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Travel time changes in the Groningen gas reservoir by train noise interferometry of borehole data

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Summary

In this study we show that time-lapse measurements of a reservoir can be made by noise interferometry of borehole data. We used borehole geophone array data of monitoring well SDM-1 in the Groningen gas field in the Netherlands. The ambient, anthropogenic noise allows accurate determination of the P and S velocity structure (Zhou & Paulssen, 2017), but is not stable enough in time and space to measure temporal travel time variations. With deconvolution interferometry of high-frequency train signals, however, it is possible to detect small travel time decreases of ~0.05 ms (0.1%) over half a year, associated with compaction of the reservoir. Moreover, we identified a strong travel time anomaly over a period of 1.5 months that is caused by drilling of a new borehole in the reservoir at ~5 km distance.

Introduction

Monitoring the temporal variations of a reservoir is essential to calibrate geomechanical models that relate compaction and subsidence to the extraction or injection of fluids in reservoirs. Time shifts are often measured by 4D reflectivity seismics (e.g., MacBeth et al., 2019). Alternatively, as suggested by Behm (2017), it should be possible to measure temporal variations with passive data using noise interferometry. In 2013, two former production wells in the Groningen gas field in the Netherlands were equipped with geophone strings in the reservoir at 3 km depth. Zhou & Paulssen (2017) accurately determined the P- and S-wave velocity structure in the reservoir along one of these boreholes (SDM-1) using noise interferometry by cross-correlation. However, it was also clear that diurnal variations in anthropogenic noise had a strong impact on the interferograms, impeding the detection of travel time variations caused by changes in the medium. In the current study, we isolated noise from nearby passing trains and show that these train signals can be used to obtain more accurate and stable travel times that allow the measurement of time-lapse variations in the Groningen reservoir.

Train noise interferometry

Various studies have shown that downward propagating P and S waves can be retrieved from noise interferometry by cross-correlation using geophone data in deep vertical boreholes (e.g., Miyazawa et al., 2008; Grechka & Zhao, 2012; Vaezi & Van der Baan, 2015). Detecting time-lapse variations caused by changes in medium properties is much more difficult, because the ambient noise sources are generally not stable in time and space. Zhou & Paulssen (2017) used ambient (anthropogenic) noise to measure inter-geophone travel times in borehole SDM-1 of the Groningen gas field, and calculated the P and S velocity structure in the reservoir for one month of data in 2013. Furthermore, they recognized signals from nearby passing trains in the high-frequency part of the noise spectra. In this study we also use data from SDM-1, for two separate deployments in 2015: Jan 23 – Jun 28 and July 3 – Dec 1. Borehole SDM-1 is located between stations Stedum (1.2 km) and Loppersum (3.1 km) at 0.5 km distance from the railway. The 10 geophones are located at reservoir level at depths between 2750 and 3000 m.

Figure 1 shows two spectrograms recorded by the lowermost geophone. The left panel shows the noise associated with a train leaving Stedum station, reaching its maximum amplitude close to the borehole 60 to 80 s later, the right panel shows the noise by a train from Loppersum reaching its maximum amplitude 60 to 80 s before it arrives at Stedum. Such train noise is identified at regular intervals (twice per hour during the day and once per hour in the evening) for trains travelling in both directions.

