Time-lapse surface seismic processing for Stage 2C of CO2CRC Otway Project

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SUMMARY

Stage 2C of the Otway project aims to detect a small injection of CO_2-rich mixture into a saline aquifer, verify stabilisation of the injection and evaluate the detectability threshold of CO_2 achievable by surface seismic. Over the past three years, we have produced five vintages of high-quality 4D seismic data showing the evolution of the 15,000 tonnes of injected $scCO_2/CH_4$ gas mixture into the saline aquifer at 1500 m depth. The time-lapse seismic processing workflow was built based on the findings from a synthetic feasibility study and processing of the baseline dataset. Through this workflow we processed the time-lapse data which allowed monitoring of small incremental injections (about 5 000 tonnes each). Here we elaborate on effect of various processing routines on the quality of 4D image, namely, amplitude restoration, prestack cross-equalization and imaging. We aim at preservation and restoration of time-lapse signal and suppression of time-lapse noise. We evaluate the results of the processing efforts in post-stack domain through estimates of 4D signal-to-noise ratio in vicinity of the injection interval. The usefulness of individual processing routines for improvement of time-lapse signal cannot be established independently from other routines in the same workflow. Surprisingly, images with pre-stack AGC applied have consistently higher time-lapse signal-to-noise ratio compared to images produced without it. Improvement of the resolution and appearance of 3D images does not guarantee increase of time-lapse signal-to-noise ratio.

Key words: 4D seismic processing, CO_2 geosequestration, seismic monitoring, cross-equalization, AGC.

INTRODUCTION

Time-lapse processing of onshore seismic data is a challenging task due to prominent time-lapse noise. This non-repeatability partly comes from temporal variations of near-surface conditions and ambient noise. Time-lapse (4D) noise manifests on seismic records as poorly repeatable ground roll as well as signature variations of reflections due to changes of source and receiver coupling. Although, to some extent, 4D noise can be accounted for in a time-lapse processing workflow, it is crucial to ensure that every effort is made to enhance repeatability at the acquisition stage of a monitoring and verification (M&V) programme. Seismic M&V programme for the Stage 2C of Otway project was designed to fight non-repeatable noise at the time of acquisition. A permanent geophone array buried at 4 m depth allowed reducing ambient noise level compared to the surface geophones and improving repeatability of ground roll (Shulakova, et al. 2014). The issue of source coupling was addressed through the use of identical seismic sources with identical sweeps. Vibroseis trucks were positioned at the shot points using differential GPS that ensured low positioning errors. About 3000 shot locations (shot spacing of 15 m) were shot along 27 source lines. The permanent receiver spread consisted of about 900 geophones (geophone spacing of 15 m) positioned along 11 receiver lines (Figure 1).

The field data acquired so far for the M&V of the Stage 2C comprise a baseline survey acquired prior to injection and then 4 monitor surveys acquired during and after the injection. We processed each vintage through the same workflow that included elevation statics, ground roll suppression, spiking deconvolution, automatic gain control (AGC), residual statics, NMO, stretch muting, stacking, FXY deconvolution, and finite-difference post-stack time migration. The last step in the workflow was CDP-consistent time-shifts that were estimated between the baseline image and each monitor image and then applied to better align the vintage images before subtraction. We applied AGC to weaken the high energy remnants of ground roll before stacking and compensate for energy decay. The obtained time-lapse images of the plume exhibit high signal-to-noise ratio and low NRMS values in the signal-free area of high fold. The images allow tracking plume evolution during an about 15 kt CO_2-rich mixture injected into a saline aquifer at a depth of about 1500 m (Pevzner, et al. 2017).

