Horizon 2020 - Marie Sklodowska-Curie Actions
Innovative Training Network (ITN)
Complex **R**h**E**ologies in **E**arth dynamics and industrial **P**rocesses

Universiteit Utrecht

P wave travel time changes in the Groningen reservoir

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Introduction

The **Groningen gas field in The Netherlands** (Fig. 1) is one of the largest onshore gas fields in the world. Production started in 1963, causing induced seismicity and damage to houses especially in the last two decades, leading to a production decrease and a production stop planned for 2030. It is suggested that the triggering of earthquakes in Groningen is related to **reservoir compaction** as a result of **gas depletion** (Bourne et al., 2014). Thus, in situ monitoring of reservoir compaction is essential to assess its relation with seismic activity. Temporal variations of a reservoir can be inferred from 4D reflectivity seismics (e.g., MacBeth et al., 2019). Here we show that it is also possible to measure travel time variations with downhole passive data using noise interferometry.

In 2013, two former production wells (SDM-1 & ZRP-1; Fig. 1,3) were equipped with **geophone strings at 3 km depth** to monitor the seismicity in the reservoir.

Using **ambient noise interferometry** by **cross-correlation** for borehole SDM-1, Zhou & Paulssen (2017) showed that the P and S velocity structure of the reservoir could be accurately retrieved.

Now we find that **deconvolution** of **isolated train signals** gives very accurate travel time measurements that can be used to monitor temporal variations in the reservoir.

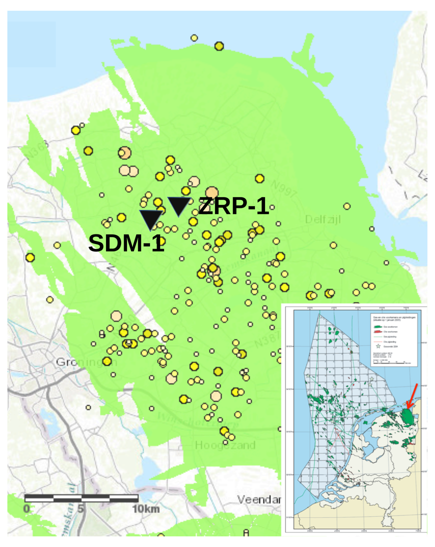

Fig.1. *Location of Groningen field, seismicity and location of well SDM-1 & ZRP-1.*

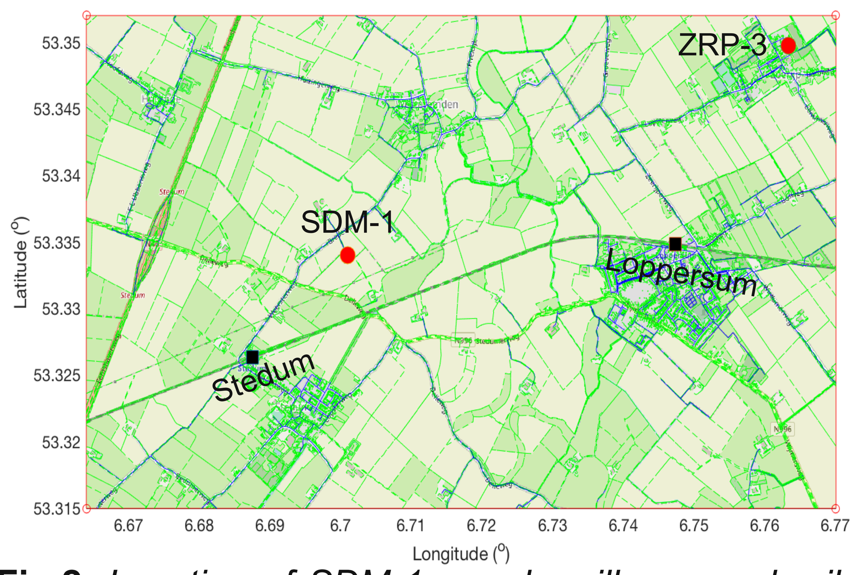

Fig.2. *Location of SDM-1, nearby villages and railway track. Distance from SDM-1 to the railway is ~500 m.*

