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Evaluation of Distributed Acoustic Sensing for 3D Time-lapse VSP Monitoring of the Aquistore CO_2 Storage Site

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Summary

Distributed acoustic sensing (DAS) has the potential to provide a cost-effecient, high-resolution alternative to traditional downhole geophone methods for vertical seismic profiling (VSP). This study undertakes a comparison of seismic data and images obtained during a baseline DAS and traditional geophone VSP survey at the Aquistore CO_2 geological storage site near Estevan, Saskatchewan. Previous studies have evaluated DAS alongside geophones in 2D VSP walk-away surveys, whereas the Aquistore project aims to conduct 3D time-lapse monitoring of stored CO_2 at a depth of 3200 m. The baseline survey results indicate that the reservoir can be located with elementary imaging methods using the DAS data.

Introduction

The Aquistore CO_2 storage site is part of a carbon capture and storage (CCS) project where captured CO_2 will be stored in a deep saline aquifer in the Williston Basin. The CO_2 is captured from SaskPower's Boundary Dam Power Station and is transported via pipeline to an injection well at the storage site.

The Williston Basin is ideal for CO_2 storage due to its abundance of depleted petroleum reservoirs, saline formations, and coal seams. The thickness of the basin at the Aquistore site is approximately 3000 m, and is made up of Paleozoic carbonates and evaporites, and Mesozoic sandstones and shales. Immediately overlying the Precambrian basement rocks are the shales and porous sandstones of the Winnipeg-Deadwood formations. The Deadwood and the lower Winnipeg formations form the target reservoir for CO_2 injection and storage. Together, they constitute a deep saline aquifer system approximately 150 m thick that is overlain by the Icebox shale, the principal sealing unit. Drill core analyses have been performed extensively on the aquifer and it has been shown to have suitable injectivity potential, with regional permeabilities of ~100-1000 mD and porosities of ~11-17 % (Whittaker and Worth, 2011).

An injection well and an observation well have been drilled 150 m apart from each other at the storage site. At several times over the course of the project, a 57-level geophone wireline will be deployed down the observation well to perform VSP surveys. Single mode and multimode optical fiber cables were installed permanently behind casing in each of the wells although only the fiber cable in the observation well was ultimately operational.

The practicality of using fiber optic cables for seismic surveying (particularly in geophysical surveillance and in-well monitoring) has greatly improved in recent years as the need for discrete point sensors has been removed by using the fiber itself as the sensor; i.e., DAS. This allows the fiber to be employed as a continuous array of sensors, and is the principle behind DAS. Unlike discrete sensor systems, DAS does not require manufactured sensors, nor does it require multiple fibers or optical multiplexing (Miller, 2012). In DAS, strain on the fiber induced by seismic waves results in variations in optical backscatter locally. This requires that the fiber is coupled in some way (via friction or pressure) with the surrounding acoustic field to generate longitudinal strain on the fiber. The amplitude and timing of the detected variation in optical backscatter can be related back to the seismically induced strain, and can thus be utilized as a distributed acoustic array capable of recording thousands of channels (Miller, 2012; Mestayer, 2011). Nearly any optical cable can be used as a distributed array acoustic sensor, and can remain installed in a down-hole environment for years (Mestayer, 2011). The DAS technology offers a reduced cost alternative to the traditional geophone methods, as each subsequent survey will require only new seismic sources and equipment, while temporary deployment of geophones downhole via wireline can be very costly.

Objective and Method

Time-lapse monitoring at the Aquistore CO_2 storage site will be conducted by performing a series of 3D VSPs. A pre-injection baseline VSP was acquired in November 2013 and will be followed-up by monitoring surveys performed throughout the CO_2 injection schedule.