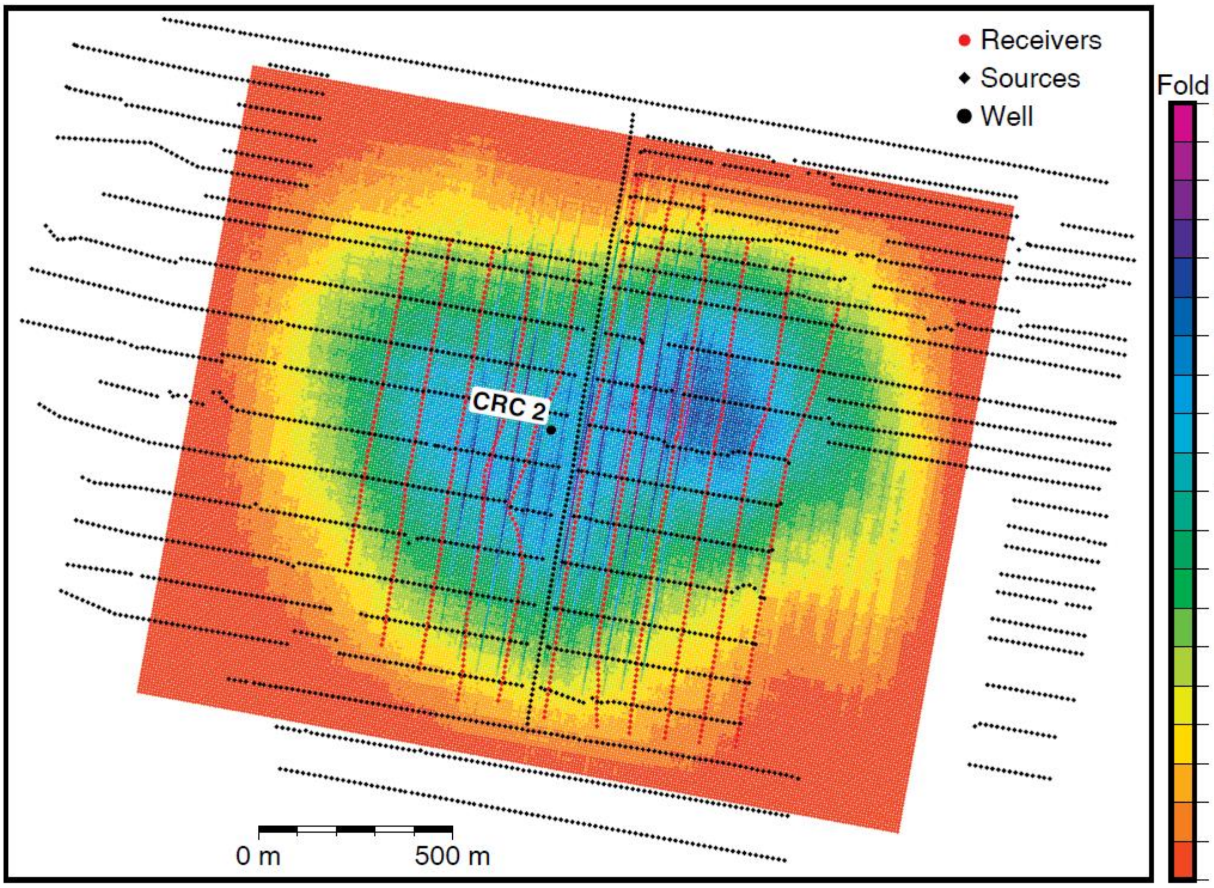

Figure 1 Map showing acquisition geometry and CMP fold for the surface seismic programme of Stage 2C of the project.

We further investigate effects of processing routines on time-lapse signal and noise. We shift our focus from the express processing of time-lapse seismic to the case when amplitude restoration and better imaging become of prime importance. On one hand, we check robustness of our express processing workflow to the changes in processing parameters and routines. On the other hand, we enrich our workflow with the routines that should bring our images closer to “true amplitude” ones. The objective is still stacked migrated volumes so we assess our processing efforts on the stacked data through estimates of 4D signal-to-noise ratio in vicinity of the injection interval. This study uses the baseline dataset and the, so called, monitor 3 dataset acquired straight after the end of injection so we expect highest possible time-lapse signal for this pair of vintages. These two vintages have been acquired during the same period of the year (March 2015 and 2016) and require minimal cross-equalization effort.