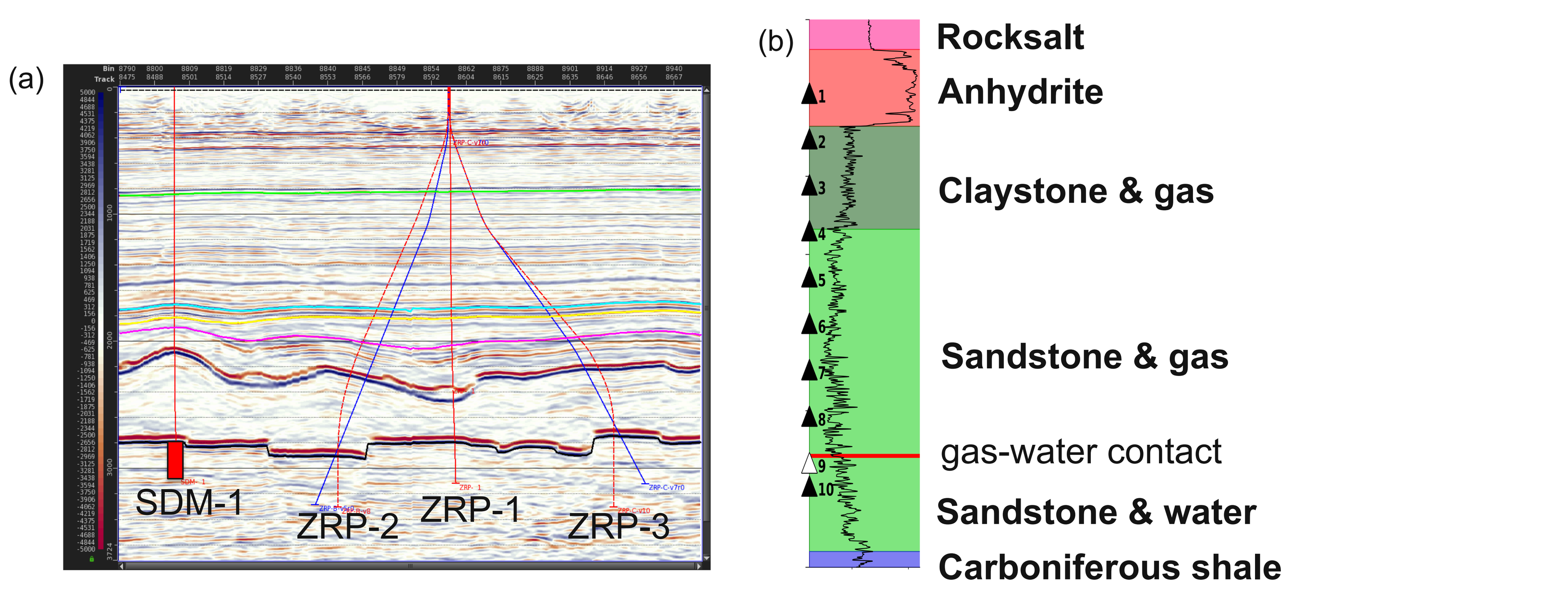

Fig.3. *(a) Seismic section with monitoring wells. (b) Lithology of borehole SDM-1 and geophone locations (black triangles, geophone 9 was out of order).*

