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A new passive seismic monitoring strategy for the exploration of natural Hydrogen and Helium occurrences.

Introduction

Geophysical exploration strategies for exploring naturally occurring green gases resources, such as helium and hydrogen, are needed to detect and map potential subsurface reservoirs or pathways and improve our understanding of the subsurface dynamics of this newly sought-after resource, which to date remains largely unknown.

An exemplary case of these needs is the exclusive "Fonts-Bouillants" research permit, held by the company 45-8 Energy and located in France, which aims to capture and develop gases rich in helium and carbon dioxide that escape naturally from the subsoil into the atmosphere through thermomineral sources known since antiquity.

Geophysical and geological (GG) exploration was carried out on the permit site, which significantly increased the knowledge of the subsurface and led to the update of the geological model. This exploration phase included the use of several methods and analyses such as gravimetry, magnetic data reprocessing, electrical resistivity (ERT), controlled source electromagnetic (CSEM) and audio-magnetic-telluric (AMT) profiles, 2D and 3D seismic reflection, geochemical analyses, drilling and well testing.

In this paper, we present the Coherence analysis of Cross-correlated Waveforms (CCW) method. This innovative geophysical approach based on ambient-noise seismic interferometry (ANSI) helps detecting and tracking gas movements within the subsurface, as was demonstrated during the first application of the method in the context of geological gas storage site monitoring (Kremer et al., 2022a, 2022b). In this paper we investigate how the method can be used to track naturally occurring green gases location and which type of information can be provided to complement the global exploration strategy. We successively detail the method's theoretical foundations, the field survey implementation, the data processing strategy, and finally the results obtained by applying the CCW approach on the Fonts-Bouillants permit area.

CCW methodology

The CCW methodology denotes a specific analysis strategy applied to seismic waves that have been reconstructed through ANSI processes. ANSI methods (Shapiro and Campillo, 2004) globally refer to the analysis of a complex seismic wavefield which has been reconstructed through cross-correlation of passive seismic noise recordings along an array of sensors. Those methods have been developing increasingly during the last two decades partly because they allow analysing the seismic properties of the subsurface for a much lower implementation cost than active seismic methods (although with a lower resolution limit). ANSI-based analysis methods are hence relatively diverse, but thanks to their easiness in data acquisition they are particularly suited for monitoring applications where a high number of measurements need be repeated in time.

The classical approach for passive seismic monitoring is to estimate variations of seismic velocities by measuring the change of arrival time of the reconstructed surface or body waves (e.g., Olivier et al., 2016). This approach has been applied to diverse shallow subsurface contexts such as landslide monitoring (Voisin et al., 2016, Le Breton et al., 2021), geothermal fields characterization (Toledo et al. 2022) and groundwater monitoring (e.g., Garambois et al. 2019, Gaubert-Bastide et al. 2022). Recently, instead of phase arrival, the coherence of the reconstructed seismic waveforms has been proposed as a new seismic wave attribute that can be used for subsurface monitoring purposes. Specifically, coherence is proposed as a proxy for variations of the seismic attenuation properties of the subsurface (Voisin and Delouche, 2019) and is thus particularly appropriate to detect fluid movements within the Earth. Fluid substitution modelling (Amoroso et al., 2017, Pride et al., 2005) indeed shows that attenuation properties of the subsurface can yield variations one order of magnitude superior to velocity changes. Kremer et al. (2022a, 2022b) showed that coherence measurements are sensitive to gas injection occurring within a natural gas storage site. In the present paper, we explore the possibilities provided by the CCW method for the exploration and localisation of naturally produced gas reservoirs at Fonts-Bouillants.

Survey site and acquisition

The Fonts-Bouillants License is located at the southern edge of the Paris Basin: bounding the north of the Massif Central (northern edge of the Limagnes Tertiary rift) and located westward of the Morvan Massif (extension of the Massif Central). Mesozoic sedimentary formations of the Paris Basin outcrop in the region, superimposing a variable pre-Mesozoic basement formed by small basins aged from the Permo-Carboniferous period, as well as Hercynian granites and former metamorphic terrains (Fig. 1).

