measurements are averaged over a wide range of azimuths of station pairs. Under this assumption, they obtained reasonable attenuation models for South California and the western United States. However, Tsai (2011) argued that the assumption of noise coherency is not generally valid, and attenuation parameters estimated using Prieto *et al.* (2009)'s method may not be directly comparable to traditional attenuation measurements based on earthquake signals. Bowden *et al.* (2015, 2017) applied a wave front tracking approach, as used by Lin *et al.* (2012), to ambient noise correlation waveforms across the USArray and Long Beach dense array to obtain simultaneous measurements of attenuation and site amplification. This approach offers the advantage of accounting for focusing/defocusing effects accurately, but it typically requires dense 2-D arrays to construct the whole wave field. Liu (2015, 2022) and Zhou (2016) utilized the Two Station Method (TSM; Xie & Mitchell 1990) to estimate attenuation by calculating amplitude ratios of EGFs from linear triplets of stations. This method can partially mitigate the influences of noise directionality and site amplification, while the strict requirement of linear station triplets limits the ray coverage and resolution.

Despite facing those challenges mentioned above, ambient noise attenuation tomography holds great potential for providing relatively high-frequency attenuation measurements, which are often lacking in previous earthquake-based surface wave attenuation tomography. Hence, it may enhance the constraints on anelastic structure in the crust and upper mantle. Besides, similar to ambient noise velocity tomography, this method does not rely on non-uniformly distributed earthquake sources and can easily achieve a dense ray coverage, thus contributing to improved resolution.

This study aims to provide a comprehensive workflow for ambient noise attenuation tomography, which is applicable to real-Earth scenarios. Our methodology is based on Weaver's theoretical framework (2011, 2013). To obtain high-quality EGFs and more accurate amplitude measurements, we have adopted the asynchronous temporal flattening (ATF) method proposed by Zhou *et al.* (2020a) in the data preprocessing stage. Additionally, we propose utilizing the symmetry of causal and anticausal arrivals (t-symmetry) as an auxiliary criterion, along with SNR, to select reliable amplitude measurements. In order to mitigate the effect of focusing/defocusing, we estimate that effect between each station pair through the 2-D sensitivity kernel based on finite-frequency theory (Zhou *et al.* 2004; Bao *et al.* 2016) and subsequently correct the measured amplitudes.

Finally, we perform an iterative inversion to simultaneously determine the seismic attenuation, site amplification and noise intensity through a linear inversion system. The efficacy of this workflow has been assessed through an application to the linear array NCISP-6 located in Northeast China. The obtained attenuation profile corresponds well with geological structures and exhibits reasonable variation with frequency and depth.

Compared to previous works on ambient noise attenuation tomography methods, this study provides more detailed steps to help address some potential challenges in real dataset practices. Furthermore, compared to methods based on wave front tracking (e.g. Bowden *et al.* 2017) or power spectral density (e.g. Magrini & Boschi 2021), our method relies less on dense seismic arrays. Thus, our workflow can be easily applied to various regions with sparse seismic stations.

2 THEORETICAL BASIS AND DATA

2.1 Theoretical framework

Our approach is grounded in the theoretical derivation by Weaver (2011, 2013). According to this theory, in a non-fully diffuse noise field, the amplitude of the CC function is determined by the site amplification term s , noise field intensity B and attenuation coefficient α . In the 2-D condition, the amplitude of the narrow-band CC from site i to site j can be expressed as follows:

$$X_{ij} = 2s_i s_j B_i(\hat{n}_{i \rightarrow j}) \sqrt{\frac{2\pi c}{\omega_o |x_i - x_j|}} \exp(-\alpha |x_i - x_j|), \quad (1)$$

where s_i and s_j represent the site amplification terms at the two stations; $B_i(\hat{n}_{i \rightarrow j})$ is the ambient noise intensity at station i in the direction from i to j ; c is the wave velocity; ω_o is the frequency; $\sqrt{1/|x_i - x_j|}$ corresponds to the geometrical spreading; α is the average attenuation between the two stations. This expression is asymptotically valid for sufficiently large station separations and noise fields changing smoothly with direction and location (Weaver 2011).

Based on this surprisingly simple result, we can construct a linear inversion system relatively easily. By taking logarithms on both sides of eq. (1) and accounting for the variation of α , the formula can be expressed as

$$\ln(X_{ij}/G) = \ln s_i + \ln s_j + \ln B_i(\hat{n}_{i \rightarrow j}) - \int_{x_i}^{x_j} \alpha \, dx + C, \quad (2)$$

where G represents the geometrical spreading term, and C is a constant specific to a given wave speed and frequency. Considering that the Earth's surface is nearly spherical, we estimate G by

$$G = \left(R_0 \sin \left(\frac{R}{R_0} \right) \right)^{-1/2} \quad (3)$$

in which $R = |x_i - x_j|$, and R_0 denotes the Earth's radius, instead of the original form for the 2-D condition.

Through this inversion system, with measurements from a sufficient number of stations, the site terms, noise intensity, and attenuation can be retrieved. Additionally, Weaver (2011) further suggested that B , the noise field intensity, is not arbitrary; its variation with space and direction is governed by the radiative transfer equation (RTE; Turner & Weaver 1994; Ryzhik *et al.* 1996). In the case where the seismic traces between stations are not influenced by nearby internal scattering and sources, $B_i(\hat{n}_{i \rightarrow j})$ can be further represented

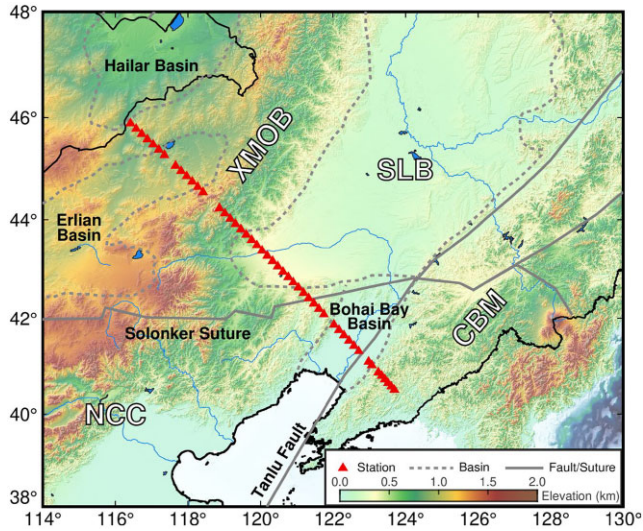


Figure 1. Distribution of stations and geological settings. Red triangles indicate the 48 NCISP-6 stations used in this study; grey dashed lines outline major sedimentary basins in NE China; grey solid lines represent some major faults and sutures in this region. (XMOB: Xing'an-Mongolia orogenic belt; SLB: Songliao basin; CBM: Changbai mountain range; NCC: North China Craton.)

by

$$B_i(\hat{n}_{i \rightarrow j}) = B_0(\theta) \exp \left(\int_{x_0}^{x_i} -2\alpha \, dx \right), \quad (4)$$

where $B_0(\theta)$ represents the noise intensity at the reference location x_0 in the same direction as i to j . If this assumption holds true in the real Earth condition, the number of unknown parameters in the inversion system could be further reduced. In this study, instead of using this formula directly, we independently invert for B in two opposite directions at every station and compare the variation trend of measured B to the theory expectation.

Numerical simulation tests based on this framework have already been conducted by Weaver (2013) and Zhou *et al.* (2020a) for a 1-D array setting and Zhou (2016) for a 2-D array setting. In those tests, non-isotropic noise fields with strong 'local' intensity from specific directions, variable local amplification terms and changing attenuations were considered. According to their results, as long as relative amplitudes between records in different stations are preserved, precise attenuation information can be retrieved from synthetic noise data.

2.2 Seismic data and NCISP-6 array

In this study, we use seismic data from the linear seismic array NCISP-6 (North China Interior Structure Project-Experiment 6) (Fig. 1). Deployed by the Institution of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS), this array operated between September 2007 to September 2008, consisting of 60 CMG-3ESP broadband seismometers in total. Due to data gaps in the records of certain stations, 48 out of 60 stations were ultimately used for CC and stacking, striking a balance between the stacking time length and the number of station pairs. The station interval is less than 20 km between most adjacent stations. This array serves as an ideal testbed for evaluating the ambient noise tomography method for two reasons. First, the stations are approximately distributed

along a great arc, closely resembling the 1-D numerical simulation setting used by Weaver (2013). Secondly, this array spans a long distance and traverses multiple prominent geological structures, such as the Bohai Bay Basin, Songliao Basin, Erlian Basin, Tanlu Fault and Solonker Suture. Those geological features can serve as valuable natural indicators for the evaluation of attenuation tomography results.

3 AMPLITUDE RETRIEVAL FROM AMBIENT NOISE

The workflow for extracting amplitudes from ambient noise and inverting for attenuation is illustrated in Fig. 2 comprising three distinct phases. This workflow provides detailed steps from data processing to inversion of attenuation, which interpolates several novel steps, such as (1) an asynchronous temporal flattening method for preprocessing; (2) a t-symmetry criterion for data selection; (3) the finite frequency theory for estimation and correction of the focusing/defocusing effect and (4) an iterative inversion framework for a joint constraining of attenuation, site amplification and noise intensity. The former two steps contribute to high-quality measurements while preserving the 'relative amplitudes' between station pairs, and the latter two distinguish attenuation from other factors. In this section, we will introduce the first and second phases, while the third phase will be presented in Section 4 along with the inversion results.

3.1 Data pre-processing and ATF normalization method

The basic procedures for retrieving EGFs share similarities with previous studies that extract traveltimes from ambient noise interferometry (e.g. Bensen *et al.* 2007). Those studies typically involve temporal normalization and spectral whitening to suppress undesired signals, such as earthquakes, and enhance the SNRs. However, many of those methods would impose non-linear modifications to individual station waveforms, leading to the distortion of relative amplitudes. Consequently, those non-linear methods should be prohibited in ambient noise attenuation tomography; and therefore, retrieving high-quality EGFs while preserving the relative amplitudes between different station pairs becomes more challenging. To address these issues, we use the asynchronous temporal flattening (ATF) normalization method proposed recently by Zhou *et al.* (2020a) during the CC and stacking processes. The steps to extract amplitude measurements from ambient noise are as follows. Given that our study primarily focuses on the Rayleigh waves, we only use Z-component records. However, the processing approach for other components would be similar.

(1) Raw waveform data are prepared individually for each station. After removing the mean value, trend, and instrumental response of each station, the data sequences are segmented into slices of equal length (1 d in this study). According to tests conducted by Zhou *et al.* (2020a), the ATF method is robust to different lengths of data slices, as long as they are not excessively long. The results of 2, 6 and 24 hr have shown minimal differences. Besides, it is necessary to remove instrumental response for amplitude-related studies, as the amplitude and phase response of instruments in different stations are unlikely to be identical, which can impact measured amplitudes.

(2) The waveform data underwent bandpass filtering by a Butterworth filter to isolate the frequency range of interest. In this study, for short-period Rayleigh waves, the lower cut-off frequency was set at 0.02 Hz and the higher cut-off frequency was set at 0.4 Hz.

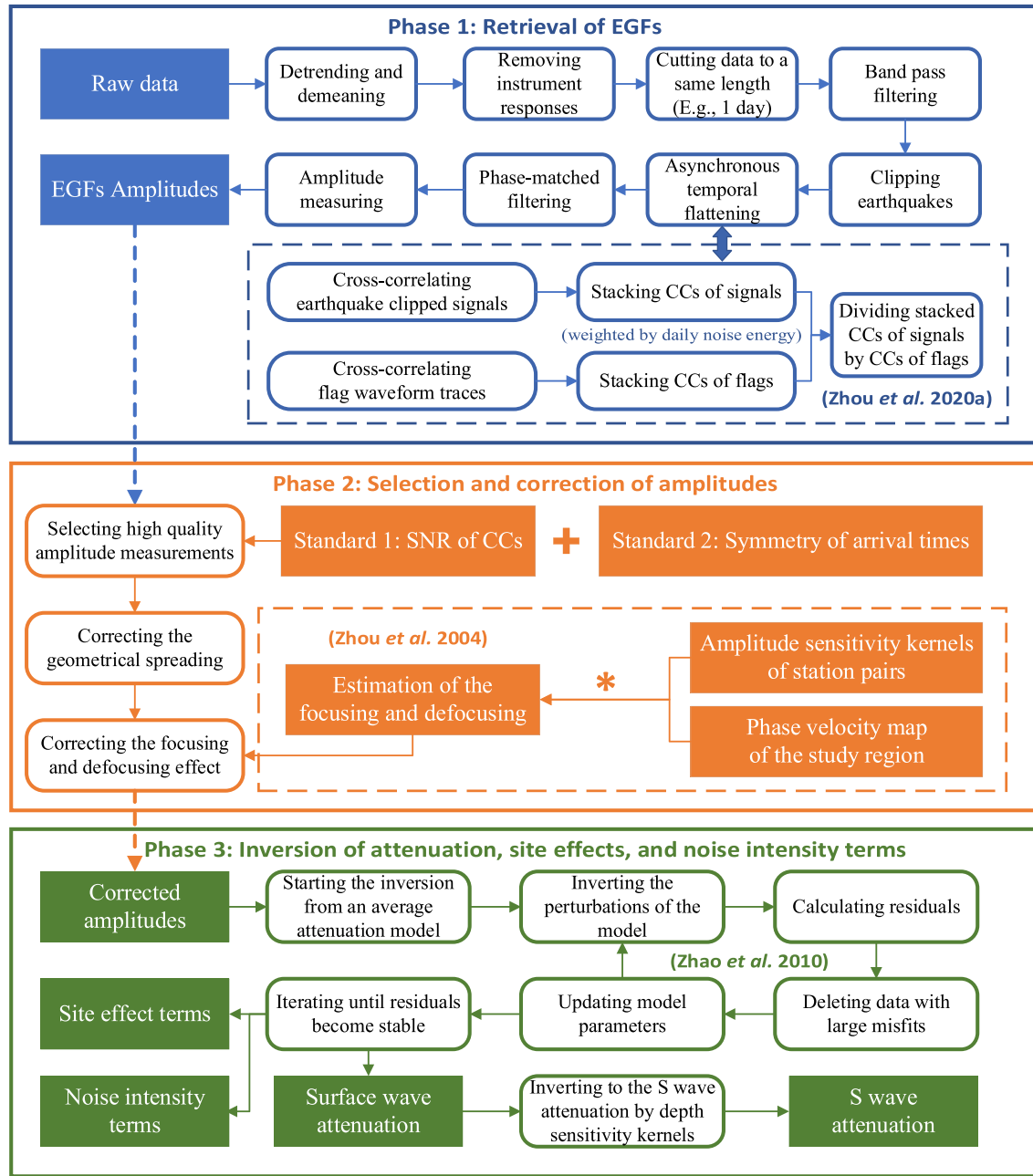


Figure 2. Schematic representation of the data processing and inversion workflow. Phase 1 (described in section 3.1) illustrates the pre-processing steps of single-station data, the asynchronous temporal flattening cross-correlation and stacking procedure, and amplitude measurement approaches; Phase 2 (Sections 3.2 and 3.3) encompasses the data selection and corrections processes; Phase 3 (Section 4.1) introduces the inversion of attenuation, site amplification, and noise intensity terms from the corrected amplitude measurements, as well as the conversion from surface wave attenuation in frequencies to *S* wave attenuation in depths (Section 5.1).

