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Seismic attenuation from seismic ambient noise recordings:
application to short-term nodal deployment

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Declaration

I hereby declare that this thesis is my own work and that I have not submitted it, in whole or in part, for any previous degree. I confirm that I have only used the sources and aids directly referenced here. All sections that are quoted or paraphrased from other works are clearly cited and attributed. Additionally, this thesis has not been presented in the same or a similar form to any other academic institution, nor has it been published in any other context.

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Zusammenfassung

Der östliche Teil des Wiener Beckens ist Österreichs Hauptzielgebiet für die Exploration tiefer geothermischer Ressourcen. Eine effektive Bewertung der geothermischen Ressourcen erfordert detaillierte Kenntnisse der Gesteinsbeschaffenheit unter der Oberfläche, einschließlich Porosität, Durchlässigkeit und Flüssigkeitsgehalt. Während die Umgebungsgeräuschtomographie sich als kostengünstige geophysikalische Methode etabliert hat und sich für ihre Untergrundsabbildung bewährt hat, bleibt die Erweiterung dieser Techniken auf eine zuverlässige Bestimmung der Dämpfung eine Herausforderung. Letztere kann wichtige Erkenntnisse über die für die geothermische Charakterisierung erforderlichen Gesteinseigenschaften liefern und damit eine wertvolle Ergänzung zu teuren aktiven seismischen Untersuchungen darstellen. Hier präsentieren wir eine erste Anwendung des von Boschi et al. (2019) entwickelten Rahmens zur Messung der Umgebungsgeräuschkämpfung für dichte, kurzzeitige Knotenarrays.

Dies wird angewandt auf Daten aus dem Eastern Vienna Array, bestehend aus 44 Nodes, die entlang eines 15 km langen NW-SE-Profiles mit einem Abstand von etwa 350 Metern positioniert waren und im Sommer 2023 36 Tage lang kontinuierlich Daten aufzeichneten. Wir berechneten Kreuzkorrelationsfunktionen des Umgebungsrauschens für Stationspaare entlang des Profils und wandten sie in den Frequenzbereich um. In Anlehnung an den Ansatz von Boschi et al. (2019) haben wir die Kreuzkorrelationsfunktionen anhand der durchschnittlichen spektralen Leistungsdichte normiert und Qualitätskontrollen durchgeführt. Anschließend haben wir Enveloppen berechnet und frequenzabhängige Dämpfungskoeffizienten durch Rasteroptimierung unter Verwendung des gedämpften Bessel-Modells und der zuvor von Esteve et al. (2025) ermittelten Phasengeschwindigkeiten zwischen den Stationen geschätzt.

Unsere Ergebnisse zeigen eine erfolgreiche Extraktion von Dämpfungskoeffizienten im Bereich von 10^{-5} bis 10^{-3} m^{-1} über das Frequenzband von 0,2 bis 0,7 Hz, wobei die räumliche Variation entlang des Profils eine geringere Dämpfung im mittleren Bereich bei niedrigeren Frequenzen und eine zunehmende Dämpfung in Richtung der südlichen Region bei höheren Frequenzen zeigt. Am bedeutendsten ist jedoch, dass wir über alle analysierten Frequenzen hinweg ein konsistentes Antikorrelationsmuster zwischen Dämpfungskoeffizient und Phasengeschwindigkeit beobachten, was ein starker Hinweis darauf ist, dass die intrinsische Dämpfung als primärer Dämpfungsmechanismus im untersuchten Tiefenbereich ent-

lang unseres Untersuchungsprofils im Wiener Becken dominiert. Obwohl die Methode bei dichten, lokalisierten Arrays Einschränkungen aufweist, zeigen unsere Ergebnisse das Potenzial von Umgebungsgeräuschmethoden für kostengünstige, lokale Dämpfungsstudien, die für geothermische Untersuchungen relevant sind.

Schlagwörter: Seismische Dämpfung, Seismisches Umgebungsrauschen, Wiener Becken, Geothermische Exploration

Abstract

The eastern part of the Vienna Basin represents Austria’s primary target for deep geothermal exploration. Effective geothermal resource assessment requires detailed knowledge of sub-surface rock properties, including porosity, permeability, and fluid content. While ambient noise tomography has emerged as a cost-effective geophysical method and proven successful for velocity imaging, extending these techniques to reliable attenuation estimation remains challenging. Seismic attenuation measurements could provide the critical insights into rock properties needed for geothermal characterization, offering a valuable supplement to expensive active seismic surveys. In this work, we present the first implementation of the Boschi et al. (2019) ambient noise attenuation framework for dense, short-duration nodal arrays.

We used data from the Eastern Vienna Array, consisting of 44 nodes positioned along a 15-km NW-SE profile with approximately 350-meter spacing, recording continuous data for 36 days during summer 2023. We computed ambient noise cross-correlation functions for station pairs along the profile and converted them to the frequency domain. Following the approach of Boschi et al. (2019), we normalized cross-correlation functions by average power spectral density and applied quality control procedures. We then calculated envelope functions and estimated frequency-dependent attenuation coefficients through grid search optimization using the damped Bessel model and interstation phase velocities previously obtained by Esteve et al. (2025).

Our results show successful extraction of attenuation coefficients ranging from 10^{-5} to 10^{-3} m^{-1} across the 0.2 - 0.7 Hz frequency band, with spatial variation along the profile revealing lower attenuation in the central portion at lower frequencies and increased attenuation toward the southern region at higher frequencies. Most significantly, we observe a consistent anti-correlation pattern between attenuation coefficients and phase velocities across all analyzed frequencies, indicating strong evidence that intrinsic attenuation dominates as the primary attenuation mechanism in the sampled depth range along the studied profile in the Vienna Basin. While the method shows limitations for dense, localized arrays, our results demonstrate the potential of ambient noise methods for cost-effective, local-scale attenuation studies relevant to geothermal studies.

Keywords: seismic attenuation, ambient noise interferometry, Vienna Basin, geothermal exploration

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1 Introduction

Austria aims to achieve carbon neutrality by 2040, requiring a shift from fossil fuels to renewable energy sources (Jensen and Roniger, 2024). Geothermal energy is particularly important for district heating (Romanov and Leiss, 2022), and the Vienna Basin (Figure 1) possesses potential in this regard, due to its high geothermal heat flow (Goetzl et al., 2010). The Vienna Basin formed approximately 18 to 16 million years ago in the Miocene epoch at the junction of the Alpine and Carpathian mountain belts (Prochác et al., 2012). The basin developed in multiple stages, initially forming on top of moving crustal blocks from the Alps and Carpathians (Salcher et al., 2012). Around 16.5 million years ago, these blocks hit the stable Bohemian Massif, changing the stress patterns and turning the area into a pull-apart basin (Mikunda et al., 2020). This created space for sediments to accumulate, resulting in several deep sub-basins and depressions reaching depths of over 5 kilometers (Prochác et al., 2012).

Decades of oil and gas exploration have provided extensive data on the Vienna Basin's subsurface properties, revealing a complex tectonic history (Rupprecht et al., 2018). The basin consists of two main geological levels: an upper level containing thick Neogene sediments (Kováč et al., 2024) deposited over the last 23 million years that filled the pull-apart basin as it formed, and beneath these, the 'pre-Neogene basin' (Šamajová et al., 2019) - older rock formations including Triassic carbonates approximately 200-250 million years old. A first attempt to drill into the Triassic reservoir began with drilling the Geotief1 well in 2011 (Schreilechner et al., 2022). Although the well missed its intended target, it provided valuable data for subsequent drilling campaigns aiming to access the geothermal potential.

The Aderklaa Conglomerate, the main target, lies within the Neogene basin fill and spans over 1,000 km² (Keglovic, 2023). Within the Schwechat depression (Figure 2), it occurs at depths of 3,000 - 4,000 m, with temperatures reaching up to 130°C. The secondary target consists of fractured Triassic limestones and dolomites within the pre-Neogene basin. These formations occur at greater depths (exceeding 5,000 m) and present more challenging drilling conditions. Despite these challenges, they represent a significant additional resource for future geothermal development.

Given the economic constraints of geothermal development and the need for detailed subsurface characterization, cost-effective geophysical methods are essential for the geothermal sector.

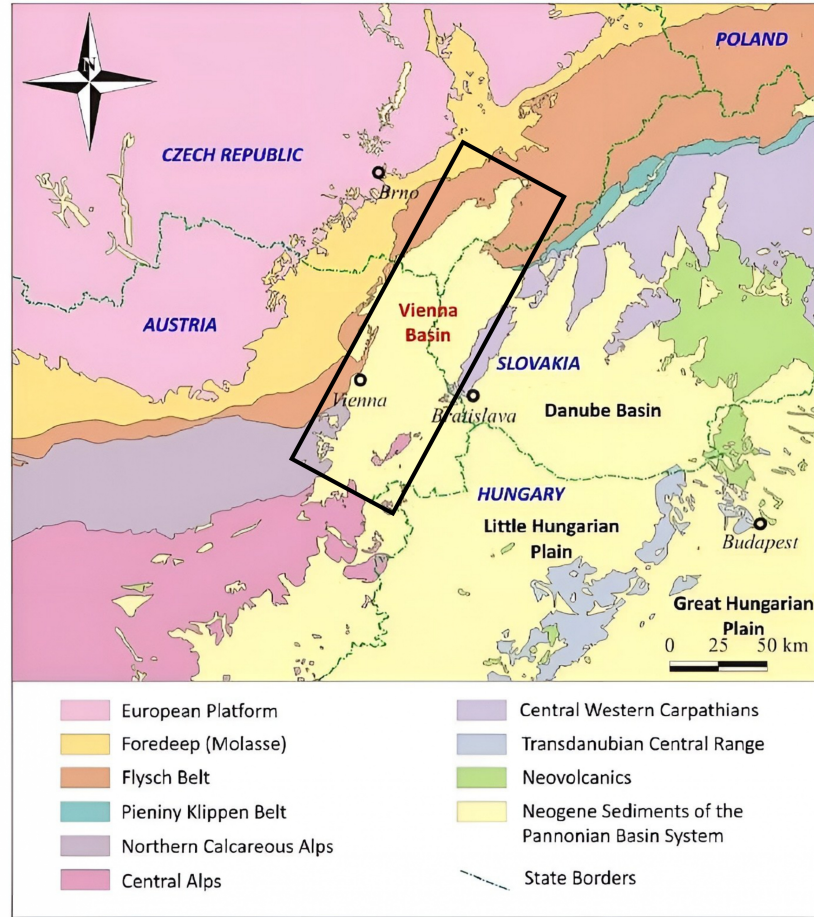


Figure 1: Regional geological setting of the Vienna Basin. Location of the Vienna Basin (indicated with black rectangle) within the Alpine-Carpathian system, showing major geological units and tectonic zones. The Vienna Basin is situated at the transition between the Eastern Alps and Western Carpathians, extending approximately 200 km in length and 50 km in width. Modified after Prochác et al. (2012).

Ambient noise interferometry has emerged as a particularly valuable tool for this purpose, offering the ability to study subsurface properties without the expense of active seismic surveys.

Seismic ambient noise refers to continuous ground vibrations during periods when there are no seismic events, such as earthquakes, creating a signal excited by various natural and human-generated sources (Saadia and Fotopoulos, 2023). The noise sources vary across different frequency bands (Nakata et al., 2019). At short periods (0.1 - 1 s), the noise typically originates from human activities such as machinery and traffic, with energy levels that fluctuate strongly over time and follow patterns related to daily and weekly human routines (Campillo and Roux, 2015). Ocean waves are the main source of ambient noise in the period band from 1 - 30 s (Nakata et al., 2019), generating seismic waves through two different

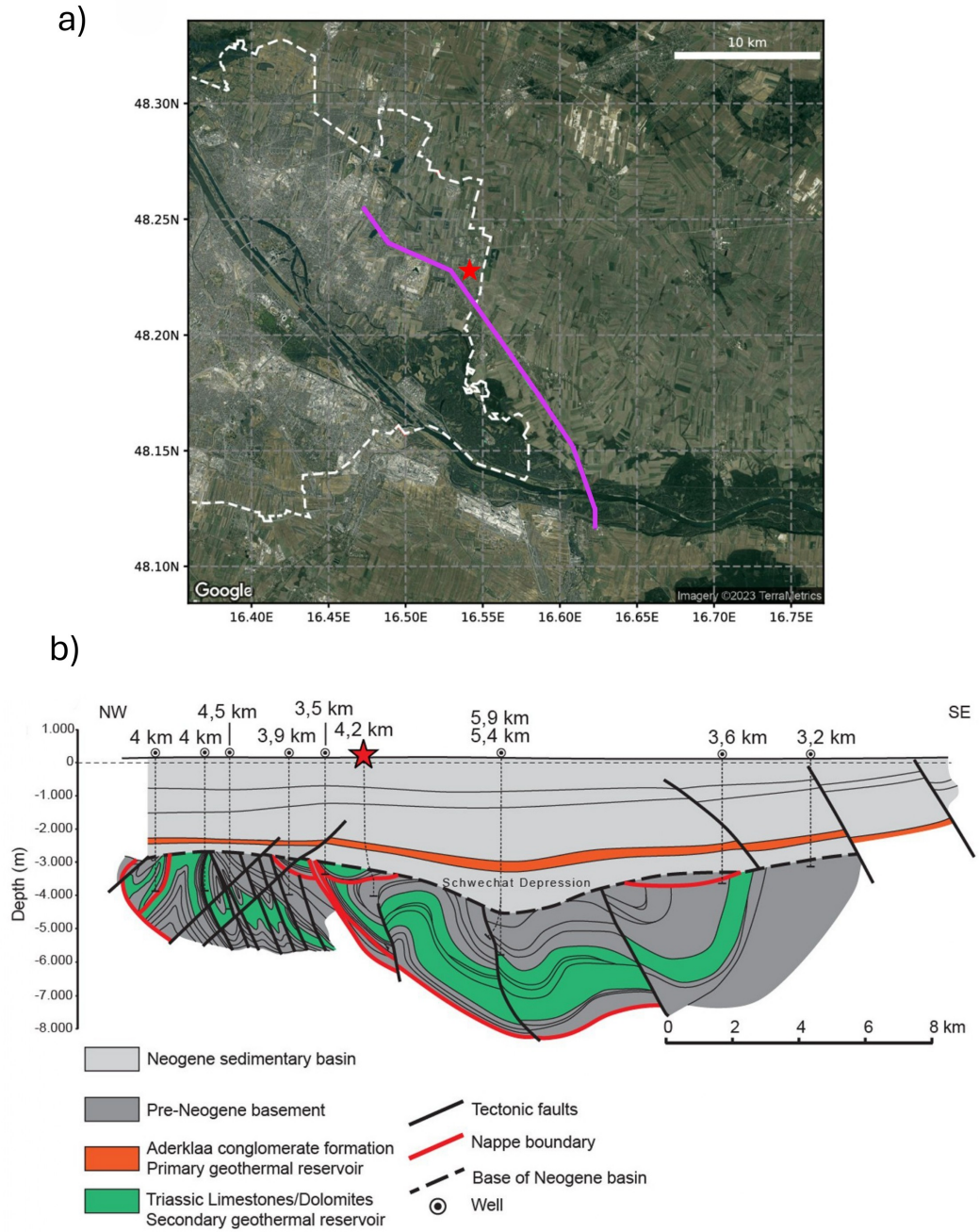


Figure 2: Geological cross-section through the Vienna Basin showing geothermal targets. (a) Satellite view showing the location of the geological cross-section (purple line). The red star marks the location of the Geotief1 exploration well. Modified after Esteve et al. (2025). (b) NW-SE geological profile illustrating the basin structure and main geothermal reservoir targets. The Aderklaa Conglomerate Formation (orange) represents the primary shallow geothermal target, while Triassic carbonates (green) form the secondary deeper geothermal reservoir within the pre-Neogene basin. Modified after Elster et al. (2016).