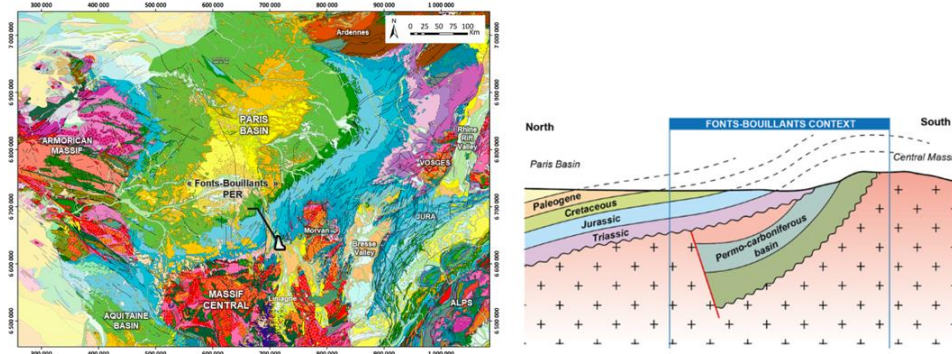


Figure 1: Map of the location of the "Fonts-Bouillants" License and associated schematic section (1M Geological map, BRGM).

The raw seismic ambient noise signals were recorded continuously over a period of 159 days (02-04-2022 to 07-07-2022) using 112 vertical components seismic sensors (SG-5Hz) displayed at the surface as illustrated on Fig. 2a. The array was originally designed to address several characteristic dimensions, hence the extension with few stations in all cardinal directions. In this paper though, only the central part of the array has been used for CCW analysis, where the seismic ray path density is high (Fig. 2b).

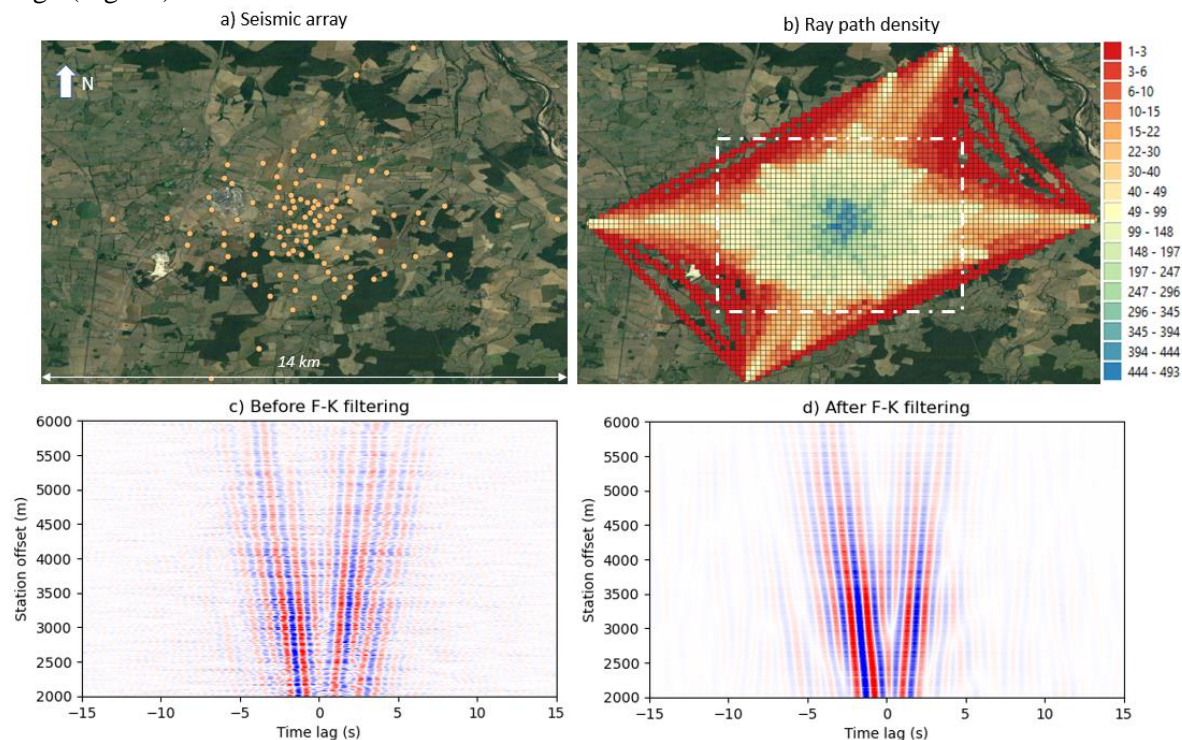


Figure 2: Illustration of the seismic sensors array used for the seismic noise acquisition. a) Illustration of all station positions. b) Map of the ray path density (ray path / pixel) associated with the array. Dashed lines represent the limits chosen for the array analysed in this paper, where ray path density is high. c) Gather-offset representation of the seismic wavefield reconstructed through interferometry in the frequency range 0.3-1.3 Hz before F-K filtering is applied. d) After F-K filtering.

