Exploring continuous seismic data for monitoring CO_2 injection at the CaMI Field Research Station, Alberta, Canada

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Summary

Three passive seismic data surveys were recorded at the CaMI Field Research Station. They cover different period of time and include different number of 3C geophones with different array aperture. We explore the different techniques that can be used to exploit the continuous seismic signal. First is the possibility of micro events detection to characterize the background micro seismicity as well as better understand the reservoir response to CO_2 injection. Second is the ambient noise correlation technique which approximate the Green's function between receivers. The dispersion curves obtained from the Green's function can be inverted for 3D elastic parameters models for tomography purposes. The correlations can also directly be used for monitoring purposes as they are directly sensitive to any changes of the subsurface.

Introduction

Carbon Capture and Storage is one way to reduce our GHG emissions. The CaMI (Containment and Monitoring Institute) Field Research Station has been developed in Southern Alberta (Canada) to facilitate and accelerate research and development leading to improved understandings and technologies for geological containment and secure storage of CO_2. Rather than focusing on the volume of CO_2 that can be potentially stored, our site focuses on the testing and development of technologies and methods that ensure storage performance, conformance and acceptance, and de-risk CCS in general. This is accomplished with the injection of small controlled CO_2 volumes (~500 t/year) at shallow depth (300m) that simulate a potential gas leakage from a deeper CO_2 storage (Macquet and Lawton, 2018).

Among the permanently deployed geophysical instruments at the Field Research Station are:

- 112 electrical resistivity tomography (ERT) electrodes permanently installed in a 1.1 km horizontal trench;
- Three permanents installed sources (Spakman and Lawton, 2018);
- Distributed acoustic sensing (DAS) straight and helical fibre optic cables deployed in a 1.1 km long horizontal trench and in 2 observation wells (Gordon *et al*., 2018);
- Two heavily instrument observation wells (350m deep, located 20m up-dip and 30m down-dip of the injection well). One observation well has both downhole geophones and ERT electrodes attached to the exterior of the well casing; and
- A permanent 100m × 100m surface array of 100 3-component geophones buried 1m deep.

The site is also used for instrumentation testing's and experiments as foe example the deployment of a multicomponent seismic DAS (Innanen *et al.*, 2019) or the acquisition of a dense walkaway low frequency VSP (Hall *et al.*, 2019).

We focus this paper on the potential of using continuous seismic data at the FRS and on CO_2 storage in general. Three datasets have been acquired at the Field Research Station over the last year and half:

- 100 3C geophones for 14 days in October 2017;
- 200 3C geophones for 25 days in February 2018;
- 10 3C geophones for 7 days in October 2018.

Very few amounts of CO_2 were injected during the acquisition of the two first ones. They will be used as baseline datasets and to characterize the environmental changes effects on the subsurface under the extreme conditions of Alberta province. The last survey was smaller and centered at a maximum distance from 7 to 21m from the injector well. It was acquired during an unusual but repeatable behavior of CO_2 injection: when the bottom-hole pressure reaches a certain threshold, we observe a decrease of the reservoir temperature while the injection is still going. The injected CO_2 being warmer than the reservoir temperature, one of the possible explanations is the presence of small induced fracturing due to CO_2 gas expansion.

Continuous seismic signal

This paper aims to demonstrate the useful of using continuous seismic signal for monitoring of CO_2 storage and injection purposes. The first valuable output of recording continuous seismic recording is the potential of immediate event detection trough the STA/LTA method for example. We explore this method in the present study on the October 2018 dataset. Other methods included match field processing and machine learning application which will be studied in the near future using the CaMI.FRS datasets.

Second valuable study that can be done with continuous seismic record is using ambient noise correlation (or ambient noise interferometry). It is demonstrated that seismic ambient noise correlation between two stations approximates the Green function between these two stations (Shapiro and Campillo, 2004). First application is tomography. If this method is now widely used for crustal scale studies, applications for exploration scale are less current. One of the reasons is the quality of reflection data that can be reconstructed using ambient noise correlation is still limited compared to what can be achieved with active surveys (Boullenger *et al*., 2015). Indeed, because of the noise sources and the configuration of the surveys, surface waves are dominant in the approximated Green's function. Subsurface elastic parameters models can still be produced trough the inversion of the dispersion curves of the reconstructed surface waves. Nevertheless, the still low resolution of subsurface image is compensated by the low cost and low environment impact of using ambient noise interferometry.

