3C Multi-Wave Ambient Noise Tomography Applied to the Horex Scientific Pilot for Natural Hydrogen Exploration

Introduction

The transition toward decarbonized energy systems has placed hydrogen at the core of global strategies aimed at achieving climate neutrality. Within this context, the exploration of natural hydrogen has emerged as a strategic and rapidly growing field, driving the search for geophysical methods capable of characterizing the subsurface with high resolution, low operational impact, and controlled costs. Among these approaches, Ambient Noise Tomography (ANT) has become a robust and particularly well-suited tool for such applications (Kremer et al., 2023).

Unlike conventional active seismic methods, ANT relies exclusively on the continuous recording of ambient seismic noise, enabling the reconstruction of virtual Green's functions between pairs of sensors without the need for controlled sources. This characteristic makes ANT especially attractive in settings where access, logistics, or environmental constraints limit the deployment of active sources, a situation frequently encountered during early-stage natural hydrogen exploration.

In this study, we demonstrate that the use of three-component (3C) recordings in ANT not only improves the final inversion through the joint exploitation of Rayleigh and Love waves, but is also critical for reliable modal identification and robust interpretation of dispersion panels, particularly at low frequencies. This results in a significant reduction of uncertainty in deep Vs velocity models, where modal interference can otherwise lead to substantial errors in velocity estimation.

We show that relying solely on the vertical component may lead to confusion between the fundamental (mode 0) and higher-order (mode 1) Rayleigh modes, whereas the inclusion of horizontal components enables clear modal separation, greater interpretational stability, and a substantial reduction in the correlation time required to obtain reliable dispersion information. As a result, even with relatively short acquisition times, the combined use of the three components allows the recovery of more realistic, stable, and better-resolved velocity models, reaching frequencies as low as 0.2 Hz and providing key subsurface information relevant for natural hydrogen exploration.

Data acquisition

Data acquisition was carried out as part of the HOREX Scientific Pilot, a Multiphysics exploration workflow developed to de-risk natural hydrogen system. The HOREX survey involved the deployment of 1000 sensors across 500 stations, recording continuously over a period of 38 days using three-component seismic sensors deployed across the study area shown in Figure 1. The stations were arranged in a variable-geometry network designed to image the full hydrogen system, including potential deep sources, migration pathways, and shallow reservoir domains. The acquisition design and sensor deployment were carried out by the Mantle8 team. Only the subset highlighted in purple was selected for the detailed processing and interpretation presented in this work. The autonomous accelerometers employed are characterized by high sensitivity and low instrumental noise, enabling the reliable recording of very low-amplitude signals associated with ambient seismic noise.

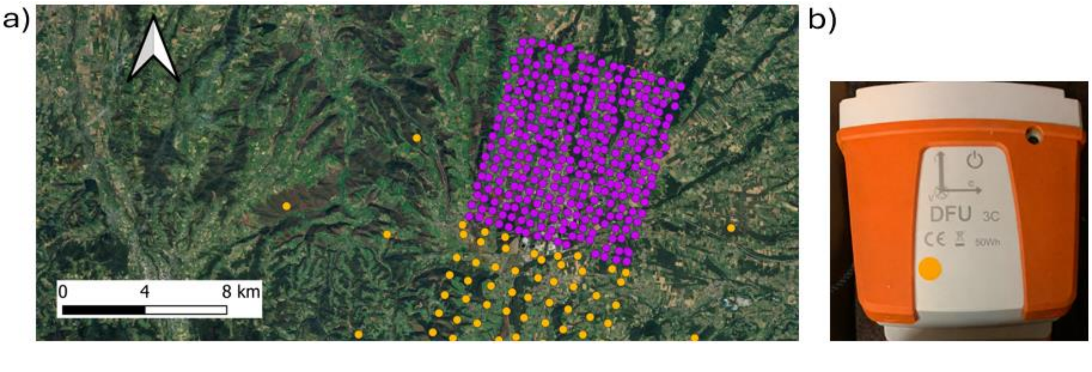

***Figure 1** a)Montl8 HOREX spatial deployment of sensors in the survey area. Purple markers correspond to the 3-component (3C) receivers used in this study, while yellow markers indicate additional stations from the extended monitoring network. b) Sensors orientation (Inline aligned North-South & Crossline aligned East-West)*

