3D VERTICAL SEISMIC PROFILING ACQUIRED USING FIBRE-OPTIC SENSING DAS – RESULTS FROM THE CO2CRC OTWAY PROJECT

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SUMMARY

Distributed Acoustic Sensing (DAS) is an optical interferometric method for acquisition of acoustic and seismic signals. It uses laser pulses that travel along the length of a fibre-optic cable and backscatter as they encounter small inconsistencies in the fibre. Impinging seismic waves cause strain on the cable, resulting in differences in phase of the backscattered light. Interest in DAS has increased significantly in the past decade as it is particularly suited for VSP acquisitions, including for permanent reservoir monitoring. Fibre-optic cables can be installed permanently in the well, cemented behind the casing or attached to tubing; they offer a relatively cheaper and efficient solution when compared to conventional borehole sensors.

This study is part of the CO2CRC Otway Project. The Otway Project site is located approximately 240 km south-west of Melbourne, Australia. The Stage 2C of the project aims to monitor a small injection (15 kt) of CO_2/CH_4 gas mixture at a depth of approximately 1500 m. Here, we show the results of a 3D VSP survey acquired using DAS cable deployed on production tubing in the injector well.

The DAS up-going wavefield shows a high level of noise. However, DAS is able to record the main reflections, including at the injection depth. After 3D migration of the data, noise levels reduce significantly. Events on DAS inline match with events on a corridor stack produced from a geophone check-shot data. Due to the directionality pattern, DAS was only able to image up to approximately 300 m radius from the well.

Key words: Distributed Acoustic Sensing; Vertical Seismic Profiling; 3D VSP; fibre-optics sensing.

INTRODUCTION

Distributed Acoustic Sensing (DAS) is a fibre-optic sensing technique that detects the acoustic signal along a fibre-optic cable. One of the main advantages in the use of DAS is that it can measure thousands of sections along the fibre at the same time, delivering seismic records almost instantaneously. DAS has been extensively studied in the past decade as it is especially suited to Vertical Seismic Profiling (VSP), potentially revolutionizing how such acquisitions are done.

3D VSP surveys can aid in assessing the risk of a field development, especially when complex structures in the area limit the results of surface seismic. Conventional VSP surveys can take an extensive amount of time as the acquisition is limited to the number of point receivers deployed in the well. The rig time needed for repeatedly moving receiver arrays can result in costly surveys. In contrast, DAS acquires the entire length of the fibre simultaneously and can easily be installed permanently in the well. As a result, DAS can significantly reduce time, and thus cost, of VSP acquisitions (Mateeva et al. 2013).

DAS works similarly to an OTDR (Optical Time Domain Reflectometer), commonly used in telecommunications to measure optical loss along the length of a fibre, but provides phase information of backscattered light. It generates a range of distributed sensors that detect perturbations along a section of the cable. The interrogator unit sends a series of laser pulses along the fibre. Through Rayleigh scattering, a portion of the light is reflected due to variations in the refraction index. DAS thus records the backscattered light, with changes in the natural properties of the backscaterred light attributed to microbends on the cable as a result of the impingment of acoustic waves (Parker et al. 2014).

A 3D VSP survey was acquired using DAS at the CO2CRC Otway Project site. The Otway Project is Australia's first demonstration of injection and storage of carbon dioxide (Jenkins et al. 2012) in subsurface. The Otway Project site is located in southwest Victoria, Australia; its primary objective is to demonstrate the safe and effective storage of CO_2 in the subsurface as a way to mitigate climate change. The current stage of the project, Stage 2C, uses seismic methods to monitor the injection of 15 kt of CO_2/methane gas at a depth of approximately 1500 m, and resolve the evolution of the subsequent gas plume. We consider repeat 3D VSP surveys as a potential cost-effective alternative for 3D surface reflection surveys. Here, we assess the performance of a 3D VSP survey acquired with DAS. We aim to produce a 3D image using the DAS VSP data, and assess the quality and possible use of DAS for future 3D VSP applications.

SEISMIC MONITORING ARRAY IN THE OTWAY PROJECT AND DAS VSP ACQUISITION

The Stage 2C seismic surveys used a permanently installed array of surface sensors. The array consists of 908 buried geophones deployed along 11 receiver lines (Figure 1). Approximately 40 km of fibre-optic cable was installed continuously;and covers the entire length of CRC-2 well, as well as the surface lines, where it is buried together with the geophones. The fibres installed on-site are standard single-mode fibres. The fibre cable is installed in the tubing in CRC-2 well. DAS 3D VSP was acquired with 1 m spatial interval.