processes, namely primary (14 s, Essen et al., 2003) and secondary (7 s, Landès et al., 2010) microseism. At long periods (30 - 500 s), the ambient noise known as hum exhibits characteristics similar to Earth's free oscillations, resulting from the interaction between ocean infragravity waves and the solid Earth (Kobayashi and Nishida, 1998; Tanimoto et al., 1998; Rhie and Romanowicz, 2004). Since these noise sources originate primarily at the Earth's surface (Figure 3), the resulting ambient noise field is dominated by surface waves (Haubrich and McCamy, 1969; Friedrich et al., 1998; Nishida et al., 2008). For Europe specifically, the noise field is dominated by surface waves from the North Atlantic Ocean, with additional significant contributions from the eastern Mediterranean Sea that are strongest during summer months (Lu et al., 2021).

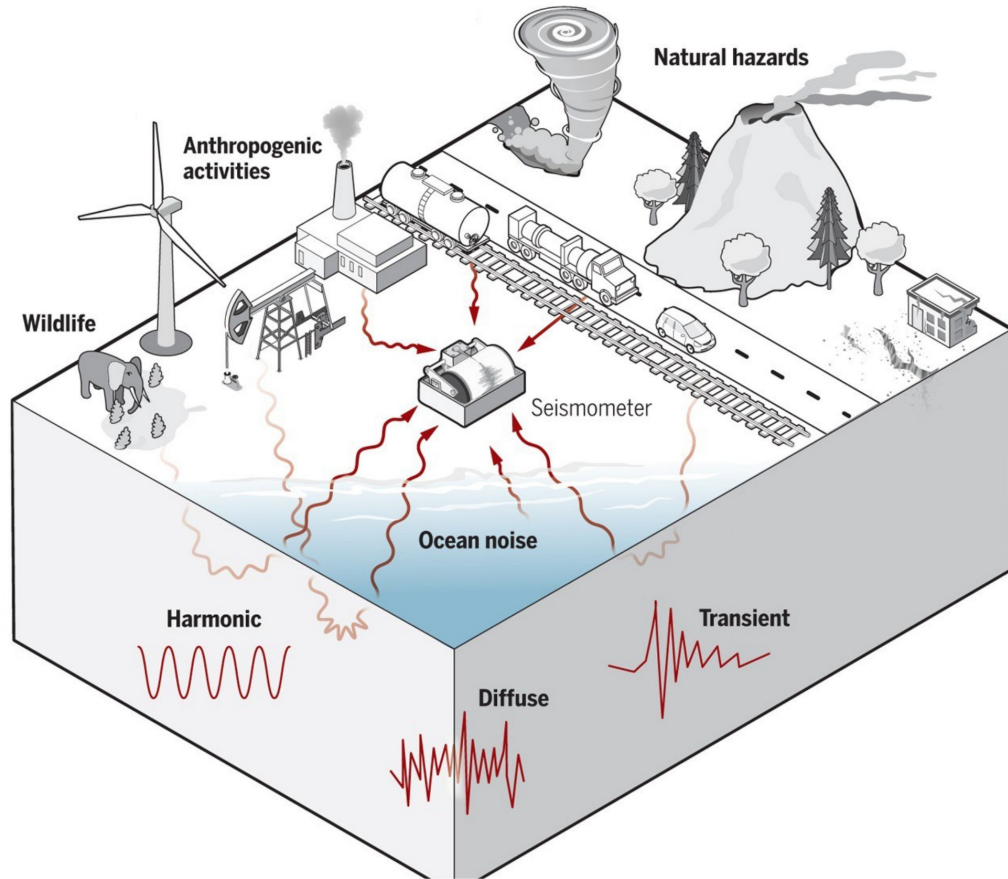


Figure 3: Schematic diagram showing various sources of seismic waves detected by seismometers. The image was modified after Denolle and Nissen-Meyer (2020).

Understanding these noise-generation mechanisms and their spatial patterns provides the basis for investigating how to utilize this continuous wavefield. Ambient noise interferometry fundamentally relies on the principle that cross-correlation of diffuse wavefields recorded

at two receivers converges toward the Green's function between those points (Lobkis and Weaver, 2001; Wapenaar, 2004). The Green's function represents the seismic response that would be observed at one location if an impulsive source were activated at another location (Aki and Richards, 2002), effectively transforming Earth's natural background noise into a virtual seismic survey where each receiver becomes a "virtual source" (Shapiro and Campillo, 2004).

The breakthrough application to real seismic data came with Shapiro and Campillo (2004), who demonstrated the extraction of broadband Rayleigh waves directly from ambient seismic noise. Their work proved that dispersive wave trains from noise cross-correlations exhibited group velocities consistent with traditional earthquake-generated surface waves (Shapiro et al., 2005), establishing the foundation for passive imaging techniques. Nevertheless, for exact Green's function retrieval, the method requires a diffuse wavefield (Sergeant et al., 2020), where seismic energy propagates uniformly in all directions with equal intensity across random seismic wave modes. This can be achieved through either homogeneously distributed, uncorrelated noise sources (Larose et al., 2006; Wapenaar et al., 2010) or strong-scattering media where structural heterogeneities redistribute incoming seismic energy across multiple directions (Hennino et al., 2001; Campillo and Paul, 2003; Malcolm et al., 2004; Larose et al., 2008). However, ambient seismic noise sources are heterogeneously distributed across Earth's surface (Fichtner et al., 2017), concentrating in oceanic regions due to ocean-wave interactions (Longuet-Higgins, 1950; Kedar et al., 2008) or populated areas from human activities, with distributions varying seasonally and geographically (Stehly et al., 2006). Furthermore, noise fields are often imperfectly diffusive across observable frequency bands (Tsai, 2009; Weaver et al., 2009), and transient earthquake signals frequently contaminate recordings (Bensen et al., 2007). Despite these limitations, the method has proven remarkably robust, enabling successful applications in ambient noise tomography (Sabra et al., 2005; Shapiro et al., 2005), crustal imaging (Lin et al., 2008), anisotropy studies (Huang et al., 2010), and continuous monitoring (Brenguier et al., 2008; Kramer et al., 2025).

Besides imaging Earth's interior and monitoring the shallow subsurface, researchers began exploring whether ambient noise interferometry could also be applied to measure seismic attenuation. Seismic attenuation measurement represents a crucial advancement beyond traditional imaging and monitoring approaches because it provides unique insights into the

subsurface properties that other seismic observables alone cannot capture. Attenuation reveals critical information about the rock porosity (Biot, 1956a,b), permeability (Payne et al., 2007), and saturation level (Toksoz et al., 1979), proving to be useful in hydrocarbon exploration and reservoir characterization (Raji and Rietbrock, 2013). Additionally, observational studies in the field have demonstrated that attenuation measurements can distinguish between different rock types (Stainsby and Worthington, 1985; Dasgupta and Clark, 1998; Singleton, 2008) and allow for analysis of fracture-related anisotropy (Maultzsch et al., 2007; Zhu et al., 2007).

Attenuation in the broadest sense refers to the decrease in a wave's amplitude as it propagates (Aki and Richards, 2002). Gaebler et al. (2015) consider three processes, schematically illustrated in Figure 4, that contribute to the total attenuation of seismic waves:

1. Geometric spreading - describes the reduction in seismic wave amplitude that occurs as the wave travels from its source, caused entirely by the expansion of the area across which the wave's energy is spread.
2. Scattering - deflection of seismic waves from their original propagation path due to heterogeneities within the Earth's subsurface, resulting in the redistribution of seismic energy.
3. Intrinsic (anelastic) attenuation - seismic energy is converted into heat through different mechanisms.

Distinguishing between these processes is challenging (Murillo, 2024), due to several reasons. Firstly, practical measurements make it difficult to isolate these effects since they overlap with one another and are obscured by experimental uncertainties and gaps in our knowledge of Earth's structure (Morozov, 2010). Secondly, attenuation is a frequency-dependent parameter (Aki and Richards, 2002), with different physical mechanisms preferentially affecting different frequency ranges. This frequency selectivity means that observed attenuation patterns represent the combined effects of multiple processes, complicating efforts to isolate the contribution of a single physical mechanism (Cheng and Kennett, 2002). Lastly, the size and nature of heterogeneities differ across regions (Shapiro and Kneib, 1993), creating complicated effects on how waves scatter. These challenges require careful interpretation when quantifying seismic attenuation in different geological settings. While geometric

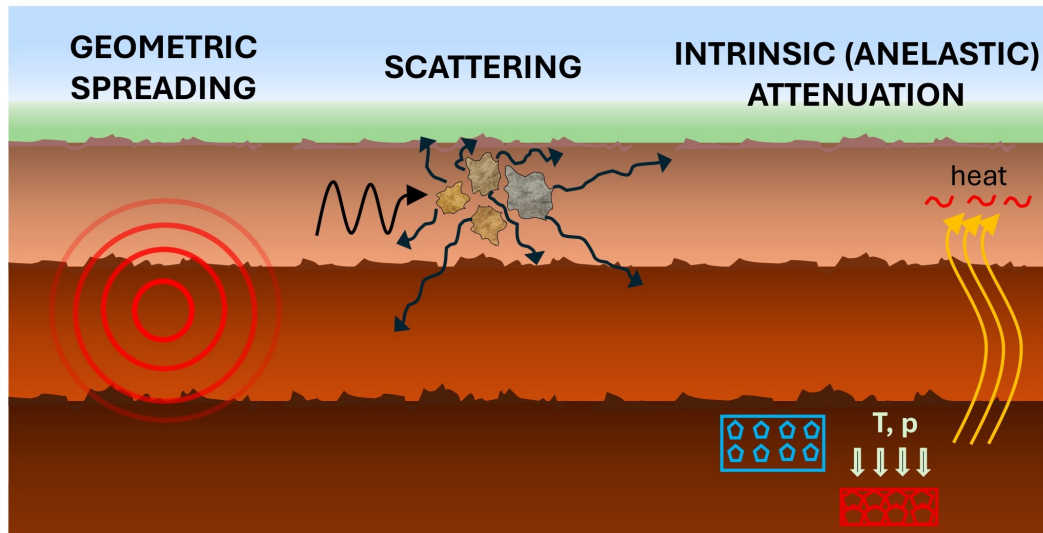


Figure 4: Processes controlling seismic wave attenuation. Geometric spreading (left) shows energy distribution over expanding wavefronts, scattering (center) depicts wave deflection by subsurface heterogeneities, and intrinsic attenuation (right) illustrates energy conversion to heat through rock deformation and thermal expansion.

spreading and scattering contribute to total attenuation as discussed, understanding the dominant physical processes behind intrinsic attenuation is essential for interpreting our measurements.

The mechanisms controlling this energy conversion generally include temperature-induced volume changes, movement of crystal imperfections, stress-related atomic rearrangement, and crystallographic transformations (Li and Cormier, 2002), reflecting the varying pressure-temperature conditions and material properties throughout the Earth's interior. In the crust, different attenuation mechanisms dominate due to its strong thermal and physical heterogeneities caused by variations in rock structure and composition (Natale Castillo et al., 2022). In dry, consolidated rocks, friction along cracks and grain boundaries represents the dominant attenuation mechanism under typical upper crustal conditions (Johnston et al., 1979). In porous and permeable rocks, fluid flow within the pore spaces and cracks (Müller et al., 2010; Pride et al., 2004), in addition to friction, governs intrinsic attenuation.

Morozov (2010) suggests that the most straightforward approach to quantify attenuation is through attenuation coefficients, which directly measure seismic wave amplitude reduction. There have been several attempts to measure seismic attenuation coefficients. Prieto et al. (2009) demonstrated that the amplitude decay of surface waves retrieved from ambient noise cross-correlations contained information about subsurface attenuation. They found that the observed amplitude decay was stronger than what would be expected from simple geomet-

ric spreading alone, indicating additional energy loss due to the Earth's anelastic properties (Aki and Richards, 2002). Lawrence and Prieto (2011) extended this methodology to create large-scale attenuation maps of the western United States using ambient noise, successfully identifying highly attenuating regions such as sedimentary basins along the West Coast and volcanic areas like Yellowstone. The method was also applied at much smaller scales, with Weemstra et al. (2013) demonstrating that meaningful attenuation estimates could be obtained even from short-duration ocean-bottom surveys.