Special attention was paid during deployment to ensure a consistent orientation of all sensors. The vertical axis was calibrated at installation to guarantee proper vertical alignment, while the horizontal components were oriented in the field using a compass so that the inline axis was aligned North–South and the crossline axis East–West. This consistent sensor orientation, combined with the high sensitivity and long-term stability of the instrumentation, allows a stable and coherent recording of the ambient seismic wavefield over extended periods. As a result, high-quality correlations can be obtained, preserving low-frequency energy that is critical for resolving surface-wave dispersion at long wavelengths and for investigating greater depths.

Methodology and Processing Strategy

In this study, we take advantage of the 3C sensor deployment to simultaneously exploit the information carried by Rayleigh and Love waves. After applying an RZ rotation to the instrumental horizontal components (Inline and Crossline) together with the vertical component, the recordings are transformed into radial (R), transverse (T), and vertical (Z) components. This transformation enables a consistent separation of surface-wave propagation modes: Love-wave energy is primarily concentrated in the transverse component, whereas Rayleigh-wave energy dominates the radial and vertical components. This modal separation constitutes the foundation for the joint retrieval of phase and group velocities, integrating information related to coherent wave propagation with energy distribution and lateral sensitivity, thereby reducing inversion non-uniqueness and enhancing the stability and resolution of the final velocity model.

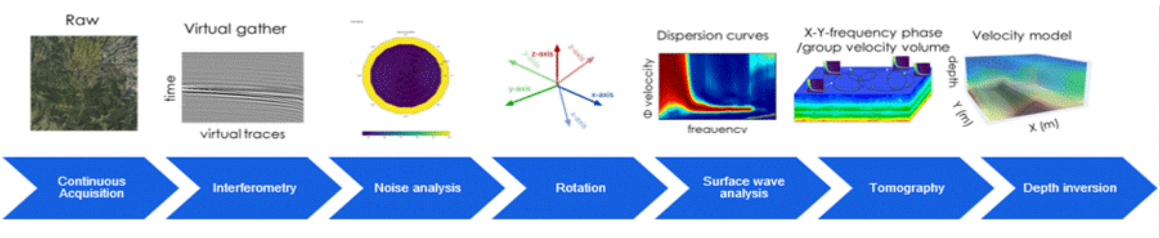

***Figure 2** Processing workflow from continuous passive acquisition to depth inversion.*

The workflow illustrated in Figure 2 first allows the reconstruction of virtual Green's functions through interferometric correlation and the characterization of the azimuthal distribution of ambient noise sources. From these virtual responses, dispersion panels are generated using Matched Field Processing (MFP), applied independently to each component. This approach enables the extraction of frequency–velocity panels for both Rayleigh and Love waves, as shown in Figure 3. The analysis considers both phase and group velocities, as they provide complementary constraints: phase velocity is primarily linked to spatial resolution, whereas group velocity offers greater robustness against noise and lateral heterogeneities.

Figure 3 compares dispersion panels obtained from correlations accumulated over 7, 18, and 37 days for the three components. The results show that relying exclusively on the vertical component can lead to misleading interpretations, particularly at frequencies below 1 Hz. In this case, a clear mixing between the fundamental and higher-order Rayleigh modes is observed (Figure 3a-c and 3d-f), complicating the correct identification of dispersion curves. Such modal interference may result in overestimation of velocities at low frequencies, errors in effective investigation depth, and increased instability in deep Vs inversion results (Tarnus et al., 2024).

