Borehole Seismic Monitoring at Otway using the Naylor-1 Instrument string

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Thomas M. Daley[1]
[1]Lawrence Berkeley National Laboratory

with support and assistance from
Sandeep Sharma[24], Aleksander Dzunic[23], Milovan Urosevic[23], Anton Kepic[23], Don Sherlock[5]

[2]CO2CRC
[3]Curtin University
[4]Schlumberger Carbon Services
[5]Chevron

Introduction and Background

The Naylor-1 monitoring completion, a unique and innovative instrumentation package, was designed and fabricated in FY 2007 at Berkeley Laboratory. Tom Daley, Barry Freifeld and Duo Wang (all from Berkeley Lab) were on site at the Otway Project between September 26 and October 14, 2007, working with CO2CRC and their subcontractors, AGR Asia Pacific and Eastern Well Services to complete Naylor-1 and initiate baseline data collection. Figure 1 shows a schematic of Naylor-1's sensor layout. There are three U-tube geochemical samplers, with one located near the top of the residual CH_4 gas cap and two located beneath the gas-water contact. The 21 geophones are used for performing three distinct seismic measurements, high resolution travel time (HRTT), walkaway vertical seismic profiling (WVSP), and microseismic monitoring. These activities are separated in to active source seismic and microseismic monitoring, and will be described separately.

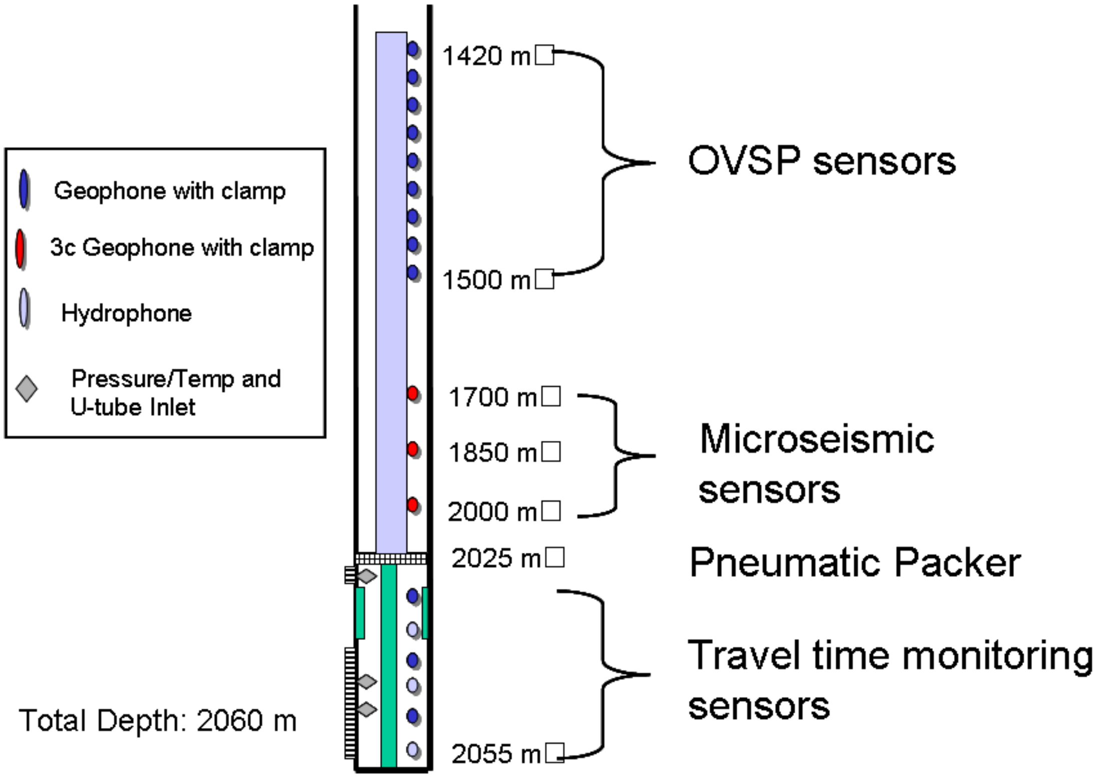


Figure 1. Schematic of sensors installed in Naylor-1 monitoring wellbore

Micro-seismic Monitoring

The Naylor-1 microseismic monitoring began collecting preinjection background data after the initial installation. The seismic recording system is remotely accessible via the internet for data transfer and changing of recording parameters. Each microseismic event is recorded with an 8 second length at 2000 samples per second per channel, and a 3 second pre-trigger length (leaving 5 s of post trigger recording). The trigger parameters have been changed multiple times during this initial recording period to try and reduce the number of 'false' triggers, mainly from electrical noise bursts.