For the initial baseline 3D VSP, data were acquired simultaneously using both the DAS and wireline geophone array. This allows a direct comparison of VSP results from the two systems. A total of 670 source locations were occupied on a semi-regular 3000 x 3000 m grid, centered on the observation well, with in-line and inter-line spacings of 72 m and 144 m, respectively. Each source consisted of a single 1 kg dynamite charge detonated at a depth of 15 m. The downhole wireline consisted of 57 three-component geophones deployed with a vertical spacing of 15 m, and centered at a depth of 1900 m. The geophones are analogue electro-mechanical sensors that measure ground velocity, and were installed in a Sercel Maxiwave tool, which was clamped in the observation well. The geophones have a resonant frequency of 15 Hz, and an output of 0.402 V/cm/s at 0.47% damping. The single-mode fiber in the observation well was used for the comparisons in this study. The deep end of the fiber was damaged during installation, and the optical time-domain reflectometry report shows it is functional from the surface to a depth of 2766 m. The raw optical data from the fiber was processed to emulate a sensor spacing of 2 m, resulting in 1383 traces per shot.

Similar processing flows are used for each shot gather acquired using both DAS and traditional geophones, such that controlled comparisons could be made at various stages of analysis. In general, the processing flow includes the following steps: trace balancing, spherical divergence correction, notch and low-pass filtering, and f-k filtering of the downgoing wavefield. A common depth point transformation (CDP) program that employs the algorithm developed by Dillon and Thomson (1984) was written to create an image of the subsurface based on the upgoing wavefield and a 1D velocity model. In this program, a 2D grid of bins is used to represent the subsurface. Rays are traced assuming each depth grid interval is a reflecting surface, and travel times of these rays are referenced to the processed traces, and then amplitudes in the trace are added to their appropriate spatial bins. Bins located where actual reflectors exist will accrue large amplitudes, while non-reflective bins will not. Multiple gathers are then stacked to build coherent images. In this work, the velocity model was based on the sonic log from the observation well, and first arrivals in the zero-offset shot.

Results

The November 2013 VSP survey yielded 670 DAS and geophone shot gathers. DAS data were acquired with the Silixa iDAS system and pre-processing of the DAS data was performed by Silixa LTD. An example of a shot gather for both the wireline geophone data and the DAS data is presented in Figure 1. For purposes of comparison, the DAS gather is overlain by the geophone traces over the depth range of 1455 – 2295 m, thus there are 963 single-mode DAS traces and 57 vertical-component geophone traces plotted. Of the 57 geophones deployed, 3 did not record and thus yielded dead traces. In these images, the geophone data clearly exhibits a greater signal-to-noise ratio, and in fact has a signal frequency bandwidth approximately 2 times wider than the DAS signal (5-150 Hz vs 7-70 Hz) between 1455 – 2295 m. However, the DAS signal-to-noise ratio can be greatly improved upon with noise suppression techniques and by averaging over larger cable lengths such as the 15 m used in geophone data (Daley et al, 2014a 2014b),(Cocker et al 2014). In the geophone data, many primary reflections are clearly visible throughout this depth range of the wireline, as well as their multiples, while many of the corresponding reflections are buried within the noise in the DAS data.