TIME-LAPSE DATA PROCESSING

The essential elements of a processing workflow for reflection seismic data are suppression of noise, deconvolution, amplitude decay compensation, and positioning of reflectors. Another element necessary for 4D seismic is cross-equalization which targets 4D noise present. This study focuses on the influence of the effect of processing routines on 4D signal and does not include results of testing of the cross-equalization approaches. Table 1 compares the express processing workflow used in Pevzner et al., 2017 and the final workflow to date. Below we describe key differences between the two.

Elevation ranges from 12 to 58 meters above the mean sea level within the survey area, which suggests that processing on a flat datum is appropriate for the target depth of ~1500 m. Elevation static corrections are estimated using replacement velocity of 1800 m/s and datum level of 30 m above the sea level.

Two iterations of velocity analysis and two iterations of residual surface-consistent static estimations yield to the velocity model and residual static corrections that are used in all the workflows for the both vintages. To cross-equalize the datasets we apply CDP-consistent time shifts estimated on final images before subtraction of the monitor 3 image from the baseline image. We then investigate the influence of various processing routines and parameters for noise-suppression, cross-equalization, amplitude restoration, and imaging to explore how we can improve the time-lapse signal from the injection.

Table 1 Time lapse data processing flows

Initial workflow	Final workflow to date
CMP binning with bin size 7.5 x 7.5 m	
Elevation statics to final datum of 30 m with replacement velocity of 1800 m/s	
Linear Radon filter and surface wave noise attenuation. AGC in 500 ms window is applied before and removed after ground roll suppression.	Singular value decomposition and adaptive subtraction of ground roll.
Zero-phase spiking deconvolution, 160 ms filter length, 0.1% white noise. AGC in 500 ms window is applied before and removed after deconvolution.	Amplitude correction using $(t*Vrms(t)^2)$ function followed by Surface-consistent spiking deconvolution with individual filters for different vintages, 110 ms filter length, 0.1% white noise.
	Ormsby bandpass zero-phase filter, 5-8-130-145 Hz
Two iterations of residual surface-consistent statics	Two iterations of residual surface-consistent statics
Automatic gain control in 500 ms window	Automatic gain control in 500 ms window
Normal moveout correction with 30 % stretch muting	3D Kirchhoff prestack time migration, Two-sided aperture of 1400 m at the target interval of 1200 ms
Ormsby bandpass zero-phase filter, 6-10-110-140 Hz	
	Manual top mute and FK filtering of common image gathers
Stacking, power for stack normalization – 0.5	Stacking, power for stack normalization – 0.5
FXY deconvolution, spatial size of operator 7 x 7 traces, 600 ms operator length	FXY deconvolution, spatial size of operator 7 x 7 traces, 600 ms operator length
FK filtering to suppress steeply dipping artefacts.	FK filtering to suppress steeply dipping artefacts.
3D explicit finite-difference post-stack time migration – aperture 50 degrees	

Ground roll suppression is a challenge in time-lapse seismic processing as it has high energy and poor repeatability, it contaminates the final processing results. Thus, ground roll should be suppressed as much as possible separately in each data vintage. Our initial approach was to employ the linear Radon filtering followed by spectral mixing in the source domain. After further testing we substituted that ground roll suppression method with the one based on singular value decomposition for ground roll estimation followed by adaptive subtraction of ground roll from the original shot gathers (Franco and Musacchio 2001). Figure 2 illustrates the ground removal.