Noise interferometry

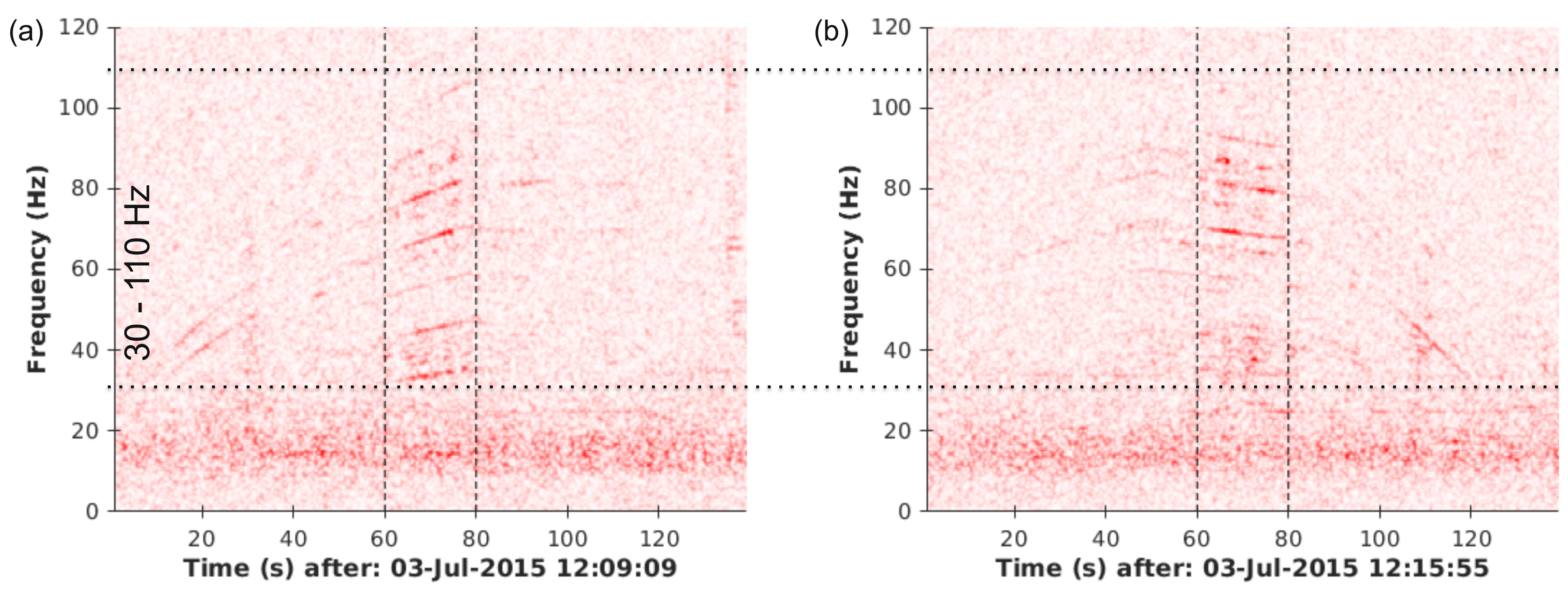

Fig.4. *Spectrograms of train signals recorded by geophone 10. (a) A train departing from Stedum station (to Loppersum). (b) A train approaching Stedum station (from Loppersum).*

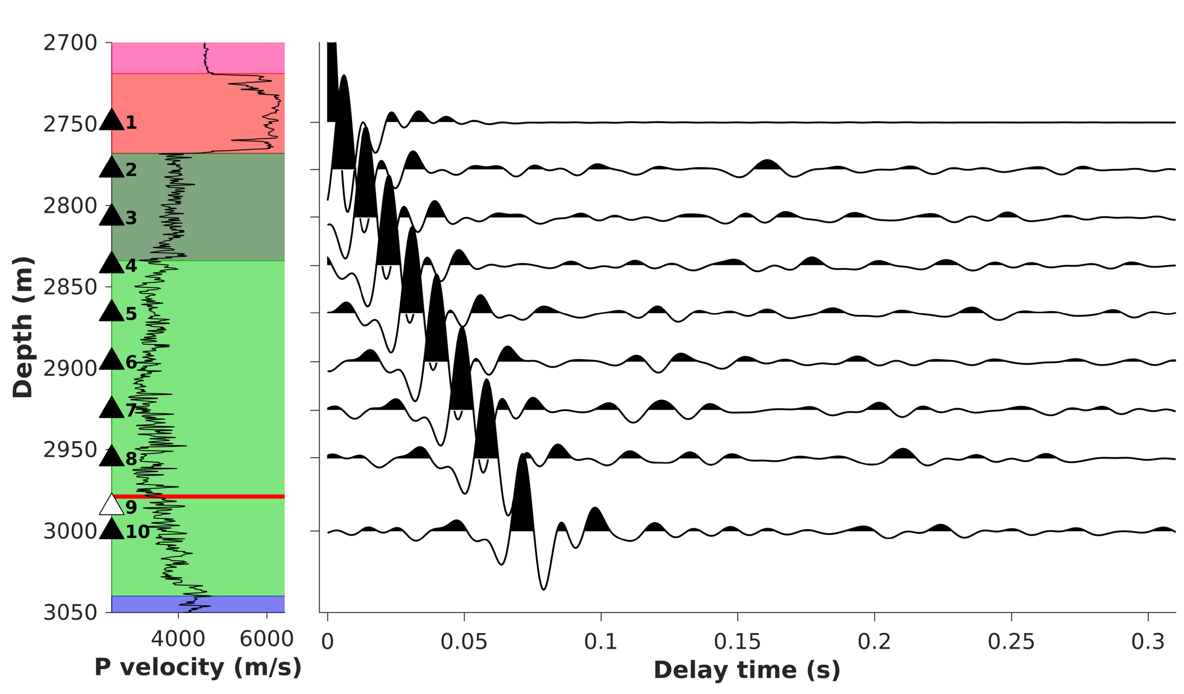

Fig.5. *Stacked deconvolutions of train signals, using the signal of geophone 1 (~9000 trains, 03 Jul – 1 Dec 2015).*