The CRC-2 well was used for the injection of the CO2/methane gas mixture (Figure 1). Four seismic surveys were conducted after the initial gas injection. The first monitoring survey was acquired after the injection of 5 kt of gas mixture. The second and the third after the injection of 10 kt and 15 kt, respectively. The fourth monitoring survey was acquired in the beginning of 2017. For each survey, we acquired 3D surface seismic with both geophone and DAS; 3D VSP with geophones in CRC-1 well, and with DAS in CRC-2 well; and offset VSP surveys also with geophones and DAS.

A check-shot was previously acquired in CRC-2 well using a conventional borehole geophone tool with 15 m spatial interval, so a comparison can be established between both types of receivers. The source used was a 26000 lb vibroseis, with sweep from 6 to 150 Hz. In total, 3003 shots were acquired in the area with 15 m source spacing.

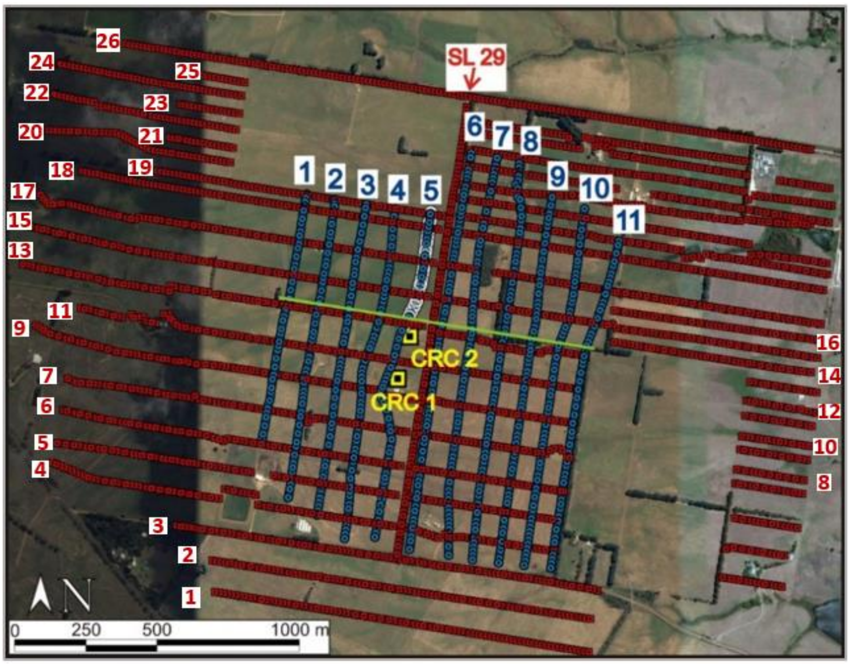

Figure 1: 3D survey design at the Otway site. Buried geophones and fibre-optic cable are deployed along eleven surface lines (blue). In total, 3003 shot points acquired (red). DAS 3DVSP was acquired in CRC-2 well.

IMAGING WITH DAS VSP

While DAS offers the benefits of high spatial resolution with broad areal coverage, it has a signal-to-noise ratio that lags behind conventional geophones. While much of the noise is Gaussian and can be reduced through stacking, certain sections of the fibre can yield noisy channels. The installation of the fibre cable can highly dictate on the quality of the final dataset. By improving the contact with the formation, limiting acoustic impedance contrast with surrounding materials the overall sensitivity of DAS can be increased. For borehole installations, signal-to-noise can be significantly improved by cementing the DAS cable behind the well casing (Correa et al. 2017).

DAS VSP data acquired in CRC-2 well presents a high level of noise (Figure 2). The poor quality of the shot records is mostly attributed to installation of the fibre cable strapped onto the tubing, which leads to low coupling and a less sensitive system. Down-going and up-going PP reflections can be hardly identified on the raw records (Figure 2 a, b, and c). The data contains strong random noise, which increases as the source distances from the well. Certain sections of depth, especially at 600 m and 1150 m depth, present strong linear noise, possibly as a result of correlation with the sweep and spikes present in the data. Datasets also show strong tube wave noise.