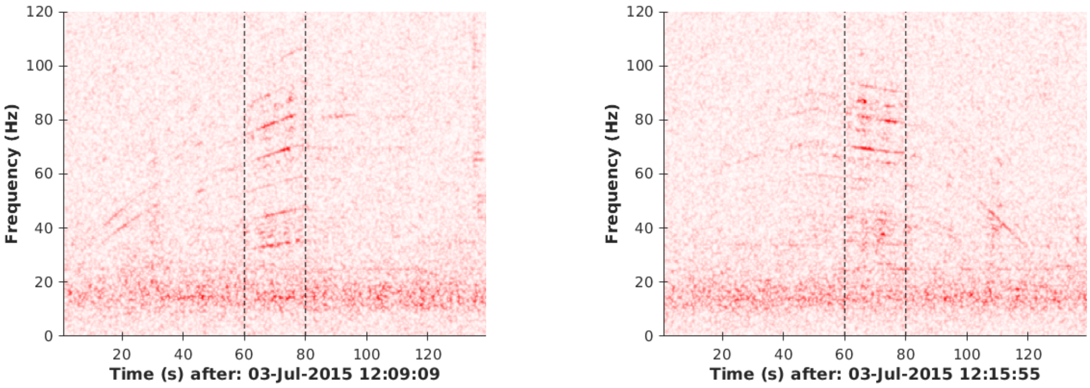

Figure 1 *Vertical component spectrograms of train noise recorded by the bottom geophone. Left panel: train from Stedum to Loppersum. Right panel: train from Loppersum to Stedum. Dashed lines indicate the time intervals used for deconvolution interferometry.*

The characteristic signature of train noise combined with its high-frequency content (30-100 Hz) allows accurate measurement of inter-geophone travel times by interferometry. Deconvolutions were calculated for 20 s windows of train noise centered around its maximum amplitude. During the two monitoring periods, over 18000 trains were detected. Figure 2 shows the stacked deconvolutions of over 9000 train signals for the period Jul 3 – Dec 1, 2015, using the signal of the top geophone (virtual source). Apart from the clear downgoing P wave, weak bottom and top reflections from the reservoir can be recognized.

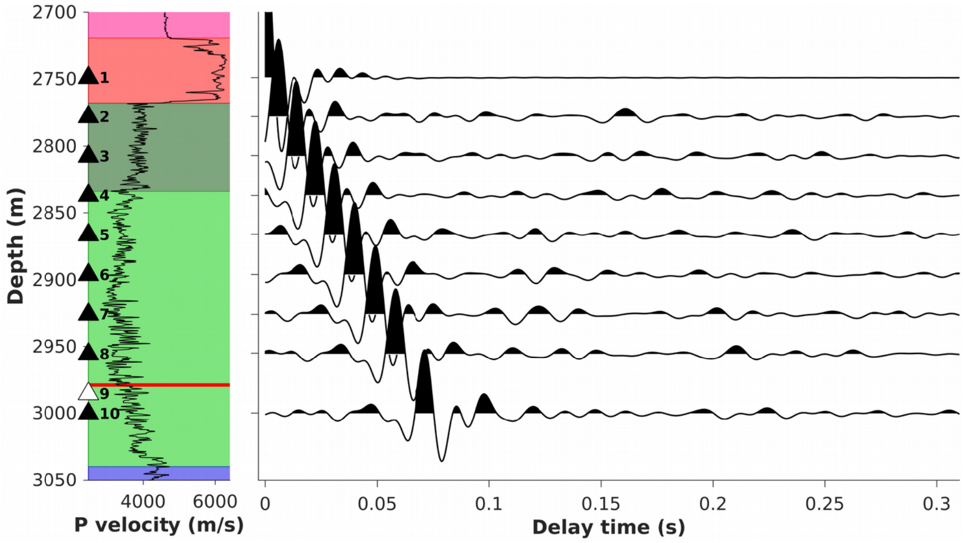

__Figure 2__ Right: Stacked vertical component deconvolutions using the signal of the top geophone for the period Jul 3 - Dec 1 2015. Left: Location of the geophones with lithology (Pink: Zechstein salt; Orange: anhydrite; Dark green: Ten Boer claystone; Light green: Slochteren sandstone; Purple: Carboniferous shale; Red line: gas-water contact). Geophone 9 was out of order.

P velocity structure

Similar to Zhou & Paulssen (2017), we determined the P wave velocity profile using all possible inter-geophone P wave travel times for the two independent data sets of trains travelling in opposite directions. The P velocity structure calculated from each of these data sets has a much smaller error (defined as twice the standard deviation) than the previous study and both velocity structures agree within the error bar (Fig. 3).