However, these approaches faced several important limitations that affected their reliability and broader applicability. The distribution of ambient noise sources was found to significantly influence the accuracy of attenuation measurements, with Harmon et al. (2010) showing that non-uniform source distributions could introduce systematic errors and create apparent attenuation signals that were artifacts of the source geometry rather than true Earth structure. The methods also require very specific data conditions to work effectively, including dense station coverage, long recording periods, and sufficient signal-to-noise ratios (Tsai, 2009), which are not always available in practice. Additionally, the techniques could not easily distinguish between different types of attenuation, whether the amplitude decay was due to the Earth's intrinsic properties or due to scattering from small-scale heterogeneities (Prieto et al., 2009). Nonetheless, concerns remain about whether standard processing steps in ambient noise interferometry, such as those proposed by Bensen et al. (2007), are appropriate when studying amplitude information, as these steps can distort the signal needed for attenuation analysis.

This review reveals that while ambient noise interferometry has achieved remarkable success in imaging Earth's structure and monitoring subsurface changes applications, the extension to reliable attenuation measurements remains challenging due to source distribution effects, data processing challenges, and the fundamental difficulty of separating different attenuation mechanisms. The development of more rigorous theoretical frameworks, such as the approach by Boschi et al. (2019), represents progress toward addressing these limitations. This thesis builds upon these foundations to test the approach of Boschi et al. (2019) through its application to short-duration seismic array data from the Eastern Vienna Basin, ultimately deriving attenuation coefficients that characterize the subsurface properties of this region.

2 Goals of the Thesis

This thesis aims to obtain seismic attenuation across the Vienna Basin using ambient noise cross-correlation analysis. This work represents the first known implementation of the framework developed by Boschi et al. (2019) and validated by Magrini and Boschi (2021); Magrini et al. (2021) for dense, short interstation distance nodal arrays.

The specific objectives are:

- a) **Adapt and implement Boschi et al. (2019) approach for dense nodal deployment:**
Develop computer codes to adapt the ambient noise cross-correlation framework of Boschi et al. (2019) specifically for dense nodal arrays, addressing the unique computational and methodological challenges posed by relatively short inter-station distances and recording times.
- b) **Quantify seismic attenuation:** Extract frequency-dependent attenuation coefficients to understand how seismic energy is absorbed and scattered within the Vienna Basin's subsurface.
- c) **Validation, interpretation, and limitation assessment:** Validate the effectiveness of the adapted ambient noise cross-correlation technique for attenuation estimation for temporal nodal arrays, potentially interpret observed attenuation patterns in relation to known tectonic structures and geological features within the Vienna Basin, and assess the limitations of the approach for dense local arrays.

These objectives address a critical knowledge gap in ambient noise attenuation studies. As the first implementation of the Boschi et al. (2019) approach for dense nodal arrays, this work contributes significantly to the broader application of ambient noise methods for local attenuation studies, while establishing a methodological foundation for short nodal deployments.

3 Data and Methods

3.1 Eastern Vienna Array - EVA

The Eastern Vienna Array (EVA) was deployed across the eastern area of Vienna city to investigate subsurface structures across the central Vienna Basin (Figure 5, Esteve et al., 2025). The array consists of 44 seismic nodes aligned along a 15-km long northwest–southeast (NW–SE) profile, with approximately 350-meter spacing to ensure good spatial coverage and later obtain high spatial resolution of, e.g., velocity models, as shown in Esteve et al. (2025). An additional 48 seismic nodes with an average spacing of about 2 kilometers were distributed across the surrounding area, extending spatial coverage and resulting in a total of 92 seismic nodes. The nodes are FairfieldNodal three-component geophones with GPS synchronization and integrated data storage (Farrell et al., 2018).

All data is processed on the advanced computing cluster maintained by the Department of Meteorology and Geophysics at the University of Vienna. Python is the primary programming environment for processing, analysis, and visualization tasks.

For the attenuation analysis, we used only vertical-component ambient noise data from the 44 profile stations over the 36-day recording period (June 7 to July 13, 2023).

3.2 Computation of Ambient Noise Cross-Correlation Functions

The computation of ambient noise cross-correlation functions involves three main steps: initial data processing, anomaly removal, and cross-correlation calculation. Each stage addresses specific data quality issues that affect the reliability of the final correlation functions.

Initial Data Processing

Raw seismic data recorded by the EVA consist of continuous three-component recordings (vertical, north-south, and east-west) stored in the Fairfield-specific FCNT format. We first reorganized the continuous raw seismic waveforms into daily miniseed files. This simplifies data management for large datasets. However, each daily recording requires several corrections to eliminate measurement biases. DC offsets caused by instrumental drift are commonly observed in seismic recordings (Bensen et al., 2007), which we eliminate by applying demeaning to each seismic waveform. Long-term trends that could interfere with ambient noise analysis are removed through linear detrending.

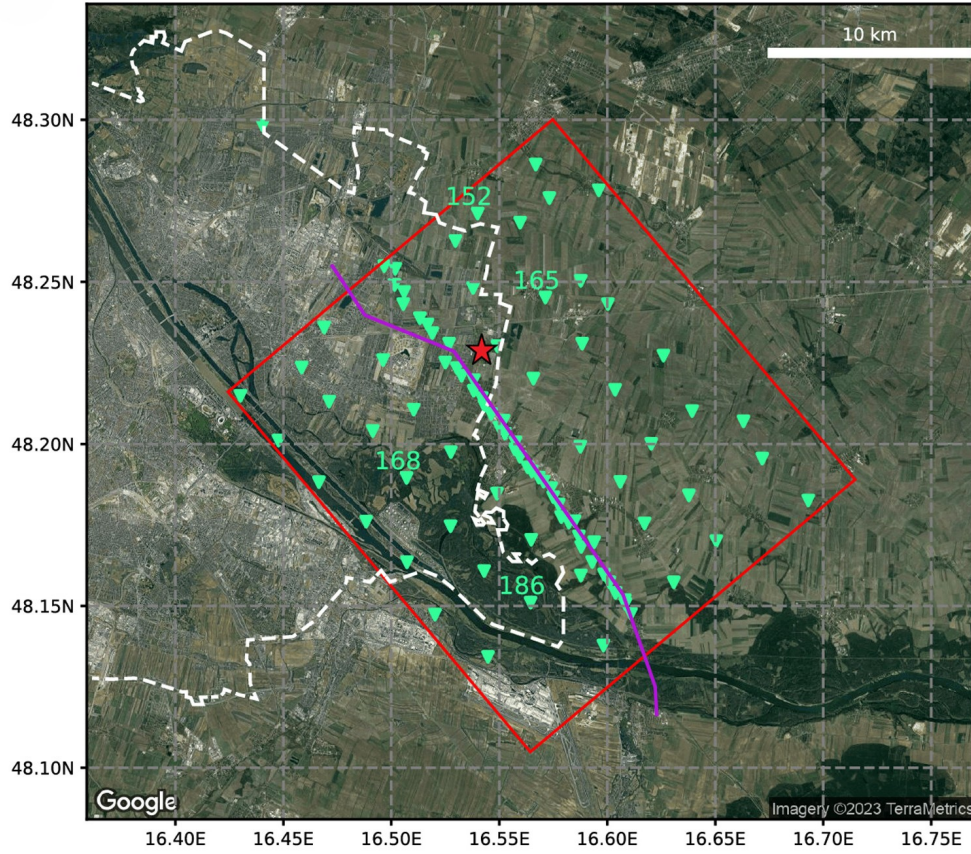


Figure 5: EVA Station Configuration. Spatial distribution of the 92 seismic nodes comprising the Eastern Vienna Array (EVA) deployed across the central Vienna Basin. Green inverted triangles indicate seismic node locations, with 44 stations positioned along the 15-km-long geological cross-section presented in fig. 2, with approximately 350-meter spacing. An additional 48 nodes were distributed across the surrounding area with an average spacing of 2 kilometers. Modified after Esteve et al. (2025).

To convert the data from digital counts to physical units of ground velocity, we remove instrument response using station-specific response files. This correction accounts for the frequency-dependent sensitivity of each seismometer and ensures that amplitude measurements reflect actual ground motion (Haney et al., 2012; Krischer et al., 2015). Finally, we apply a bandpass filter (0.1 – 12 Hz) and decimate the processed data by a factor of 10 from the original sampling frequency of 250 Hz to 25 Hz to reduce computational requirements while maintaining adequate sampling for the ambient noise frequency range. Figure 6 shows an example of a 24-hour ambient noise recording after initial data processing, displaying the normalized amplitude variations of seismic data over time. The recording demonstrates typical background seismic noise characteristics with relatively low-amplitude fluctuations throughout most of the recording period, punctuated by occasional higher-amplitude events.

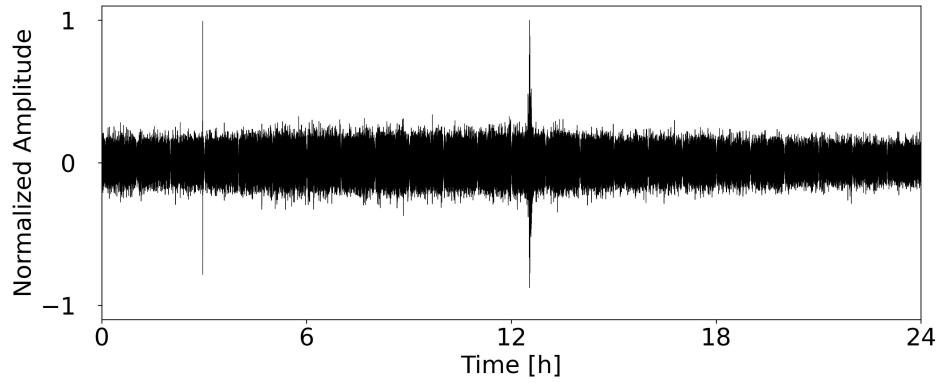


Figure 6: Daily Ambient Noise Recording After Initial Processing. Twenty-four-hour vertical-component seismic recording after initial data processing including DC offset removal (demeaning), linear detrending, instrument response correction, and bandpass filtering (0.1-12 Hz). The data has been decimated from 250 Hz to 25 Hz sampling rate. Normalized amplitude variations throughout the day reflect natural fluctuations in ambient noise sources.

Outlier Removal

The second processing stage identifies and removes signals that contaminate the ambient noise field (Bensen et al., 2007). Each daily recording is divided into 2-minute segments (720 segments per day) to enable statistical analysis of signal characteristics. The energy content of each segment is calculated as the sum of squared amplitudes and compared to the median energy for that day. Segments with energy exceeding 1.5 times the median are identified as strong ground shaking events or smaller earthquakes in the vicinity of the deployment and are zeroed out. This threshold effectively removes large amplitude signals not associated with ambient noise, while preserving the diffuse nature of ambient noise. Additionally, instrumental glitches — temporary recording artifacts that produce anomalous high-amplitude signals—are removed by eliminating segments that exceed 10 times the standard deviation of each segment. Figure 7 shows an example of ambient noise data after anomaly removal and quality control processing. The 24-hour recording demonstrates the effectiveness of the aforementioned procedure, where data segments containing earthquakes or transient events exceeding 1.5 times the median daily energy have been identified and removed, resulting in a more uniform and statistically stable ambient noise dataset suitable for cross-correlation analysis. Additionally, the seismic data exhibit a diurnal pattern with reduced ambient noise amplitudes during nighttime hours (approximately 6 PM to 6 AM), likely reflecting decreased anthropogenic activity.

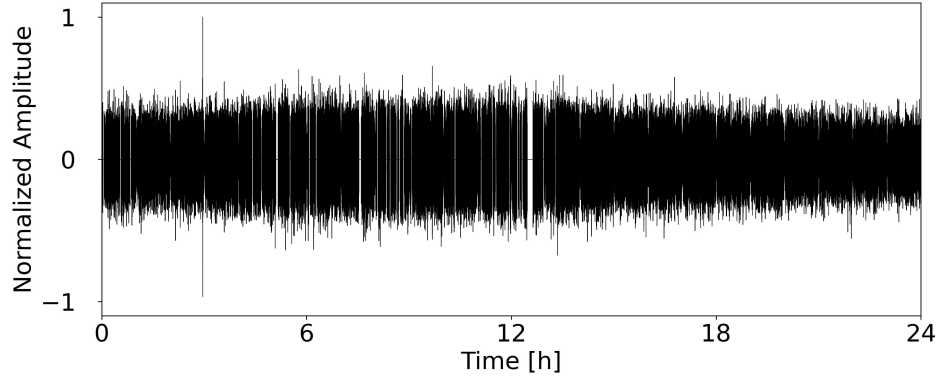


Figure 7: Daily Ambient Noise Recording After Outlier Removal. Twenty-four-hour vertical-component recording following quality control procedures applied to the preprocessed data from Figure 6. Data segmentation into 2-minute windows enabled statistical analysis, with segments exceeding 1.5 times the median daily energy identified as containing earthquakes or transient events and subsequently zeroed out. Sample-level quality control removed instrumental glitches exceeding 10 standard deviations, resulting in cleaned ambient noise suitable for cross-correlation analysis.

Cross-Correlation Computation

Cross-correlation functions of the vertical component are calculated for each station pair using Fast Fourier Transform method. This approach transforms each time segment to the frequency domain, where cross-correlation reduces to multiplication, avoiding the computationally expensive convolution operations required in the time domain.

The computation process uses non-overlapping 2-minute segments, producing cross-correlation functions that span ± 120 seconds of lag time. This time window captures both direct arrivals and scattered waves across the array geometry. To save memory and increase the SNR, five consecutive 2-minute cross-correlation functions are stacked to create 10-minute cross-correlation functions, resulting in 144 correlation functions per day per station pair. The final correlation functions are stored in HDF5 (The HDF Group, 2024) format.

This processing workflow successfully converts raw ambient noise recordings into empirical Green's functions while preserving amplitude information crucial for attenuation analysis. The resulting correlation functions from 44 stations along the NW-SE profile then undergo frequency-domain processing (section 3.3) to extract quantitative attenuation measurements.

To improve the SNR and exploit the symmetry properties of ambient noise cross-correlation functions, we stack the causal and acausal sides. For visualization purposes only, we also apply a bandpass filter from 0.1-3.0 Hz. Each cross-correlation function contains both pos-

itive lag times (causal side, representing energy travelling from station A to station B) and negative lag times (acausal side, representing energy travelling from station B to station A). Under ideal conditions with diffuse ambient noise, these two sides should be symmetric and contain equivalent information about the Green's function between the stations (Bensen et al., 2007). We stack the causal and acausal sides by time-reversing one side and adding it to the other, effectively doubling the signal energy while random noise components tend to cancel out, improving the clarity of wave arrivals.