Results

Data processing:

The data processing operations is divided into three distinct steps. 1/ Interferometric processes are applied to all pairs of stations to reconstruct the seismic wavefield that propagates within the inter-station area. Pre-processing operations including band-pass filtering and spectral whitening were applied onto 1 min duration signals, after which cross-correlation operations were applied, followed by stacking over a duration of 24 hours. Such process results in the emergence of a coherent surface wavefield, as illustrated on the gather-offset graphs presented in Fig. 2c.

2/ A second important step within the CCW method is the careful selection of the surface wavefield and elimination of noisy components by mean of an innovative f-k filtering approach based on visual filter design. For the present data set this allowed significant improvement of the signal-to-noise ratio of the reconstructed waves (Fig. 2d).

3/ Finally, the surface waves propagating within each inter-station area are selected based on amplitude maxima and the coherence values of each ballistic waveform are computed taking as a reference waveform the first time-step of the monitoring period. Uncertainties about the coherence values are computed by implementing a bootstrap strategy upon the stacking process and the subsequent coherence calculation. Operations are repeated for several frequency ranges to probe multiple depths of the subsurface.

Inversion strategy:

The results of the data processing phase are a set of coherence time-series for each pair of stations composing the seismic array. To enhance the possibilities of interpretation, two different inversion procedures are being tested to produce 2D coherence maps for every time-step of the monitoring period.

The first method is similar to that employed by Obermann et al. (2019) to spatialize decoherence values measured on coda waves. It involves the use of a sensitivity kernel derived from the radiative transfer theory. The second method is a tomographic procedure that relies on a linear inversion scheme based on ray-theory (Barmin et al., 2001, Mordret et al., 2014).

Figure 3 shows a sample of the time-lapse maps obtained by using the radiative transfer theory-based kernels in the inversion. This sample illustrates the dynamics of the permit site, with stable periods alternating with anomaly periods centred on the St-Parize fault and along secondary transversal faults located south-east and north-west of the area (green areas in Figure 4).

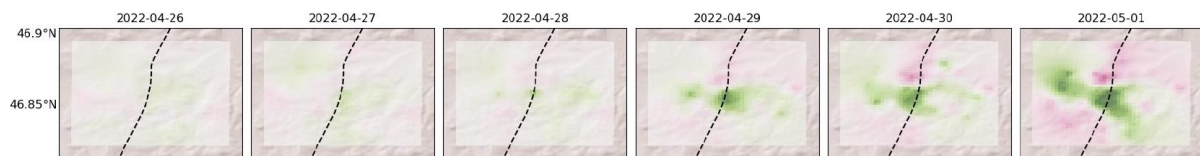


Figure 3: Coherence inversion results obtained through the inversion procedure based on radiative transfer theory, for a period of 6 days, in the frequency range 0.4-0.8 Hz. Reconstructed maps show a homogenous distribution of inverted parameters at first, then the emergence of anomalies in the central part and along a South-West / North-East orientation occurs. The colorscale indicates the effective diffusion section variation. The dashed line indicates the main St-Parize fault location at the surface.

The anomalies shown in Fig. 4 are observed several times during the monitoring period. The areas highlighted by those anomalies are globally matching the areas where other geophysical and geological investigations locate the main gas reservoirs. Quality control analysis indicated that those anomalies are not correlated in time to variations in the seismic sources forming the ambient noise. Hence, we favour the hypothesis of physical changes occurring within the subsurface which affect the waveforms of seismic surface waves.

An intense anomaly occurs during a well-test, strongly suggesting that the CCW method is able to capture gas movement areas at depths induced by surface flux.

Anomalies are also emerging at periods where the system is not solicited by anthropic intervention, suggesting that the changes of CCW capture the natural fluid movements within the subsurface.

Conclusions

The CCW method is a passive seismic monitoring approach that is sensitive to the movement of fluids within the subsurface. Its application upon the permit site of Fonts-Bouillants provided information about the possible localisation of CO₂ and helium reservoir that are in accordance with the general geophysical and geological exploration results performed at this area.

In terms of methodology, the signal processing operations developed in this study have allowed to effectively extract a clear surface wavefield from interferometric results that initially showed low signal-to-noise ratio. The inversion strategies studied within this paper to spatialize the coherence anomalies are promising, but demand further theoretical developments and assessments, for instance to improve the resolution and enhance the scope of information provided by the method towards the design of a drilling strategy.

Hence, the CCW method is a geophysical tool that helps locating the areas where attenuation variations associated with fluids movements within the Earth are occurring. It is therefore relevant to integrate this new technique CCW in a global geological and geophysical strategy for the exploration of naturally occurring green gases exploration, as well as any context where gas movements within the subsurface are expected such as geological gas storage.

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