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Feasibility of Retrieving Time-lapse Reflection Signals Using Ambient-noise Seismic Interferometry at Ketzin, Germany

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SUMMARY

Ambient-noise seismic interferometry (ANSI) applied to passive body-wave measurements retrieves an estimate of the reflection response as if from a source at a receiver position. Often, the limited compliance with theoretical assumptions causes erroneous absolute amplitudes of the retrieved physical reflections, and additional artefacts. Nevertheless, the retrieved reflection data may be further used for time-lapse interpretation, since the latter exploits relative amplitude differences. Here, we study the feasibility of applying ANSI to time-lapse passive seismic data to extract the time-lapse reflection signal produced by the exploitation of a reservoir. We base our study on the case of the demonstration site for CO2 storage at Ketzin, Germany. With numerical experiments, we apply ANSI to two passive datasets using a base and a repeat scenario (after velocity decreases in the CO2 reservoir) and modelled by random distributions of band-limited noise sources. We show that the retrieval of an unambiguous time-lapse signal is enabled by increased common illumination between the two datasets. Finally, we apply ANSI by auto-correlation to Ketzin field data and show the retrieval of responses consistent with modelled and active field data. We conclude that ANSI applied to field data has the potential for time-lapse differences extraction and interpretation.

Introduction

Passive seismic acquisition aims to record seismic waves emitted from passive sources in the subsurface, including natural and induced tremors. By cross-correlating body-wave-dominated ambient-noise records, passive seismic interferometry retrieves an estimate of the reflection response as if from a source at the position of receivers (Draganov et al., 2009, 2013). We refer to this technique as ambient-noise seismic interferometry (ANSI). In general, ANSI succeeds to retrieve kinematically-correct physical events but often with wrong absolute amplitudes and additional artefacts.
Time-lapse seismic interpretation is based on the extraction of relative amplitude differences and time shifts. Therefore, the reflection responses retrieved by ANSI may still be used for time-lapse interpretation to monitor impedance changes in exploited reservoirs. Here, we study the feasibility of time-lapse ANSI for the demonstration case of geological CO_2-storage at Ketzin, Germany. From 2008 to 2013, CO_2 was injected in a saline aquifer at a depth of around 650 m. Previous studies have shown that the ambient-noise characteristics at Ketzin exhibit good potential for successful applications of ANSI (Xu et al., 2012).

Theory

Wapenaar and Fokkema (2006) derive a simplified (acoustic) representation for passive seismic interferometry based on the reciprocity theorem of the correlation type. They consider a lossless, but arbitrary inhomogeneous, spatial domain enclosed by a boundary K with two receivers at positions x_A and x_B inside the domain. K is regularly sampled with seismic sources with mutually uncorrelated signatures, permitting the sources to act simultaneously. Assuming that the medium at and outside K is homogeneous and that the receivers are in the far field, we obtain in the space-frequency domain,

$$\{\hat{G}(x_B,x_A,\omega)+\hat{G}^*(x_B,x_A,\omega)\}\hat{S}(\omega)\propto\langle\hat{u}^*_{rec}(x_B,\omega)\hat{u}_{rec}(x_A,\omega)\rangle, \tag{1}$$

where ω is the angular frequency, $\hat{u}_{rec}(x_{A,B},\omega)$ are the recorded wavefields at $x_{A,B}$ and $\langle.\rangle$ denotes a spatial ensemble average, $\hat{S}$ is the power spectrum of the sources (the same for all sources) and $\hat{G}(x_B,x_A,\omega)$ is the Green's function from x_A to x_B. The left hand-side of the above relation corresponds to the retrieved seismic response and is obtained by cross-correlating the ambient-noise records at x_A and x_B. The accuracy of the retrieved response depends on the validity of the assumptions made. In practice, K may not be a smooth, neither closed, surface and the passive sources may not be regularly sampled. This leads to artefacts and amplitude errors in the retrieved reflections. It is, however, less well understood how these violations would affect the retrieval of a time-lapse signal.