The ambient noise cross-correlation functions reveal interesting waveform characteristics. Figure 8 shows bandpass-filtered (0.1-3 Hz) cross-correlation functions for two representative station pairs with different inter-station distances. For the short-distance station pair (101-105), both the daily correlations and the stacked function exhibit characteristics resembling autocorrelation functions. This autocorrelation-like behaviour occurs because the stations are separated by less than one dominant wavelength of the surface waves, causing them to record nearly identical ambient noise waveforms with minimal travel time differences. The longer distance station pair (101-140) exhibits a more scattered and dispersed energy pattern compared to the clear, coherent waveform of the shorter distance pair. This pattern reflects the natural attenuation and scattering of seismic energy over greater propagation distances, as well as the influence of heterogeneous subsurface structures along the wave path (Aki and Richards, 2002; Stein and Wysession, 2003). Additionally, we observe that both station pairs show sharp, symmetric, high-amplitude arrivals centered around zero lag time. The significant energy around zero lag time likely occurs because both stations record identical noise sources simultaneously, creating a strong correlation at zero delay, which differs from the expected surface wave signals that typically arrive at lag times corresponding to inter-station travel times. (Lin et al., 2008). The clear symmetric arrivals correspond to surface wave propagation and are consistent with the empirical Green's functions from ambient noise correlations (Shapiro and Campillo, 2004; Campillo and Paul, 2003).

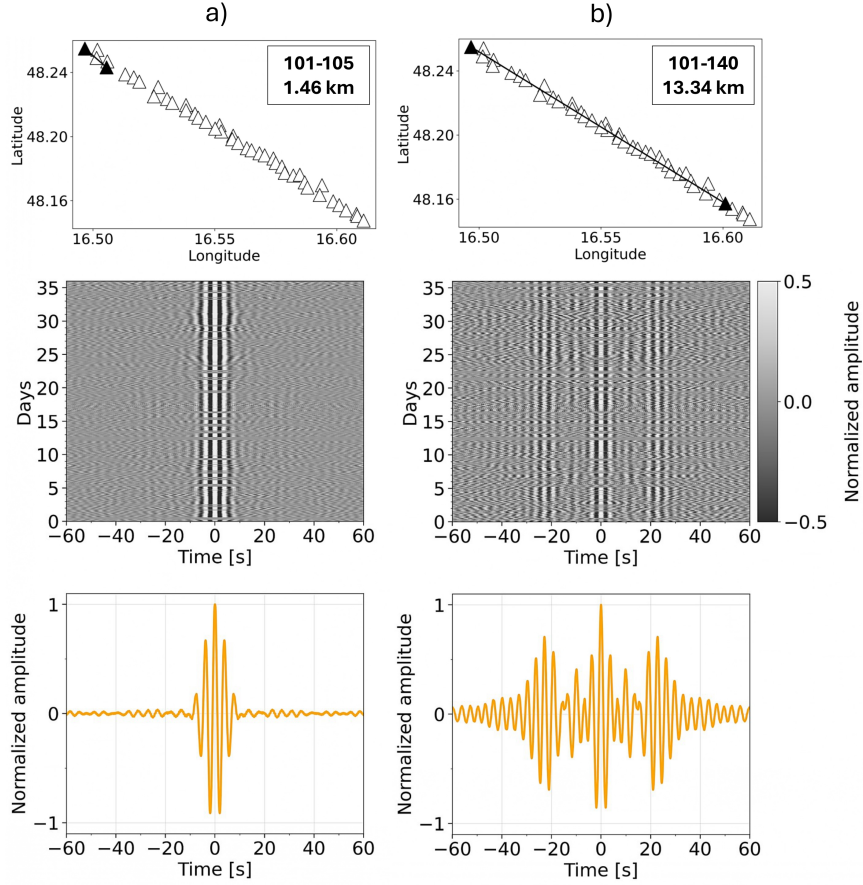


Figure 8: Cross-Correlation Functions for Representative Station Pairs. Vertical-component ambient noise cross-correlations filtered between 0.1 and 3 Hz for two station pairs with contrasting inter-station distances: (a) stations 101-105 separated by 1.46 km, and (b) stations 101-140 separated by 13.34 km. The top panels show station locations within the EVA network. Middle panels display correlation amplitude as a function of lag time and recording day over the 36-day deployment period. Bottom panels represent the stacked correlation functions across all recording days.

The ambient noise cross-correlation processing workflow, summarized in Figure 9, transforms continuous seismic recordings into empirical Green's functions through a systematic three-stage approach. Initial data processing prepares the raw recordings by removing the instrument response and applying a bandpass filter, followed by anomaly removal to eliminate transient signals and ensure data quality. The final computation stage applies the Fast Fourier transform to individual 2-minute segments to obtain the cross-correlation functions. These CCFs represent the observed seismic wavefield between station pairs and serve as the foundation for the subsequent attenuation analysis.

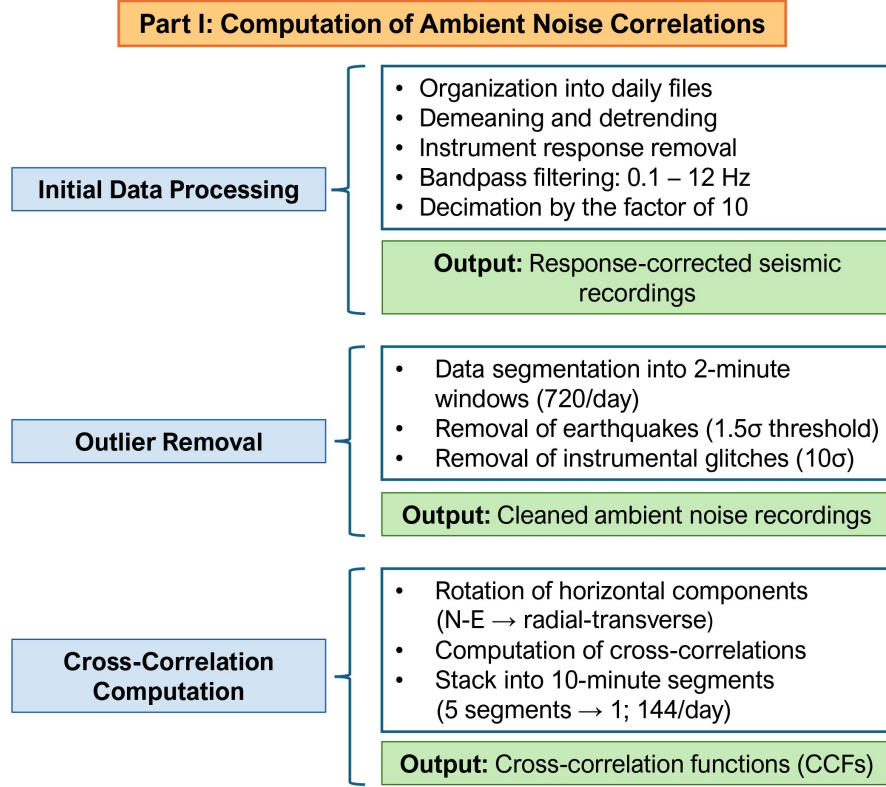


Figure 9: Workflow diagram illustrating the data processing chain for computation of cross correlation functions.

3.3 Attenuation Estimation

Theoretical Foundation of the Boschi et al. (2019) Method for Attenuation Estimation

To understand the attenuation estimation method applied in this work, it is essential to establish the theoretical development that provides the mathematical foundation for extracting attenuation properties from passive seismic recordings. The method unfolds through three interconnected stages, each building upon the previous to connect observable cross-correlation data with theoretical attenuation models.

The initial challenge lies in the computational complexity of modelling seismic wave propagation through the full three-dimensional elastodynamic equations in heterogeneous, anelastic media. To address this complexity, Boschi and Weemstra (2015) adopt the "potential" representation framework established by Tanimoto (1990), which decomposes the three-dimensional surface-wave problem into separable components. In this approach, Rayleigh wave displacement is expressed as the product of depth-dependent eigenfunctions and a laterally varying potential. The eigenfunctions describe how wave amplitude varies with depth, while the potential captures horizontal propagation characteristics. When this mathemat-

ical representation is substituted into the three-dimensional equation of motion, the problem reduces to a two-dimensional wave equation, which is mathematically equivalent to the equation governing a stretched membrane. This means that membrane waves can be used to model Rayleigh wave propagation in a laterally smooth, lossless half-space (Boschi et al., 2018).

Building upon this dimensional reduction, the next step involves establishing the mathematical relationship between ambient noise cross-correlation functions and Green's function of membrane (resp. Rayleigh) waves. Boschi et al. (2018) extend the derivation of the reciprocity theorem to create this connection for lossless (non-dissipative) media, which states that under ideal conditions: uniform source distribution and a perfectly diffuse wavefield, the cross-correlation of ambient recordings approximates the imaginary part of the Green's function. However, the authors note an important limitation: if all noise sources share the same spectrum, the cross-correlation of the recorded ambient signal would exhibit that spectrum squared, meaning the reconstructed response is not the pure Green's function but rather its convolution with a source-related spectral term. This spectral "contamination" explains why ambient-noise cross-correlations are dominated by oceanic microseism peaks rather than providing an ideal Green's function reconstruction.

In the last stage, Boschi et al. (2019) further extend this framework to realistic attenuating media, where seismic energy dissipates as waves propagate through the Earth, and derive a special normalizing term that effectively deconvolves the source-related spectral contamination from the Green's functions. To establish this approach, they first derive the Green's function for lossy (dissipative) media and again extend the reciprocity theorem that connects the lossy Green's function with the ambient noise cross-correlation functions. Following Tsai (2011), surface-wave attenuation is incorporated by modifying the lossless membrane equation to include a damping term that represents energy dissipation mechanisms within the Earth. Under weak attenuation assumptions ($\alpha \ll \omega/c$), which are reasonable for most crustal applications, and high frequency ($\frac{\omega x}{c} \gg 1$) the lossy Green's function can be approximated as the product of the lossless Green's function and an exponential decay factor $e^{(-\alpha x)}$, where x represents propagation distance.

The key breakthrough involves recognizing that when cross-correlations are normalized by the power spectral density averaged over all receivers, the unknown source parameters cancel out mathematically. This occurs because both the cross-correlation numerator and the power

spectral density denominator depend on the same source characteristics in the same way, effectively eliminating source contamination while preserving the attenuation information. The resulting relationship provides a direct pathway for measuring attenuation coefficient, α , from ambient noise amplitudes without requiring knowledge of the source distribution or characteristics. The culmination of this theoretical development yields the fundamental relationship that connects observable measurements with theoretical models. After applying the power spectral density normalization and incorporating the corrected algebraic factor (Boschi et al., 2020), the final expression becomes:

$$\frac{s(x_A, \omega)s^*(x_B, \omega)}{\langle |s(x, \omega)|^2 \rangle_x} \approx J_0 \left(\frac{\omega |x_A - x_B|}{c} \right) e^{-\alpha |x_A - x_B|}, \quad (1)$$

where:

- $s(x_A, \omega)$... vertical-component, Rayleigh-wave displacement recorded at receiver location x_A in the frequency domain
- $s(x_B, \omega)$... vertical-component, Rayleigh-wave displacement recorded at receiver location x_B in the frequency domain
- $s^*(x_B, \omega)$... complex conjugate of the displacement at receiver x_B
- $\langle |s(x, \omega)|^2 \rangle_x$... ensemble average of the power spectral density over all available receiver locations x
- J_0 ... zeroth-order Bessel function of the first kind
- ω ... angular frequency [rad/s]
- $|x_A - x_B|$... interstation distance between receivers at positions x_A and x_B [m]
- c ... phase velocity of Rayleigh waves [m/s]
- α ... attenuation coefficient [m^{-1}]
- $e^{-\alpha |x_A - x_B|}$... exponential damping term accounting for anelastic attenuation

This equation represents the theoretical endpoint of the method, where the left-hand side contains only observable quantities, cross-correlation amplitudes and power spectral density computed directly from ambient noise recordings, while the right-hand side provides the

theoretical model expressed in terms of the unknown attenuation parameter α . The Bessel function J_0 describes the oscillatory behaviour of the Green's function with frequency, while the exponential decay term $e^{-\alpha|x_A-x_B|}$ contains the attenuation information.

Using equation 1 to directly determine attenuation is challenging because attenuation coefficients, α , only affect the overall envelope of the oscillating signal, not the individual oscillations themselves. Therefore, Magrini and Boschi (2021) introduced a cost function - a measure of how well the model reproduces the data - that focuses on matching the envelopes of observed and modelled signals rather than trying to fit every individual oscillation. The cost function is defined as:

$$C(\alpha, \omega) = \sum_{i,j} |\mathbf{x}_i - \mathbf{x}_j|^2 \left| \text{env} \left[\frac{s(\mathbf{x}_i, \omega) s^*(\mathbf{x}_j, \omega)}{\langle |s(\mathbf{x}, \omega)|^2 \rangle_x} \right] - \text{env} \left[J_0 \left(\frac{\omega |\mathbf{x}_i - \mathbf{x}_j|}{c_{ij}(\omega)} \right) e^{-\alpha |\mathbf{x}_i - \mathbf{x}_j|} \right] \right|^2, \quad (2)$$

where:

- $C(\alpha, \omega)$... cost function quantifying the misfit between observed and theoretical envelope functions
- $\sum_{i,j} |\mathbf{x}_i - \mathbf{x}_j|^2$... summation over all station pairs weighted by the squared interstation distance [m²]
- $\text{env}[\cdot]$... envelope function that extracts the amplitude trend from oscillatory signals
- $\frac{s(\mathbf{x}_i, \omega) s^*(\mathbf{x}_j, \omega)}{\langle |s(\mathbf{x}, \omega)|^2 \rangle_x}$... normalized cross-correlation functions in the frequency domain
- $J_0 \left(\frac{\omega |\mathbf{x}_i - \mathbf{x}_j|}{c_{ij}(\omega)} \right) e^{-\alpha |\mathbf{x}_i - \mathbf{x}_j|}$... theoretical model combining Bessel function with attenuation term, where $c_{ij}(\omega)$ is the interstation phase velocity [m/s]

The equation 2 thus serves as the primary equation for the attenuation estimation, in which the envelope function directly reflects energy loss during wave propagation between two stations, allowing for the extraction of the attenuation coefficient from amplitude measurements of ambient noise cross-correlation functions. Since the cost function assumes that the attenuation coefficient is the only unknown parameter, interstation phase velocities must be determined through an independent inversion. Interstation phase velocities for this array were previously calculated by Esteve et al. (2025), and we use their results for the subsequent attenuation analysis. Since phase velocity measurements were not available for all required

periods, we applied cubic spline interpolation to obtain velocity values at the necessary frequencies for the cost function evaluation.