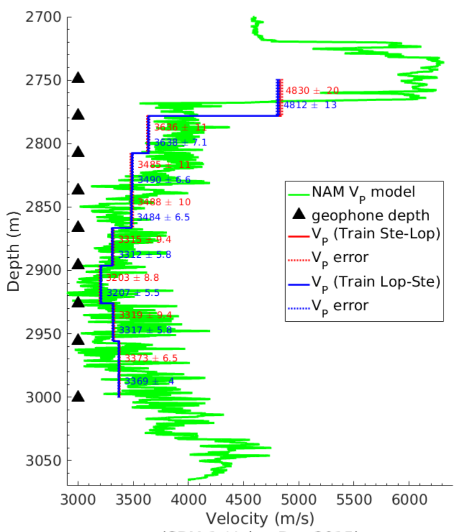

__Figure 3__ P velocity profile from inter-geophone P wave travel times (Jul 3 - Dec 1 2015) for train signals Stedum-Loppersum (red), and Loppersum-Stedum (blue). The well log data are in green.

P wave travel time changes

To investigate the temporal variations within the reservoir, we made daily stacks of the deconvolved train signals from geophone 2 to geophone 8. Linear fits to the data show a slight travel time decrease of ~0.022±0.028 ms for the first half year of 2015 for the two independent data sets (Fig. 4). The travel time decrease for the second half year of 2015 is 0.024±0.024 ms for trains from Stedum to Loppersum (blue) and 0.048±0.035 ms for trains in the opposite direction. Although just barely significant, such travel time decreases of 0.05 – 0.1% cannot be explained by vertical shortening only. 7 mm shortening per year, as measured by distributed strain sensing (DSS) at borehole ZRP-3 at 5 km distance (Cannon & Cole, 2017), would only give a travel time decrease of ~0.003%. An additional P wave velocity increase associated with compaction (e.g., Hatchell & Bourne, 2005) seems therefore needed to explain the data.

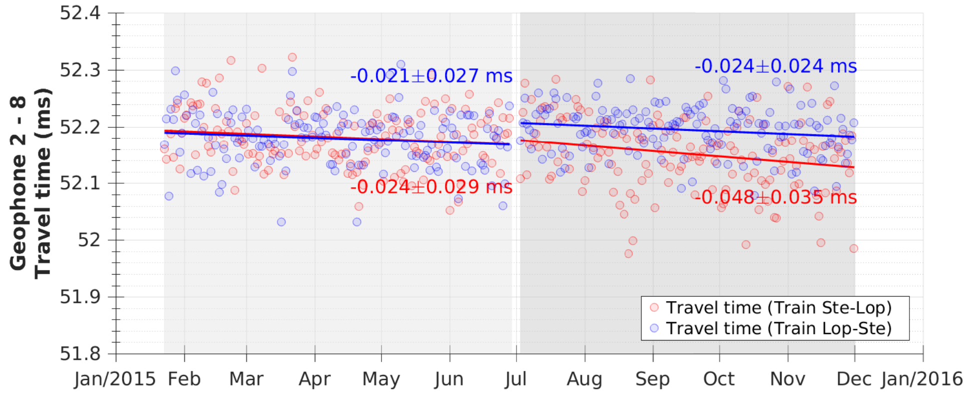

Figure 4 *Travel times from geophone 2 to 8 obtained from daily-stacked deconvolutions with linear fit. Blue measurements are for Stedum-Loppersum trains, red for Loppersum-Stedum trains.*

We also measured the travel times from geophone 1 (anhydrite) to geophone 2 (Ten Boer claystone). The first half year shows a negligible travel time decrease, but the second half year gives a travel time decrease of ~1%. Such a travel time decrease can partly be explained by downward movement of the high velocity anhydrite layer, replacing the lower velocity claystone. GPS subsidence data of the Groningen field show a similar trend with limited subsidence during the first half year and larger subsidence in the second half year (NAM). Note that the travel times from geophone 1 to 2 are larger during the second deployment because the geophones were placed back slight lower lower compared to the first deployment.