The current trigger parameters are as follows:
STA = 100 ms
LTA = 3000 ms
Ratio = 3
Monitoring channels: 10, 14, 15, 16, 17, 18
Minimum number of monitoring channels over ratio needed to trigger: 3

To date, several thousand triggers have been recorded with almost all of the events inspected being electrical noise triggers. Many of the other events have signal on only one or two sensors and are most likely due to near-borehole noise. Modification of the trigger parameters during the course of injection has lowered the 'false' trigger rate. Currently the trigger rate is about 5 events per week. Individual inspection of events has found only a few events of interest. A good system functional test was obtained when five perforation shots were performed in CRC-1, which all generated events with similar characteristics, demonstrating the performance of the seismic string. The moveout of low-frequency energy observed on sensors within the Waarre reservoir implies functional coupling of these three sensors, which had not 'seen' any arrivals in the HRTT surveys. This discrepancy remains unexplained.

CRC-1 Perf Shots: In early February 2008, the CO_2 injection well, CRC-1, was perforated with a wireline perf gun. This activity provided the possibility of detecting seismic events with a know source location, about 300 m lateral offset, within the reservoir zone. Figure 2 shows all of the events within 2 days of the perf shots which appear to be true seismic events. Most notably, every perf shot was accompanied by a triggered event – events 5175, 5192, 5252, 5262 and 5280., which correspond to shots at depths of 2062.5, 2061, 2057, 2055 and 2053 m, respectively, in well CRC-1. The timing between perforation and recording system was unfortunately not synchronized, but all the shots had just one event (ranging from 7 to 25 s before the recorded shot time), and no other events triggered within minutes. These 5 perf events can be compared to the other three events in Figure 2 (5160, 5312 and 5319). The non-perf events have arrivals only on channel 16, 17, and 18 – the 3-C sensor at 2000 m. The perf events have arrivals on sensors at 1850, 2000, 2030, 2040 and 2050 m. Therefore, we conclude that these 5 events were all caused by the perf shots in CRC-1.

The perf shot events have a low frequency energy arrival about 50 ms before the high frequency arrival. The low frequency arrival at first appears to be electrical crosstalk noise because of the lack of moveout, except on the deeper sensors below the packer there is moveout is seen. It seems possible this low frequency energy is a combination of seismic energy and spurious electrical noise. Event 5252 is the only event which has an appearance of this low frequency energy, at 3300 ms, separate from the high frequency arrivals. Figure 3 shows a true amplitude plot of three perf events, all of which show the large low-frequency arrival on chan 19 which is the sensor at the top of the Waarre-C reservoir, in the gas zone and in the casing patch of Naylor-1. It is possible that the large amplitude on chan 19 is responsible for electrical crosstalk noise on other channels. Nonetheless the consistent delay between the low and high frequency components indicates seismic propagation, as does the moveout seen in a low-pass filtered data plot (Figure 4).

An important conclusion from Figure 4 is that the three geophones in the Waarre reservoir (channels 19, 21 and 23) are coupled well enough to see the energy of the perf shots. This is important because the initial controlled source effort (high resolution travel time monitoring, HRTT) is not obtaining sufficient signal-to-noise ratio for these three geophones.

The moveout of the perf events is difficult to interpret since the propagation is largely horizontal. Nonetheless, the low-frequency moveout between the 2030 and 2050 m sensors (chan 19 and 23) is about 7 ms, giving an apparent velocity of 2850 m/s. While the high frequency component has little moveout from 2000 to 2050 m, but about 35 ms between the 2000 m and 1850 m sensors, giving an apparent velocity of 4300 m/s. This

high velocity could indicate propagation in the steel (casing or sucker rod), or simply horizontal propagation with high apparent vertical velocity.
The spectral content of a perf-shot event is shown in Figure 5. The signal is broadband with a peak at 20-30 Hz (the low frequency arrival) and energy within 20 dB to 300 Hz. In addition to the power line notch filters, a 15-500 Hz bandpass filter has been applied.