(3) Energetic waveforms are muted from the seismic noise records. Those waveforms are usually contributed from energetic localized sources, such as earthquakes and storms, forming abrupt spikes in continuous noise records, which tend to obscure ambient noise and slow down the convergence of EGFs. To remove those spikes, we calculate the RMS amplitude of each data slice and detect data points with absolute amplitudes more than five times of RMS. Subsequently, 10-min windows are placed around those abnormal data points, and the amplitudes of all points within those windows are set to zero. Throughout this muting process, a flag waveform is constructed for each data slice, consisting of binary

values (1 and 0) representing effective points and removed points, respectively.

(4) ATF normalization method. In traditional normalization methods, if an energetic spike signal is detected in one station, muting all stations' records for the same time window is necessary to preserve relative amplitudes. However, since spikes may appear at different times in different stations' records, this approach would largely reduce the amount of usable data. To overcome this difficulty, we adopted the ATF normalization method (Zhou et al. 2020a) during the CC and stacking procedure. After the same cross-correlating and then stacking, the stacked CC of signals $CC_s(t)$ is

divided point-by-point by the stacked CC of flag traces $CC_f(t)$, yielding the final EGF at each station pair. After CC and sufficient time for stacking, the $CC_f(t)$ contains no zeros point, so it can serve as the divisor. This process normalizes the effective stacking time of non-zero data for each data point in all EGFs, preserving undistorted relative amplitudes between different station pairs. Besides, similar to the temporal flattening (TF) method proposed by Weaver (2013), the stacking process utilizes the reciprocal of the total energy of each day's noise field as a weight for each day's CC. This weight can be represented by the root mean square (RMS) of amplitudes at all non-zero data points in all stations' records during 1 d. Compared to the equal-weighted raw stacking method, this temporal-weighted stacking approach further improves the quality of the EGFs.

According to synthetic and real data tests by Zhou *et al.* (2020a), the ATF normalization method yields relative amplitudes with minimal differences (less than 5 per cent) compared to the TF and raw stacking methods. Additionally, the ATF method effectively mutes energetic signals while retaining the most usable data, contributing to the quality of EGFs. This improvement is supported by our retrieved EGFs in NE China (Fig. 3). The results show considerable enhancement in EGFs obtained with the ATF method, as compared to both the TF and raw stacking methods. The ATF method exhibits reduced undesired 'noise' between and after the peaks of negative and positive sides. Moreover, the overall SNRs of the ATF method are substantially higher (Fig. 4), which demonstrates the crucial role of accurately removing energetic spikes in seismic records. However, though SNR is an effective tool for evaluating the overall quality of EGFs, it is noteworthy that only high SNR can not guarantee accurate EGFs (Fichtner *et al.* 2020). Besides, as discussed later in Section 3.2, it may lead to certain biases with path lengths in data selection and comparison.

(5) After the retrieval of EGFs, the amplitudes of the positive and negative lags, generated by noise signals from opposite directions, are extracted separately. First, the EGFs are filtered into narrow bands with cutoff frequencies set at 0.85 and 1.15 times the central frequency. Subsequently, a phase-matched filter (Herrin & Goforth 1977; Levshin & Ritzwoller 2001), defined by group velocity measurements, is applied to isolate the surface wave signals from undesired 'noise' signals. For amplitude measurements, we extract both the peak amplitude of the EGF envelop, and the RMS amplitude of signals within a signal window (three times of central period width) around the peak amplitude. Additionally, we calculate the RMS of the noise in an 800-s noise window occurring after the signal window, with a 400-s interval between the two windows. The SNR is defined as the ratio of the peak amplitude to the RMS amplitude of the noise, while the RMS amplitudes of signals are used later for the inversion of attenuation. Compared to the peak amplitudes, RMS amplitudes of signals are generally more robust and can mitigate the dispersion effect caused by frequency-dependent wave speeds, thereby providing more reliable amplitude measurements (Weaver 2013).

3.2 Data selection strategies

Due to the complexity of the real-Earth noise field, underground structures, and seismographs, some EGFs exhibit poor convergence and contain interference signals overlapping the surface wave signals. Hence, it is significant to carefully select the traveltime and amplitude information extracted from EGFs before inversion. In

this study, we apply several strategies to distinguish high-quality measurements from unreliable ones.

First, we use the SNR selection strategy, which is commonly applied in noise-based velocity tomography. Through tests of several SNR thresholds at different periods, it is observed that a high threshold (e.g. $\text{SNR} > 12$) is generally unsuitable for amplitude data selection. This is because the SNR is highly proportionate to the measured amplitudes (Fig. 5a), which tend to decrease with the increasing distances between station pairs. To assess the impact of different selection strategies on data distribution, we performed linear fitting on the data before and after selection. Since other terms in eq. (2) do not correlate to distance, the slopes of fitted lines can represent the approximated regional average attenuation factor (α). As shown in Fig. 5(b), a strict SNR threshold would reject more measurements in longer distances, and therefore, it might significantly impact subsequent attenuation measurements. Thus, for attenuation tomography, we recommend setting a relatively lower SNR threshold to ensure the stability of amplitude–distance distribution.

Furthermore, to discard more unreliable measurements, we propose a 't-symmetry' selection strategy based on the symmetry of causal and anticausal traveltimes (Fig. 6), with reference to Weaver & Yoritomo (2018) and Li *et al.* (2020). For each EGF, in addition to the SNR, we also measure the observed arrival times (t_L , t_R) corresponding to the peak amplitudes, and then calculate the observed velocities (V_L , V_R) by dividing the distance between the station pair by t_L or t_R . Additionally, a reference velocity (V_{ref}) is also determined based on the average group velocity of the study region at a specific central period. If the observed velocity of one lag deviates far from both V_{ref} and the observed velocity of the other lag (e.g. by more than 0.3 km s^{-1} in this study), the attenuation information derived from this lag is likely to be unreliable and should be rejected, even if its SNR is relatively high. In both Figs 5(c) and (d), α before and after selection are relatively close, which proves the 't-symmetry' strategy can maintain the stability of amplitude–distance distribution. By incorporating this 't-symmetry' strategy alongside a relatively lower SNR threshold, we can effectively exclude poor-quality amplitude data while avoiding bias to attenuation measurements (Fig. 5d).

Lastly, similar to previous velocity tomography studies (e.g. Shapiro *et al.* 2005), measurements with too short interstation distances should also be discarded. To summarize, we reject amplitude measurements with SNRs smaller than 4, with ΔV larger than 0.3 km s^{-1} (to both the V_{ref} and the observed velocity in the other lag), and with paths shorter than 2 wavelengths. These selection criteria help ensure the reliability of the amplitude measurements used in the subsequent attenuation tomography.

3.3 Correction of geometrical spreading and focusing/defocusing effect

Since the amplitude of the surface wave is influenced by various factors, it is crucial to separate them before or during the inversion of attenuation. If it is possible, separating those factors before inversion is more reasonable, which avoids the trade-offs of attenuation with other factors. In this study, the influence of geometrical spreading and focusing/defocusing effect are estimated and separated before the inversion, while site amplification and noise intensity terms are considered during the inversion. First, geometrical spreading (G) is estimated using eq. (3), as introduced in Section 2.1. In this section, we mainly focus on the correction of the focusing/defocusing effect.

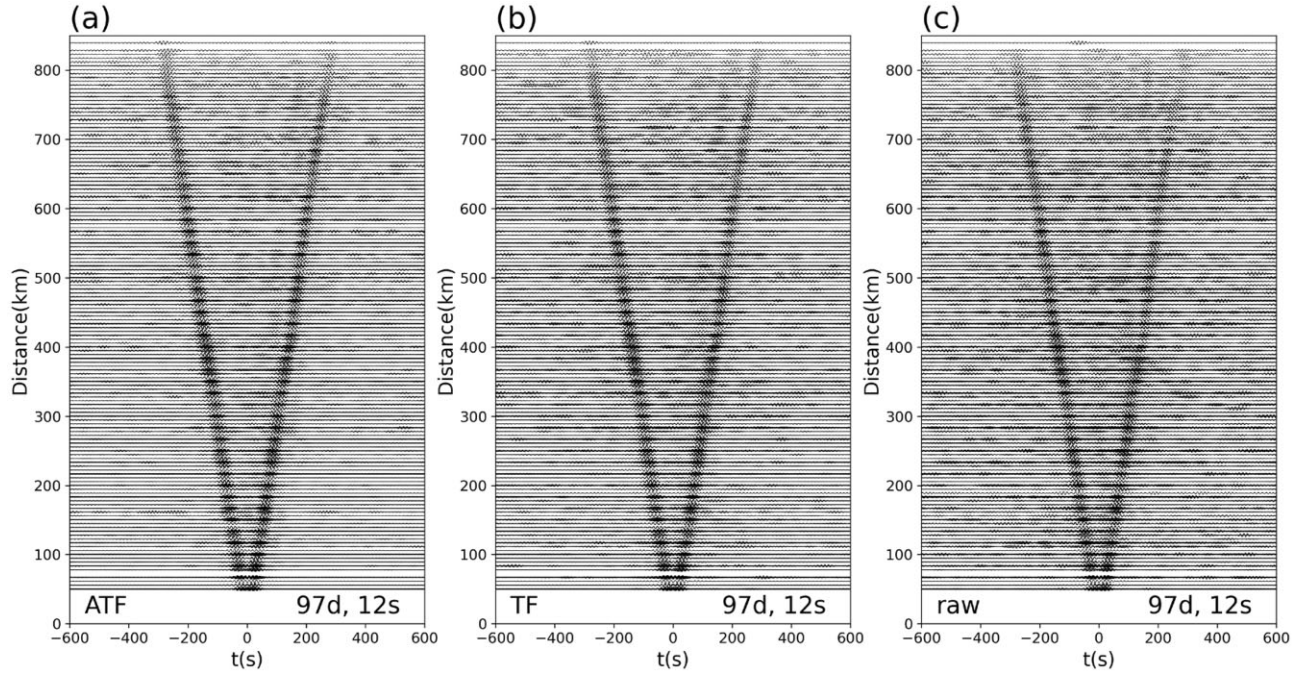


Figure 3. Retrieved EGFs at 12 s (narrow-band filtered to 10.2–13.8 s) after stacking 97 days' data using (a) asynchronous temporal flattening, (b) temporal flattening and (c) equal-weighted raw stacking method. The average SNRs of all EGFs are 19.63, 16.00 and 12.49, respectively.

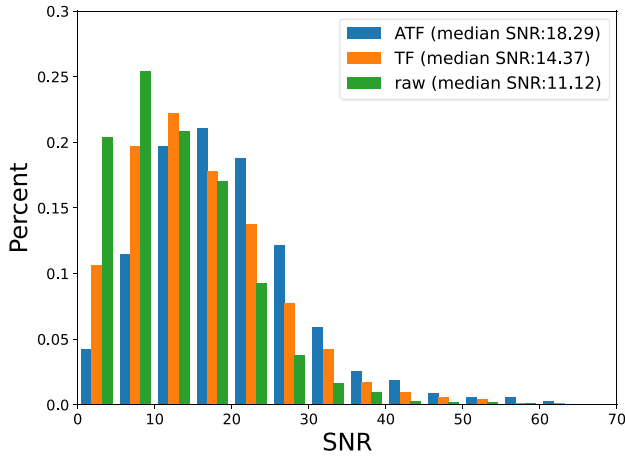


Figure 4. The histogram of SNRs of EGFs at 12 s from asynchronous temporal flattening (blue), temporal flattening (orange) and raw stacking (green) methods. The energetic spikes in seismic records were muted asynchronously in ATF, muted synchronously in TF, and left unmuted in the raw method. The SNR is defined as the ratio of the peak amplitude of the signal to the RMS amplitude of the noise in the noise window, and it is measured, respectively, for each lag of each EGF.