Second application of ambient noise correlation method is to directly use the correlation as a tool for monitoring the subsurface changes. As they approximate the Green's function, the correlations are sensitive to the changes in elastic properties of the medium. The comparison between a correlation at a given time and a reference correlation can show the effect of the changes of the subsurface.

STA/LTA

In the CaMI.FRS case, the study of 7 deployed broadband stations does not show any evidence of preexisting microseismicity (Storke *et al.*, 2018). We apply the Short Time Average-Long Time Average (STA/LTA) method to the October 2018 dataset. During the 7 days, several CO_2 injection tests were done. Figure 1 shows the reservoir temperature and pressure profiles as well as the cumulative number of events detected by at least 7 of the 10 stations deployed for that period. We can observe a small increase of detected events for the two last periods of injection.

The unusual drops of reservoir temperature highlighted by the red vertical lines do not seems to be correlated with increases of detected events.

Despite a notch filter was applied to remove the 60Hz (and multiple electrical noise), we can exclude that the detected events are being due to other human generated sources. Careful analyzes of the spectra of the detected event have to be performed to discriminate the source of the event.

Ambient noise correlation

The 100 stations survey of October 2017 (14 days) was used to start the exploration of the possibility of using ambient noise monitoring for CO2 injection and storage. During this period, very small amount of CO2 was injected leading to probably negligible effect on the change of elastic parameters of the subsurface. We use the Python open source code developed by Lecocq *et al*. (2014) to process the continuous data (mean and trend removals, 1bit temporal normalization, [0.5 - 30] Hz spectral whitening) and compute the correlations.

Application of using interferometry for monitoring purposes requires a good stability in the correlations. The October 2017 dataset can be considered as baseline as negligible

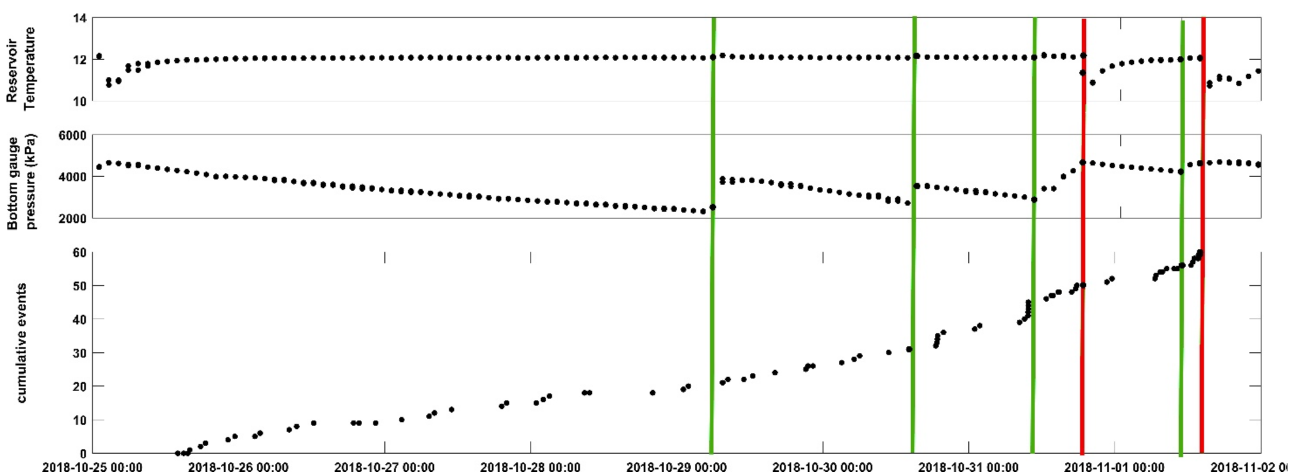
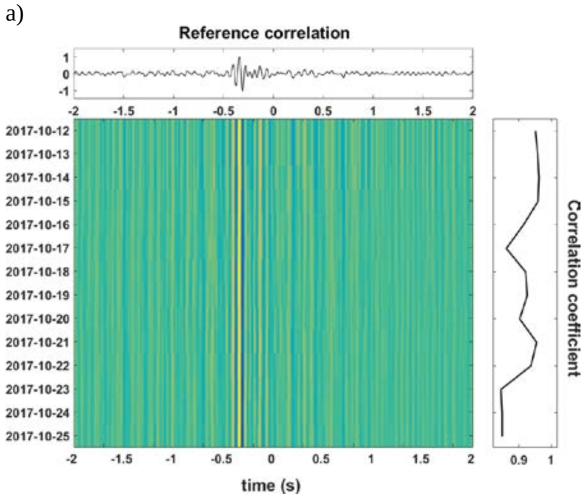