Numerical experiments

The numerical experiments aim to study the feasibility of time-lapse ANSI and the conditions on the body-wave noise that would allow the retrieval of the time-lapse reflection signal from the CO_2 reservoir at Ketzin (see also Boullenger et al. (2015)). Based on well log data and previous 3D seismic surveys, we designed a horizontally layered acoustic model of the subsurface at the injection site. Figure 1 shows the velocity model for the base scenario (as expected before the start of storage). Note in particular the high-impedance layer at around 550-meters depth corresponding to an anhydrite formation (Förster et al., 2006) and the CO_2 reservoir modelled as a relatively thin layer at around 650-meters depth. For the time-lapse experiments, we consider a repeat scenario with a decline of the P-wave velocity by 20% in the reservoir. The two (base and repeat) numerical passive datasets are obtained by modelling the full response from randomly acting noise sources distributed in the subsurface model.
The modelling of the passive records is illustrated in Figure 1. In this example, we choose a distribution of 100 noise sources in the area from x=-300 m to x=300 m and from z=800 m to z=900 m (red stars in Figure 1(a)). As shown in Figures 1(b) and 1(c), the sources have band-limited noise signatures with

a maximum allowed duration of 2 s. The sources are triggered randomly in space and time and we record the response from this sequence continuously at receivers placed every 10 m at the free-surface (z=0) from x=-60 m to x=60 m. The results of the two passive experiments represent modelled body-wave ambient-noise records. The results of the application of ANSI to the two passive experiments

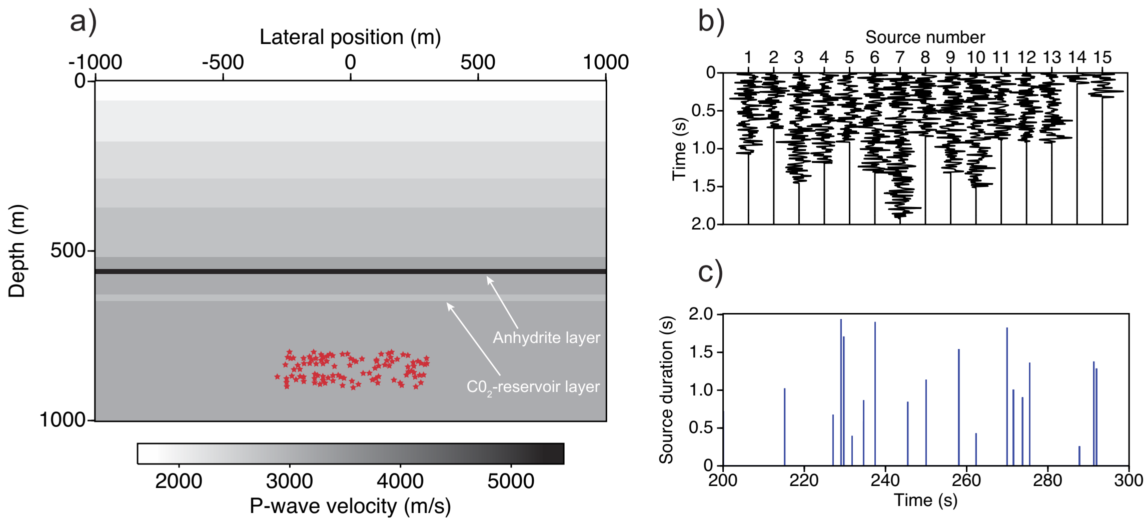

Figure 1 *Modelling of the passive body-wave noise measurements. a) Velocity model with red stars indicating a random distribution of 100 sources in the region between x=-300 m and x=300 m and between z=800 m and z=900 m. b) The signatures of 15 out of the 100 sources. c) The triggering sequence of the modelling between t=200 s and t=300 s.*