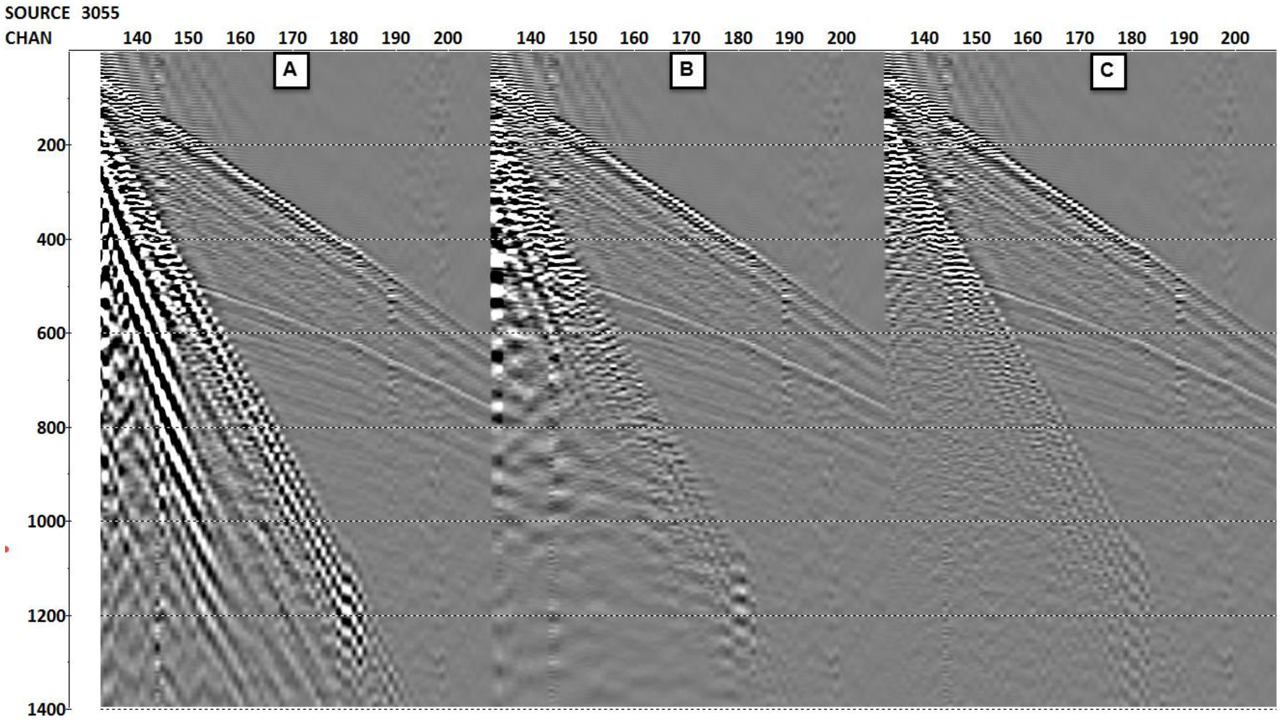

Figure 2. Testing of ground roll removal. A – one receiver line of a shot gather before ground roll suppression; B – same gather after linear Radon filter and surface wave noise attenuation; C – same gather after singular value decomposition and adaptive subtraction of ground roll.

We compare individual-trace spiking deconvolution to spiking surface-consistent deconvolution (SCD). The SCD using a single set of filters obtained from baseline data was applied to both vintages as well as using individual set of filters estimated and applied to each data vintage separately. SCD with individual filters turns out to be valuable for time-lapse processing as it works as a cross-equalization tool and suppresses time-lapse noise. CDP-consistent time shifts estimated between the baseline and monitor images with SCD are smaller than the time shifts estimated for the images with individual trace-by-trace deconvolution.

Our approach to amplitude restoration for express processing relies on a large window (500 ms) automatic gain control (AGC) applied prior to CDP stacking in case of post-stack imaging and prior to migration in case of pre-stack imaging. This routine compensates for amplitude decay but also sensitive to strong noise events which might be present along a trace. In all our experiments data with AGC applied before stacking exhibit higher 4D signal-to-noise ratio than the data without AGC. However, application of AGC in a workflow is controversial. Our modelling study shows that AGC for high-fold dataset such as the one under consideration can preserve spatial distribution of reflectivity change in stacked domain (Glubokovskikh, et al. 2016) while AGC will distort AVO response in the presence of strong remnants of the ground roll present on small offsets. As the goal is to obtain stacked migrated volumes we keep AGC in the workflow.

