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Monitoring pore-pressure depletion in the Groningen reservoir using ghost reflections from seismic interferometry

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Summary

Seismic interferometry (SI) retrieves new seismic responses between receivers or sources using, e.g., cross-correlation. Applying SI to a reflection survey with active sources and receivers at the surface, one retrieves ghost reflections besides the physical reflections. Ghost reflections are retrieved from the correlation of two primary reflections or multiples from two different depth levels. They are only sensitive to the changes in the layer that cause them to appear in the result of SI.

Using ghost reflections from SI, we investigate the possibility of monitoring pore-pressure depletion due to gas extraction in the Groningen gas field, Netherlands. We performed an active-source transmission laboratory experiment to measure S-wave velocities at pore pressures of 50, 80, 100, 200, and 300 bar. Using these values; we numerically model scalar reflection data with sources and receivers at the surface for the Groningen subsurface model. Applying SI by auto-correlation to these datasets, we retrieve zero-offset ghost reflections. We show that using only the reflections from the top and the bottom of the reservoir is essential for retrieving a specific ghost reflection from inside the reservoir. The retrieved ghost reflections showed clear time differences, indicating they can be utilized to monitor reservoir pore-pressure depletion changes.

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Introduction

The Groningen gas field in the Netherlands is the largest onshore gas field in Europe. Due to gas production since 1963, induced seismicity has occurred in the Groningen region that can be caused by reservoir pressure depletion (Bourne et al., 2018). Monitoring the temporal variations of the reservoir is essential for forecasting future seismicity. Many studies have shown that it is possible to detect temporal changes in subsurface properties from the changes in seismic wavefields (e.g., MacBeth et al., 2020). However, most monitoring methods suffer from interference due to complex overburden structures and small reservoir changes at the level of detectability.

We propose using ghost reflections from seismic interferometry (SI) to monitor the Groningen gas reservoir. SI refers to retrieving seismic responses through, e.g., cross-correlation of seismic observations at different locations of seismic receivers (Wapenaar and Fokkema, 2006). Several studies showed the potential of SI for monitoring the Groningen subsurface. Zhou and Paulssen (2020) investigated the approach of deconvolution SI applied to passively data recorded by a deep borehole array. They showed the possibility of monitoring small temporal changes in the subsurface if repeating noise sources are available. In another study, Brenguier et al. (2020) used a passive-seismic monitoring approach to detect velocity changes in ballistic waves recovered from seismic noise correlations. Their methodology requires dense arrays of seismic sensors.

In this study, we use reflection data from active sources and receivers at the surface, which leads to retrieving ghost reflections from SI because of insufficient destructive interference (Snieder et al., 2006). Ghost reflections propagate inside a specific layer so they can advantageously be used for monitoring changes inside that specific layer, e.g., a gas reservoir.

We use numerical modelling to show the feasibility of using ghost reflections for monitoring pore-pressure depletion inside the Groningen reservoir (thickness of 270 m) at a depth of 3 km. We performed a laboratory experiment to measure the direct S-wave velocities for variations in the pore pressures using in-situ conditions of pore pressure, stress, and confining pressure. We used the velocities measured in the laboratory experiment for building up the subsurface model of Groningen. Then, we applied SI by auto-correlation (SI by AC) to the modelled data to retrieve ghost reflections from inside the Groningen reservoir for the base survey and monitoring surveys.

Method

For an active-source reflection seismic survey, where the sources (the red stars in Figure 1) and receivers (the blue triangles in Figure 1) are restricted to the surface, the frequency-domain response $\hat{G}(\boldsymbol{x}_B, \boldsymbol{x}_A, \omega)$ and its complex conjugate at $\boldsymbol{x}_B$ from a virtual source at $\boldsymbol{x}_A$ can be obtained from the relation (Halliday et al., 2007):

$$\hat{G}^*(\boldsymbol{x}_B, \boldsymbol{x}_A, \omega) + \hat{G}(\boldsymbol{x}_B, \boldsymbol{x}_A, \omega) \propto \sum_{n=1}^{N} \hat{G}^*(\boldsymbol{x}_A, \boldsymbol{x}_n, \omega)\, \hat{G}(\boldsymbol{x}_B, \boldsymbol{x}_n, \omega), \quad (1)$$

where the right-hand side of the relation is a cross-correlation of two observations at $\boldsymbol{x}_A$ and $\boldsymbol{x}_B$ from surface sources at $\boldsymbol{x}_n$. The asterisk (*) denotes complex conjugate in the frequency domain, and N represents the number of active sources. In relation 1, if we substitute the at response $\boldsymbol{x}_A$ instead of at $\boldsymbol{x}_B$, the retrieved Green's function is the result of AC of the arrivals at the receiver $\boldsymbol{x}_A$ (the right-hand side of relation 1), which means $\boldsymbol{x}_A$ acts as a collocated virtual source and receiver. The retrieved traces would thus represent a zero-offset reflection section. The theory behind SI requires having sources which surround the receivers completely. When the positions $\boldsymbol{x}_n$ are at the surface like for relation 1, as in a typical active-source exploration survey, the requirement of effectively surrounding the receivers is not met. As a result, ghost events are retrieved in the Green's function estimates.