The practical application of this theoretical framework requires adherence to key assumptions: uniform distribution of noise sources across the Earth’s surface, weak attenuation ($\alpha \ll \omega/c$), dominance of surface waves in the ambient field, and sufficient temporal averaging to achieve a diffuse wave field. While this approach establishes a rigorous, physics-based methodology that avoids some limitations of previous methods discussed in chapter 1, certain challenges remain, such as the effects of scattering, the presence of body-wave signal not accounted for by the theory and site amplifications (Roisenberg et al., 2024).

To obtain attenuation coefficients from the theoretical framework presented above, we structure our work into three distinct stages: spectral processing, envelope calculation, and attenuation estimation. Each stage builds upon the previous one, enabling us to extract frequency-dependent attenuation information from the ambient noise data.

Spectral Processing

First, the time-domain cross-correlation functions are transformed into the frequency domain using Fast Fourier Transform (FFT). This conversion allows for the extraction of the real, imaginary, and absolute components of the spectra for each 10-minute segment.

Subsequently, we implement the normalization procedure established by Boschi et al. (2019) to address the influence of source spectra on ambient noise amplitudes. This process begins by calculating an average power spectrum from the autocorrelation functions across all stations, effectively characterizing the ambient noise source spectrum for the region (Figure 10). The dominant energy contribution in our dataset originates from the secondary microseism band (0.2-0.4 Hz). Additional spectral peaks appear at higher frequencies, including signatures from windmills around 1.2 Hz and the distinctive monochromatic signal at 1.72 Hz corresponding to water turbine harmonics from the Danube power plant (Fuchs et al., 2021). The windmill signatures show variable intensity across different days, likely reflecting changes in wind strength. The water turbines exhibit a clear pattern, where periodic gaps in activity may correspond to weekends. Additionally, the average spectrum shows, for example, five distinct blocks of higher energy between 1.5 and 2 Hz from day 0 to day 5, with these increased amplitudes occurring during daytime hours and lower amplitudes during nighttime periods. This average spectrum then serves as a normalization factor for all

cross-correlation functions between different station pairs.

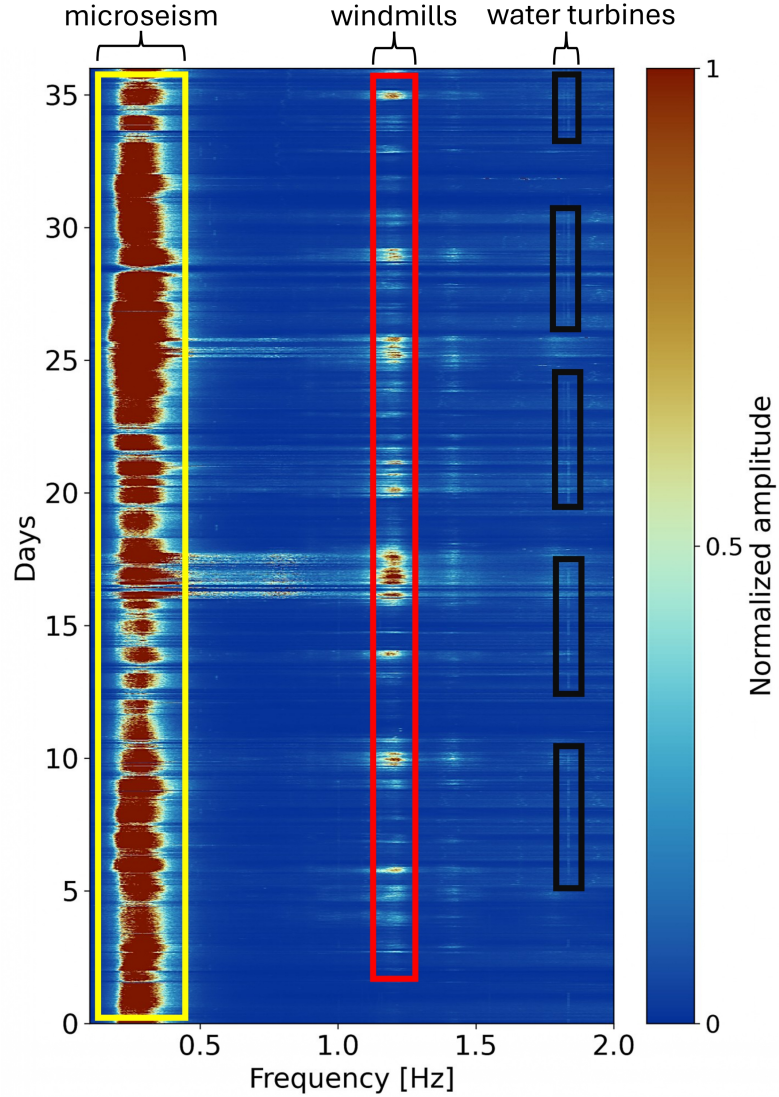


Figure 10: Average Power Spectral Density. Regional ambient noise source spectrum calculated from autocorrelation functions across 44 EVA nodes. Dominant energy appears between 0.2-0.4 Hz, corresponding to the secondary microseism band, with additional peaks at 1.2 Hz (windmill signatures) and 1.72 Hz (water turbine harmonics).

The normalized cross-correlation functions reveal distinct spectral characteristics that vary with inter-station distance (Figure 11). For shorter distances, such as the 101-105 station pair (1.46 km distance), the secondary microseism peak continues to dominate the frequency spectrum throughout the recording period. In contrast, longer distances like the 101-140 pair (13.34 km distance) show smoother energy distribution across all frequencies, reflecting the cumulative effects of propagation and attenuation over greater distances.

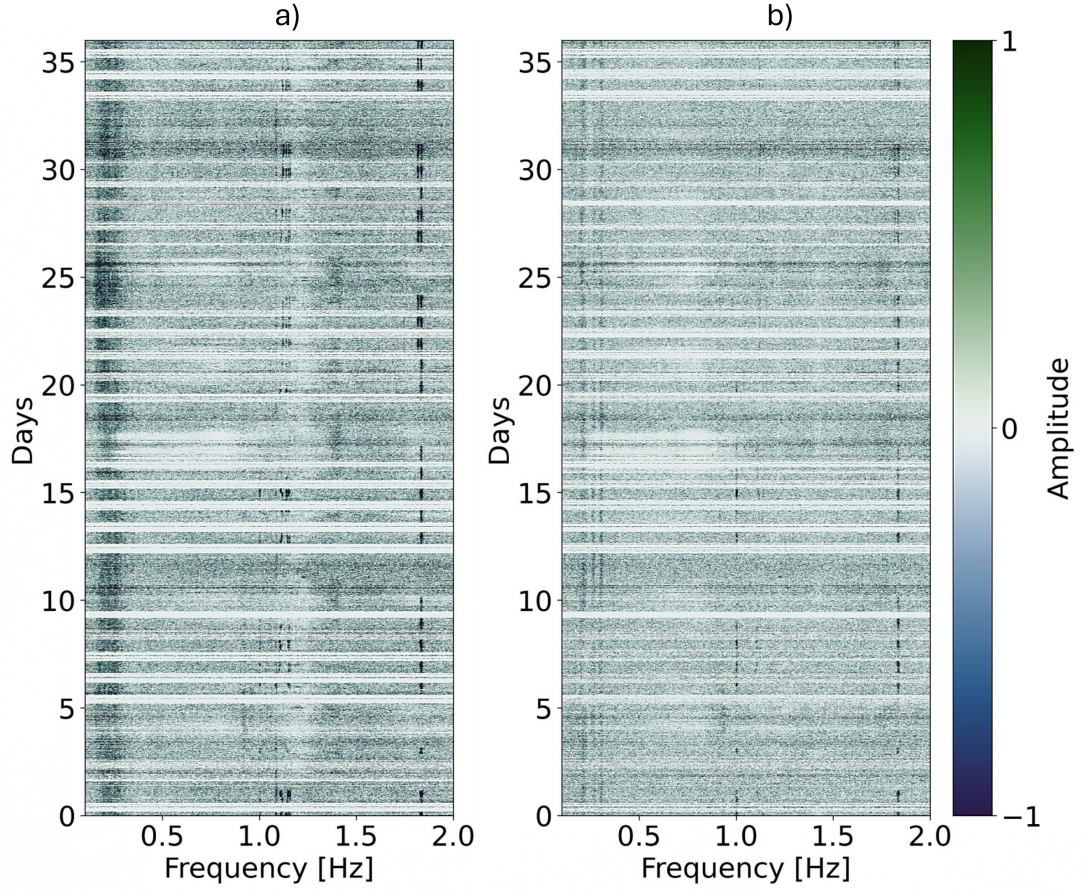


Figure 11: Normalized Cross-Correlation Functions in Frequency Domain. Spectral representation of normalized correlation functions over the 36-day recording period for station pairs: (a) 101-105 (1.46 km) showing persistent microseism dominance, and (b) 101-140 (13.34 km) displaying distributed energy across frequencies.

Quality Control and Envelope Calculation

We apply a 0.7-Hz lowpass filter to the normalized cross-correlation functions to avoid the high-frequency range where scattering effects can contaminate intrinsic attenuation measurements (Stehly et al., 2006). Then, we implement a robust quality control procedure to identify and remove outliers from the filtered spectral data. The approach systematically separates each segment into three temporal categories: combined day-night, day period (6 AM - 6 PM), and night period (6 PM - 6 AM), acknowledging the significant diurnal variations in ambient noise characteristics. For each category and segment, the median and standard deviation are calculated at each frequency point. Segments containing any frequency values that deviate by more than two standard deviations from the median are identified as outliers and excluded from further analysis. After quality control, the remaining segments are stacked, creating representative spectral stacks for each category. To minimize interference from high-frequency urban noise, the nighttime stack from 0.2 - 0.7 Hz is selected for subse-

quent envelope calculation and attenuation estimation. The quality control procedure (Figure 12) successfully removes the high-amplitude oscillations present in the original night stack of both station pairs, resulting in a much cleaner and smoother signal.

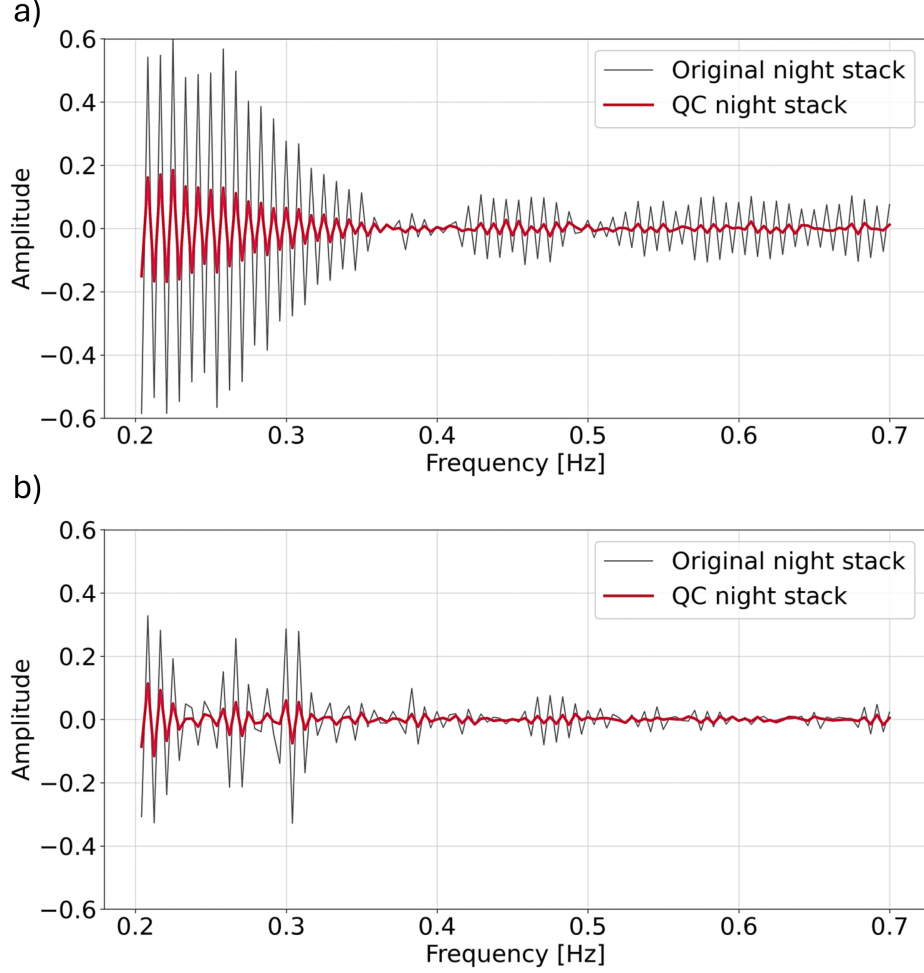


Figure 12: Quality Control Results. Comparison of spectral stacks before (grey) and after (red) quality control for station pairs: (a) 101-105 and (b) 101-140. The procedure effectively removes outliers while preserving the underlying signal structure.