When a wave propagates through a media with elastic heterogeneity, its amplitude is influenced by the gradient of phase velocity perpendicular to the propagation path, known as the focusing and defocusing effect. Since the scale of phase-velocity heterogeneity is close to the seismic wavelength, the finite-frequency effects should be taken into account. Therefore, we applied finite-frequency theory based on the work of Zhou *et al.* (2004), which has also been compared with other methodologies by Dalton *et al.* (2014) and Bao *et al.* (2016). The computational complexity of this method is more manageable compared to finite-element synthetic tests. According to 2-D finite-frequency theory, the amplitude variation caused by the

focusing/defocusing effect for each frequency and source–receiver pair can be related to the frequency-dependent phase-velocity perturbation $\frac{\delta c}{c_0}(\omega, \theta, \phi)$ by:

$$\ln(A_F(\omega)) = \int_{\Omega} K_A^c(\omega, \theta, \phi) \frac{\delta c}{c_0}(\omega, \theta, \phi) d\Omega, \quad (5)$$

where ω is frequency, θ is latitude, ϕ is longitude and the integration is carried out over the unit sphere Ω . The 2-D sensitivity kernel for amplitude can be expressed as follows:

$$K_A^c(\omega, \theta, \phi) = -Re \left(\frac{2k^2 S' R'' e^{-i[k(\Delta' + \Delta'' - \Delta) + \pi/4]}}{SR\sqrt{8\pi k} |\sin \Delta'| |\sin \Delta''| / |\sin \Delta|} \right) \quad (6)$$

where k is the wavenumber, which varies with frequency ω ; Δ , Δ' and Δ'' denotes the angular path length of source-to-receiver, source-to-scatterer and scatterer-to-receiver, respectively. The source-radiation factor S and receiver-polarization factor R are assumed to be the same along source-to-receiver, source-to-scatterer and scatterer-to-receiver propagation paths. An example of a sensitivity kernel at the central period of 18 s is given in Fig. 7, and the sensitivity kernels are truncated to $\Delta' + \Delta'' - \Delta \leq 2\frac{3}{4}\pi$, which excludes energy arriving at the receiver outside of the measurement window (Dalton *et al.* 2014). Negative values in sensitivity kernels indicate that a positive phase-velocity variation ($\delta c/c_0 > 0$) at those locations would lead to a negative amplitude perturbation, and vice versa. Besides, a high-resolution phase-velocity model is also crucial for the estimation of the focusing/defocusing effect. In this study, we have used a regional phase-velocity map of NE China constructed by Guo *et al.* (2016). To balance computational efficiency and accuracy, this approach did not take velocity heterogeneity's impact on the sensitivity kernel itself into account, which needs wavefield simulations for each station and frequency.

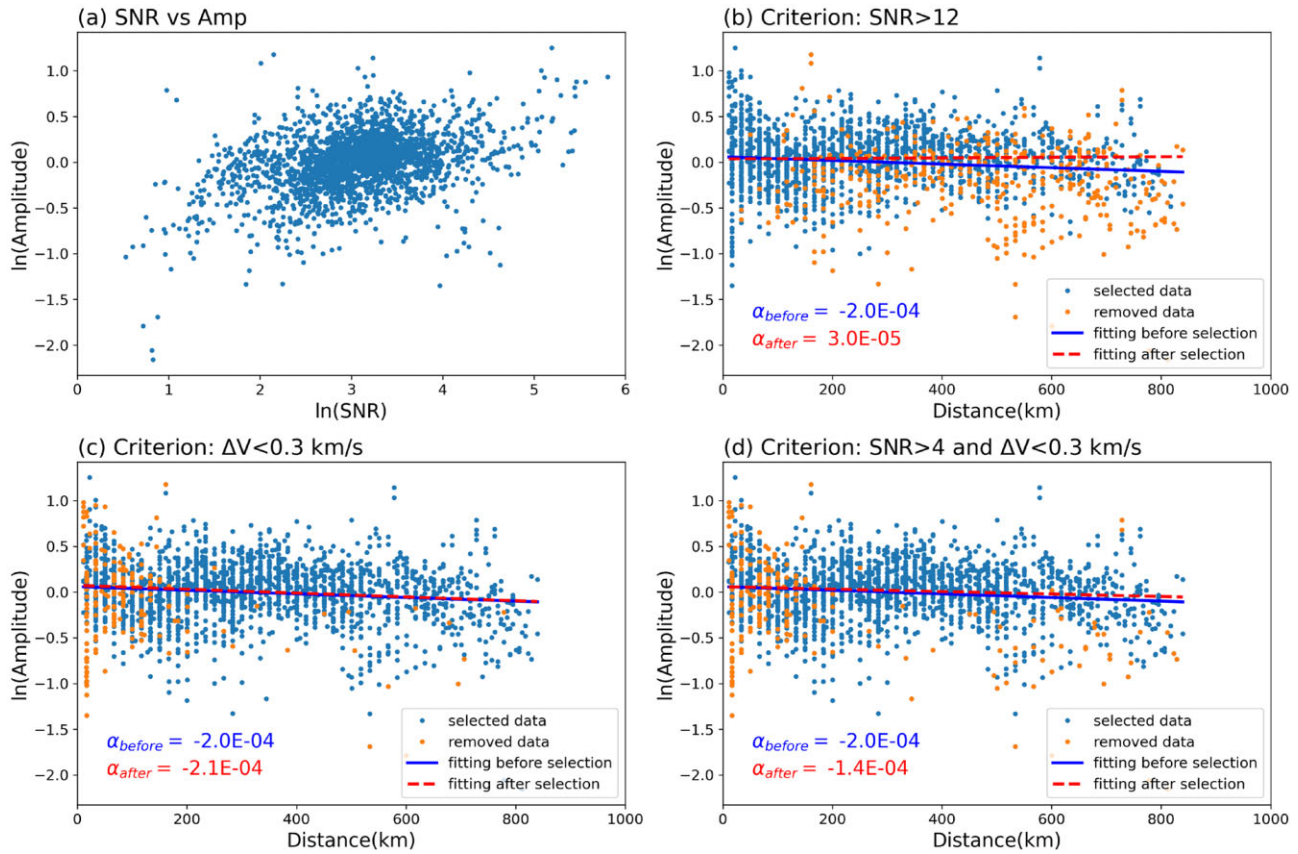


Figure 5. The variation of RMS amplitudes of EGFs at 12 s (a) with SNRs, and (b–d) with distances of station pairs. In (b–d), the blue dots represent the selected amplitude measurements, while the orange dots represent the removed measurements after applying different data selection criteria. The linear fit before (solid blue lines) and after (dashed red lines) data selection are also shown with the slopes (α). Note that the amplitudes have been corrected for geometrical spreading.

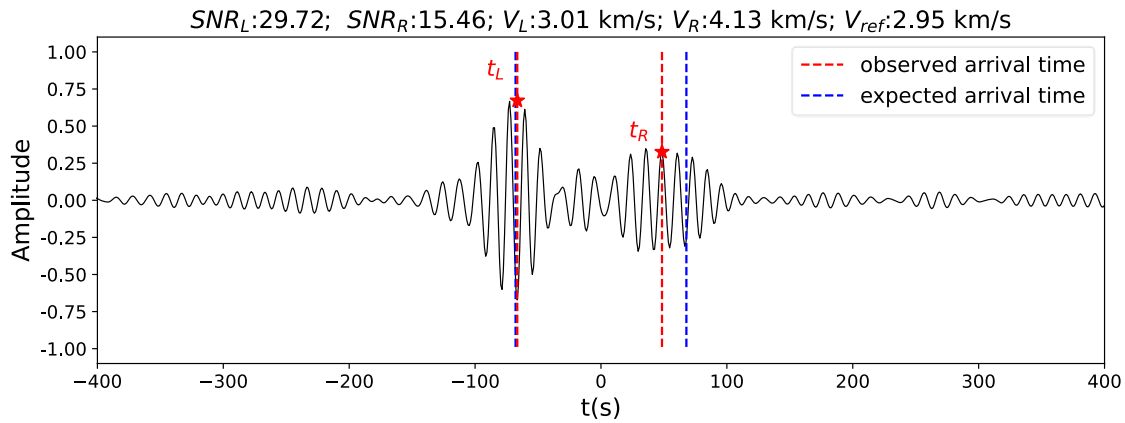


Figure 6. Example of data selection based on the retrieved EGF at 12 s of the station pair NE43 to NE55. The SNR (SNR_L , SNR_R) and observed velocity (V_L , V_R) are measured on both lags. In this example, the amplitude measurement from the positive lag is rejected due to the large deviation of V_R from both V_L and regional reference group velocity (V_{ref}). The red and blue dashed lines represent the observed and expected arrival time, respectively, and the red stars highlight the peak amplitudes.

To assess the accuracy of the finite-frequency theory method in estimating the focusing/defocusing effect, we conducted a comparison with synthesized amplitude measurements, which were calculated by the SPEC2FEM2D wave propagation solver. Based on the spectral element method, SPEC2FEM2D can simulate realistic seismic wave propagation in inhomogeneous velocity structures,

and the focusing/defocusing effect can be accurately recorded in its simulated waveforms. Fig. 8 establishes a positive correlation between the estimations from both methods across all periods, though there is a slight discrepancy between them. Besides, we observed that shorter periods and longer propagation paths tend to result in larger amplitude perturbations, consistent with previous findings

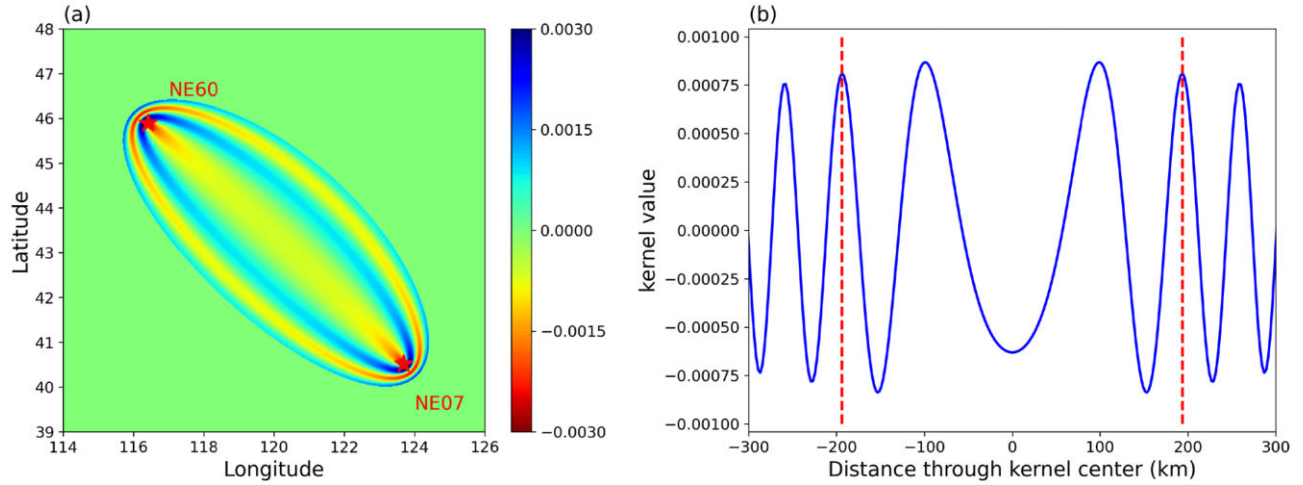


Figure 7. (a) A sample of 2-D sensitivity kernel for amplitude at the central period of 18 s between station NE07 and NE60. The kernel is truncated to $\Delta' + \Delta'' - \Delta \leq 2\frac{3}{4}\pi$. (b) Variation of kernel value along the middle of sensitivity kernel, depicted by the blue curve. For illustration, the blue curve is determined for a wider kernel, which is then truncated to the narrow kernel in (a) at the width indicated by the red dashed lines.

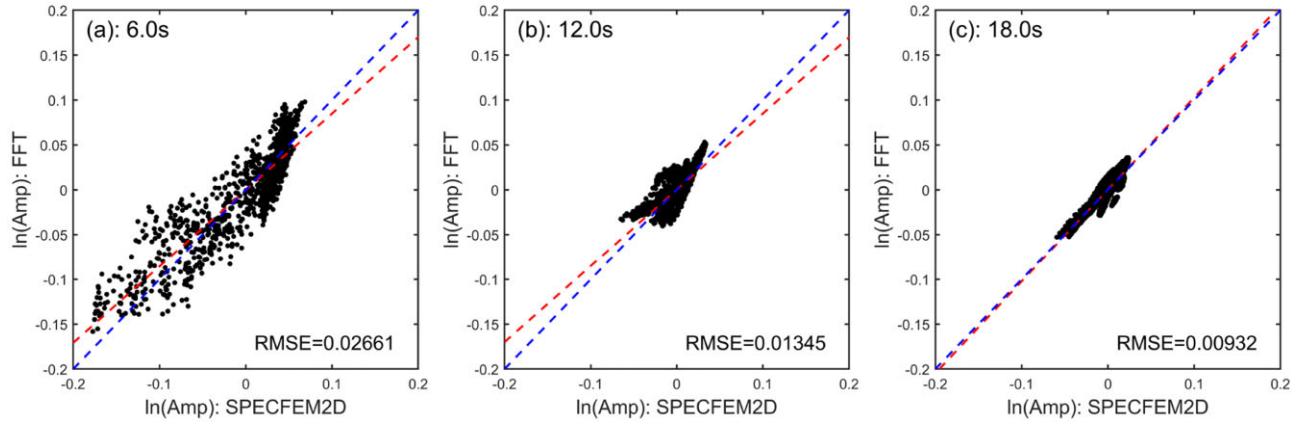


Figure 8. Comparison of estimated amplitude perturbation caused by the focusing/defocusing effect for all station pairs at different central periods: (a) 6.0 s, (b) 12.0 s and (c) 18.0 s. The root mean square errors (RMSE) between estimations from the finite-frequency theory method and SPECFEM2D are also shown. Red dashed lines are the best-fitting lines, calculated with linear regression, and the blue dashed lines are diagonal lines for comparison.

by Dalton *et al.* (2014). Across this array, the overall influence of the focusing/defocusing effect is not strong, likely due to the relatively short array length (<850 km) and ray paths passing through similar geological structures along the array. The discrepancies between the two estimation methods may be partially caused by the approximation of sensitivity kernels. However, due to the small overall influence of the focusing/defocusing effect, we consider the discrepancies to be acceptable, which have minimal impact on the subsequent attenuation inversion process.