Post-stack explicit finite-difference time migration was used to produce the express processing results. Although the geology of CO2CRC Otway site is relatively simple, a few faults present near the injection interval might require pre-stack imaging. We use pre-stack Kirchhoff time migration (Figure 3, right). These images have better spatial resolution and imaging of the deeper events compared to the post-stack migrated ones. Our study shows that time-lapse signal strongly depends on the parameters of the pre-stack migration like aperture and stack scaling.

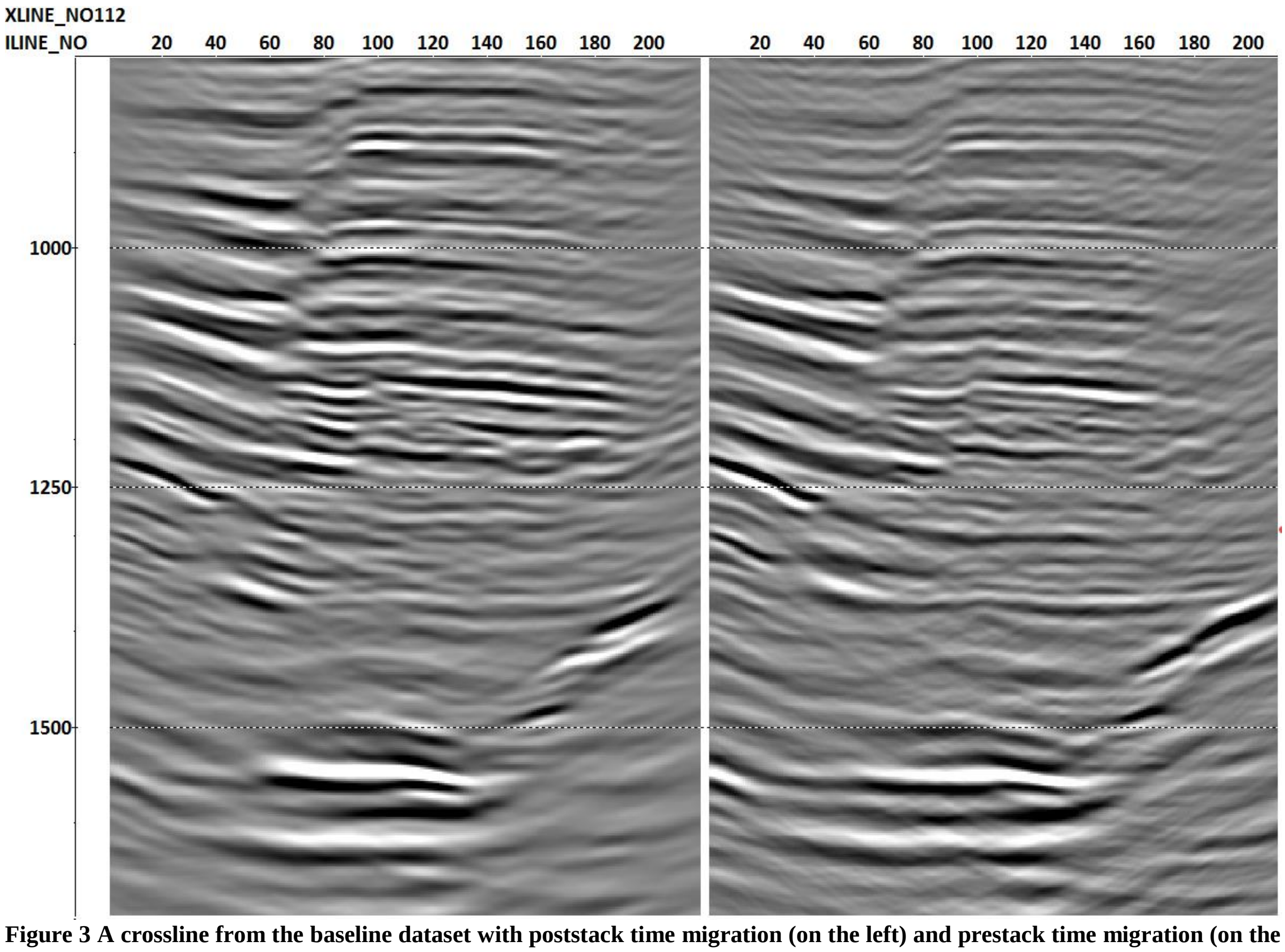

Figure 3 A crossline from the baseline dataset with poststack time migration (on the left) and prestack time migration (on the right). Prestack imaging improves imaging of deeper structures while distorting shallower reflections.

4D IMAGING RESULTS

Figure 4 shows the image of the plume for the express processing workflow (Table 1, left column). Figure 5 shows the image of the plume for the final workflow (Table 1, right column). To produce these figures baseline images are subtracted from the monitor ones and then RMS amplitudes