We compute envelope functions using the Hilbert transform. This converts the stacked signals into complex analytic signals, where the absolute value (magnitude) yields envelope functions that represent amplitude variation across frequencies. To further enhance signal clarity, a Savitzky-Golay filter with a window length of 11 points and a first-order polynomial is applied to smooth the envelope function within the targeted frequency range. In figure 13, both panels show a clear exponential decay in the envelope amplitude with increasing frequency, consistent with the expected attenuation behaviour of surface waves. The Savitzky-Golay filtering effectively smooths the original envelope (blue and pink lines), removing high-frequency noise while preserving the underlying decay trend needed for ac-

curate attenuation estimation.

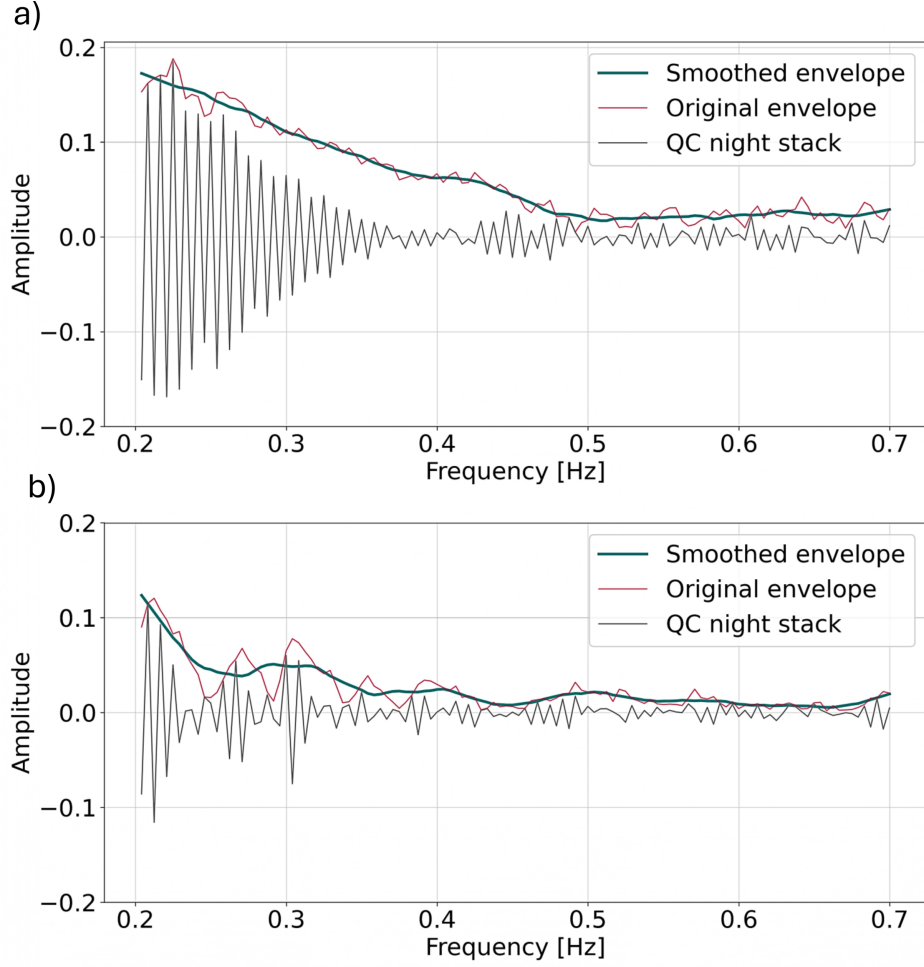


Figure 13: Envelope Functions. Smoothed (dark lines) and original (light lines) envelope functions derived from quality-controlled spectral stacks for station pairs: (a) 101-105 and (b) 101-140, showing the effect of Savitzky-Golay filtering.

Computation of Attenuation Coefficients

In the final stage, the attenuation coefficient, α , is estimated through a comprehensive grid search optimization approach: we parameterize the attenuation as a frequency-dependent function chosen to vary logarithmically from 10^{-5} to 10^{-3} m^{-1} , encompassing 200 discrete values across the chosen frequency interval. This range was selected based on values reported for sedimentary basins in the greater Alpine region (Roisenberg et al., 2024). For each frequency and attenuation coefficient, synthetic envelope functions are generated using a damped Bessel function. The optimal attenuation coefficient, α , at each frequency is determined by minimizing a distance-weighted cost function that compares observed and synthetic envelopes. This distance-based weighting accounts for the expected amplitude decay with distance and ensures that the optimization focuses on the physically meaningful

differences between observed and modelled envelopes. The grid search systematically evaluates all attenuation coefficients at each frequency, storing the combination that produces the minimum residual as the optimal attenuation coefficient for that frequency.

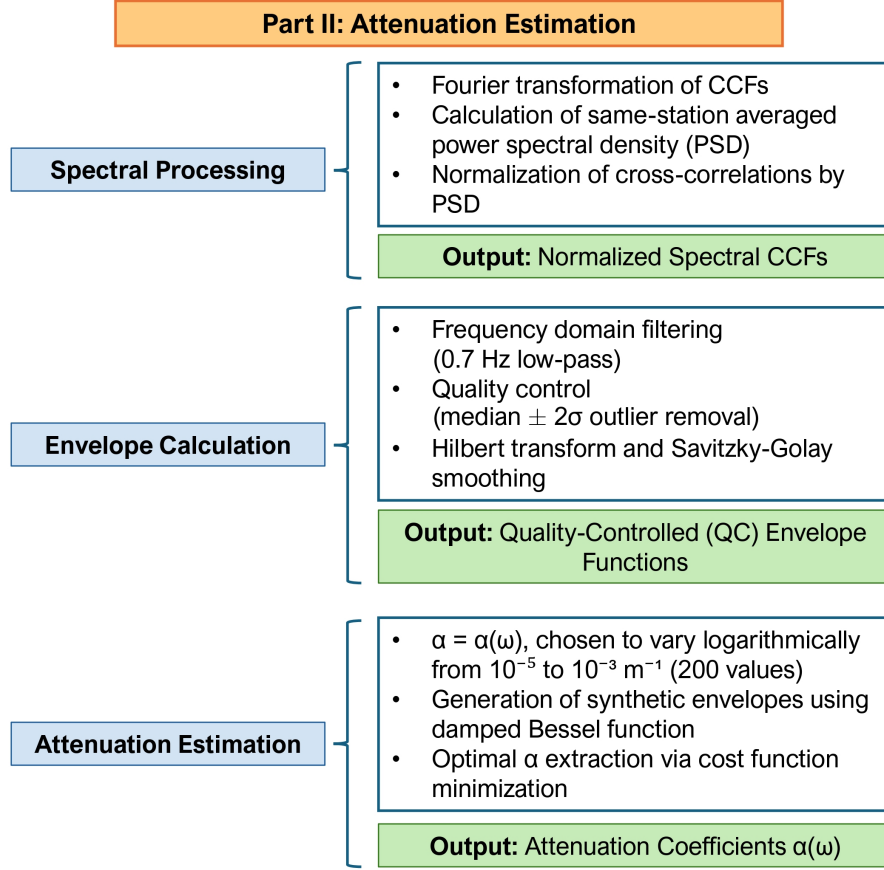


Figure 14: Workflow diagram illustrating the data processing chain for ambient noise attenuation estimation.

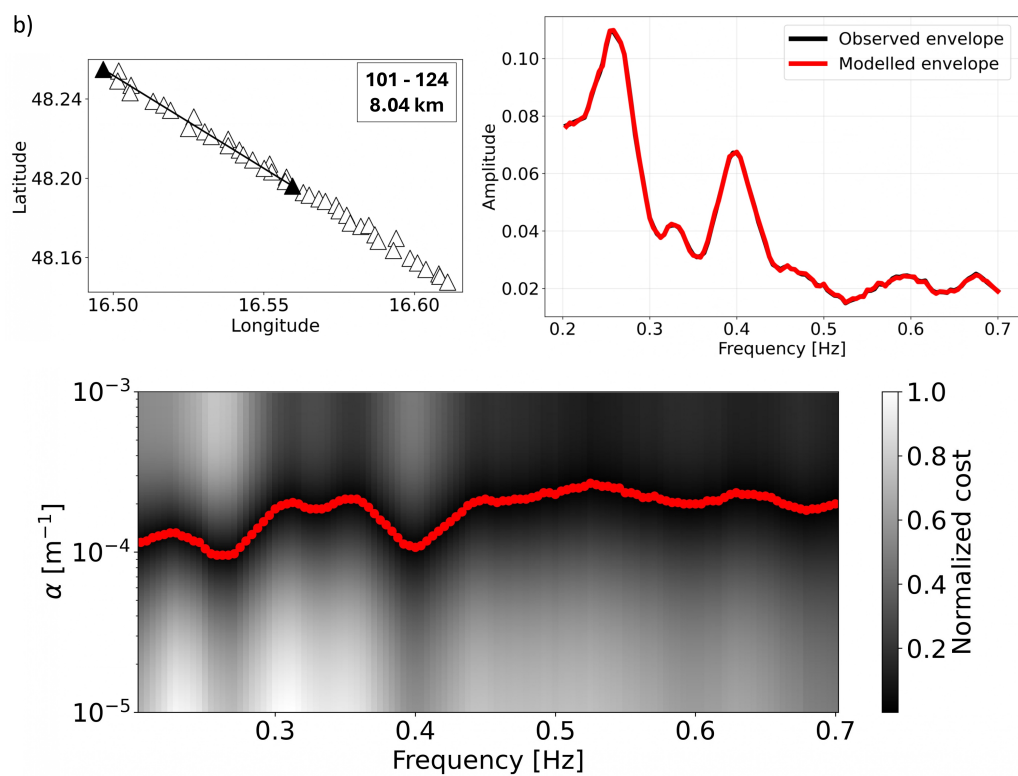
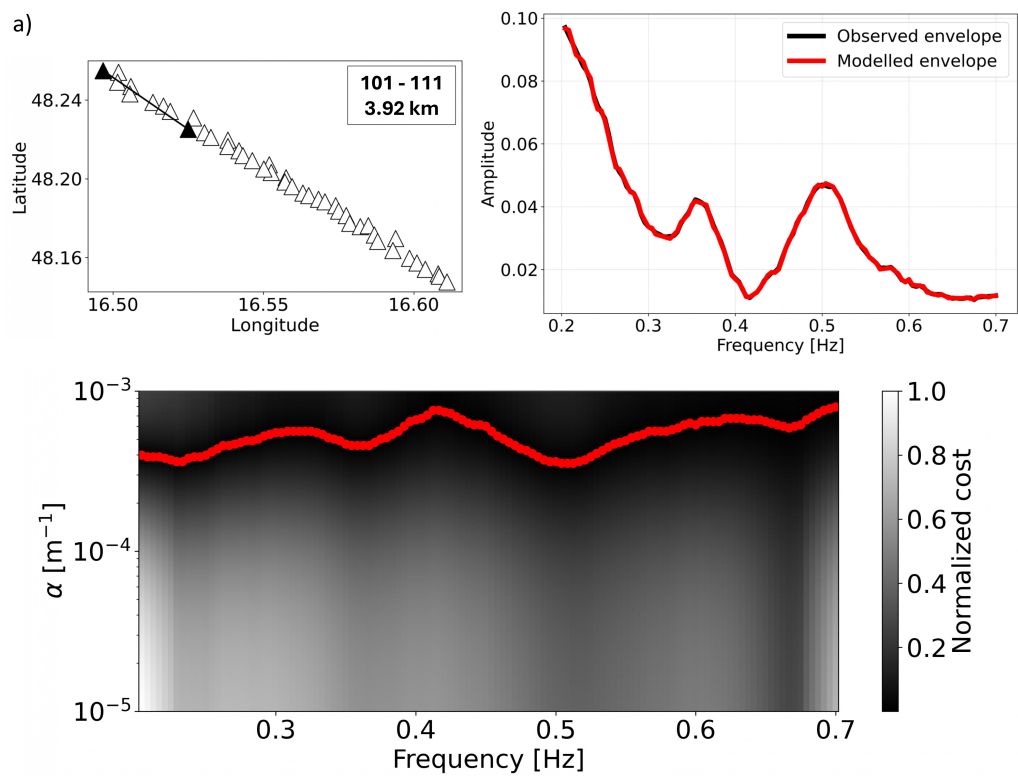
The attenuation estimation workflow, summarized in Figure 14, transforms the empirical Green's functions into attenuation coefficient measurements through a systematic three-stage approach. Spectral processing converts the cross-correlation functions to the frequency domain and normalizes them by average power spectral density. Envelope calculation then extracts the amplitude decay information through frequency domain filtering, quality control, and Savitzky-Golay smoothing. The final attenuation estimation stage employs a comprehensive grid search optimization over frequency-dependent attenuation coefficients, using a damped Bessel function model to determine the optimal values through cost function minimization. These estimated attenuation coefficients serve as the primary result of this study, which are presented and discussed in the following sections.

4 Results and Discussion

This section presents and discusses the attenuation coefficients derived from ambient noise data using the framework established in the previous chapter.

4.1 Attenuation Estimates

Figure 15 demonstrates the successful application of the Boschi et al. (2019) attenuation estimation method to three representative station pairs with increasing inter-station distances of 3.92 km, 8.04 km, and 14.64 km. The upper panel shows that the modelled envelope functions (red lines) provide remarkable fits to the observed envelope functions (black lines) across all three distance ranges. The lower panels reveal frequency-dependent attenuation coefficients ranging from approximately 10^{-5} to 10^{-3} m^{-1} across the 0.2 - 0.7 Hz frequency band. The relationship between spectral features on the observed envelopes and the optimal attenuation coefficients demonstrates a clear correspondence across all three station pairs. At frequencies with prominent spectral peaks, lower α values are required to reproduce these features, since higher α values would suppress the amplitudes. Additionally, the broad regions of similar cost function values indicate that multiple attenuation coefficients can produce acceptable fits to the data. However, the clear optimal coefficients suggest that a meaningful distinction exists between the solutions and that the grid search successfully identifies parameter combinations that best balance data misfit and model constraints. Although the attenuation curves provide valuable insights, it is not possible to conclude which process dominates solely from these coefficients, as their frequency dependence alone does not provide unique differentiation between intrinsic absorption and scattering effects.