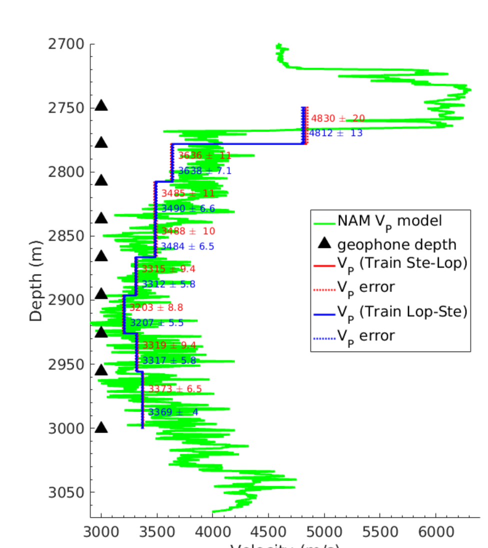

Fig.6. *P velocity profiles (in red and blue) of the reservoir obtained from trains travelling in two directions. Well log data are in green.*

SDM-1 is located ~500 m from the railway track between Stedum and Loppersum (Fig. 2). High-frequency train signals are identified in noise spectrograms for trains traveling in both directions (Fig. 4). Train signals of 20 second duration were used to calculate deconvolutions between all geophone combinations. Stacked deconvolutions (of geophone 1) show the direct P wave and multiple reflections within the reservoir (Fig. 5).

Two essentially identical P velocity profiles are obtained from the P wave travel times of all possible deconvolution combinations for trains traveling in opposite directions (Fig. 6).

P wave travel time changes

Data were analysed for two separate deployments in 2015: 23 Jan - 28 Jun, and 03 Jul - 1 Dec. Although barely significant, the travel time along the reservoir (from geophone 2 to 8) decreased 0.05 - 0.07 ms over 10 months (Fig. 8). This cannot be explained by vertical shortening only. A velocity increase with a fractional change in velocity R of 25 is required for a travel time decrease of 0.05 ms and 7 mm of vertical shortening ($dv/v = -R\, e_{zz}$, Hatchell & Bourne, 2005).

Travel times from geophone 1 to 2, across the Anhydrite-Ten Boer claystone interface, show no change in the first half year, but a decrease of ~1% in the second half year of 2015 (Fig. 9). The cause of this travel time decrease is still unclear, and can only partly be explained by downward movement of the interface. Note that the pattern over 2015 resembles that of surface subsidence (Fig. 7). (The geophones were not exactly placed back at their original locations, causing the shift in travel time between geophone 1 and 2 for the two deployments.)