4 INVERSION OF ATTENUATION, SITE AMPLIFICATION AND NOISE INTENSITY

4.1 Inversion method

After the selection and correction of amplitude measurements, data are now prepared for the final inversion process. As mentioned above, for ambient-noise-based attenuation tomography, it is essential to simultaneously consider the site amplification and noise intensity terms in the inversion framework. To ensure the stability of the solutions, we construct an iterative inversion system, similar

to that proposed by Zhao *et al.* (2004, 2010). Assuming attenuation coefficient α , site amplification S , and noise intensity term B can be separated into background components (α_0 , S_0 , B_0) and perturbations, eq. (2) can be reformulated as:

$$\ln(X_{ij}/G) = (\ln S_{i0} + \delta \ln S_i) + (\ln S_{j0} + \delta \ln S_j) + (\ln B_{i0}(\hat{n}_{i \rightarrow j}) + \delta \ln B_i(\hat{n}_{i \rightarrow j})) - \int_{x_i}^{x_j} (\alpha_0 + \delta \alpha) dx + C. \quad (7)$$

The relationship between α and quality factor Q is:

$$\alpha = \frac{\pi f}{U Q}, \quad (8)$$

where f is the frequency of the wave, and U is the group velocity. In this study, an averaged U along this array for each frequency is utilized, which was calculated from the regional velocity model by Guo *et al.* (2016). Then, taking differentiation on both sides of eq. (8), we obtain:

$$\delta \alpha = -\frac{\pi f}{U Q_0^2} \delta Q. \quad (9)$$

To represent the discrepancy between the observed and model-predicted amplitudes, we introduce the residue h :

$$h = \ln(X_{ij}/G) - \ln S_{i0} - \ln S_{j0} - \ln B_{i0}(\hat{n}_{i \rightarrow j}) + \int_{x_i}^{x_j} \alpha_0 dx - C. \quad (10)$$

Substituting eq. (8), eq. (9) and eq. (10) into eq. (7), we replace $\delta\alpha$ with δQ and obtain:

$$h = \delta \ln S_i + \delta \ln S_j + \delta \ln B_i(\hat{n}_{i \rightarrow j}) + \frac{\pi f}{U Q_0^2} \int_{x_i}^{x_j} \delta Q dx. \quad (11)$$

Thus, the complete inversion system, which consists of multiple ray paths, can be represented as:

$$H = A \begin{bmatrix} \delta Q \\ \delta \ln S \\ \delta \ln B \end{bmatrix}, \quad (12)$$

where H is a vector of the residues between measurements and model predictions, and A is a coefficient matrix that links the perturbations of model parameters to H . Additionally, we parametrize Q into 30 nodes using splines and assume that B varies for the SE and NW directions at each station. As A contains coefficients with different scales for different model parameters, we use a preconditioned matrix to improve the convergence speed of the solution (Xu & Song 2010; Zhou *et al.* 2020b).

Based on eq. (12), we initiate the inversion with a regional-averaged Q model and iteratively solve the perturbation of Q value, site amplification, and noise intensity terms by minimizing the norm of residual vector H . During this process, we constrain the sum of site amplification perturbations to zero to avoid the trade-offs between the mean value of site amplification and noise intensity terms, and we also discard data with misfits larger than 3.5 times the standard deviation of residuals. The iteration continues until the residuals become stable in successive iterations. Such an inversion scheme offers an opportunity to regulate the variation of Q with moderate damping and smoothing factors, thereby avoiding the presence of unrealistically large or negative Q values in the solution. In this study, we used a linear least-square solver from MATLAB, the lsqin, to solve this inversion problem, which can incorporate linear constraints easily.

To prove the reliability of the inversion method, we performed synthetic tests based on the real path coverage of several different periods (e.g. 6, 12 and 18 s, in Figs S1–S3). We generate the input attenuation models by a cosine function, whose wavelength is 150 km. The $\ln(S)$ terms are generated randomly between -0.5 and 0.5 , and $\ln(B)$ for two different directions are increased or decreased with distance from -0.5 to 0.5 , with a small random variation being added. The synthetic amplitudes are generated from those predefined model parameters based on eq. (2), with 5 per cent random noise. As shown in Figs S1–S3, most model parameters are recovered successfully, except those attenuation terms at the edge of the seismic array, where ray path coverage is sparse and in a single direction. Such a phenomenon has also been reported and discussed by Weaver (2013). In addition, due to the deletion of ray paths shorter than two times the wavelength, the $\ln(B_{NW})$ and $\ln(B_{SE})$ are not constrained near the SE and NW edge of the array, respectively. Nevertheless, the overall accuracy of inverted model parameters indicates the trade-off between different terms

is limited. Our ray coverage and inversion method are adequate to constrain the local attenuation structure stably.

Finally, we obtained frequency-dependent Q values, site amplification, and noise intensity terms for 33 individual periods between 6 and 22 s, with a 0.5 s interval. The number of ray paths used in tomography, after data selection, is shown in Fig. 9(a), with over 1100 paths for every period. According to Fig. 9(b), the data variance reduced substantially after the inversion at all periods, reaching a maximum reduction of 84.8 per cent at 9.5 s, and a minimum reduction of 46.5 per cent at 16.5 s.

4.2 Attenuation tomography profile

Fig. 10(a) shows the obtained Rayleigh wave attenuation profile beneath the NCISP-6 array in Northeast China. To depict the rapidly changing attenuation in short periods more clearly, a zoomed-in profile, Fig. 10(b), is also plotted, with a smaller interval (0.2 s) between the central periods of successive narrow bands. This profile traverses several major faults and basins across the North China Craton (NCC), Songliao Basin (SLB) and Xing'an-Mongolia Orogenic Belt (XMOB), exhibiting apparent variations in Q values among different geological structures. Similar to Rayleigh wave velocity, Rayleigh wave attenuation at longer periods is generally sensitive to structures at greater depths. At short periods between 6 and 8 s, particularly at 6 s, pronounced high attenuation anomalies are observed below the Bohai Bay Basin and Erlian Basin, corresponding to thick sedimentary layers in those regions. In contrast, the section across the Songliao Basin shows relatively weak attenuation, possibly due to the shallow sedimentary layer at the corner of this basin (Li *et al.* 2016). At intermediate periods ranging from 8 to 14 s, the attenuation becomes much weaker, which is most notably under the Songliao Basin, while relatively higher attenuation is still observed beneath the Tanlu Fault and Solonker Suture. Finally, at longer periods above 14 s, the attenuation gradually increases under the NCC and XMOB, while a continuous low attenuation remains under the SLB. Overall, the attenuation profile shares similar large-scale features with the phase velocity profile interpolated from the model by Guo *et al.* (2016) (Fig. S4). However, some additional anomalies related to faults and high-temperature structures are more clearly presented in attenuation tomography, which we will further discuss in Section 5.1.

To further investigate the frequency dependence of Rayleigh wave attenuation, we calculate the mean $1/Q$ across 33 discrete narrow period bands (Fig. 11), which is more robust than the $1/Q$ measured in any specific location. In the period between 6 s and 10 s, the $1/Q$ decreases rapidly, with 10 s acting as a turning point, after which the $1/Q$ starts to gradually increase. This trend suggests that the middle crust generally exhibits lower attenuation compared to the upper crust, the lower crust, and the upper mantle in the study region. As shown in Fig. 11, our measurements are very close to the ones by Zhou *et al.* (2020b) and Yang *et al.* (2004) at 10 and 20 s, which are based on earthquake signals. However, due to the lack of previous noise-based attenuation tomography results near NE China, we chose two results measured in the continental US for comparison. The averaged $1/Q$ of the US by Bowden *et al.* (2017) is lower but still comparable to our result, while the result of the West US by Magrini & Boschi (2021) is significantly larger. Even though the average crustal thickness of the western US and NE China is close, the difference between regional structures and specific methods may lead to a discrepancy between attenuation results. Therefore, we emphasize the large spatial variation and potential uncertainty

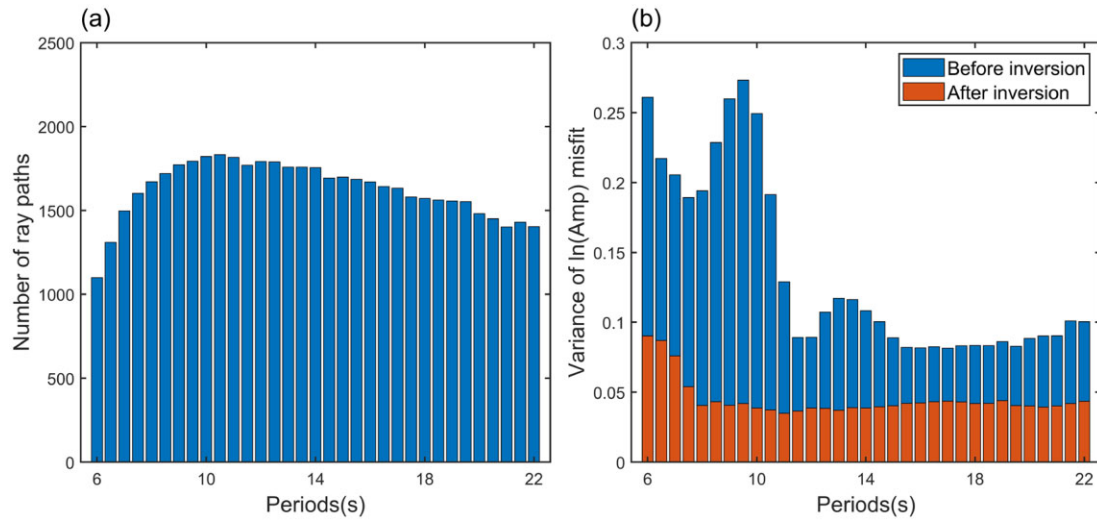


Figure 9. (a) Number of ray paths used in attenuation tomography at each period. (b) Comparison of the data variance (before inversion) and residual variance (after inversion) at each period. Note that the amplitude before inversion has been corrected for geometrical spreading and the focusing and defocusing effect.

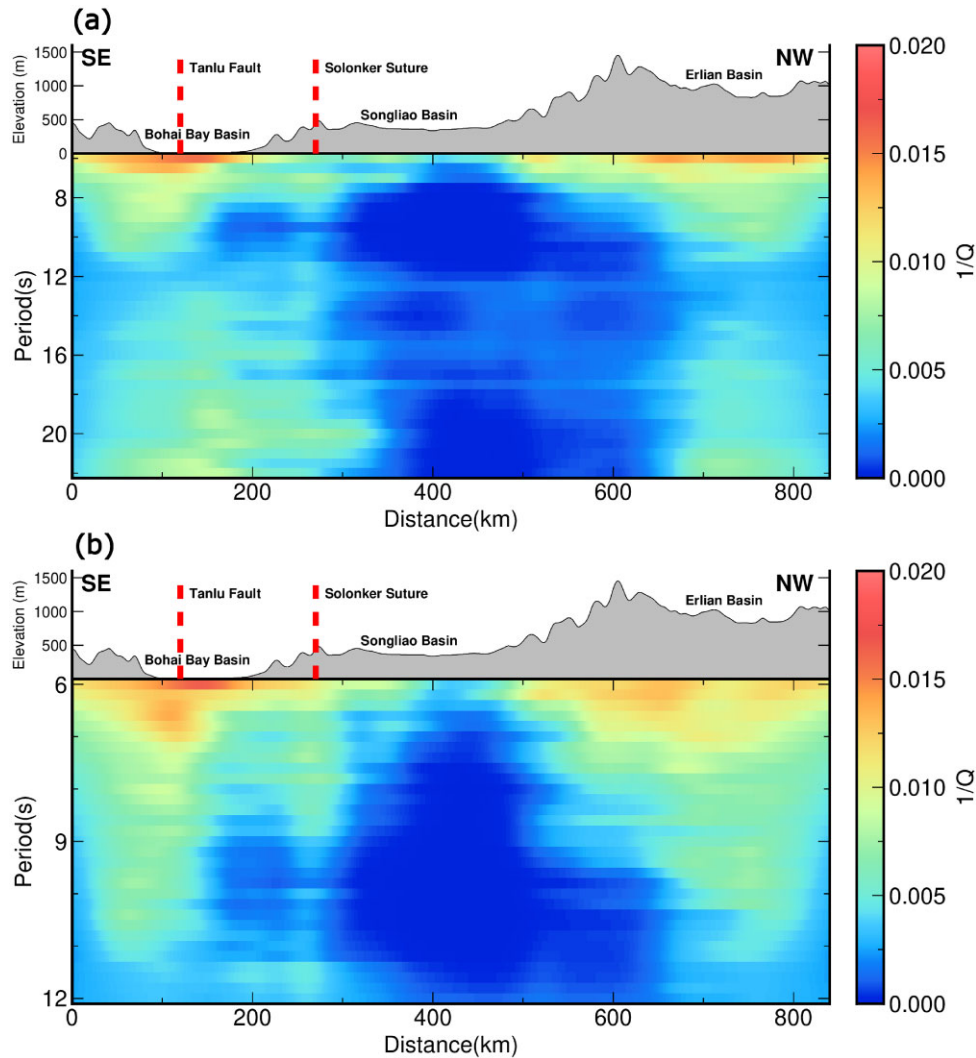


Figure 10. (a) Profile of Rayleigh wave attenuation, across periods from 6 to 22 s. (b) Zoomed-in profile, across periods from 6 to 12 s, with a smaller interval (0.2 s) between the central periods of successive narrow bands. Topography and geological elements are illustrated, with red dashed lines indicating the locations of major faults and sutures.