are shown in Figures 2(a) and 2(b). In the repeat passive experiment, we use a different spatial and temporal distribution of the noise sources. The other parameters (i.e. number of sources, maximum source duration, etc) are the same in both experiments. Note in particular the retrieval of the strong reflection at around 0.5 s produced by the modelled anhydrite formation and known as K2 reflector at Ketzin. Figure 2(c) shows the time-lapse reflection signal obtained after normalization and subtraction of the panels in Figures 2(a) and 2(b). Although several artefacts are present, the result gives a clear indication of the impedance change at the reservoir level. Figure 2(d) shows the time-lapse panel when the exact same noise-source distribution (and other parameters) is used for the repeat experiment. It contains the same time-lapse signal at the reservoir level, but, since the sources of two passive datasets are now perfectly consistent, the artefacts are identical and not present anymore in the extracted time-lapse signal.

This indicates that obscuring artefacts may be suppressed when the ambient-noise records tend to match. In Figure 3, we show the extracted time-lapse reflection signal after ANSI for an increasing number of noise sources (the base and repeat noise-source distributions differ). For these experiments, we confine the noise-source positions to the region of the model between x=-150 m to x=150 m and between z=800 m to z=900 m. The time-lapse signal becomes more accurate when the number of sources increases. This is caused by the increased common illumination of the receivers between the base and repeat experiments. We achieve better matching thanks to higher spatial density of the noise sources. In the field, the concordance of base and repeat surveys can be enhanced using illumination diagnosis prior to ANSI (Almagro Vidal et al., 2014).

Field-data results

We applied ANSI to passive measurements from the vertical component of the particle velocity at Ketzin. The measurements were taken after the start of injection of CO_2 and were collected by 13 geophones buried at 50-meters depth and placed every 10 m. We pre-selected a period of three days in January 2012 based on the data quality and the presence of significant, nearly vertically incident, body-wave

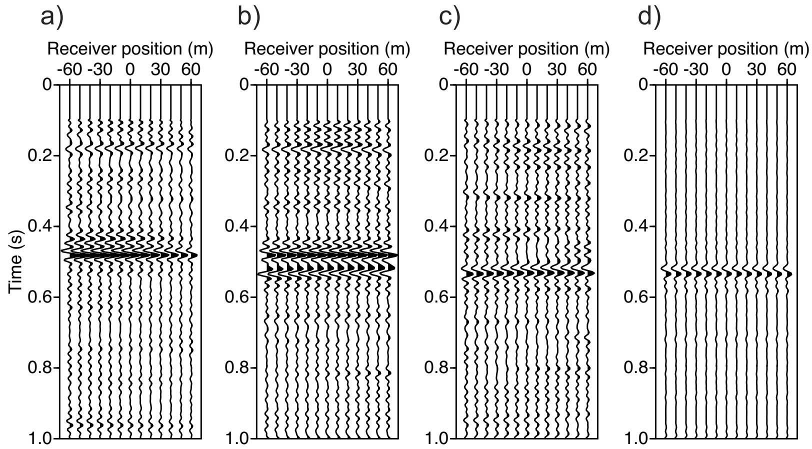

Figure 2 *Retrieved virtual reflection response from a) the base and b) the repeat experiment using a different noise-source realization. c) The extracted time-lapse signal. d) The extracted time-lapse signal when the noise-source realization in the base and repeat experiments is the same.*