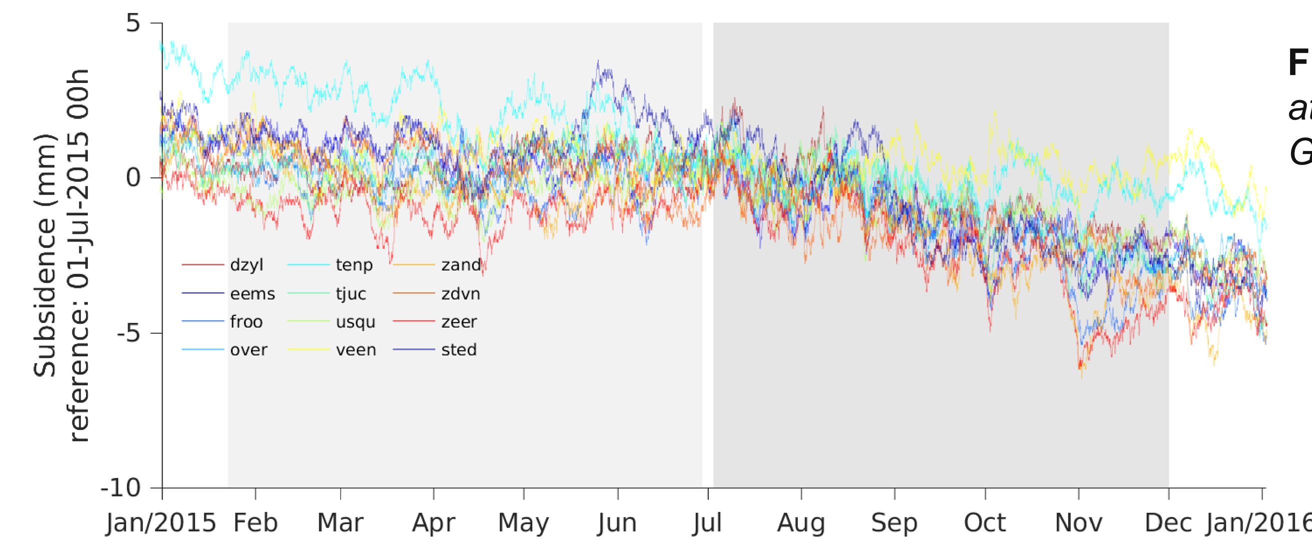

Fig.7. *Subsidence measured at 12 GPS stations in the Groningen field.*

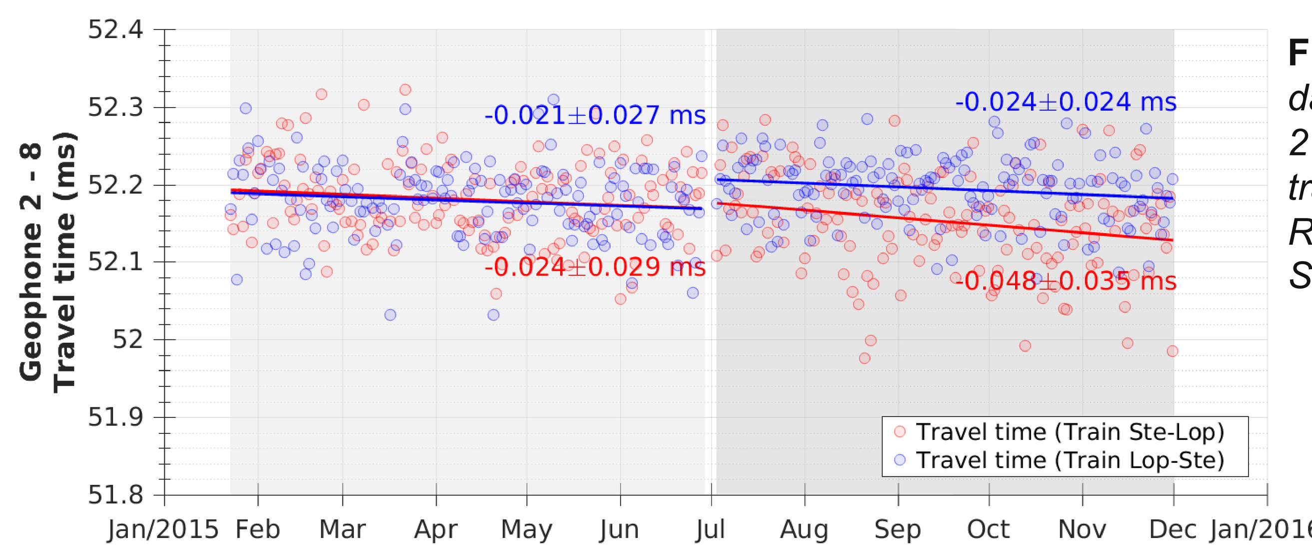

Fig.8. *Travel times (from daily stacks) from geophone 2 to 8 with linear fit. Blue: trains Stedum → Loppersum; Red: trains Loppersum → Stedum.*