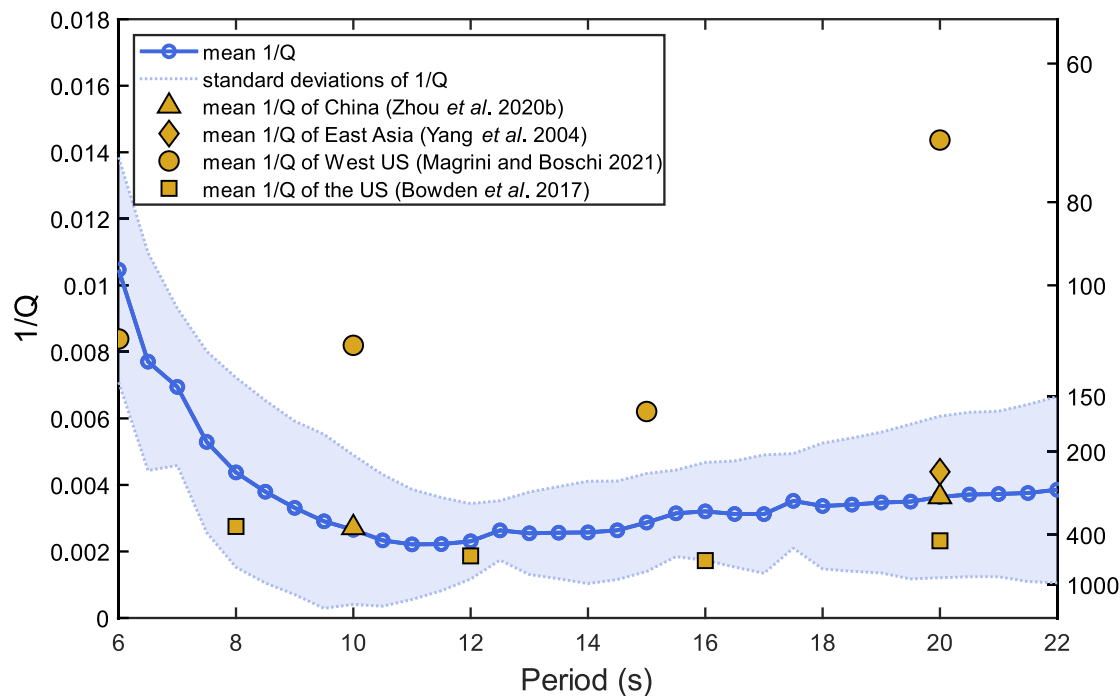


Figure 11. Average Rayleigh wave attenuation under NCISP-6 array at periods between 6 and 22 s. Mean values and standard deviations of $1/Q$ are indicated by blue dots and dashed lines, respectively. Average measurements from previous studies (i.e. Yang *et al.* 2004; Zhou *et al.* 2020b) are represented by yellow triangles. Note that some of those measurements were originally represented by attenuation coefficient α , which was converted to Q using regional Rayleigh wave group velocity maps (i.e. Shen & Ritzwoller 2016; Shen *et al.* 2016).

of attenuation measurements, which require careful consideration when analysing and using models. Nevertheless, the estimated Q_0 for NE China is around 400 (Mitchell *et al.* 2008), which can represent the attenuation properties of the entire crust and demonstrate the validity of our results.

4.3 Site amplification and noise intensity

Additionally, we also invert for the site amplification and noise intensity at different stations and periods. As shown in Fig. 12, the logarithms of site amplification terms are generally close to zero and vary smoothly with periods. Notably, distinct differences in the trend of variation can be observed among different geological blocks. At short periods (< 8 s), the mean site term in the NCC and XMOB is slightly higher than that in the SLB, especially around the Bohai Bay Basin and Erlian Basin (Fig. 12e). At the intermediate periods (9–13 s), the site terms gradually decrease from the east side to the west side (Fig. 12f). However, at longer periods, a reversal of lateral features is evident, with an overall higher value in the XMOB compared to the NCC and SLB (Figs 12g and h). According to Bowden *et al.* (2017), the site amplification is sensitive to the seismic velocity beneath the station. At short periods, surface waves experience amplification when propagating into low-velocity sedimentary basins. However, for longer periods, when Rayleigh waves become partially sensitive to the upper mantle material, areas with thinner crust encounter the high-velocity mantle earlier, resulting in lower site amplification. Thus, the retrieved site amplification terms are reasonably correlated with both the locations of sedimentary basins and the increase in Moho depth from the SLB to XMOB. Site amplification plays a crucial role in ground motion prediction and seismic hazard mitigation. For a more comprehensive analysis

this term, please consult the works of Bowden & Tsai (2017) and Chen *et al.* (2018).

Based on the linear array, we perform inversion for two different noise intensity terms, B_{SE} and B_{NW} , corresponding to noise signals from opposite directions, SE and NW, respectively. The noise intensity terms and their variation trends at four example periods are shown in Figs 13(a)–(d), where distance corresponds to station locations ranging from SE to NW. It can be observed that both $\ln(B_{SE})$ and $\ln(B_{NW})$ exhibit linear trends with distances, though the mean values and slopes of $\ln(B_{SE})$ and $\ln(B_{NW})$ vary significantly across different periods. At periods between 6 and 12 s, which coincide with the secondary microseism band, the noise intensity from the SE direction is stronger than that from the NW direction. Conversely, at periods above 12 s, around the primary microseism band, the relationship reverses (Fig. 13e). Regarding the slopes of variation trends, $\ln(B_{SE})$ holds negative slopes, indicating that it tends to be larger in stations closer to the SE side, while $\ln(B_{NW})$ holds positive slopes at periods between 7 and 14 s and negative slopes at others. The observed variation of noise intensity in this study deviates far from the variation trend expected in a noise field with no or weak internal scatterings and sources, as proposed by Weaver (2011, 2013). Possible reasons for the deviation include noise sources from off-line directions and energy redistribution by backscattering in the near field, though further research based on 2-D arrays is still required for definitive interpretations. Therefore, a direct application of eq. (4) to reduce the number of noise intensity terms might not be valid in the real-Earth situation, where the variation trend of B is more complex due to the variability of media and sources. For 2-D array conditions, without any prior constraint, a direct inversion of all noise intensity terms at every station and direction can be challenging. Consequently, under that circumstance, noise attenuation tomography should be based on a precise model

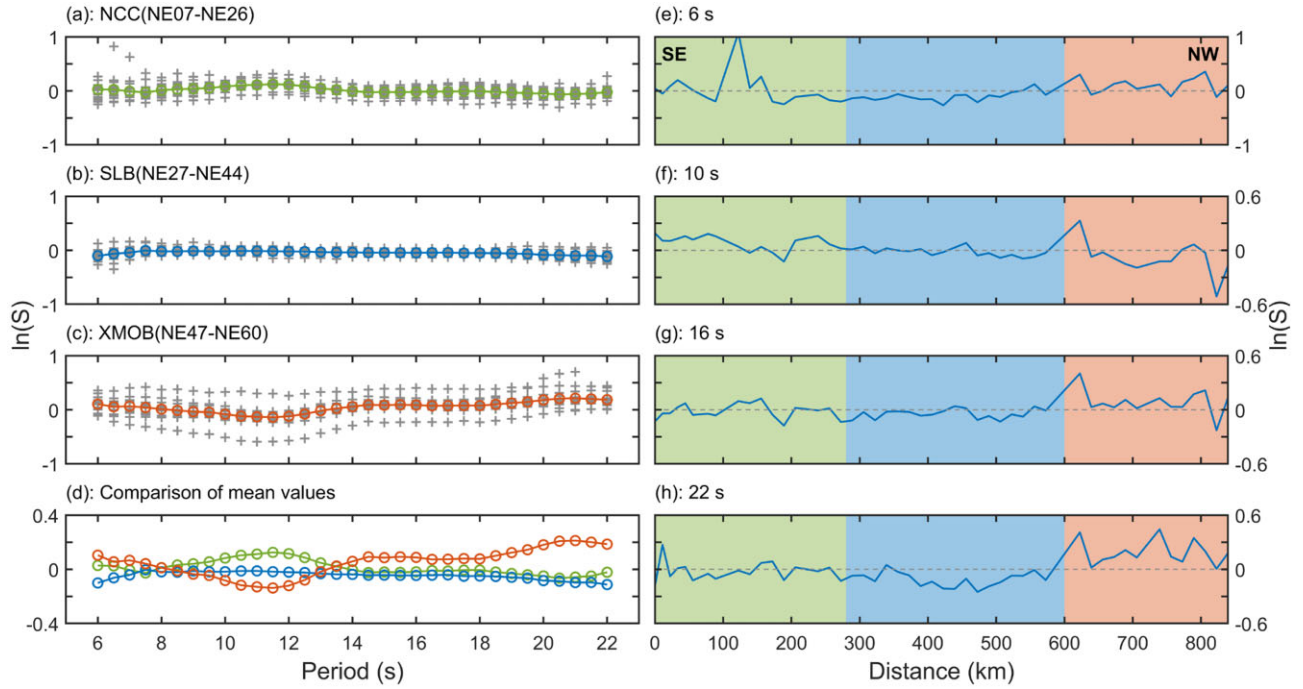


Figure 12. (a–c) The logarithms of site amplification terms at different stations within the NCC, SLB and XMOB, respectively. The coloured lines represent the mean site effect terms in each geological block. (d) Comparison of mean site effect terms among the above blocks. (e–h) Site effect terms of all stations at 6, 10, 16 and 22 s. The background colours delineate the ranges of the NCC (green), SLB (blue) and XMOB (orange).

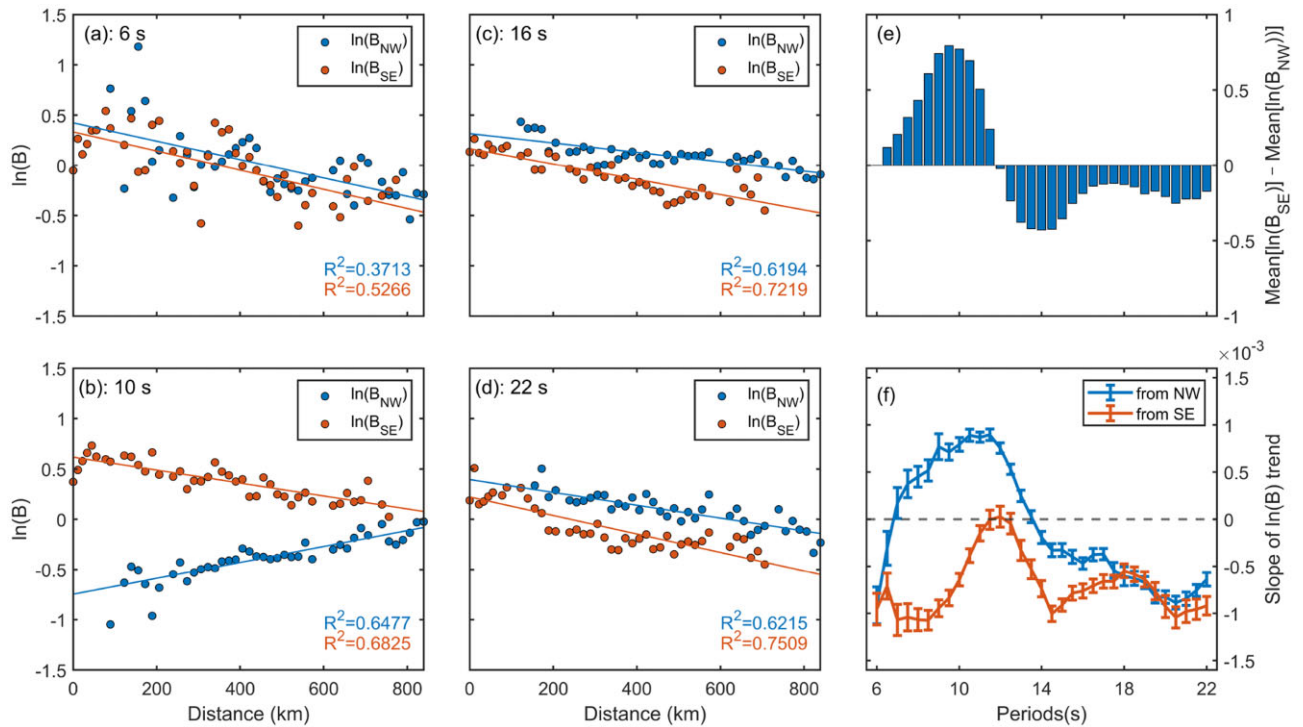


Figure 13. (a–d) The logarithms of noise intensity terms in different stations and directions at 6, 10, 16 and 22 s, along with the corresponding linear fitting trends, and R -squared values. The horizontal axis, 'Distance', corresponds to station locations from SE to NW. (e) The differences between the mean values of $\ln(B_{SE})$ and $\ln(B_{NW})$ at different periods. (f) The slopes of $\ln(B)$'s variation trends at different periods.

of the noise intensity, or alternative methods such as the two-station method should be used to eliminate the influence of noise intensity in advance. Additionally, note that the noise intensity's variation at 6 s is relatively drastic (Fig. 13a), which may deviate from the

idealized smooth variation requirement for eq. (1). Therefore, to enhance the accuracy and quantitatively estimate the uncertainty of attenuation tomography, more knowledge about the ambient noise field is still sought.