Ghost reflections are retrieved from the correlation of two primary reflections from two different depth levels. For example, the ghost reflection inside the reservoir (red arrows in Figure 1) can be retrieved by AC of the primary reflection from the top and bottom of the reservoir (the blue and the purple dotted arrows, respectively, in Figure 1). If we apply this to all the receivers, the zero-offset gather can be retrieved (such as red arrows in Figure 1). These ghost reflections propagate only inside the reservoir without any kinematic effect of the overburden and underburden, and they are the same as the reflections which are recorded by virtual receivers (the green starts in Figure 1) due to virtual sources (the black stars in figure 1) at the same location above the reservoir.

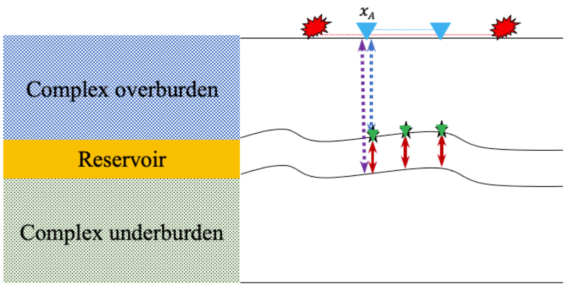

Figure 1 *Schematic representation of seismic interferometry by auto-correction. The ghost reflections (red arrows) are retrieved from the correlation of the primary reflections from the top and the bottom of the reservoir (the blue and the purple dotted arrows, respectively) from the active sources (the red stars) and receivers (the blue triangles) at the surface. The black stars and the green triangles show the virtual sources and receivers.*

Numerically modelled data

We aim to retrieve ghost reflections from inside the Groningen reservoir for monitoring. One of the causes of changes inside the Groningen reservoir is pressure depletion due to gas extraction. Therefore, we performed a laboratory experiment to measure velocity changes from pressure depletion. The rock sample was a Red Pfaelzer sandstone, considered an analogue to the Rotliegend sandstones of the Groningen gas reservoir. The porosity of the sample was 19%, and the dimensions were 30 mm in diameter and 60 mm in length. We performed active-source acoustic transmission measurements using two S-wave transducers integrated into the pistons of the loading system, with a source at the top and a receiver at the bottom. S-wave velocities were obtained using a centre frequency of 1 MHz. We decreased the pore pressure from 300 bar to 10 bar with steps of 5-10 bar, while the axial stress (650 bar) and confining pressure (330 bar) were constant to investigate the effect of pore-pressure depletion.

We used the measured S-waves velocities for the pore pressures of 50, 80, 100, 200, and 300 bar for the Rotliegend reservoir in the Groningen subsurface model (NAM, 2017). We used a finite-difference modelling code (Thorbecke and Draganov, 2011) in a scalar mode to generate a seismic reflection dataset. We used S-wave velocities in our numerical modelling because, in a 2D field survey, it is possible to use S-wave sources and horizontal-component receivers oriented in the direction perpendicular to the line. As a result, the recorded horizontal S-waves are completely decoupled from the compressional and vertical S-waves. Figure 2 shows the location of the Groningen region, the velocity model, and the geometry of the sources and receivers used in our numerical modelling. The fixed receiver positions range from 3000 m to 7000 m, and the sources are placed from 2001.25 m to 8001.25 m at the surface. The receivers and sources were regularly sampled with 1.25 m and 40 m spacing. We also used an absorbing boundary at the surface to remove free-surface multiples in the numerically modelled data to better retrieve ghost reflections.

Figure 3a shows the modelled common-source gather for a source at 5001.25 m for the subsurface model for 80 bar pore pressure as a base survey. In the gather, we can see primary reflections from subsurface layers, including the reflections from the top and bottom of the reservoir (black arrows).

We applied SI by AC by turning active sources into virtual receivers. Figure 3b shows the results of SI by AC while all events in the shot gathers are used. We retrieved several ghost reflections from inside different layers of the subsurface model, such as events indicated by the magenta arrows. They result from the correlation of all primaries and internal multiples in the shot gathers. To better retrieve the specific ghost reflection that propagates only inside the reservoir, before applying SI by AC, we muted all undesired events before the reflection from the top of the reservoir and after the reflection from the bottom of the reservoir. Figure 3c shows the retrieved result for the muted shot gathers. The event indicated by the red arrow is the ghost reflection from inside the reservoir, which propagates only inside the reservoir, and results from the correlation of the primary reflections from the top and the bottom of the reservoir (black arrows in Figure 3a).