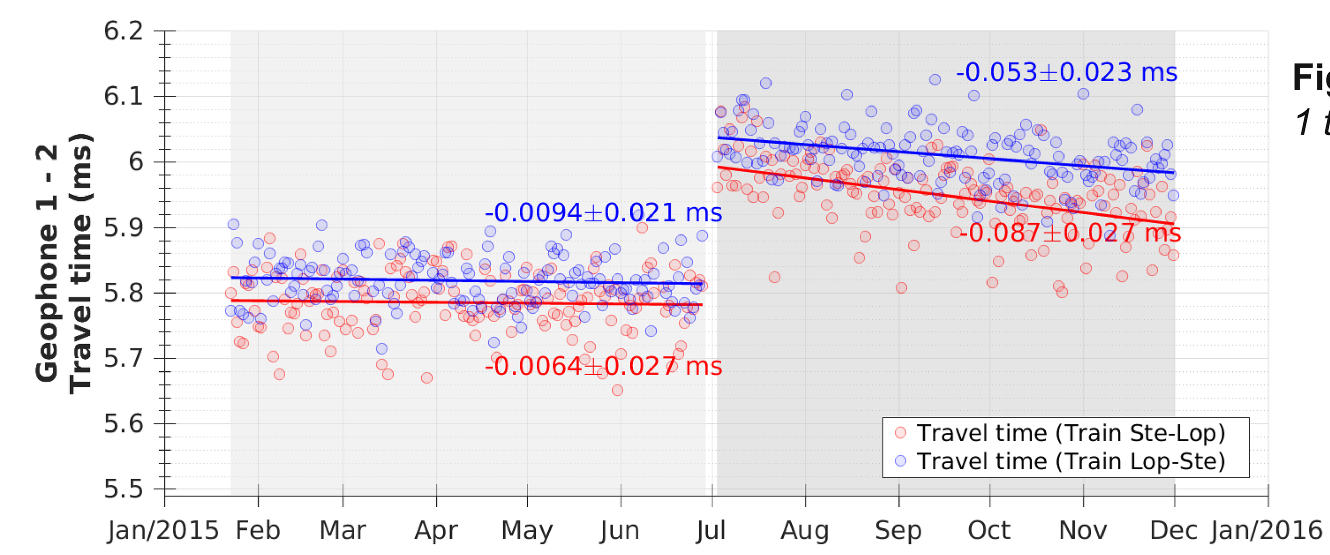

Fig.9. *As Fig. 8 for geophone 1 to 2.*

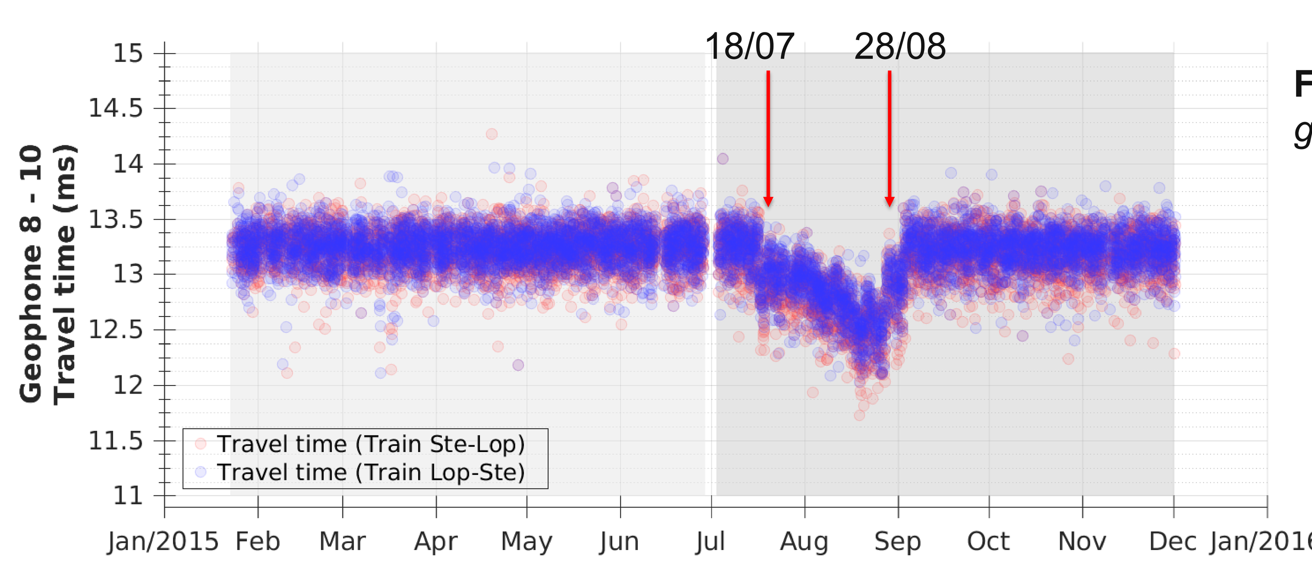

Fig.10. *Travel times from geophone 8 to 10.*

A large travel time anomaly of up to 0.8 ms (6%) is observed for the time span 17 Jul – 2 Sep between the bottom geophone and the one above (Fig. 10), or any of the shallower geophones. This anomaly appears to be related to the drilling of borehole ZRP-3 at 5 km distance, only affecting the travel times to the bottom geophone below the gas-water contact. The Z drilling report mentions "downhole losses" at the Ten Boer claystone on 18/07, and drilling stopped on 28/08.

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 estimated travel time decrease along the reservoir requires a medium velocity increase associated with compaction. The drilling of another deep well at 5 km distance has affected the travel times to the bottom geophone below the gas-water contact, although the mechanism causing this is not yet understood.

Acknowledgements

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