5 DISCUSSION

5.1 Correlations of attenuation with geological structures

The anelastic properties of solids are mainly governed by defect and thermal properties (Jackson & Anderson 1970). Compared to seismic velocity, seismic attenuation exhibits higher sensitivity to factors such as porosity, defect concentration and mobility, temperature, grain size, as well as the presence of molten and volatile components of Earth materials (Sato *et al.* 1989; Jackson *et al.* 1992; Rietbrock 2001). Thus, attenuation can provide valuable insights into both the geological structures and mechanisms at various scales.

In the sedimentary layer and brittle upper crust, the sliding motion between crack surfaces during the passage of a seismic wave results in frictional dissipation of energy. Besides, if the cracks are saturated with water, viscous damping would further increase attenuation (Walsh 1966). Previous tomography studies have consistently observed high attenuation anomalies associated with faults and thick sedimentary basins (e.g. Sertcelik 2012; Zhao *et al.* 2013; Tsuru *et al.* 2018). Similarly, our results (Fig. 10) reveal pronounced high attenuation anomalies at short periods under the Bohai Bay Basin and Erlian Basin, where the sedimentary layer is much thicker than the surroundings. Moreover, relatively high attenuation anomalies are observed just beneath the Tanlu Fault and Solonker Suture, two of the deepest block boundaries across NE China. Although smaller and shallower faults are not identified in this study, likely due to the limitation of the period band (≥ 6 s) and shallow-depth resolution, noise-based attenuation tomography has the potential to reveal shallow rock damages when denser arrays are provided (Liu *et al.* 2021, 2022).

With increasing depth, cracks of rocks close quickly due to elevated pressure. In media characterized by high pressure and temperature, the dominant contributors to attenuation are viscous grain-boundary damping and dislocation damping of crystals (Gordon & Nelson 1966; Farla *et al.* 2012; Jackson *et al.* 2014), which are influenced by the temperature, grain size and volatile fraction (Sato *et al.* 1989; Karato 1993). Besides, some studies also associated the enhanced attenuation in specific regions (e.g. magma chambers, mantle transition zone) with partially molten rocks (Yamauchi & Takei 2020; Havlin *et al.* 2021; Lyakhovsky *et al.* 2021). Attenuation anomalies in regional and global tomography are commonly linked to tectonic and dynamic processes, providing insights into the driving forces of plate motion (Debayle *et al.* 2020), the formation and dynamic mechanisms of mantle wedges in subduction zones (Wei *et al.* 2018; Zhao *et al.* 2021), and the distribution of mid-lower crustal flow (Zhao *et al.* 2013; Dai *et al.* 2020). In this study, at periods longer than 12 s, we observed ‘high-low-high’ attenuation anomalies between the NCC, SLB and XMOB. This pattern is consistent with previous velocity tomography (Guo *et al.* 2016; Kang *et al.* 2016), which reveals relatively high velocities beneath SLB extending from the lower crust to 200 km in the upper mantle. This anomaly suggests a colder and denser mantle under the SLB and hotter ones under the NCC and XMOB. A common explanation for this high-velocity anomaly is ongoing lithospheric delamination beneath the southwestern SLB (Chen *et al.* 2017). Nevertheless, some recent studies (eg., Guo *et al.* 2016; Liang *et al.* 2022) also attribute the observed velocity anomaly to a mantle convection system driven by mantle upwelling beneath the Changbai Mountain range, with a downwelling limb and a secondary upwelling limb beneath the SLB and XMOB, respectively. Given that the upwelling mantle material is characterized by high temperatures and may even

contain partially molten rocks, it could substantially increase attenuation. Thus, our observed high attenuation beneath the NCC and XMOB may lend support for the mantle upwelling model. However, to explore the origin of low attenuation beneath SLB, attenuation measurements for greater depths are needed.

Apart from lateral variations, the radial/vertical variation of Q is also investigated. Inconsistencies still exist among various radial Q models, particularly in the crust and deep mantle, which can be attributed to the wide range of Q variations in Earth’s media and the use of different data and processing methods (Resovsky *et al.* 2005). The frequency-dependent Rayleigh wave attenuation Q_R , could be related to the depth-dependent shear wave attenuation Q_β , through depth sensitivity kernels (Anderson *et al.* 1965; Liu *et al.* 2022):

$$Q_R^{-1} = \sum_l \left(\frac{\beta_l}{c_R} \frac{\partial c_R}{\partial \beta_l} \right) Q_{\beta l}^{-1} + \sum_l \left(\frac{\alpha_l}{c_R} \frac{\partial c_R}{\partial \alpha_l} \right) Q_{\alpha l}^{-1}, \quad (13)$$

where α_l and β_l are the compressional velocity and shear velocity, which vary with depth layer l . The term c_R is Rayleigh wave phase velocity, which varies with frequency. Since the term $\frac{\partial c_R}{\partial \alpha_l}$ is usually assumed to be close to zero, the second integral is considered negligible. Using eq. (13), with regional averaged α_l , β_l and c_R , we calculate the attenuation sensitivity kernel of Rayleigh waves to shear waves and invert for a radial profile of the regional average Q_β (Fig. 14). Through this process, an open-source Python package ‘disba’ was applied to calculate $\frac{\partial c_R}{\partial \beta_l}$ for different periods, and this package can be obtained from (<https://github.com/keurfonluu/disba>). One intriguing feature observed in this profile is the remarkable Q_β variation between different layers. Starting at approximately 90 in the sedimentary layer, Q_β increases fast with depth to around 1000 in the middle and lower crust, and then rapidly decreases after passing the Moho discontinuity to approximately 70 in the upper mantle. While the low Q_β in upper mantle has been a consensus amongst different radial Q models, the depth at which high attenuation begins is still subject to debate. According to our results, the decrease of Q_β has already started at the depth of Moho. However, due to the relatively weak ambient noise signals at periods larger than 22 s, we are unable to explore the variation trend of Q_β at deeper layers below the top of upper mantle. Future research incorporating earthquake and ambient noise data might help address this issue. Although, in this study, we only use data from NE China, similar variation trends of Q_β have also been observed in other areas (Mitchell 1995). Nevertheless, it is important to note that the uncertainty of Q_β is usually large, so it remains to be investigated whether Q_β in the upper mantle is typically as low as 70.

5.2 Influence of different factors on the Rayleigh wave amplitude

As mentioned above, multiple factors contribute to the amplitude of Rayleigh waves. Fig. 15 presents a comparison of the magnitudes of the attenuation, site amplification, noise intensity and focusing/defocusing effect on Rayleigh wave amplitude. The mean values of the logarithms of the amplitudes are calculated for each factor and period based on the inverted model parameters. At short periods (< 7 s), attenuation is the primary contributor to amplitude, followed by noise intensity and site amplification terms, while the contribution of the focusing/defocusing effect is relatively small. However, as the period increases, the contribution of attenuation decreases quickly and becomes smaller than the influences of both

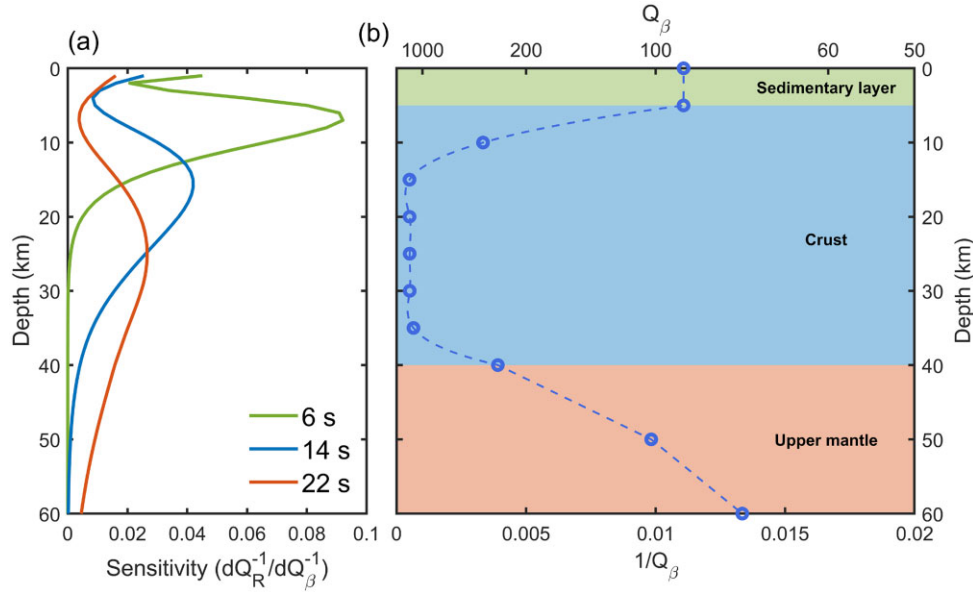


Figure 14. (a) Depth sensitivity kernels of Rayleigh wave attenuation Q_R to shear wave attenuation Q_β , at example periods. (b) Regional average Q_β radial profile, categorized into different layers: sedimentary layer (0–5 km), crust (5–40 km) and upper mantle (40–60 km).

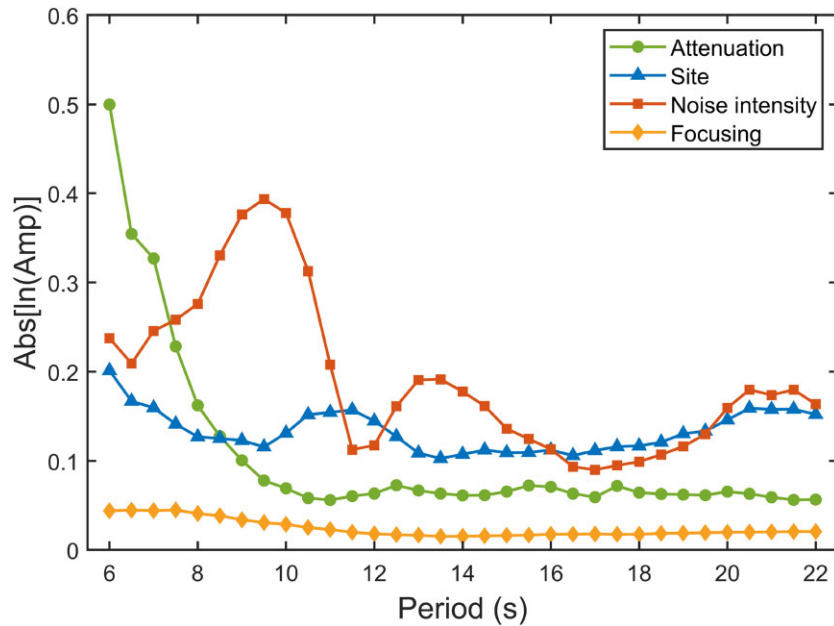


Figure 15. Mean of the absolute value of different contributors to Rayleigh wave amplitude at different periods. Green: attenuation; blue: site amplification terms; orange: noise intensity terms; yellow: focusing/defocusing effect.

noise intensity and site amplification terms. Therefore, attenuation might not be the only dominant factor determining Rayleigh wave amplitude, especially for long periods and short ray paths. The influences of site amplification, noise intensity, and focusing/defocusing effect are not negligible in Rayleigh wave attenuation tomography. Additionally, since the contribution of attenuation is proportionate to the length of ray paths, we recommend using larger-scale arrays to amplify the impact of attenuation over other factors (Mitchell 1995). In this study, the mean ray path length is only about 350 km; however, if the ray path length can be extended to over, for example, 1000 km, the contribution of attenuation may surpass that of other factors. Nevertheless, it should be noted that longer ray paths would also magnify the focusing/defocusing effect and increase the stacking time for the convergence of EGFs.

In addition to the factors we modelled or estimated in this study, several other factors might also impose certain influences on Rayleigh wave amplitude. First, topography can cause distortion of seismic waveforms, especially for high-frequency waves with shorter wavelengths. In areas with steep topography (e.g. volcanos and basins), this effect can become the dominant factor in determining Q (O'Brien & Bean 2004, 2009). Secondly, the lateral variations of anelasticity (Q) can also affect the seismic wave propagation and induce an anelastic focusing/defocusing effect on amplitudes. At short periods (~ 50 s), this effect is comparable but negatively correlates to the elastic focusing/defocusing effect (Ruan & Zhou 2012). Finally, attenuation can be further categorized into intrinsic and scattering attenuation. Intrinsic attenuation results in the dissipation of the wave energy, while scattering attenuation redistributes

energy from the primary wave to the coda wave. In the lithosphere, the magnitudes of the two types of attenuation are comparable, and their separation is essential for understanding the attenuation mechanism and exploring geological structures (Prudencio *et al.* 2017). Although these factors were not explicitly addressed in this study, they are undeniably important for extracting more information from seismic amplitudes.

6 CONCLUSIONS

Building upon the theoretical derivation and simulation tests by Weaver (2011, 2013) and Zhou (2020a), this paper summarizes and further develops a workflow for attenuation tomography based on ambient noise correlation. The workflow consists of three phases: (1) retrieval of EGFs, (2) selection and correction of amplitude measurements and (3) inversion of attenuation, site amplification and noise intensity terms. To enhance the quality of EGFs while preserving the relative amplitudes, we apply the ATF normalization method (Zhou *et al.* 2020a) in the processing of seismic records. Additionally, a ‘t-symmetry’ criterion is proposed for data selection to maintain the stability of amplitude distribution with distance; and then 2-D sensitivity kernels (Zhou *et al.* 2004) are utilized for the correction of the focusing/defocusing effect. Finally, the recovery of attenuation, site amplification, and noise intensity terms is achieved through an iterative inversion approach (Zhao *et al.* 2010).