Natural Events: The 3 non-perf-shot events shown in Figure 2 are representative of the few non-electrical noise events recorded in the initial monitoring. The signal is impulsive and broadband with about 350 ms of coda. Some events were seen in the upper section of the string (1420 – 1500 m) but never on more than 1 or 2 sensors. Of these three events, one appears to have a separate P and S phase arrival, allowing estimation of source distance (Figure 6). The identification of the S-wave is supported by the increased energy on the vertical component, because the vertical component is orthogonal to a horizontally propagating wave. The 90 ms of P-to-S time delay in event 5160 implies a distance of about 488 m (for Vp=3.7 km/s and Vs=2.2 km/s). This distance is approximate since the actual velocity depends on propagation path. An azimuth estimate will be made from particle motion analysis following the determination of horizontal sensor orientation from the controlled source data.

During the beginning of injection in April 2008, data was recorded continuously for about 3 weeks. This data has been searched for events, with no significant number of events observed. A typical event is shown in Figure 7. To look for trends in seismicity, the time of detected events is plotted against injection wellhead pressure, as shown in Figure 8. To date, no clear pattern has emerged and no significant seismic activity appears to be associated with the injection. It is notable that we now expect the CO2 to have reached the Naylor bounding fault. This is the first known case of a fault seal being tested by a sequestration pilot, therefore the lack of induced seismicity is an important observation. A notable gap in seismicity was observed during Nov. and Dec. 2008, with a few events in January and February of 2009.

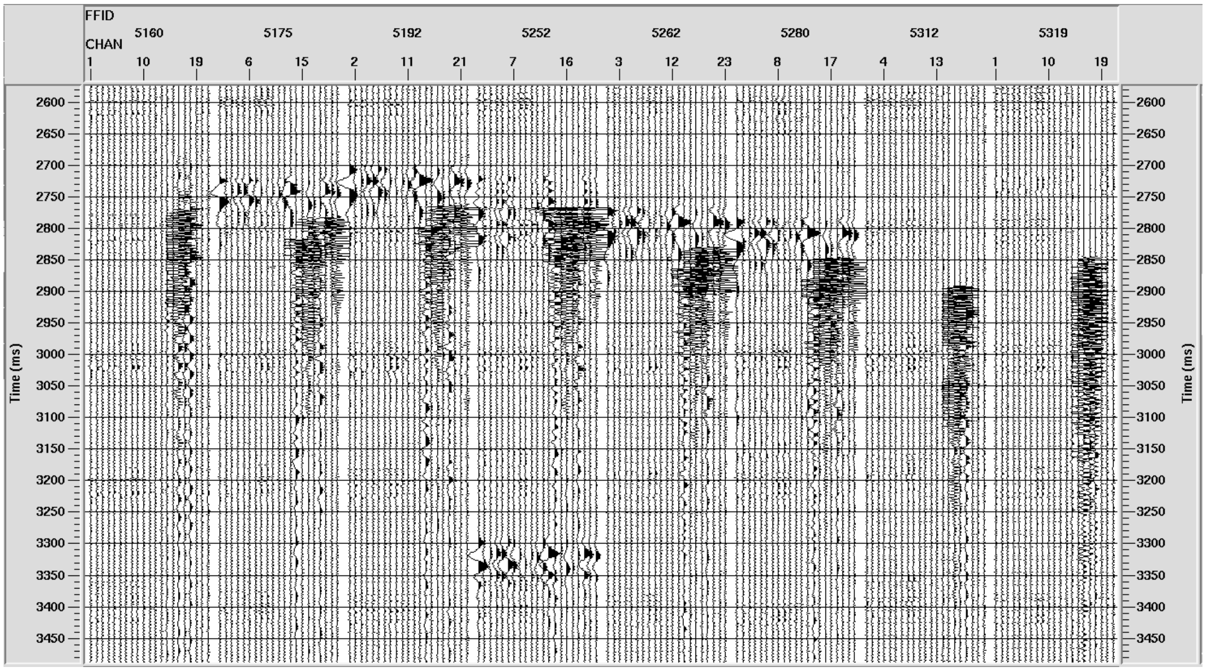


Figure 2. Eight microseismic events from the time period of the CRC-1 perforation shots. The second through sixth events (from the left) are each recorded within 25 s of a perf shot (timing was not synchronized). The other three events are separated by hours and are 'natural' events. Event 5160 (far left) is shown in detail in Figure 6.