In contrast, the horizontal components provide additional physical information that enables a clearer discrimination of propagation modes. The radial component reinforces and complements Rayleigh-wave identification, while the transverse component isolates Love-wave energy (Figure 3g-i), offering an independent criterion for modal assignment. This complementarity leads to a more robust modal separation, particularly at low frequencies, resulting in better-defined deep dispersion curves and, consequently, more reliable velocity models with increased depth penetration. The different components are spatially integrated and inverted within a three-dimensional framework, generating a 3D velocity model that accounts for lateral variations across the array.

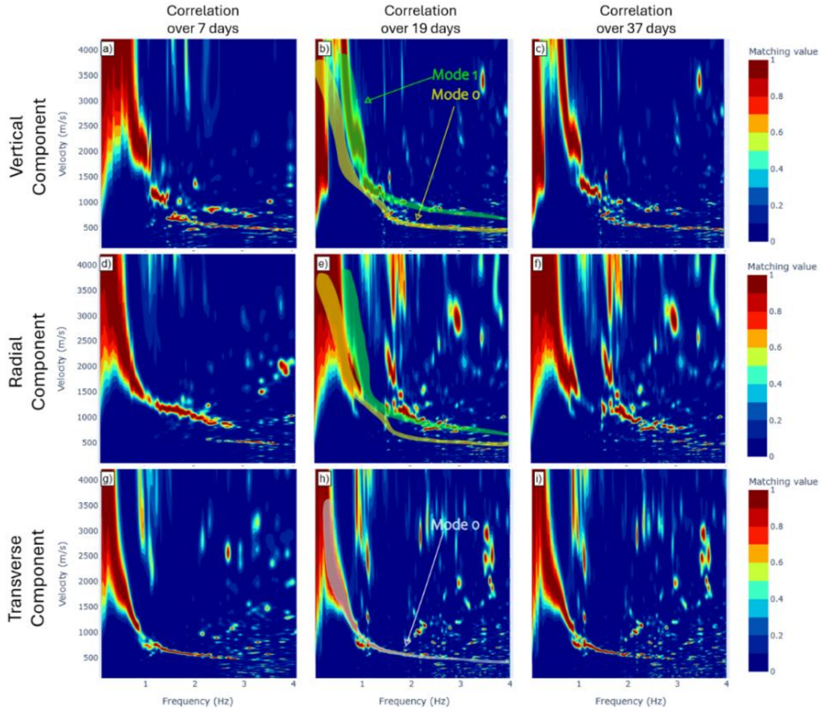

Figure 3 *Dispersion panels from 7, 19, and 37 days of ambient noise correlation for the vertical (a–c), radial (d–f), and transversal (g–i) components. Rayleigh energy dominates Z and R, while Love energy is concentrated in T. The panels were computed using a 78-sensor patch distributed over an ellipse 6.2 km long and 1.3 km wide.*

Results

Thanks to the information provided by 3c recordings, dispersion panels with clear modal separation can be obtained with as little as 7 days of correlation. While modal ambiguity persists in the vertical component particularly at low frequencies, the inclusion of horizontal components allows additional low-frequency information to be recovered and enables a more accurate identification of the different dispersion modes, stabilizing the images from early stages of correlation accumulation. This leads to a reduction in the acquisition time required to obtain reliable dispersion information, representing a significant operational advantage for early-stage exploration campaigns.

The robust modal separation achieved with 3C data is directly reflected in the multi-wave inversion stage and in the quality of the resulting Vs velocity models, as shown in Figure 4. Although the inversion is performed in three dimensions, Figure 4 presents a representative 2D vertical cross-section extracted from the 3D Vs model for visualization and interpretation purposes. Figure 4a presents the reference geological of the study area. The Figure 4b corresponds to the Vs model obtained from inversion using only the vertical component, it presents reduced reliability at greater depths. In this case, persistent low-frequency modal interference leads to the misidentification of higher-order Rayleigh modes as the fundamental mode, resulting in an overestimation of Vs velocities below approximately 2000 m depth and a loss of structural coherence in the model.