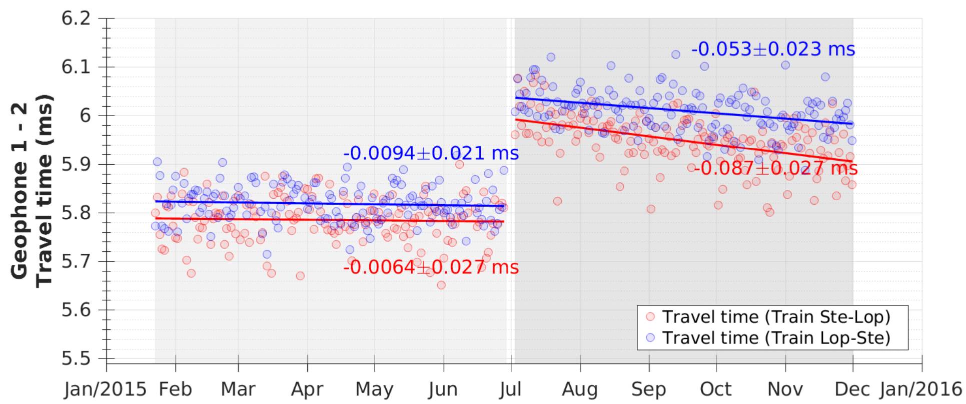

Figure 5 *Similar to fig. 4, but now for travel times from geophone 1 to 2.*

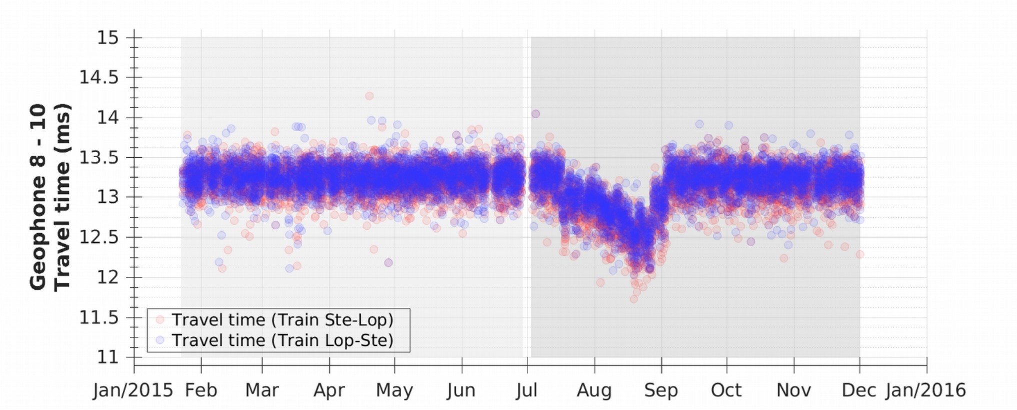

Figure 6 *Travel times from geophone 8 to 10 obtained from individual train deconvolutions (outliers removed).*

A spectacular travel time anomaly of up to 0.8 ms (6%) is observed in the time span Jul 17 – Sep 2 between the bottom geophone, located in the reservoir just below the gas-water contact, and the one just above (Fig. 6), or any of the shallower geophones. This anomaly is clearly associated with the drilling of deep borehole ZRP-3 in the reservoir at ~5 km distance in this time span, and must have affected the gas-water contact although the exact mechanism is still unclear.

Conclusions

This study shows that it is possible to measure temporal travel time variations in a borehole from noise interferometry using repetitive noise sources such as train signals. The travel times between the geophones in borehole SDM-1 at reservoir level show decreases of 0 – 0.08 ms over half a year (with uncertainties of 0.02 – 0.03 ms). These travel time decreases are associated with compaction and cannot be explained by vertical shortening only, therefore requiring additional medium velocity increases. Moreover, the drilling of a well at ~5 km distance has affected the inter-geophone travel times to the bottom geophone below the gas-water. The mechanism causing this is not yet understood.

Acknowledgements

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