are computed in 24 ms window centred at the injection interval of about 1210 ms. These RMS maps are then divided by the mode noise amplitude of the same RMS slice which then gives an estimate of 4D signal-to-noise ratio (SNR) for the area containing time-lapse signal, corresponding to the $scCO_2/CH_4$ plume in this case. Numbers indicated in the top right of each figure characterise maximum of time-lapse signal-to-noise ratio for each map.

The general trends and features of the plume are similar for both images. The apparent position of the plume on the images produced by the two migration routines appear to be slightly offset from each other. We observe overall improvement of the image sharpness for the new workflow which allow to define plume boundary better. On the other hand, the peak signal-to-noise ratio appears to be higher for the express processing workflow.

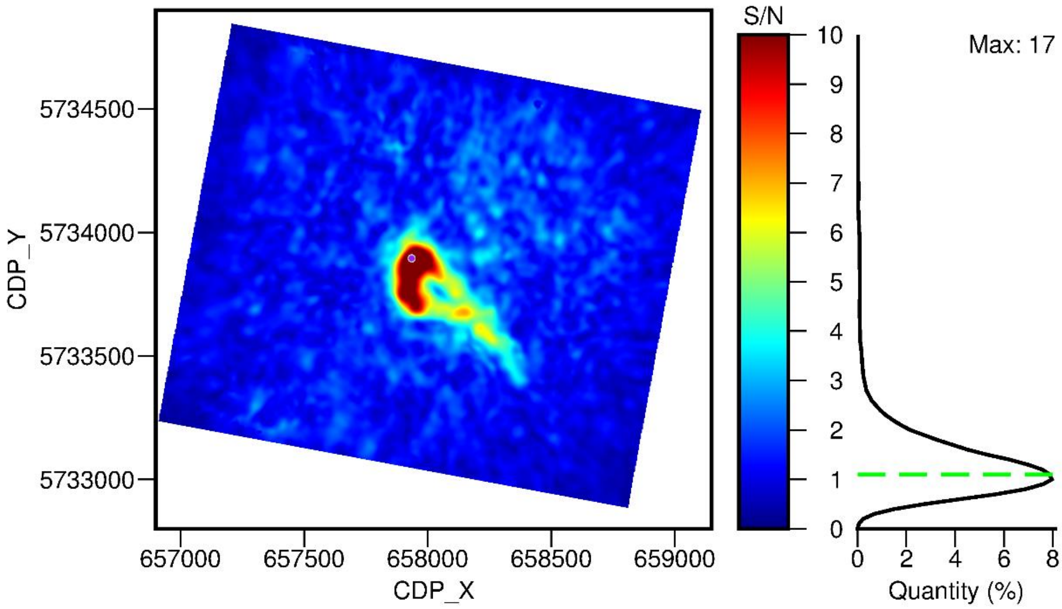

Figure 4 Map of signal-to-noise ratio for the interval of injection for express processing workflow. A histogram of the SNR values for the displayed map is shown on the right. Injector well is indicated as a purple circle.