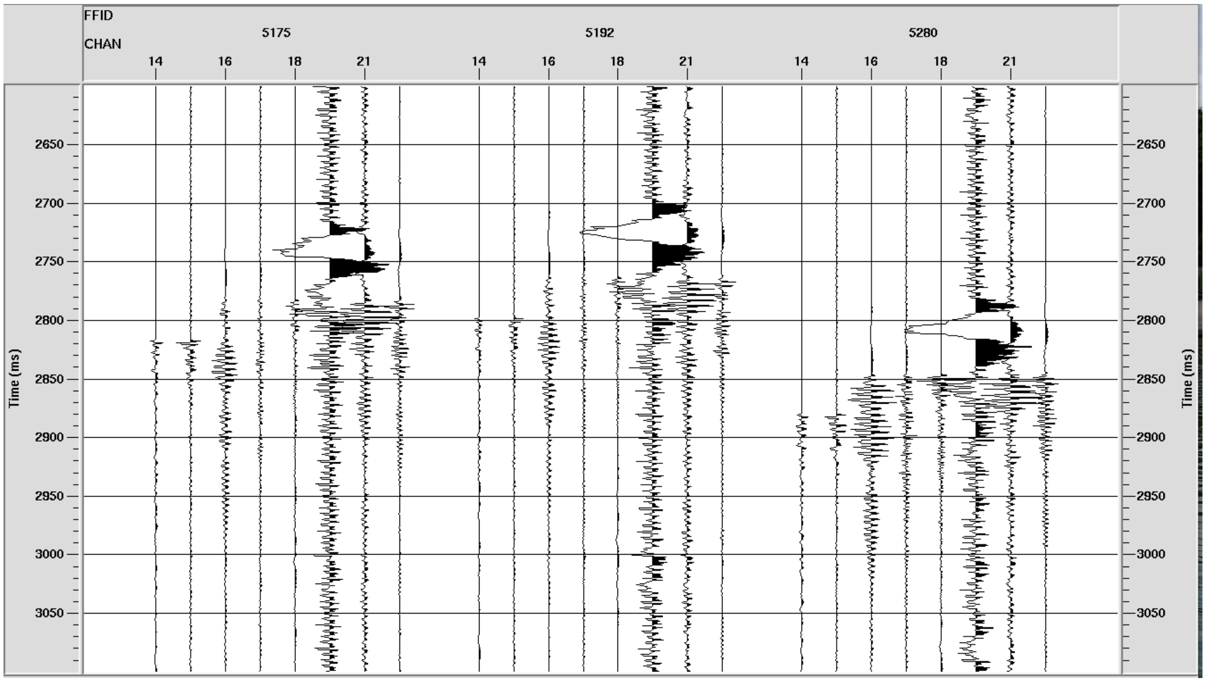


Figure 3. Three perf events shown at true relative amplitude. The dominant signal is a low frequency arrival on chan 19, with a later high frequency arrival on the other channels. Channels 1-13 had no signal and 20, 22, 24 (hydrophones) are not shown.