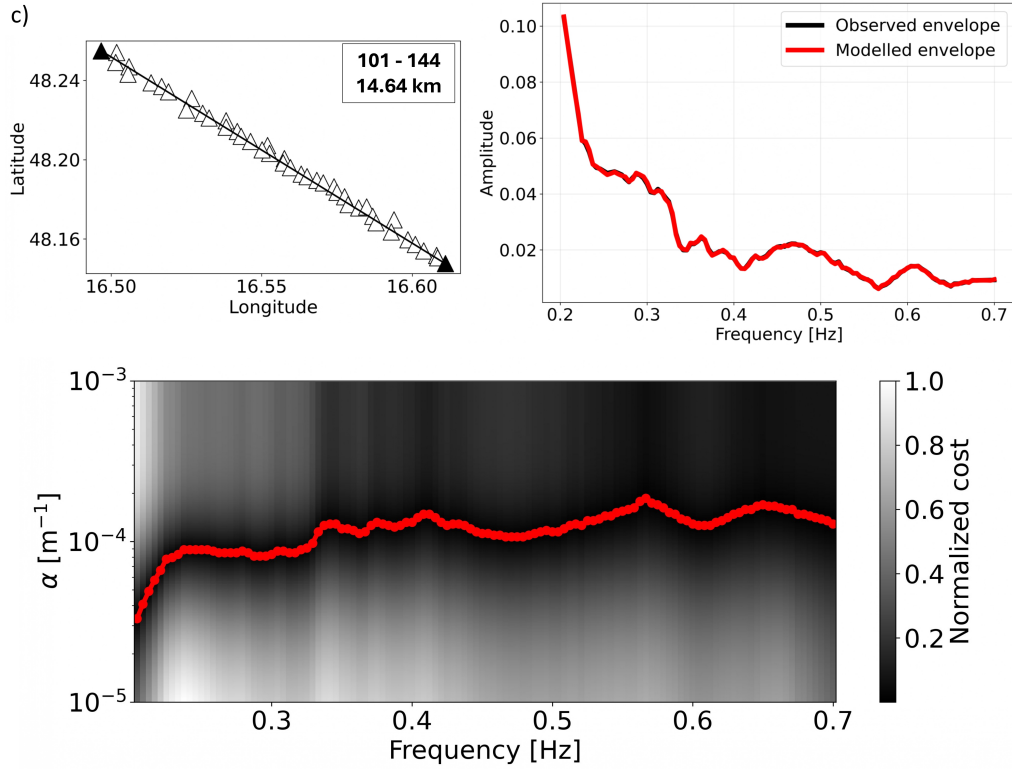


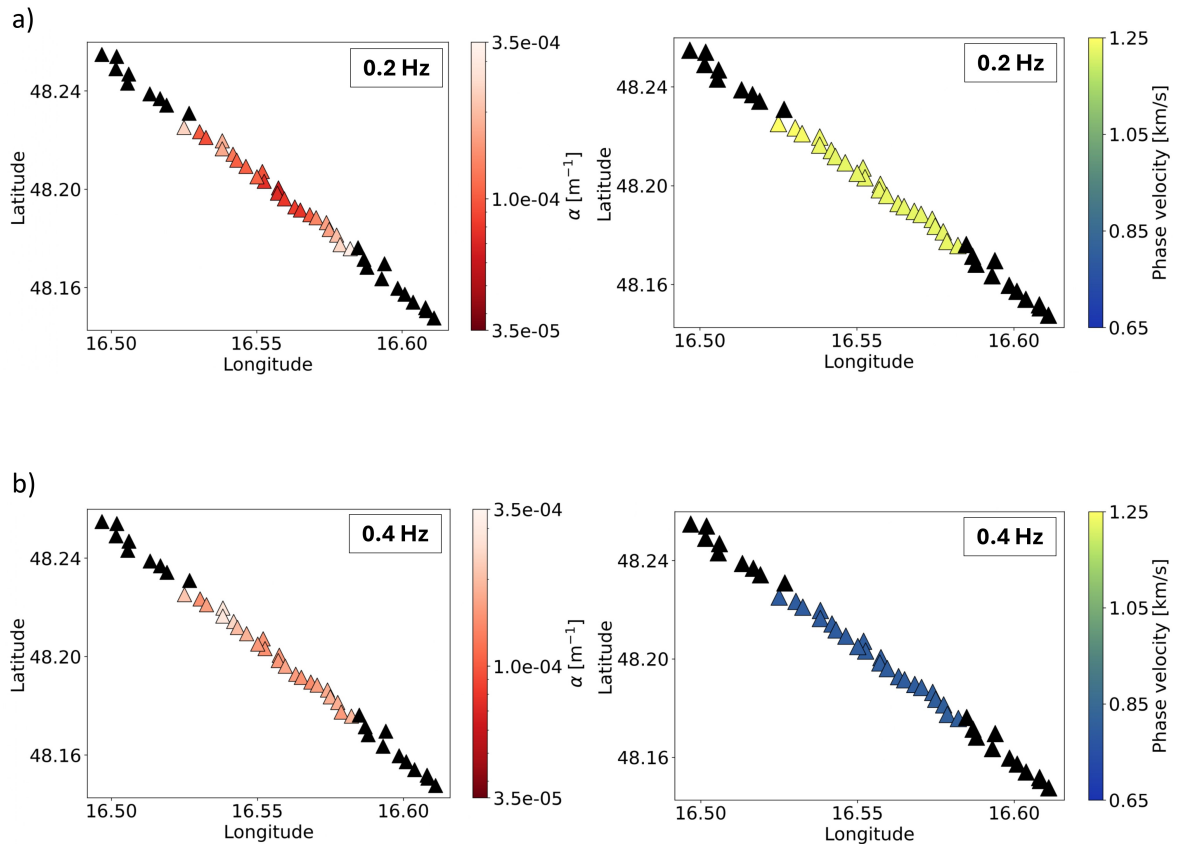
Figure 15: Attenuation curves and envelope functions for three station pairs: (a) station pair 101-111 (3.92 km), (b) station pair 101-124 (8.04 km), and (c) station pair 101-144 (14.64 km). Upper left panels show station locations within the EVA network. Upper right panels compare observed (black) and modelled (red) envelope functions. Lower panels show the normalized cost function (i.e., data misfit) as a function of period and α evaluated independently for each station pair. The cost functions are characterized by well-defined minima at each frequency point (identified by red dots), which represent the final attenuation curves.

As an attempt to constrain the dominant attenuation process, we further explore the correlation of attenuation with phase velocities, since specific intrinsic mechanisms should simultaneously reduce velocities and cause intrinsic absorption (Johnston et al., 1979), thus producing characteristic anti-correlation patterns (Magrini et al., 2021).

We calculated spatially-averaged values of both attenuation coefficients and phase velocities across the EVA profile for three distinct frequencies: 0.2, 0.4, and 0.6 Hz. To create these spatial maps, we first visually examined all 903 station-pairs attenuation curves to find a specific interstation distance at which the attenuation coefficients fall into the range from approximately 10^{-5} to 10^{-4} m^{-1} . As previously indicated in section 3.3, the values of attenuation coefficients we obtained are at the upper end of the expected values for this region, requiring us to identify and exclude station pairs that yield attenuation estimates beyond the physically reasonable range (10^{-5} to 10^{-4} m^{-1}), thereby ensuring data reliability. This visual inspection revealed that station pairs with inter-station distances of 7.5 km and

greater (203 station pairs in total) consistently produce attenuation coefficients within the target range. We then calculated the corresponding midpoints of these station pairs, which represent the center of each ray path. To spatially organize these midpoints, we defined 600×600 -meter rectangular grids centered around each station along the profile. All midpoints falling within each grid cell are grouped, and an average attenuation coefficient is calculated for each group. This averaged value is then assigned to the corresponding station at the center of that grid cell. The same procedure was applied to obtain the spatial distribution of phase velocities.

Figure 16 shows that the attenuation coefficients have the lowest values at 0.2 Hz, particularly concentrated in the central portion of the profile, with this zone of weakened attenuation gradually shifting southward and increasing as frequency increases to 0.6 Hz. Conversely, phase velocities display relatively uniform values across the spatial extent of the profile at each frequency, but exhibit a clear systematic decrease with increasing frequency, dropping from approximately 1.25 km/s at 0.2 Hz to around 0.65 km/s at 0.6 Hz, aligning with the observations from Esteve et al. (2025).



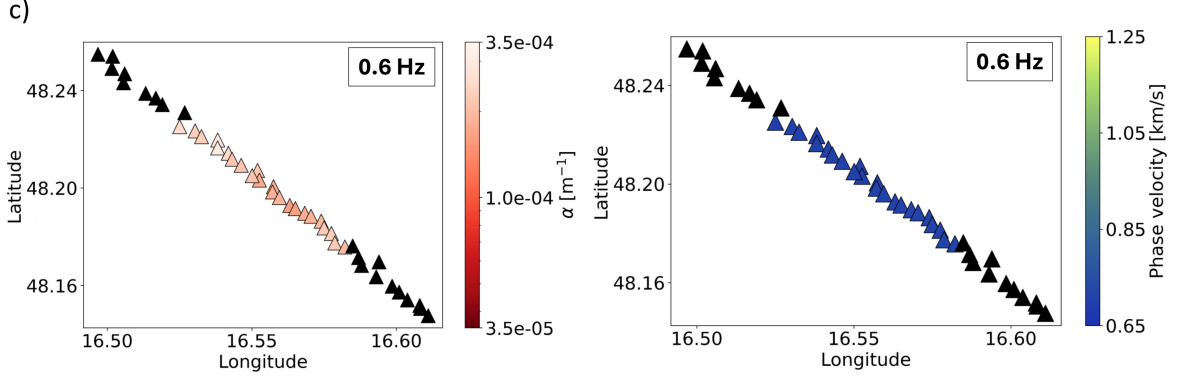


Figure 16: Spatially averaged attenuation coefficients α and corresponding averaged phase velocities for three different frequency points: (a) 0.2 Hz, (b) 0.4 Hz, and (c) 0.6 Hz.

To better visualize the pseudo-depth behaviour of both parameters, we created a vertical frequency-distance representation of the spatially-averaged attenuation coefficients and phase velocities along the 7 km long central part of the EVA profile (Figure 17). The figure demonstrates the systematic increase in attenuation coefficients with frequency (upper panel) and the corresponding decrease in phase velocities with frequency (lower panel), while confirming the spatial uniformity of phase velocities and a more heterogeneous distribution of attenuation coefficients across the studied profile length.

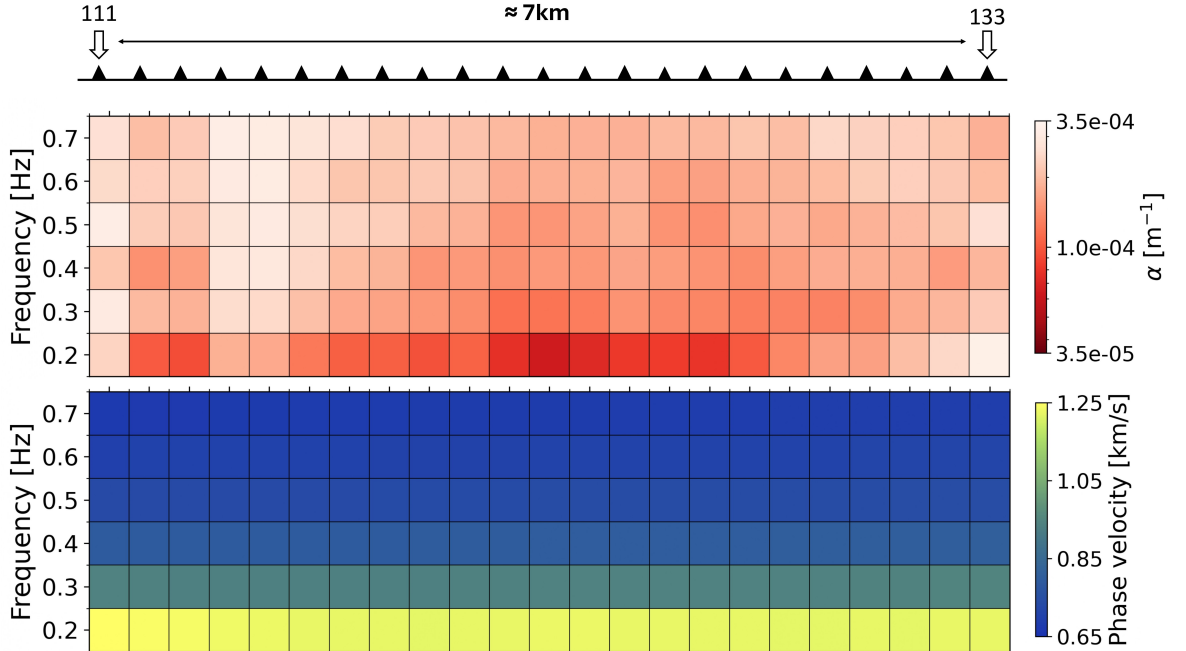


Figure 17: Averaged attenuation coefficients and phase velocities as a function of frequency/depth and station position along the EVA transect. The top panel shows attenuation coefficients (α) from station 111 to 133, spanning approximately 7 km. The bottom panel displays corresponding phase velocities.

To quantify the overall frequency-dependent trends and confirm the observations from Magrini et al. (2021); Roisenberg et al. (2024), we further average the spatially distributed values from Figure 17 across the given transect for each frequency (Figure 18). The left panel shows that attenuation coefficients increase steadily from about $1.3 \times 10^{-4} \text{ m}^{-1}$ at 0.2 Hz to approximately $2.4 \times 10^{-4} \text{ m}^{-1}$ at 0.7 Hz. The right panel illustrates the corresponding decrease in phase velocities over the same frequency range, dropping from roughly 1.23 km/s to about 0.68 km/s.