As a first processing step, we convert DAS data from its native format of strain-rate, into a geophone equivalent local particle velocity. For this, we integrate DAS along time to obtain the strain along the cable. To attenuate low and high frequency noise, the DAS data was bandpass filtered from 5 to 100 Hz. A 2D alpha-trimmed mean filter was applied in order to attenuate tube wave noise present in the raw data. The up-going wavefield was separated and additional noise attenuation and spectral sharpening was applied to filter remaining noise and enhance reflections. As a result, up-going reflections can be identified, though characterized as mainly low frequency (Figure 2d, e, and f). Strong reflections can be identified mainly at depths 900 m, 1150 m, and 1500 m, being the last coinciding with injection depth.

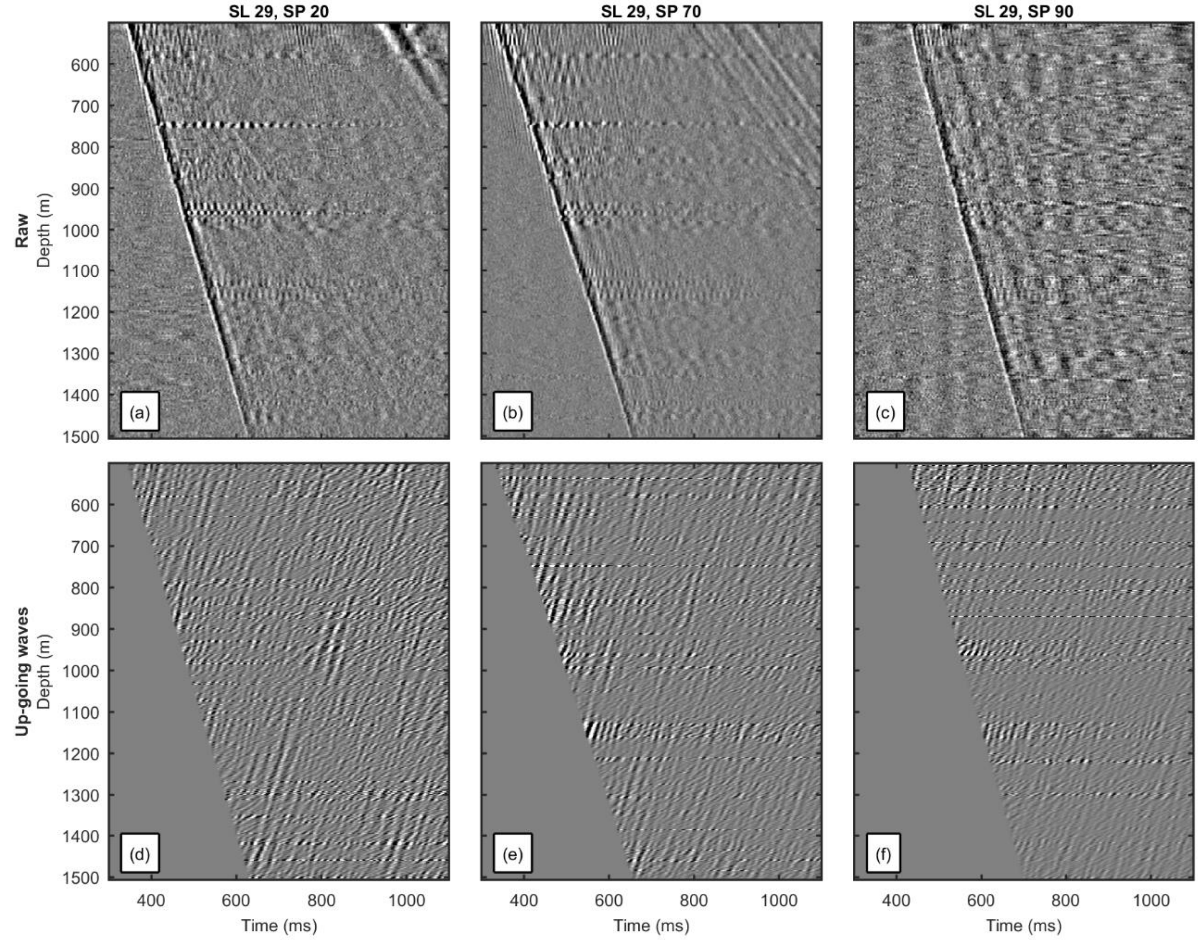

Figure 2: VSP acquired with DAS on source line 29 (SL29). First rows shows DAS data after pre-processing at shot point 20 (a), shot point 70 (b), and shot point 90 (c); second row shows DAS data after wavefield separation at shot point 20 (d), shot point 70 (e), and shot point 90 (f).