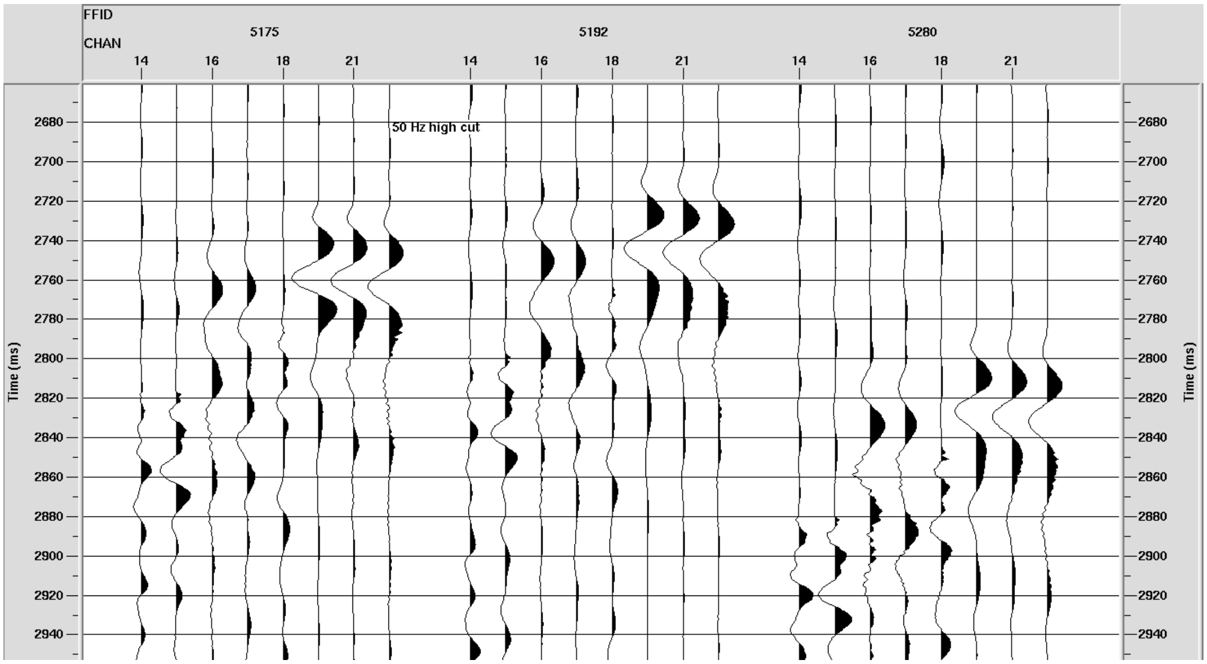


Figure 4. Same three events as Figure 3 with a 50 Hz low pass filter applied and trace amplitude equalization. The moveout of the event on the three sensors with in the reservoir (chan 19, 21 and 23) indicates the event is a seismic arrival (and not electrical noise or crosstalk).

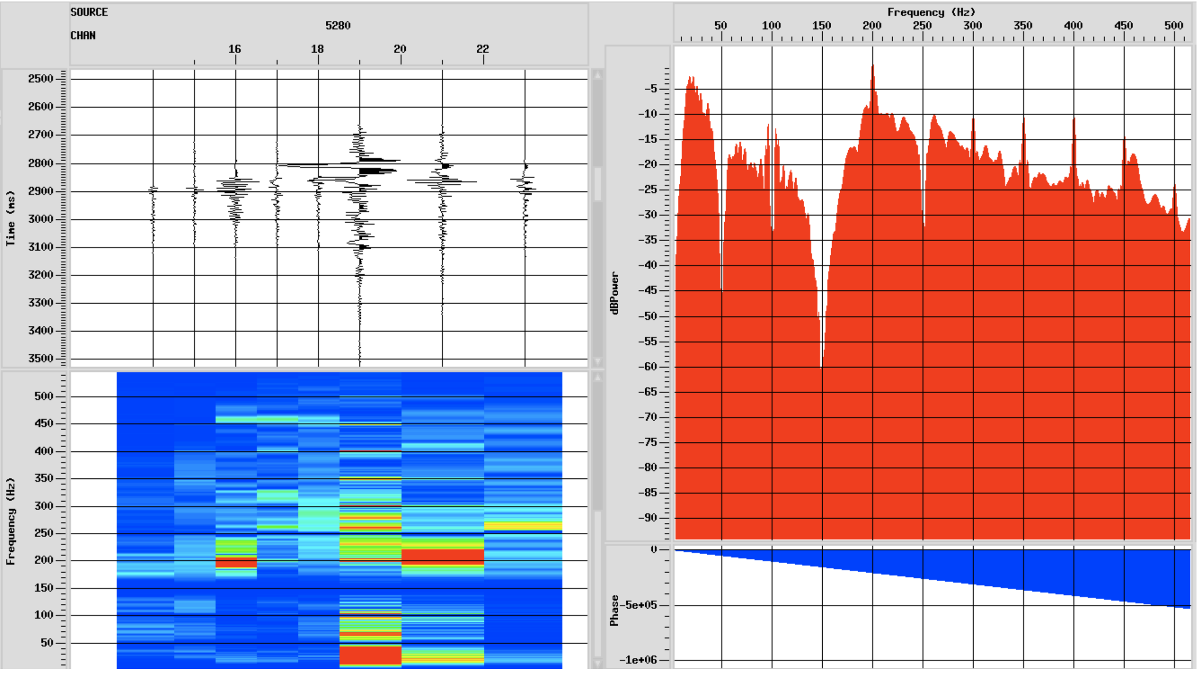


Figure 5. Spectral analysis of event 5280. The total average spectra is in red on the right, while the individual trace spectra are below the seismograms (red high amplitude, blue is low amplitude). The low frequency peak is at 20-30 Hz, while the high frequency is peaked at 200-300 Hz.