To validate the effectiveness of the proposed method, we apply it to NE China. The derived attenuation from ambient noise is reasonable and comparable with results from previous studies (Yang *et al.* 2004; Zhou *et al.* 2020b), exhibiting a strong correlation with local geological structures. Notably, the observed attenuation anomalies in intermediate periods (> 12 s) are consistent with velocity tomography results, which may lend support for the existence of a regional mantle convection system. In addition, a remarkable increase in seismic attenuation (i.e. a decrease of Q_β) is also observed near Moho depth in this area. However, to gain a comprehensive understanding of the general variation trend of Q in the crust and upper mantle, further investigations that integrate both ambient noise and earthquake data are indispensable. Besides, the retrieved site amplification and noise intensity terms also follow certain variation trends across different periods and station locations, which are related to local structures and noise source distribution. The correlation of tomography results to geological structures and substantial reduction of data misfits after inversion prove the reliability of both amplitude measurements and the inversion method.

Noise-based attenuation tomography provides a promising path to obtain short-period observations that are often scarce in earthquake signals. Those observations are important for investigating the lateral and radial variations of attenuation in the crust and upper mantle (Anderson *et al.* 1965). Besides, similar to noise-based velocity tomography, an advantage of this tomography method is that it does not rely on the specific locations of earthquakes. This allows the increase of ray path density, leading to high-resolution tomography results. Although, in this paper, the tomography is based on a 1-D array, our method can be extended to 2-D arrays, once the noise intensity is carefully parametrized and modelled or cancelled through the Two Station Method. In the future, increased applications to denser arrays and detailed simulation tests involving complex scattering situations would further enhance our understanding of noise field characteristics.

Lastly, we acknowledge several limitations in this research, which should be addressed in future studies. First, we did not consider the

effects of topography, and anelastic focusing/defocusing, and did not separate intrinsic and scattering attenuation. In the future, a more comprehensive analysis of those factors might be possible with the advance of full-waveform tomography (e.g. Zhu *et al.* 2013; Komatitsch *et al.* 2016; Song *et al.* 2023). Second, despite applying various preprocessing and stacking methods, the extracted EGFs are not exact representations of ideal Green’s functions due to the complexities of source and scattering distributions, as well as finite stacking time. Addressing this challenge requires a better understanding of noise source distribution (e.g. Cheng *et al.* 2023; Igel *et al.* 2023) and the development of effective methods for separating random noise from non-random noise in seismic records (e.g. Meng *et al.* 2019). These advancements might further improve the accuracy and reliability of noise-based attenuation tomography. Additionally, the seismic noise field exhibits complex spatiotemporal variations, which deserve more attention and effort in direct observation and interpretation.

ACKNOWLEDGMENTS

We would like to thank Xiaodong Song, Richard Weaver, Xueyang Bao, Youyi Ruan, Lianqing Zhou, Ying Zhou, Yudi Pan, Yu Zhang, Mengkui Li and Junyi Gong, for their valuable discussions and constructive comments, which improved the quality of this research. This paper also benefited from the constructive review and insightful comments from Editor Andrew Barbour, Assistant Editor Louise Alexander, reviewer Lianfeng Zhao and another anonymous reviewer. We are also grateful to Zhen Guo for providing the shear wave velocity map of NE China. The continuous seismic data in this study were downloaded from the Data Management Center of the Incorporated Research Institutions for Seismology (<https://ds.iris.edu/ds/nodes/dmc/>). Most figures were prepared using Generic Mapping Tools (Wessel & Smith 1998) and MATLAB. This study is supported by the National Natural Science Foundation of China (42174069, U1939204), and the National Key R&D Program of China (2022YFF0800601). Some numerical calculations in this paper have been done on the supercomputing system in the Supercomputing Center of Wuhan University.

SUPPORTING INFORMATION

Supplementary data are available at *GJIRAS* online.

Figure S1. Comparison of predefined input model parameters (blue dots) and inverted model parameters (orange dots) for 6 s ray coverage, with (a) attenuation terms, (b) site terms, (c) noise intensity terms from NW direction and (d) noise intensity terms from SE direction.

Figure S2. Comparison of predefined input model parameters (blue dots) and inverted model parameters (orange dots) for 12 s ray coverage, with (a) attenuation terms, (b) site terms, (c) noise intensity terms from NW direction and (d) noise intensity terms from SE direction.

Figure S3. Comparison of predefined input model parameters (blue dots) and inverted model parameters (orange dots) for 18 s ray coverage, with (a) attenuation terms, (b) site terms, (c) noise intensity terms from NW direction and (d) noise intensity terms from SE direction.

Figure S4. A Phase velocity profile below the NCISP-6 array, which is interpolated from a regional velocity model by Guo *et al.* (2016).

Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by

the authors. Any queries (other than missing material) should be directed to the corresponding author for the paper.

DATA AVAILABILITY

The continuous seismic data underlying this paper are available in the Data Management Center of the Incorporated Research Institutions for Seismology (<https://ds.iris.edu/ds/nodes/dmc/>).

REFERENCES

- Anderson, D.L., Ben-Menahem, A. & Archambeau, C.B., 1965. Attenuation of seismic energy in the upper mantle, *J. geophys. Res.*, **70**, 1441–1448. DOI: 10.1029/JZ070i006p01441.
- Bao, X., Dalton, C.A. & Ritsema, J., 2016. Effects of elastic focusing on global models of Rayleigh wave attenuation, *Geophys. J. Int.*, **207**, 1062–1079. DOI: 10.1093/gji/ggw322.
- Bao, X., Song, X. & Li, J., 2015. High-resolution lithospheric structure beneath Mainland China from ambient noise and earthquake surface-wave tomography, *Earth planet. Sci. Lett.*, **417**, 132–141. DOI: 10.1016/j.epsl.2015.02.024.
- Bensen, G.D., et al., 2007. Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements, *Geophys. J. Int.*, **169**, 1239–1260. DOI: 10.1111/j.1365-246X.2007.03374.x.
- Bowden, D.C. & Tsai, V.C., 2017. Earthquake ground motion amplification for surface waves, *Geophys. Res. Lett.*, **44**, 121–127. DOI: 10.1002/2016GL071885.
- Bowden, D.C., Tsai, V.C. & Lin, F.-C., 2017. Amplification and attenuation across USArray using ambient noise wavefront tracking: USArray noise amplitudes, *J. geophys. Res.*, **122**, 10 086–10 101. DOI: 10.1002/2017JB014804.
- Bowden, D.C., Tsai, V.C. & Lin, F.C., 2015. Site amplification, attenuation, and scattering from noise correlation amplitudes across a dense array in Long Beach, CA, *Geophys. Res. Lett.*, **42**, 1360–1367. DOI: 10.1002/2014GL062662.
- Brenguier, F., et al., 2014. Mapping pressurized volcanic fluids from induced crustal seismic velocity drops, *Science*, **345**, 80–82. DOI: 10.1126/science.1254073.
- Chen, H., et al., 2017. Mantle seismic anisotropy beneath NE China and implications for the lithospheric delamination hypothesis beneath the southern Great Xing'an range, *Earth planet. Sci. Lett.*, **471**, 32–41. DOI: 10.1016/j.epsl.2017.04.030.
- Chen, H., Tsai, V.C. & Niu, F., 2018. Observations and modeling of long-period ground-motion amplification across Northeast China, *Geophys. Res. Lett.*, **45**, 5968–5976. DOI: 10.1029/2018GL078212.
- Cheng, F., Xia, J. & Xi, C., 2023. Artifacts in high-frequency passive surface wave dispersion imaging: toward the linear receiver array, *Surv. Geophys.*, **44**, 1009–1039. DOI: 10.1007/s10712-023-09772-1.
- Dai, A., Tang, C.-C., Liu, L. & Xu, R., 2020. Seismic attenuation tomography in southwestern China: insight into the evolution of crustal flow in the Tibetan Plateau, *Tectonophysics*, **792**, DOI:10.1016/j.tecto.2020.228589.
- Dalton, C.A., Hjörleifsdóttir, V. & Ekström, G., 2014. A comparison of approaches to the prediction of surface wave amplitude, *Geophys. J. Int.*, **196**, 386–404. DOI: 10.1093/gji/ggt365.
- Debayle, E., Bodin, T., Durand, S. & Ricard, Y., 2020. Seismic evidence for partial melt below tectonic plates, *Nature*, **586**, 555–559. DOI: 10.1038/s41586-020-2809-4.
- Farla, R.J.M., Jackson, I., Fitz Gerald, J.D., Faul, U.H. & Zimmerman, M.E., 2012. Dislocation damping and anisotropic seismic wave attenuation in Earth's upper mantle, *Science*, **336**, 332–335. DOI: 10.1126/science.1218318.
- Fichtner, A., Bowden, D. & Ermer, L., 2020. Optimal processing for seismic noise correlations, *Geophys. J. Int.*, **223**, 1548–1564. DOI: 10.1093/gji/ggaa390.
- Gordon, R.B. & Nelson, C.W., 1966. Anelastic properties of the Earth, *Rev. Geophys.*, **4**(4), 457–474. DOI: 10.1029/RG004i004p00457.
- Guo, Z., Chen, Y.J., Ning, J., Yang, Y., Afonso, J.C. & Tang, Y., 2016. Seismic evidence of on-going sublithosphere upper mantle convection for intra-plate volcanism in Northeast China, *Earth planet. Sci. Lett.*, **433**, 31–43. DOI: 10.1016/j.epsl.2015.09.035.
- Havlin, C., Holtzman, B.K. & Hopper, E., 2021. Inference of thermodynamic state in the asthenosphere from anelastic properties, with applications to North American upper mantle, *Phys. Earth planet. Inter.*, **314**, DOI: 10.1016/j.pepi.2020.106639.
- Herrin, E. & Goforth, T., 1977. Phase-matched filters: application to the study of Rayleigh waves, *Bull. seism. Soc. Am.*, **67**, 1259–1275. DOI: 10.1785/BSSA0670051259.
- Igel, J.K.H., Bowden, D.C. & Fichtner, A., 2023. SANS: publicly available daily multi-scale seismic ambient noise source maps, *J. geophys. Res.*, **128**(1), DOI: 10.1029/2022JB025114.
- Jackson, D.D. & Anderson, D.L., 1970. Physical mechanisms of seismic-wave attenuation, *Rev. Geophys.*, **8**(1), 1–63.
- Jackson, I., Faul, U.H. & Skelton, R., 2014. Elastically accommodated grain-boundary sliding: new insights from experiment and modeling, *Phys. Earth planet. Inter.*, **228**, 203–210. DOI: 10.1016/j.pepi.2013.11.014.
- Jackson, I., Paterson, M.S. & Fitz Gerald, J.D., 1992. Seismic wave dispersion and attenuation in Åheim dunite: an experimental study, *Geophys. J. Int.*, **108**, 517–534. DOI: 10.1111/j.1365-246X.1992.tb04633.x.
- Kang, D., Shen, W., Ning, J. & Ritzwoller, M.H., 2016. Seismic evidence for lithospheric modification associated with intracontinental volcanism in Northeastern China, *Geophys. J. Int.*, **204**, 215–235. DOI: 10.1093/gji/ggv441.
- Karato, S., 1993. Importance of anelasticity in the interpretation of seismic tomography, *Geophys. Res. Lett.*, **20**, 1623–1626. DOI: 10.1029/93GL01767.
- Komatitsch, D., Xie, Z., Bozdağ, E., Sales De Andrade, E., Peter, D., Liu, Q. & Tromp, J., 2016. Anelastic sensitivity kernels with parsimonious storage for adjoint tomography and full waveform inversion, *Geophys. J. Int.*, **206**, 1467–1478. DOI: 10.1093/gji/ggw224.
- Lawrence, J.F. & Prieto, G.A., 2011. Attenuation tomography of the western United States from ambient seismic noise, *J. geophys. Res.*, **116**(B6), DOI: 10.1029/2010JB007836.
- Levshin, A.L. & Ritzwoller, M.H., 2001. Automated detection, extraction, and measurement of regional surface waves, *Pure appl. geophys.*, **158**, 1531–1545. DOI: 10.1007/PL00001233.
- Li, G., Chen, H., Niu, F., Guo, Z., Yang, Y. & Xie, J., 2016. Measurement of Rayleigh wave ellipticity and its application to the joint inversion of high-resolution S wave velocity structure beneath northeast China, *J. geophys. Res.*, **121**, 864–880.
- Li, J., Song, X., Yang, Y., Li, M., Li, J. & Li, Y., 2021. Strong seasonal variations of seismic velocity in eastern margin of Tibetan Plateau and Sichuan Basin from ambient noise interferometry, *J. geophys. Res.*, **126**(11), DOI: 10.1029/2021JB022600.
- Li, J., Weaver, R.L., Yoritomo, J.Y. & Song, X., 2020. Application of temporal reweighting to ambient noise cross-correlation for improved seismic Green's function, *Geophys. J. Int.*, **221**, 265–272. DOI: 10.1093/gji/ggaa001.
- Li, M., Song, X., Li, J. & Bao, X., 2022. Crust and upper mantle structure of East Asia from ambient noise and earthquake surface wave tomography, *Earthq. Sci.*, **35**, 71–92. DOI: 10.1016/j.eqs.2022.05.004.
- Liang, X., Zhao, D., Xu, Y. & Hua, Y., 2022. Anisotropic tomography and dynamics of the big mantle wedge, *Geophys. Res. Lett.*, **49**(5), DOI: 10.1029/2021GL097550.
- Lin, F.-C., Moschetti, M.P. & Ritzwoller, M.H., 2008. Surface wave tomography of the western United States from ambient seismic noise: Rayleigh and Love wave phase velocity maps, *Geophys. J. Int.*, **173**, 281–298. DOI: 10.1111/j.1365-246X.2008.03720.x.
- Lin, F.-C., Tsai, V.C. & Ritzwoller, M.H., 2012. The local amplification of surface waves: a new observable to constrain elastic velocities, density, and anelastic attenuation: the local amplification of surface waves, *J. geophys. Res.*, **117**(B6), DOI: 10.1029/2012JB009208.
- Lin, F.-C., Tsai, V.C., Schmandt, B., Duputel, Z. & Zhan, Z., 2013. Extracting seismic core phases with array interferometry: extract