Figure 1: Top pannel: reservoir temperature profile. Middle pannel: Bottom gauge pressure profile. Bottom pannel: Cumulative number of detected events on at least 7 of the 10 deployed geophones. Green lines show the start of injection periods. Red lines show reservoir temperature drops while still injecting.

amounts on CO2 were injected during this period. Figure 2 shows the reference correlation as the stack of the 14 days period on the top. Middle panel shows the 14 daily correlations. We can already see the stability in the daily correlations. Right panel shows the correlation coefficient between the reference correlation and the daily correlation (coefficient being 1 when signals are perfectly correlated).

a)



b)

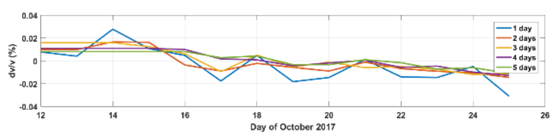


Figure 2: a) Stability of the correlation between the station 1009 and 9001 (80m apart). Top: Reference correlation (14 days stacked). Middle panel: Interferogram of the daily correlations. Right: Correlation coefficient between the reference correlation and the daily ones. b) Mean velocity variations for different number of stacked days, for a subset of 5 stations.

We use the Moving-Window Cross Spectrum analysis (MWCS, Clarke *et al*. (2011)) on a subset of 5 stations. Results are shown on Figure 2.b. Daily velocity variations show values of ± 0.02% (up to ± 0.05% for some specific pairs not shown here). We can also notice a general decrease in the velocity. Several authors (e.g. Gassenmeier *et al*. (2014), Hillers *et al*. (2015)) showed that natural phenomena such as wind, groundwater level, or temperature may have a strong influence on the results of interferometry. These listed phenomena will have a strong effect especially on the dataset October 2017 dataset as the array aperture is small and so the correlation will be mainly sensitive to the very shallow subsurface. As we expect very small changes on the elastic properties due to CO_2 injection at the Field Research Station (Macquet and Lawton, 2018), a careful study of the results needs to be done to proper understand the influence of the environmental changes on the correlations and correctly interpret the future monitoring results.

Further analysis will be carried on that dataset as well as on the 25 days dataset recorded on 200 stations (1km array aperture). The last one should allow us to image the subsurface at reservoir depth due to larger array aperture.

Future work

Visual inspection of the spectrogram shows known or unknow punctual events observed during the October 2017 recording. Figure 3 shows 4 examples. Figure 3.a shows a quiet period, where only ambient noise is recorded; Figure 3.b shows the trace of the University of Calgary seismic Vibe, when an active survey was shot on the field. Figure 3.c shows what seems to be a pump running. Finally, Figure 3.d shows an unknow punctual event. The high amplitude at 60Hz and the multiples are typical electrical noise in North America. Current work is to implement machine learning methods on the continuous seismic dataset. Supervised machine learning through template matching for example can help us to quickly classify the continuous seismic signal. Next step would be to test unsupervised machine learning on the continuous data.