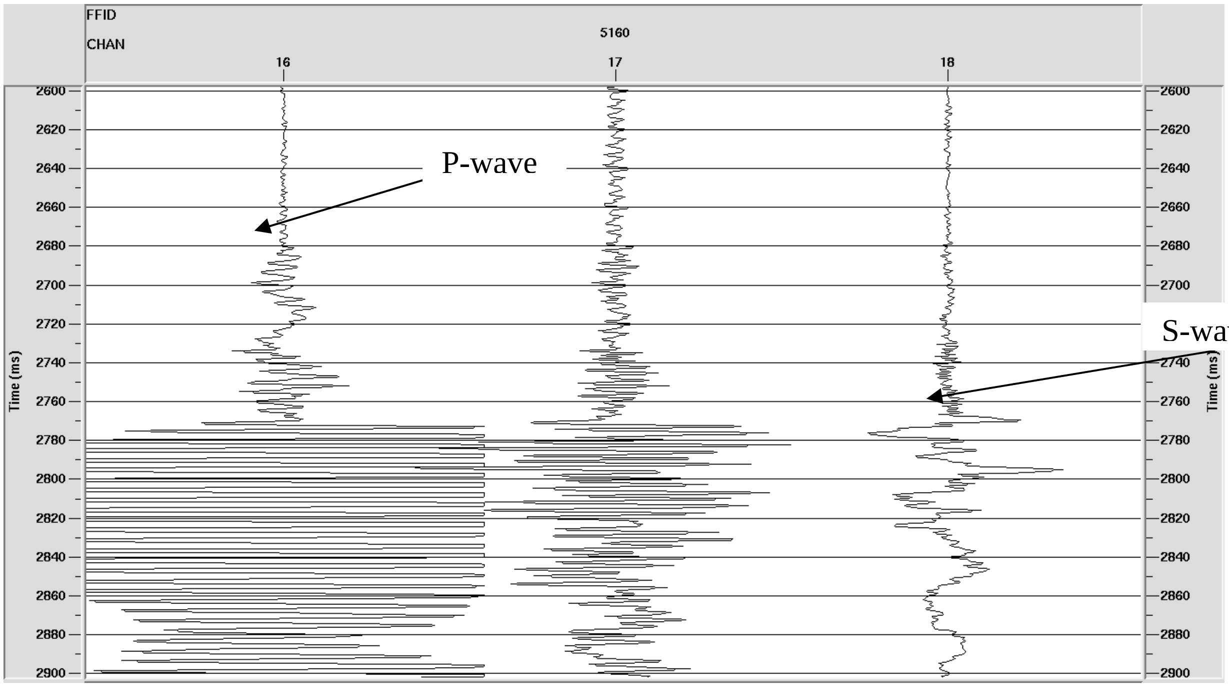


Figure 6. Event 5160 , true amplitude with high gain to view early arrival interpreted as P-wave before later arriving high amplitude S-wave. Channels 16, 17 and 18 are the 3-component geophone at 2000 m with chan 18 being vertical. Note that for this horizontally propagating event, the P-wave is on the horizontal component, while the vertical component has large amplitude for the S-wave. Other channels have no arrival for this event.