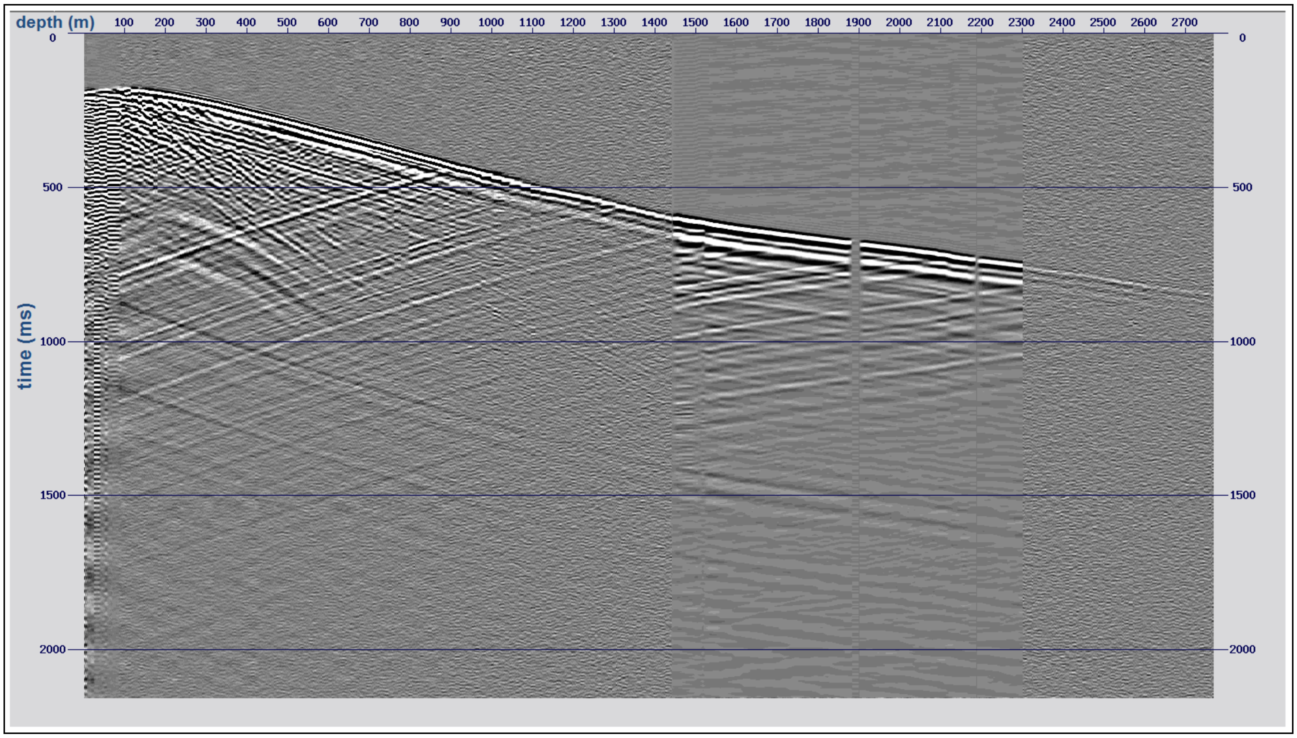

Figure 1: Raw single-mode DAS and vertical-component geophone zero-offset gathers. The geophone traces are overlain onto the DAS in the depth range of 1455 – 2295 m. Trace balancing has been applied to each image, such that the average power of each trace is constant.

Figure 2 shows a comparison of images of a 2D East-West section produced from single-mode DAS, vertical-component geophone, and surface data. The DAS and geophone images were computed using the CDP transform program described previously, using the upgoing wavefields from 8 shot gathers located to the west of the observation well. The reflections in the VSP images align well with those of the surface image, with maximum deviations of ~40 m visible in the deeper reflections. It is likely that further refinement of the velocity model will correct these deviations. Though geological boundaries are not as well defined in these VSP images compared to the surface image, clarity is expected to improve with the inclusion of more shots in the stacks.

Though the DAS and geophone images comprise the same shots, it should be noted that 11064 (8x1383) traces were transformed to create the DAS image, while only 424 (8x53) were transformed to create the geophone image. For this reason, the DAS image has a substantially higher resolution than the geophone image while also spanning a greater depth range. Though the geophone data exhibit a higher trace-by-trace signal-to-noise ratio when compared to the DAS, it is anticipated that this can be compensated by the extensive amount of traces available through DAS.

Conclusions and Future Work

Based on the results of the baseline VSP survey performed in November 2013, the DAS data appears to be of adequate quality for subsurface imaging for depths down to ~1000 m using low-fold stacking and elementary imaging techniques, while geology is still identifiable beyond a depth of 3000 m. It is anticipated that the reservoir zone will be better resolved as more shot gathers are incorporated into the images, and more sophisticated migration algorithms are applied to the data. Due to the vast amounts of data associated with DAS, a more advanced CDP transform algorithm must be developed to obtain 3D images. This algorithm will abandon the traditional raytracing techniques in favour of the more computationally efficient eikonal equation method (Hole and Zelt, 1995; Vidale, 1990).