The up-going wavefield data was migrated in 3D, with 7.5 m bin size, yielding 219 inlines, and 265 crosslines. The migration was set to image from 760 to 2400 m depth, in order to reduce running time while incorporating the target area. Figure 3 shows the DAS migrated cube, displaying a crossline, an inline, and a time slice at approximate the injection interval. The migrated cube shows that DAS was able to image the main reflections, despite the low quality of the individual shot records. The reflections are strong close to the well, however they rapidly decay in amplitude with increasing distance from the well.

Figure 4 shows an inline after 3D migration of DAS data, a corridor stack produced from check-shot acquired with geophones, and geophone check-shot data after NMO correction. The displayed DAS inline coincides with CRC-2 well location. Only half of the inline is shown for comparison purposes. Reflections on DAS inline (Figure 4a) present a good match to reflections present on the geophone corridor stack (Figure 4b). DAS is able to image the main strong events, as seen at 850, 900, 1200, 1400, 1600 ms. DAS data presents lower sensitivity to higher frequencies, resulting in lower resolution than the geophone data, with reflections being mostly low frequency. Reflection at 1250 ms, seen on both DAS and geophone, correspond to the injection location.

Although data before migration presented a low signal-to-noise ratio, after migration noise reduced considerably. This shows that the stacking performed by migration allows destructive interference of noise, greatly increasing the quality of the DAS data. The DAS image shows the characteristic VSP cone-like illumination pattern around the well location out to a radius of approximately 300 m. This is attributed to the directionality pattern of DAS data, as DAS signal decreases approximately as cosine squared of the angle of incidence (Kuvshinov, 2015).

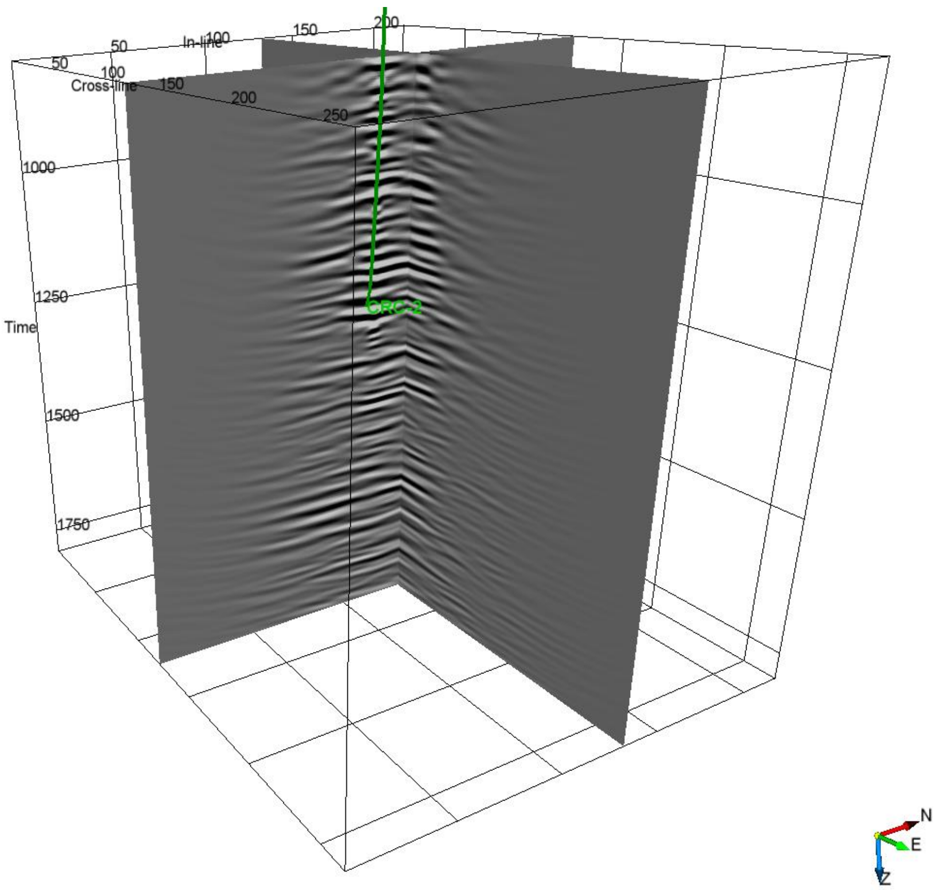

Figure 3: Migrated DAS 3D VSP seismic cube. CRC-2 well path showing in green.