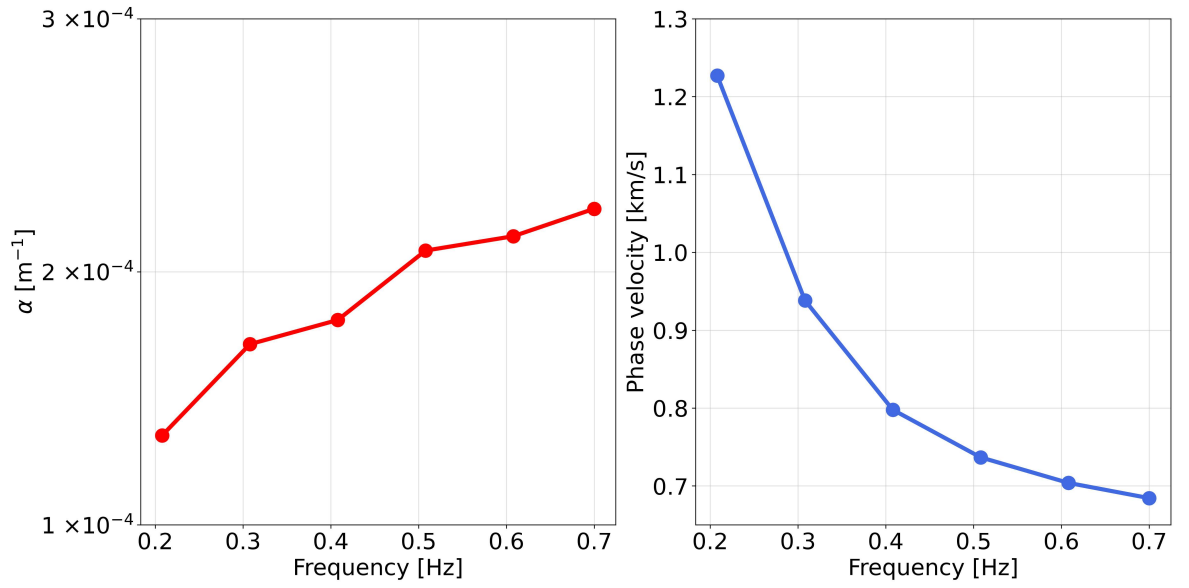


Figure 18: Averaged attenuation coefficients and phase velocities per frequency point from station 111 to 133.

4.2 Implications

The attenuation coefficients in Figure 15 exhibit characteristics that vary with inter-station distance. The shortest path (3.92 km) shows relatively high attenuation coefficients, while the longer paths (8.04 km and 14.64 km) display progressively lower attenuation coefficient values. This distance-dependent behaviour could reflect the natural separation of attenuation mechanisms with propagation distance, where shorter paths preferentially sample scattering from near-surface heterogeneities while longer paths increasingly isolate intrinsic attenuation processes by spatially averaging scattering effects (Mitchell, 1995). Additionally, the higher attenuation coefficients observed for the shortest path may be influenced by wavelength effects, as the inter-station distance of 3.92 km may not encompass even a single wavelength for certain frequencies, potentially affecting the reliability of attenuation coefficient estimation at these distances.

Figure 16 first and foremost confirms the theoretical prediction that attenuation coefficients increase with increasing frequency (Liu et al., 2022). This pattern is expected due to the greater sensitivity of higher frequency surface waves to small-scale heterogeneities (Sato et al., 2012) and anelastic processes in the subsurface, combined with the fact that different frequencies sample different depths. As frequency increases, the waves sample predominantly shallower layers and interact more strongly with finer structures, leading to increased energy dissipation, resulting in higher measured attenuation values.

In addition to the expected frequency dependence, the spatial distribution of attenuation along the EVA profile reveals significant lateral variability. As mentioned above, at lower frequencies (e.g., 0.2 Hz), attenuation is weakest in the central portion of the profile, while at higher frequencies (above 0.5 Hz), zones of increased attenuation become more prominent toward the southern part. These trends are consistent with varying subsurface lithologies, as the Vienna Basin is composed of alternating layers of sandstones, marls, claystones (Šamajová et al., 2019), and conglomerates. These layers differ in porosity, grain size, and water content, all of which influence seismic wave attenuation through both intrinsic material properties and scattering from heterogeneities. At low frequencies, deeper and more compacted sediments associated with the central basin region could dominate the wavefield and result in reduced attenuation. At higher frequencies, shallower and possibly more porous or unconsolidated materials in the southern region contribute to higher attenuation. The spa-

tial uniformity in phase velocities agrees with Esteve et al. (2025), who also observed little lateral variation in velocities along the profile in the Vienna Basin. As a result of little lateral variation, the spatial variations of attenuation coefficients likely reflect genuine subsurface heterogeneities rather than measurement artifacts, which demonstrates the reliability and stability of our attenuation estimation method.

Further insights are gained by comparing our attenuation results with independent observations of seismic anisotropy and velocity structure. Esteve et al. (2025) identified positive radial anisotropy across much of the Vienna Basin between approximately 0.15 km and 1.20 km depth. This anisotropy, attributed to sub-horizontal sedimentary layering, coincides spatially with the zones of lower attenuation observed at lower frequencies. The alignment of attenuation minima with high phase velocities and regions of positive anisotropy in periodically layered media indicates a frequency-dependent effect (Stovas and Roganov, 2010): horizontally layered sediments can support more efficient, lower attenuation wave propagation in certain frequency bands, but may increase attenuation in others. Consequently, attenuation and propagation efficiency in such media are governed by the frequency-dependent interplay between scattering and intrinsic losses. In contrast, regions where attenuation increases, especially in the southern profile, may correspond to zones of weaker stratification, presence of faults (Talone et al., 2023) or elevated fluid content, all of which contribute to higher seismic energy dissipation.

Although frequency is not a direct measure of depth, surface wave theory allows for an approximate interpretation of vertical sensitivity using the concept of frequency-dependent depth penetration. Lower-frequency surface waves have longer wavelengths and sample deeper layers (Aki and Richards, 2002), while higher frequencies are confined to shallower regions. More specifically, the depth sensitivity for Rayleigh waves is commonly approximated as one-third to one-half of the wavelength (Cox and Teague, 2016): $\lambda = v/f$, where v is the phase velocity and f is the frequency. Based on the measured phase velocities in Figure 17, the corresponding wavelengths are approximately 0.93 km to 6.25 km. This implies sensitivity to depths ranging from approximately 2 – 3 km at the low-frequency end to approximately 300–500 m at higher frequencies. Within this range, our measurements are well suited to study the Neogene sedimentary fill in the central part of the Schwechat depression (Figure 2). One of the most prominent features in Figure 17 is the consistent anti-

correlation between attenuation and phase velocity across all frequencies. As briefly mentioned above, these anti-correlation patterns have been observed in other sedimentary basins (Magrini et al., 2021), and imply that the dominant attenuation mechanism is the anelastic (intrinsic) absorption. More specifically, as discussed in chapter 1, the primary mechanisms for intrinsic attenuation in the crust are fluid-filled fractures and fluid movement. These fractures tend to reduce the stiffness of the rock, which slows down the wave speed. Together, these effects explain why attenuation increases and velocity decreases toward the surface. With depth, both the number and openness of fractures tend to decrease due to the weight of overlying material. As cracks close and sediments become more compacted, wave speeds increase and attenuation decreases.

Figure 18 summarizes the average behaviour of both attenuation and phase velocity across the central portion of the EVA profile. This inverse relationship is consistent with our previous observations and is typical for surface waves travelling through layered sediments. Lower velocities at higher frequencies suggest that waves are confined to less rigid, shallower layers, while higher velocities at lower frequencies indicate that deeper, more consolidated strata are being sampled (Xia et al., 1999). By averaging these values across the profile, this figure provides a simplified yet robust representation of the frequency-dependent properties of the small study area in the eastern part of the Vienna Basin.

These average attenuation coefficients can be important for several practical applications. In seismic modelling, attenuation plays a crucial role in accurately simulating wave propagation. Including realistic attenuation values can improve the quality of synthetic seismograms (Wang and Li, 2018) and help match observed ground motions, especially in soft sedimentary regions. Moreover, attenuation is a key parameter in seismic hazard assessment (Papoulia and Stavrakakis, 1990). Areas with high attenuation tend to experience lower ground shaking amplitudes at high frequencies, but this can also indicate the presence of soft, unconsolidated sediments that amplify long-period waves. Understanding the frequency-dependent nature of attenuation helps refine site response models and improve local hazard estimates, particularly in densely populated urban regions. However, several methodological and practical challenges must be carefully considered, as they can affect the reliability of these results.

4.3 Limitations and Challenges

Our analysis successfully obtained attenuation coefficients and revealed their implications for the study area, but several important limitations constrain the reliable interpretation and more specific application of these findings.

The fundamental challenge lies in the theoretical assumptions in the Boschi et al. (2019) framework. As previously stated in section 3.3, the method requires uniform distribution of noise sources across Earth’s surface, weak attenuation, dominance of surface waves in the ambient field, and sufficient temporal averaging to achieve a diffuse wavefield. First of all, achieving the uniform distribution of noise sources is not possible in practice, as ambient noise sources are heterogeneously distributed across the Earth’s surface, with dominant contributions from oceanic regions and human activities that vary both geographically and temporally. Secondly, our 36-day recording period may be insufficient to fully satisfy the diffuse wavefield requirement, as longer observation periods are typically needed to adequately average out temporal variations in noise source distributions and achieve the theoretical conditions assumed by the method. Furthermore, the short interstation distance example (101-105) in Figure 11 reveals cross-correlation functions dominated by microseismic energy rather than the expected frequency-distributed energy pattern required by the theory, violating the fundamental assumption that the normalization procedure should effectively deconvolve the ambient noise spectrum.

The inability to adhere to these theoretical assumptions leads to significant practical limitations in attenuation estimation. For station pairs separated by less than approximately 7.5 km, the attenuation coefficients we measured are one to two orders of magnitude higher than values typically expected for sedimentary basins in the Alpine region. This discrepancy likely stems from our high-density but spatially limited deployment configuration. While broader regional studies with sparse arrays may not capture localized frequency-dependent effects due to insufficient resolution, our concentrated array design appears to be sensitive to small-scale heterogeneities that dominate the near-surface response. The dense spacing of our stations may preferentially sample more heterogeneous and potentially more attenuative shallow conditions compared to the spatially averaged measurements obtained from broader regional arrays. Additionally, the theoretical framework does not explicitly account for scattering effects from local heterogeneities, body-wave contamination in the cross-correlation functions, or site-specific amplification effects, all of which can introduce systematic biases

in attenuation estimates.

Closely related to these practical limitations is the uncertainty observed in our cost function and phase velocity measurements. The cost function reveals broad regions of low misfit values across multiple frequencies (Figure 15). This indicates high uncertainty in the optimal parameter selection, suggesting that multiple attenuation coefficients can adequately fit the observed data. This observation makes it difficult to uniquely constrain attenuation coefficients, potentially leading to non-unique solutions. Additionally, our attenuation estimation relies heavily on the accuracy of the phase velocity data from Esteve et al. (2025). Any uncertainties or systematic errors in these velocity measurements propagate directly into the attenuation estimates. The interpolation process required to obtain velocities at frequencies not originally measured introduces additional uncertainties that reduce the reliability of our results.

To address these difficulties, several methodological improvements could enhance future studies. Longer recording periods would better satisfy diffuse wavefield requirements, while analyzing station pairs that are not aligned along the NW-SE profile might reveal different attenuation behaviour, as cross-profile measurements sample different geological structures and potentially avoid some of the systematic errors which could be observed in our transect. For future array deployments, incorporating longer interstation distances should be prioritized in the design phase to better satisfy the theoretical conditions required by the method and ensure more reliable attenuation estimation.

While these challenges highlight important considerations for future applications of the method, our results nonetheless contribute to the understanding of seismic attenuation processes in the Vienna Basin and demonstrate both the capabilities and limitations of this specific ambient noise attenuation estimation method.

5 Conclusion

We investigated seismic attenuation in the Vienna Basin by applying the theoretical framework of Boschi et al. (2019), which represents the first implementation of this approach for dense, short-distance nodal arrays at the local scale. The Eastern Vienna Array consisted of 44 seismic nodes positioned along a 15-km NW-SE profile, with approximately 350-meter spacing, and an additional 48 seismic nodes with an average spacing of about 2 kilometers, recording continuous data for 36 days during summer 2023.

We computed ambient noise cross-correlation functions for all station pairs along the profile using continuous vertical component recordings. The cross-correlations were then converted to the frequency domain, where spectral normalization by the average power spectral density was applied to remove source effects, and filtered to focus on the 0.2-0.7 Hz frequency band. After quality control procedures to remove outliers, we calculated envelope functions using the Hilbert transform and applied Savitzky-Golay smoothing. Attenuation coefficients were estimated through a grid search process by fitting synthetic envelope functions based on damped Bessel functions to the observed envelopes, using interstation phase velocities from Esteve et al. (2025) and minimizing a distance-weighted cost function.

We successfully extracted frequency-dependent attenuation coefficients, ranging from 10^{-5} to 10^{-3} m^{-1} across the studied frequency band. The spatial distribution of attenuation coefficients reveals systematic variations along the profile, with lower attenuation in the central portion at lower frequencies and increased attenuation toward the southern region at higher frequencies.

A key finding is the consistent anti-correlation between attenuation coefficients and phase velocities across all analyzed frequencies. This relationship provides strong evidence that intrinsic absorption dominates over scattering as the primary attenuation mechanism in the Vienna Basin subsurface. The frequency dependence follows expected theoretical predictions, with higher frequencies showing greater energy dissipation due to increased sensitivity to small-scale heterogeneities and anelastic processes in shallow layers.

We note that several theoretical assumptions underlying the framework may not be fully satisfied for dense local arrays. The 36-day recording period may be insufficient to achieve the required diffuse wavefield, and the theory does not account for scattering effects, body-wave contamination, or site amplifications, all of which can introduce systematic biases.

In addition to theoretical limitations, the method breaks down at short interstation distances

below approximately 7.5 km, where the values of attenuation coefficients exceed physically reasonable limits, and cross-correlation functions fail to exhibit the expected frequency-distributed energy pattern that should result from proper "deconvolution" of the ambient noise spectrum. The cost function shows broad regions of low misfit values, indicating high uncertainty in parameter estimation and suggesting that multiple attenuation models can adequately fit the observed data.

Despite these limitations, our results demonstrate both the potential and constraints of ambient noise methods for local-scale attenuation studies. The approach offers a cost-effective and environmentally friendly method for investigating subsurface attenuation properties, though with limited success for detailed characterization relevant to geothermal exploration.

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