In contrast, the model obtained from the joint inversion of the 3C (Figure 4c) shows a more stable and physically consistent velocity structure, with improved definition of lateral and vertical velocity contrasts. The correct separation of Rayleigh and Love modes allows the investigation depth to be extended with higher confidence, mitigating issues related to modal mixing and significantly enhancing deep resolution. Moreover, the 3C model shows a strong agreement with the independent geological information presented in Figure 4a, consistently reproducing the main mechanical contrasts of the subsurface. These results demonstrate that the use of 3C not only improves the stability and reliability of deep inversion results but is essential for obtaining interpretable and geologically consistent velocity models in exploration contexts.

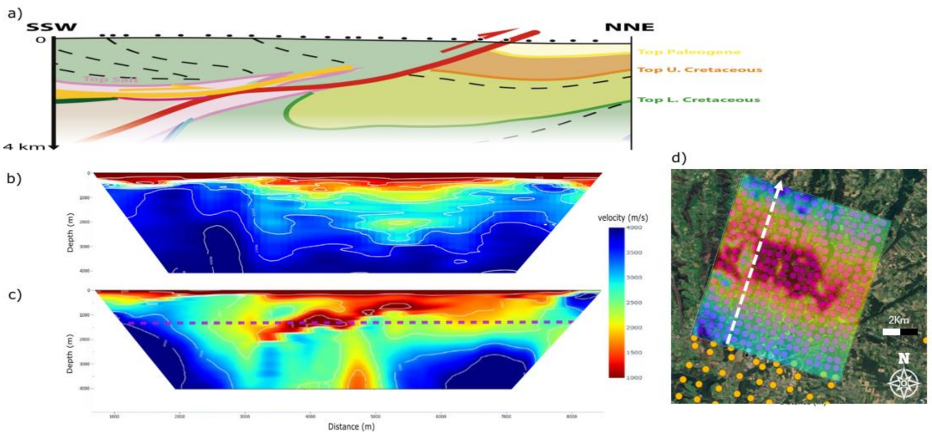

Figure 4 *Geological information and Preliminary Vs models. a) Geological cross-section of the study area. b) Vs model using only the vertical component. c) Vs model from 3C multi-wave inversion of Rayleigh and Love waves along profile indicated in (d). d) Horizontal (XY) slice of the 3D Vs model at the depth indicated in (c).*

Conclusions

The use of 3C recordings enables the retrieval of stable and reliable preliminary Vs velocity models from as little as 7 days of passive acquisition, while preserving low-frequency coherence and achieving significant investigation depth. The modal separation achieved with 3C data is critical for avoiding confusion between the fundamental and higher-order Rayleigh modes, thereby reducing the overestimation of deep velocities commonly observed when relying solely on the vertical component.

The multi-wave inversion strategy, based on the combined use of Rayleigh and Love waves together with phase and group velocities, produced physically consistent Vs models with improved definition of lateral and vertical velocity contrasts and enhanced stability at depths greater than ~2000 m. Compared to single-component approaches, the 3C inversion allows the investigation depth to be extended with greater confidence and yields results that show a strong agreement with independent geological information from the study area. These findings confirm that multi-wave ANT using 3C data not only substantially improves the quality and reliability of deep subsurface inversion, but also represents an efficient strategy for extracting meaningful geophysical information within reduced acquisition times. The versatility of the method enables the integration of wide-aperture passive data with structural and mechanical criteria, facilitating the identification of preferential pathways, mechanical contrasts, and structurally favorable domains for early-stage natural hydrogen exploration, even in operationally complex environments.

References

Kremer, T., et al. "A new passive seismic monitoring strategy for the exploration of natural Hydrogen and Helium occurrences." 84th EAGE annual conference & exhibition. Vol. 2023. No. 1. European Association of Geoscientists & Engineers, 2023.

Tarnus, R., et al. "Efficient Workflow for Near-Surface Characterization from the Joint Inversion of Surface and Compressional Wave Data." NSG 2024 30th European Meeting of Environmental and Engineering Geophysics. Vol. 2024. No. 1. European Association of Geoscientists & Engineers, 2024.