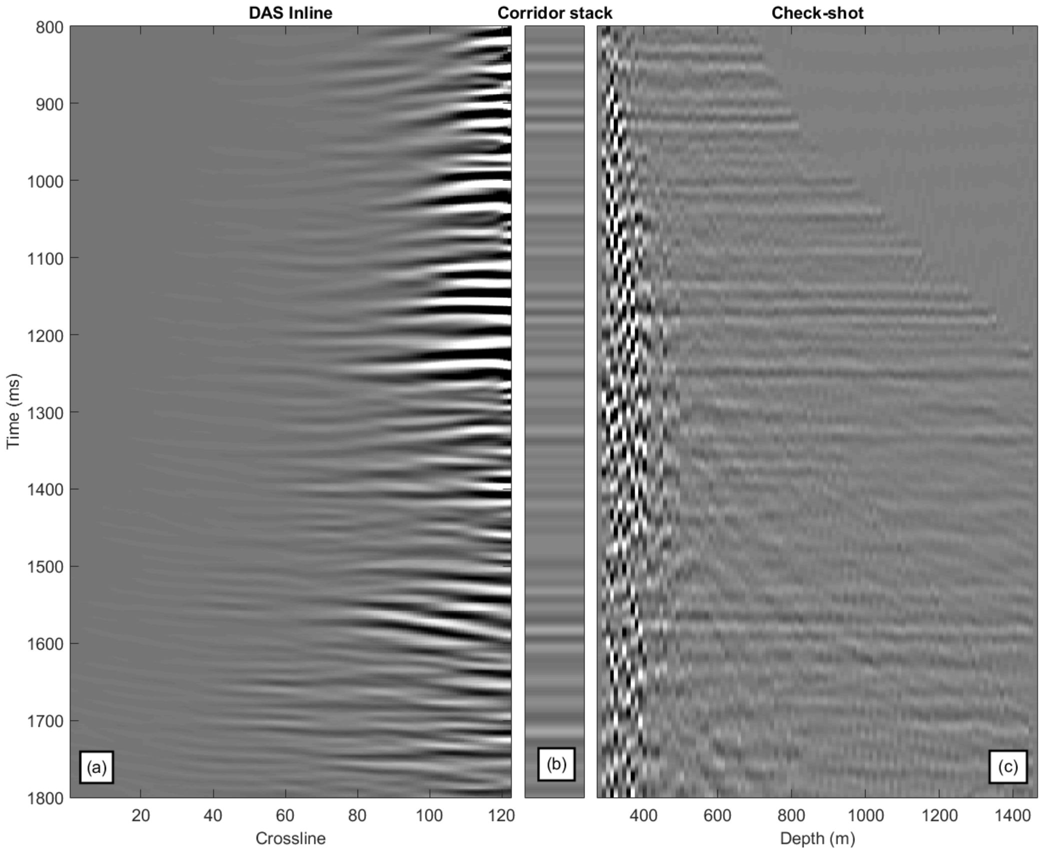

Figure 4: DAS 3D VSP migrated inline (a); corridor stack of geophones (b); check-shot VSP of geophones at CRC-2 (c).

CONCLUSIONS

A 3D VSP data was acquired with fibre-optics DAS, with a cable deployed strapped onto the tubing of the CRC-2 well. Shots recorded by DAS show considerable noise and low sensitivity. This is mostly attributed to the poor coupling caused by the installation of the fibre cable on the well tubing. After wavefield separation, up-going wave reflections can be identified, although mostly low frequency. DAS was successful in recording reflections from the injection depth.

We apply 3D Kirchoff migration to obtain the final volume. The migration routine decreases the noise level significantly. This shows that, due to the Gaussian noise characteristic of DAS, migration and vertical stacking procedures applied to DAS data can significantly increase signal-to-noise ratio. Due to the directionality pattern, in conjunction with the relatively high ambient noise level, DAS 3D VSP has a short range of illumination.

Despite these issues, we show that 3D VSP survey acquired with a tubing conveyed DAS cable and single sweep per vibration point was still sufficient to image the reflectors up to ~2 km depth.

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