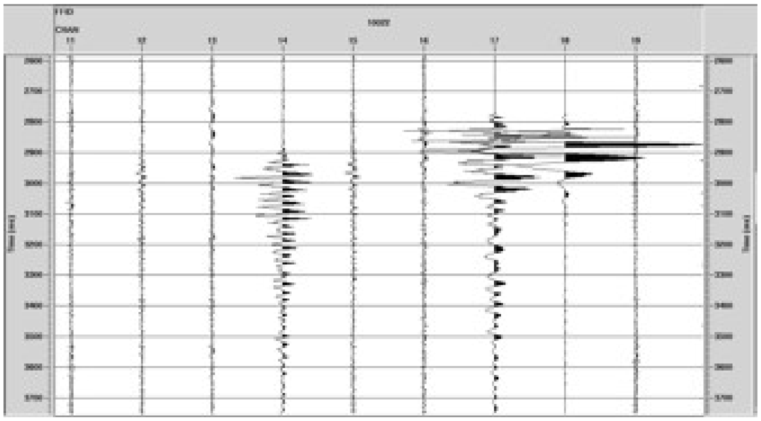


Figure 7 A microseismic event recorded using the Naylor-1 geophone array. Shown are three 3-component sensors.

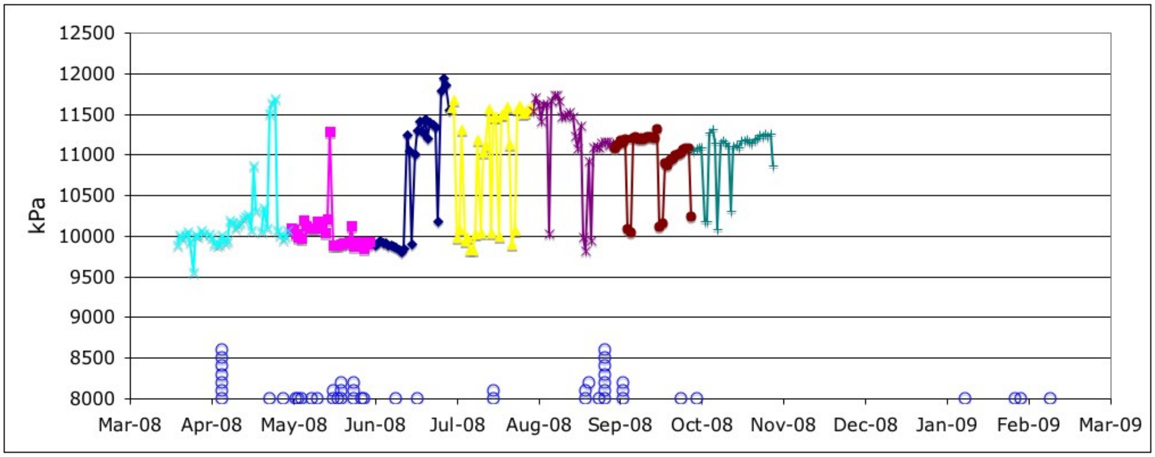


Figure 8 Occurrence time of microseismic events detected by the Naylor-1 seismic sensors (blue circles) plotted with CRC-1 well head injection pressure. No consistent relationship between injection pressure and seismic activity is observed.

Active Seismic Monitoring

The active seismic program includes high resolution travel time (HRTT) monitoring using sensors located at reservoir level and walkaway vertical seismic profiling (WVSP) using a string of 9 vertical geophones located above the reservoir horizon (Figure 1). The surveys conducted to date are summarized in Table 1. The six locations used for conducting HRTT measurements and the 22 shot point locations used in the WVSP surveys conducted April 2008, and May 2008 are shown in Figure 10.

The initial data collected in October 2007 with the surface acoustic and small weight drop source showed indicated that greater source strength would be required at the depths of the reservoir. The December 2007 data collection with the Rocktec Hurricane Force 9 was able to provide signal to the shallowest vertical component geophones but the data had low signal to noise. To get better signal to noise, a larger hurricane concrete breaker (www.rocktec.co.nz), with rated energy of 2720 Nm versus 1125 Nm for the smaller Force 9 was employed. The data collected in January 2008 with the larger source and more source stacking is good quality on nearly all sensors above the reservoir. Using the Rocktec Hurricane Force 10 seismic source, baseline data was collected at the 6 HRTT sites shown in Figure 10. The three geophones in the Waarre reservoir, however, were still showing a lack of signal. However, in our microseismic monitoring, we do see signal on these sensors, so it is possible that attenuation within the reservoir is part of the problem.