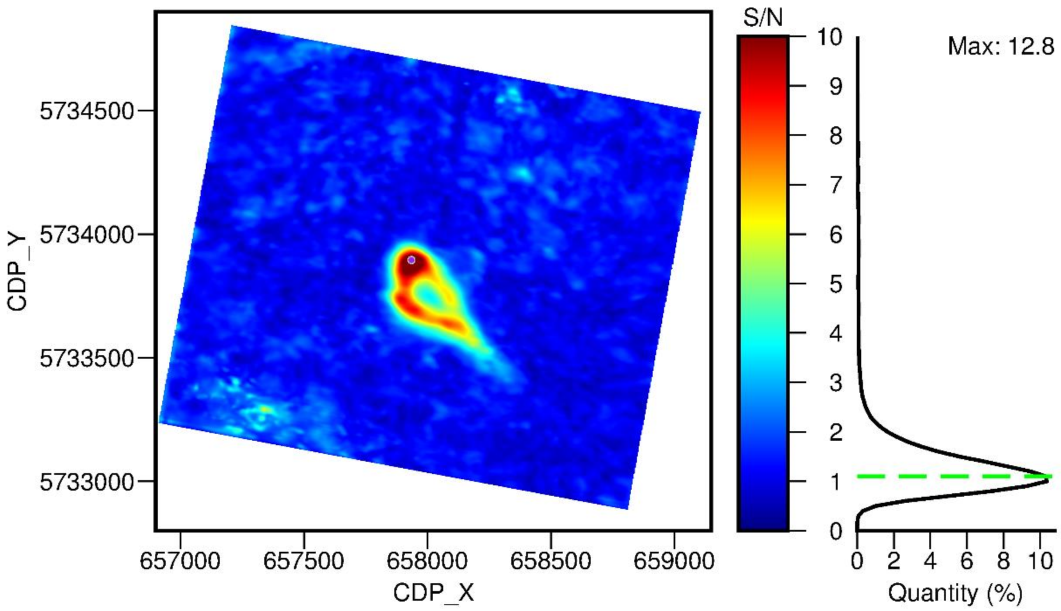

Figure 5 Map of signal-to-noise ratio for the interval of injection for express processing workflow. A histogram of the SNR values for the displayed map is shown on the right. Injector well is indicated as a purple circle.

CONCLUSIONS

In this paper we present the results of the TL processing for the CO2CRC Stage 2C 4D surface seismic data using two different processing flows. We attempt to define quality of the 4D processing via relative magnitude of the time-lapse signal on the migrated stacked volumes and structural clarity of the 4D image. The main findings of the study are summarised below:

- High quality of the raw data (high fold, low ambient noise dataset acquired using buried receiver array) allows to get good quality of the 4D image of the $scCO_2/CH_4$ plume with even a simple express processing flow;
- The greatest difference in plume appearance on the processed images is related to the choice of the migration algorithm (pre- vs post-stack); as pre-stack migration allows us to obtain sharper image of the faults (features with sharp lateral terminations), we believe the 4D plume image obtained with PSTM is better defined structurally;
- Other principal components of the workflow (such as approach for deconvolution or ground roll removal) have secondary order impact on the TL image;
- Surprisingly, application of AGC in long window causes apparent improvement in TL signal-to-noise ratio, we speculate this is related to its ability to reduce the impact of remnants of high-amplitude coherent noise events typical for the land data;

Obviously, if we define goals of the processing differently and, for instance, focus on the AVO analysis, the approach for the flow design might be different. These, along with the examining of the pre-stack cross-equalisation approaches, form our future plans.

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