Conclusions

We explore different ways to exploit the continuous seismic signal we recorded at the CaMI FRS. First one is studying directly the records and detect any preexisting or induced events. The Field Research Station does not show any background micro seismicity on the broadband stations array. We use the STA/LTA method on a 10-stations array close to the injector well (maximum offset of 21m) to detect micro events during the recording period while injection tests were performed. No clear correlation between increase in micro event detection and injection can be concluded. Further study using match field processing may be envisaged as it allows the detection of very-low amplitude events.

We obtain the ambient noise cross correlations for a 100 stations survey acquired prior to CO_2 injection. The correlation shows good stability over the 14 days of recording. The very weak velocity changes are probably due to environmental changes conditions (wind, temperature…). We are confident that elastic changes of the subsurface due to CO_2 injection should be detectable trough ambient noise correlation monitoring. In term of subsurface image, it is known that the ambient noise correlation results do not yet reach the resolution of active surveys. Nevertheless, the easy deployment, low cost and low environmental impact make

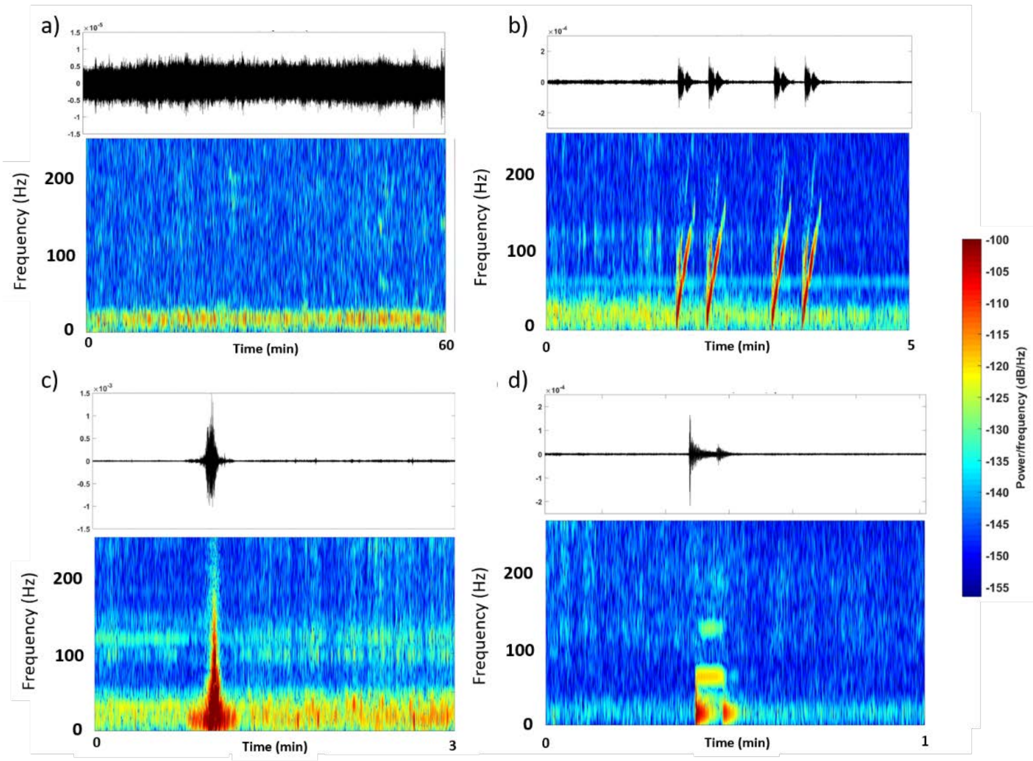


Figure 3: Example of continous seismic signasl and corresponding spectrograms. a) 1hour of noise. b) 5min including 4 vibe shots. c) 3min including a pump triggering. d) 1min still-need to de determined spunctual event.

this method an interesting one for monitoring CO_2 injection and storage. The new interest for machine learning should also bring new developments on the use of continuous seismic signal.

Acknowledgments

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