- core phases with interferometry, *Geophys. Res. Lett.*, **40**, 1049–1053. DOI: 10.1002/grl.50237.
- Liu, X., Ben-Zion, Y. & Zigone, D., 2015. Extracting seismic attenuation coefficients from cross-correlations of ambient noise at linear triplets of stations, *Geophys. J. Int.*, **203**, 1149–1163. DOI: 10.1093/gji/ggv357.
- Liu, X., Beroza, G.C. & Ben-Zion, Y., 2022. Ambient noise attenuation tomography reveals an asymmetric damage zone across San Jacinto Fault near Anza, California, *Geophys. Res. Lett.*, **49**(15), DOI: 10.1029/2022GL099562.
- Liu, X., Beroza, G.C., Yang, L. & Ellsworth, W.L., 2021. Ambient noise Love wave attenuation tomography for the LASSIE array across the Los Angeles basin, *Science Advances*, **7** (22), DOI: 10.1029/2009JB007157.
- Lyakhovsky, V., Shalev, E., Kurzon, I., Zhu, W., Montesi, L. & Shapiro, N.M., 2021. Effective seismic wave velocities and attenuation in partially molten rocks, *Earth planet. Sci. Lett.*, **572**, DOI: 10.1016/j.epsl.2021.117117.
- Magrini, F. & Boschi, L., 2021. Surface-wave attenuation from seismic ambient noise: numerical validation and application, *J. geophys. Res.*, **126**(1), DOI: 10.1029/2020JB019865.
- Mao, S., Lecointre, A., Van Der Hilst, R.D. & Campillo, M., 2022. Space-time monitoring of groundwater fluctuations with passive seismic interferometry, *Nat. Commun.*, **13**, DOI: 10.1038/s41467-022-32194-3.
- Meng, H., Ben-Zion, Y. & Johnson, C.W., 2019. Detection of random noise and anatomy of continuous seismic waveforms in dense array data near Anza California, *Geophys. J. Int.*, **219**, 1463–1473. DOI: 10.1093/gji/ggz349.
- Mitchell, B.J., 1995. Anelastic structure and evolution of the continental crust and upper mantle from seismic surface wave attenuation, *Rev. Geophys.*, **33**(4), 441–462.
- Mitchell, B.J., Cong, L. & Ekström, G., 2008. A continent-wide map of 1-Hz *lg* coda *Q* variation across Eurasia and its relation to lithospheric evolution, *J. Geophys. Res.*, **113**(B4), DOI: 10.1029/2007JB005065.
- O'Brien, G.S. & Bean, C.J., 2004. A 3D discrete numerical elastic lattice method for seismic wave propagation in heterogeneous media with topography, *Geophys. Res. Lett.*, **31**(14), DOI: 10.1029/2004GL020069.
- O'Brien, G.S. & Bean, C.J., 2009. Volcano topography, structure and intrinsic attenuation: their relative influences on a simulated 3D visco-elastic wavefield, *J. Volc. Geotherm. Res.*, **183**, 122–136. DOI: 10.1016/j.jvolgeores.2009.03.004.
- Prieto, G.A., Lawrence, J.F. & Beroza, G.C., 2009. Anelastic Earth structure from the coherency of the ambient seismic field, *J. geophys. Res.*, **114**(B7), DOI: 10.1029/2008JB006067.
- Prudencio, J., Taira, T., Aoki, Y., Aoyama, H. & Onizawa, S., 2017. Intrinsic and scattering attenuation images of Usu volcano, Japan, *Bull. Volcanol.*, **79**, DOI: 10.1007/s00445-017-1117-9.
- Resovsky, J., Trampert, J. & Van Der Hilst, R.D., 2005. Error bars for the global seismic *Q* profile, *Earth planet. Sci. Lett.*, **230**, 413–423. DOI: 10.1016/j.epsl.2004.12.008.
- Rietbrock, A., 2001. P wave attenuation structure in the fault area of the 1995 Kobe earthquake, *J. geophys. Res.*, **106**, 4141–4154. DOI: 10.1029/2000JB900234.
- Ruan, Y. & Zhou, Y., 2012. The effects of 3-D anelasticity (*Q*) structure on surface wave amplitudes: 3-D anelastic effects on surface wave amplitudes, *Geophys. J. Int.*, **189**, 967–983. DOI: 10.1111/j.1365-246X.2011.05356.x.
- Ryzhik, L., Papanicolaou, G. & Keller, J.B., 1996. Transport equations for elastic and other waves in random media, *Wave Motion*, **24**, 327–370. DOI: 10.1016/S0165-2125(96)00021-2.
- Sato, H., Sacks, I.S., Murase, T., Muncill, G. & Fukuyama, H., 1989. *Q_p*-melting temperature relation in peridotite at high pressure and temperature: attenuation mechanism and implications for the mechanical properties of the upper mantle, *J. geophys. Res.*, **94**, 10 647–10 661. DOI: 10.1029/JB094iB08p10647.
- Sertçelik, F., 2012. Estimation of Coda Wave attenuation in the East Anatolia Fault Zone, Turkey, *Pure appl. Geophys.*, **169**, 1189–1204. DOI: 10.1007/s00024-011-0368-1.
- Shapiro, N.M., Campillo, M., Stehly, L. & Ritzwoller, M.H., 2005. High-resolution surface-wave tomography from ambient seismic noise, *Science*, **307**, 1615–1618. DOI: 10.1126/science.1108339.
- Shen, W. & Ritzwoller, M.H., 2016. Crustal and uppermost mantle structure beneath the United States, *J. geophys. Res.*, **121**, 4306–4342. DOI: 10.1002/2016JB012887.
- Shen, W., Ritzwoller, M.H., Kang, D., Kim, Y., Lin, F.-C., Ning, J., Wang, W. *et al.*, 2016. A seismic reference model for the crust and uppermost mantle beneath China from surface wave dispersion, *Geophys. J. Int.*, **206**, 954–979. DOI: 10.1093/gji/ggw175.
- Song, J., Cao, H., Pan, W., Yang, Z., Li, H., Lu, M. & Hu, X., 2023. Attenuation sensitivity kernel analysis in viscoelastic full-waveform inversion based on the generalized standard linear solid rheology, *Surv. Geophys.*, **44**, 1041–1073. DOI: 10.1007/s10712-023-09767-y.
- Tsai, V.C., 2011. Understanding the amplitudes of noise correlation measurements, *J. geophys. Res.*, **116**(B9), DOI: 10.1029/2011JB008483.
- Tsuru, T., Park, J.-O., No, T., Kido, Y. & Nakahigashi, K., 2018. Visualization of attenuation structure and faults in incoming oceanic crust of the Nankai Trough using seismic attenuation profiling, *Earth planets Space*, **70**, DOI: 10.1186/s40623-018-0803-y.
- Turner, J.A. & Weaver, R.L., 1994. Radiative transfer of ultrasound, *J. acoust. Soc. Am.*, **96**(6), 3654–3674.
- Viens, L., Denolle, M., Miyake, H., Sakai, S. & Nakagawa, S., 2017. Retrieving impulse response function amplitudes from the ambient seismic field, *Geophys. J. Int.*, **210**, 210–222. DOI: 10.1093/gji/ggx155.
- Walsh, J.B., 1966. Seismic wave attenuation in rock due to friction, *J. geophys. Res.*, **71**, 2591–2599. DOI: 10.1029/JZ071i010p02591.
- Wang, T., Song, X. & Xia, H.H., 2015. Equatorial anisotropy in the inner part of Earth's inner core from autocorrelation of earthquake coda, *Nat. Geosci.*, **8**, 224–227. DOI: 10.1038/ngeo2354.
- Weaver, R.L. & Yoritomo, J.Y., 2018. Temporally weighting a time varying noise field to improve green function retrieval, *J. acoust. Soc. Am.*, **143**, 3706–3719. DOI: 10.1121/1.5043406.
- Weaver, R.L., 2005. Information from seismic noise, *Science*, **307**, 1568–1569. DOI: 10.1126/science.1109834.
- Weaver, R.L., 2011. On the amplitudes of correlations and the inference of attenuations, specific intensities and site factors from ambient noise, *C.R. Geosci.*, **343**, 615–622. DOI: 10.1016/j.crte.2011.07.001.
- Weaver, R.L., 2013. On the retrieval of attenuation and site amplifications from ambient noise on linear arrays: further numerical simulations, *Geophys. J. Int.*, **193**, 1644–1657. DOI: 10.1093/gji/ggt063.
- Wei, S.S. & Wiens, D.A., 2018. P-wave attenuation structure of the Lau back-arc basin and implications for mantle wedge processes, *Earth planet. Sci. Lett.*, **502**, 187–199. DOI: 10.1016/j.epsl.2018.09.005.
- Xie, J. & Mitchell, B.J., 1990. A back-projection method for imaging large-scale lateral variations of *lg* coda *Q* with application to Continental Africa, *Geophys. J. Int.*, **100**, 161–181. DOI: 10.1111/j.1365-246X.1990.tb02477.x.
- Xu, Z.J. & Song, X., 2009. Temporal changes of surface wave velocity associated with major Sumatra earthquakes from ambient noise correlation, *Proc. Natl. Acad. Sci. U.S.A.*, **106**, 14 207–14 212. DOI: 10.1073/pnas.0901164106.
- Xu, Z.J. & Song, X., 2010. Joint inversion for crustal and pn velocities and Moho depth in Eastern Margin of the Tibetan Plateau, *Tectonophysics*, **491**, 185–193. DOI: 10.1016/j.tecto.2009.11.022.
- Xu, Z.J., Song, X. & Zheng, S., 2013. Shear velocity structure of crust and uppermost mantle in China from surface wave tomography using ambient noise and earthquake data, *Earthq. Sci.*, **26**, 267–281. DOI: 10.1007/s11589-013-0010-7.
- Yamauchi, H. & Takei, Y., 2020. Application of a premelting model to the lithosphere-asthenosphere boundary, *Geochem. Geophys. Geosyst.*, **21**(11), DOI: 10.1029/2020GC009338.
- Yang, X., Taylor, S. & Patton, H., 2004. The 20-s Rayleigh wave attenuation tomography for central and southeastern Asia, *J. geophys. Res.*, **109**(B12), DOI: 10.1029/2004JB003193.
- Yang, Y., Ritzwoller, M.H., Levshin, A.L. & Shapiro, N.M., 2007. Ambient noise Rayleigh wave tomography across Europe, *Geophys. J. Int.*, **168**, 259–274. DOI: 10.1111/j.1365-246X.2006.03203.x.
- Zhao, D., Wang, J., Huang, Z. & Liu, X., 2021. Seismic structure and subduction dynamics of the western Japan arc, *Tectonophysics*, **802**, DOI: 10.1016/j.tecto.2021.228743.

- Zhao, L.-F., Wang, W.-M. & Yao, Z.-X., 2004. Seismic attenuation tomography using the successive linearization method, *Chinese J. Geophys.*, **47**, 787–794. DOI: 10.1002/cjg2.3550.
- Zhao, L.-F., Xie, X.-B., He, J.-K., Tian, X. & Yao, Z.-X., 2013. Crustal flow pattern beneath the Tibetan Plateau constrained by regional lg-wave Q tomography, *Earth planet. Sci. Lett.*, **383**, 113–122. DOI: 10.1016/j.epsl.2013.09.038.
- Zhao, L.-F., Xie, X.-B., Wang, W.-M., Zhang, J.-H. & Yao, Z.-X., 2010. Seismic lg -wave Q tomography in and around Northeast China, *J. geophys. Res.*, **115** (B8), DOI: 10.1029/2009JB007157.
- Zhou, L., 2016. Attenuation Tomography of the Earth Media (in Chinese), *PhD thesis*, IGCEA.
- Zhou, L., Song, X. & Weaver, R.L., 2020a. Retrieval of amplitude and attenuation from ambient seismic noise: synthetic data and practical considerations, *Geophys. J. Int.*, **222**, 544–559. DOI: 10.1093/gji/ggaa194.
- Zhou, L., Song, X., Yang, X. & Zhao, C., 2020b. Rayleigh wave attenuation tomography in the crust of the Chinese mainland, *Geochem. Geophys. Geosyst.*, **21**(8), DOI: 10.1029/2020GC008971.
- Zhou, Y., Dahlen, F.A. & Nolet, G., 2004. Three-dimensional sensitivity kernels for surface wave observables, *Geophys. J. Int.*, **158**, 142–168. DOI: 10.1111/j.1365-246X.2004.02324.x.
- Zhu, H., Bozdağ, E., Duffy, T.S. & Tromp, J., 2013. Seismic attenuation beneath Europe and the North Atlantic: implications for water in the mantle, *Earth planet. Sci. Lett.*, **381**, 1–11. DOI: 10.1016/j.epsl.2013.08.030.