Though the traditional geophones still appear to produce a higher signal-to-noise ratio than the DAS in the raw traces, the DAS has the advantage of simulating thousands of geophones within one optical fiber. This provides the means to produce images of a significantly higher spatial resolution and volume than with the traditional geophones, at a comparitively low cost. At future stages of processing and imaging, comparisons will continue to be made with the surface seismic results to evaluate the assumption that VSP will provide better resolution at the reservoir depth.

VSP surveys will continue as CO_2 injection progresses at the Aquistore site, and DAS results will be compared to predictions from fluid replacement modeling to estimate the volume and location of the CO_2 plume over time.

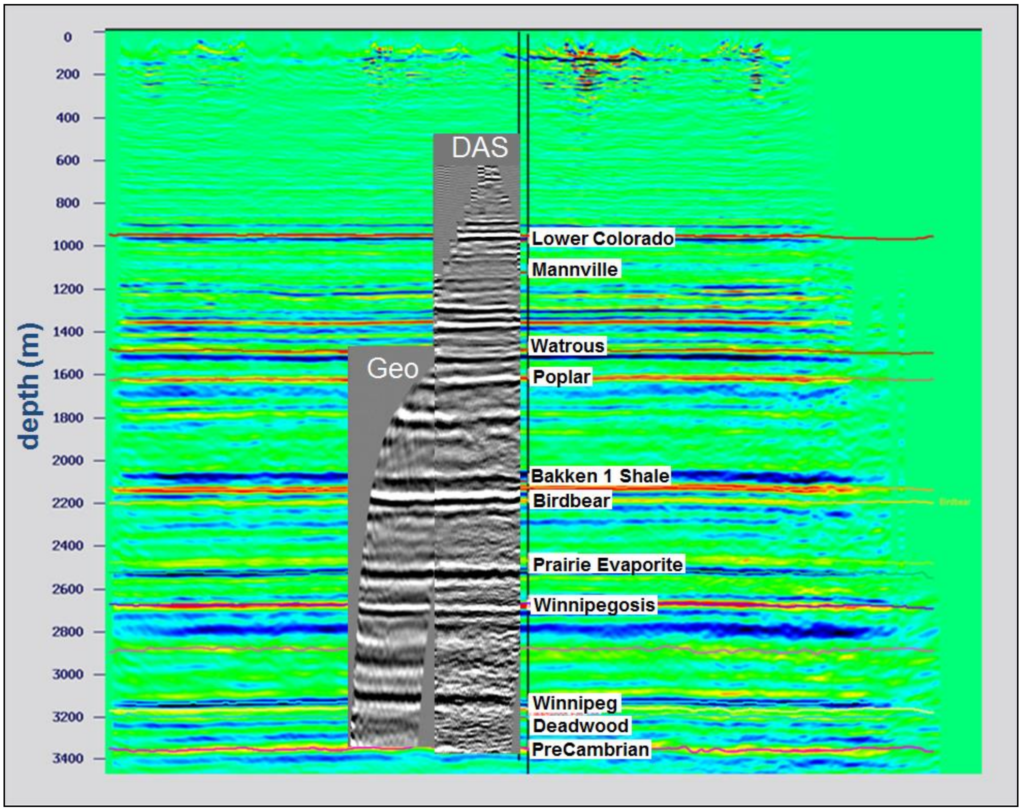

Figure 2: 8-fold CDP transforms of the single-mode DAS and vertical-component geophone VSP data (greyscale) with migrated section of surface data (blue/red) along an East-West line. Locations of various geological formations are labelled in the center of the image.

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