We applied a similar procedure for all subsurface models for the monitor surveys for pore pressures of 50, 100, 200, and 300 bar. To better compare the results of SI, we extracted one trace for a virtual receiver at 5001.25 m from the retrieved zero-offset gathers for all different pore pressures (Figure 4). As we can see in the figure, the retrieved ghost reflection shows changes in time for the different pore pressures.

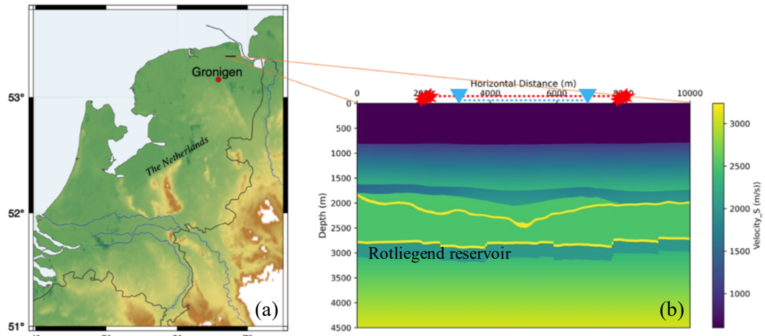

Figure 2 (a) *The location map of the Groningen region in the Netherlands,* ***(b)*** *the velocity model, red stars and blue triangles show the geometry of the active sources and the receivers at the surface used for modelling in this study.*

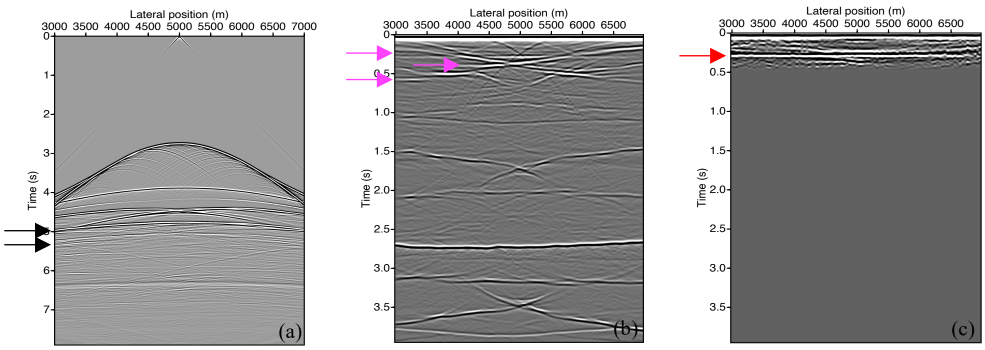

Figure 3 (a) *Common-source gather for an active shot at 5001.25 m,* ***(b)*** *the result of SI by AC when all events are used,* ***(c)*** *same as (b) but for muted shot gathers. The black arrows show the reflections from the top and the bottom of the reservoir, the magenta arrows show ghost reflections from inside different subsurface layers, and the red arrow shows the specific ghost reflection from inside the Rotliegend reservoir.*

Conclusions

We investigated the feasibility of monitoring pore-pressure depletion in the Groningen gas field using ghost reflections retrieved from seismic interferometry (SI) applied to numerically modelled data simulating a reflection survey with active sources and receivers at the surface.

To build up a realistic model, we measured in a laboratory the S-wave velocities during pore-pressure depletion in an active acoustic transmission experiment using in-situ parameters from the Groningen gas field, such as stress, confining pressure, and pore pressure. We used these S-wave velocities as the reservoir velocities in the subsurface Groningen model to generate the base and monitoring seismic reflection datasets. Then, we applied SI by auto-correlation to retrieve a virtual zero-offset gather for the base survey for pore pressure of 80 bar and for the monitoring surveys with pore pressures of 50, 100, 200, and 300 bar in the reservoir.

We showed that it is possible to retrieve the specific ghost reflection from inside the reservoir in the zero-offset gather by applying SI to shot gathers processed such that the arrivals above the primary reflection from the top and below the primary reflection from the bottom of the reservoir were muted. Our result demonstrated that the retrieved ghost reflections had time differences related directly to the changes inside the gas reservoir. The retrieved ghost reflections are only sensitive to the changes in the reservoir, while the kinematic influence of the overburden and underburden are eliminated. Thus, the ghost reflections can be used for monitoring pore-pressure depletion changes inside the reservoir.

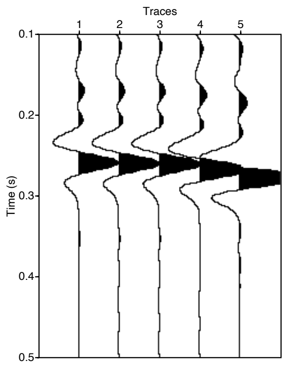

Figure 4 *Retrieved zero-offset ghost reflections for a virtual receiver at 5001.25 for reservoir pore pressure of 50 (trace1), 80 (trace2), 100 (trace 3), 200 (trace 4) and 300 bar (trace 5).*

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