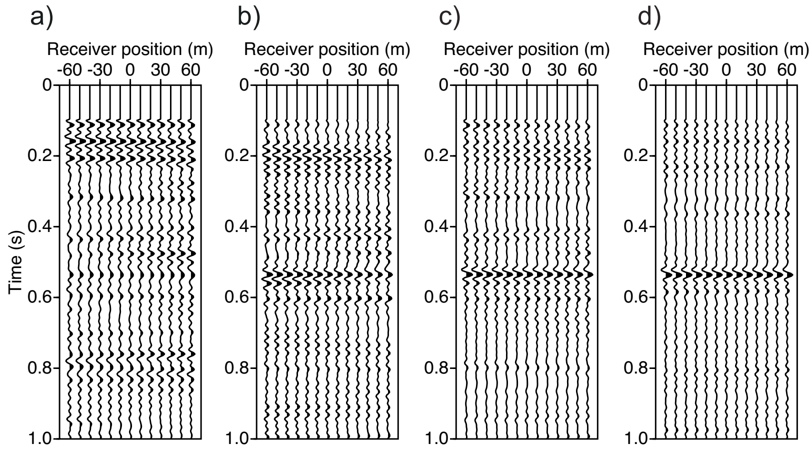

Figure 3 *The time-lapse reflection signals after application of ANSI for a) 20 noise sources, b) 40 noise sources, c) 80 noise sources and d) 160 noise sources. The sources are confined to the region between x=-150 m and x=150 m and between z=800 m and z=900 m in the model.*

arrivals. We used auto-correlation instead of cross-correlation to retrieve an estimate of the reflection response, aiming to retrieve a zero-offset section. The field-data auto-correlation is shown in Figure 4(b) using the passive data from one of the three pre-selected days. For comparison, we show in Figure 4(a) a Ketzin active field-data stack profile. Although the receivers are at the surface, we establish relatively good agreement for the retrieval of physical reflections at around 0.6 ms. In addition, the modelled auto-correlation result in Figure 4(c) using a numerical experiment with the repeat scenario also predicts the retrieval of strong arrivals at the same two-way travel time. This suggests that if there were seismic data from before the CO_2 injection, we might have seen the time-lapse changes.

Conclusions

Using numerical experiments and field-data results from the CO_2-storage site at Ketzin, Germany, we study the feasibility of time-lapse ambient-noise seismic interferometry (ANSI) to extract time-lapse reflection signals characterizing impedance changes occurring at the reservoir. The numerical experiments show that time-lapse ANSI has the potential to exhibit the expected time-lapse reflection signal. The viability of time-lapse ANSI depends on the concordance of the selected base and repeat ambient-noise records. In the numerical experiments, the concordance is governed by the spatial density of the noise-

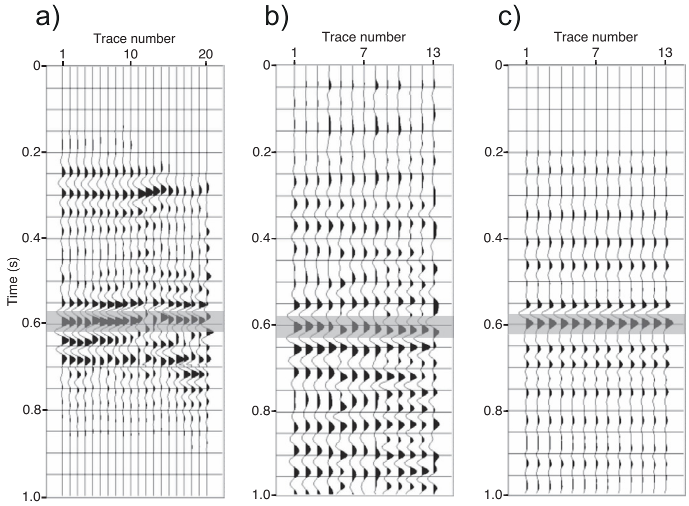

Figure 4 a) Ketzin field-data stack profile using active sources and a receiver line at the surface. b) Auto-correlation result using one day of noise recorded on the vertical component of the buried geophones. c) Auto-correlation panel from modelled passive data. The three panels are filtered to the same bandwidth. The gray stripes indicate the candidate location of the K2 reflector.

source distribution in the base and repeat surveys. In the field, it depends on the rate of occurrence and direction of the passive body-waves; hence, the concordance can be enhanced with prior illumination diagnosis. Comparison of auto-correlated field data with numerical ANSI results and active field-data stacks shows encouraging retrieval of physical arrivals for applying time-lapse difference extraction on field data.

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