The results of the January 2008 data collection were summarized in the report "Otway Project: Naylor-1 High Resolution Travel Time Monitoring Initial Results of January 2008 Acquisition" by T.M. Daley and D. Sherlock. Because of the large number of blows to reduce noise using the Hurricane Force 10 considerable surface disruption occurred in the cow paddocks. It was determined that dynamite shots (400 g at 3 m depth) would provide the best data quality with the lowest impact on the land surface for conducting subsequent HRTT and WVSP measurements. Figure 11 shows good quality data collected using the 9 shallow vertical-component geophones. The geophones within the reservoir still had poor signal-to-noise, indicating that the gas cap may be too highly attenuating for practicable data collection at the reservoir horizon using surface sources. Figure 12 shows the initial time-lapse processing result which includes time shifts to align first arriving energy at each sensor and then amplitude variance calculation in a moving window for each sensor and each source location.

Table 1 Otway Project Seismic Surveys.

Date	Source Type	Number of Locations	Walkaway Shots	Report Date
October 2007	Surface Acoustic (Hartley Source)	1	No	None
October 2007	Small Weight Drop	3	No	None
December 2007	Rocktec Hurricane Force 9	3	No	Jan. 5, 2008
January 2008	Rocktec Hurricane	6	No	March 16, 2008

	Force 10			
April 2008	Explosive (400g@3m)	6	Yes, 22 shots	April 9, 2008
May 2008	Explosive (400g@3m)	6	Yes, 22 shots	May 20, 2008
Nov. 2008	Explosive (400g@3m)	6	Yes, 22 shots	N/A

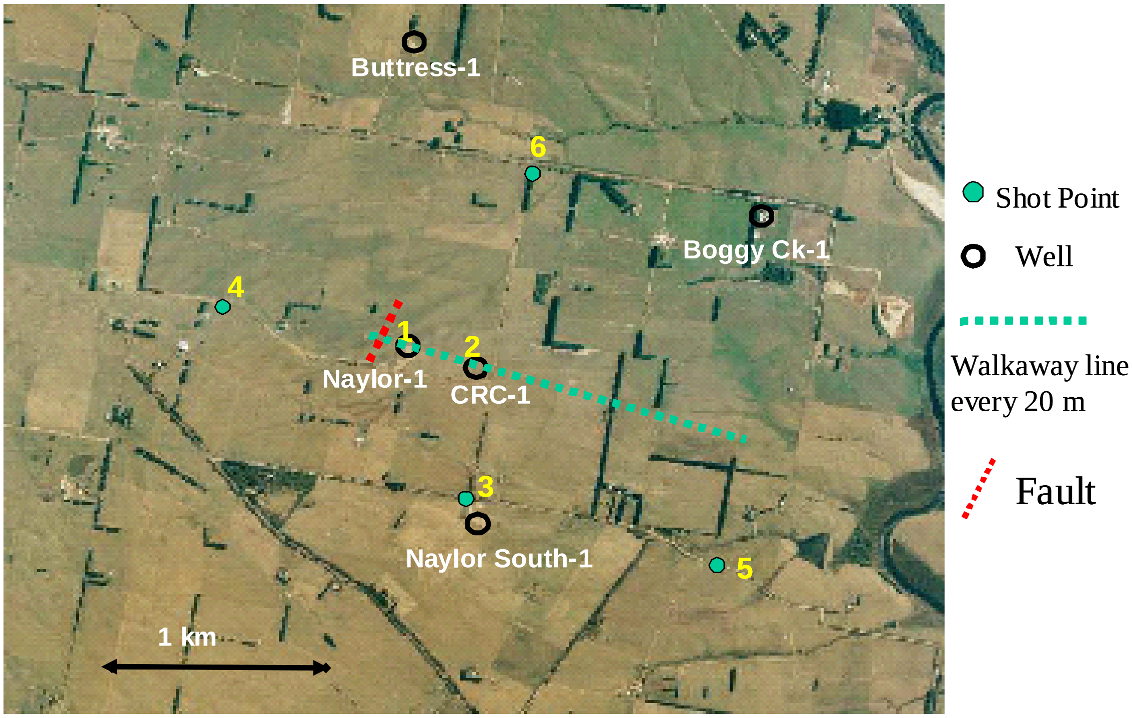


Figure 10 Location photo/map of HRTT Sites (blue circles) and wells (black circles). HRTT sites 1 and 2 are on the well pads of Naylor-1 and CRC-1, respectively. The dashed blue line are the 22 WVSP shot points.

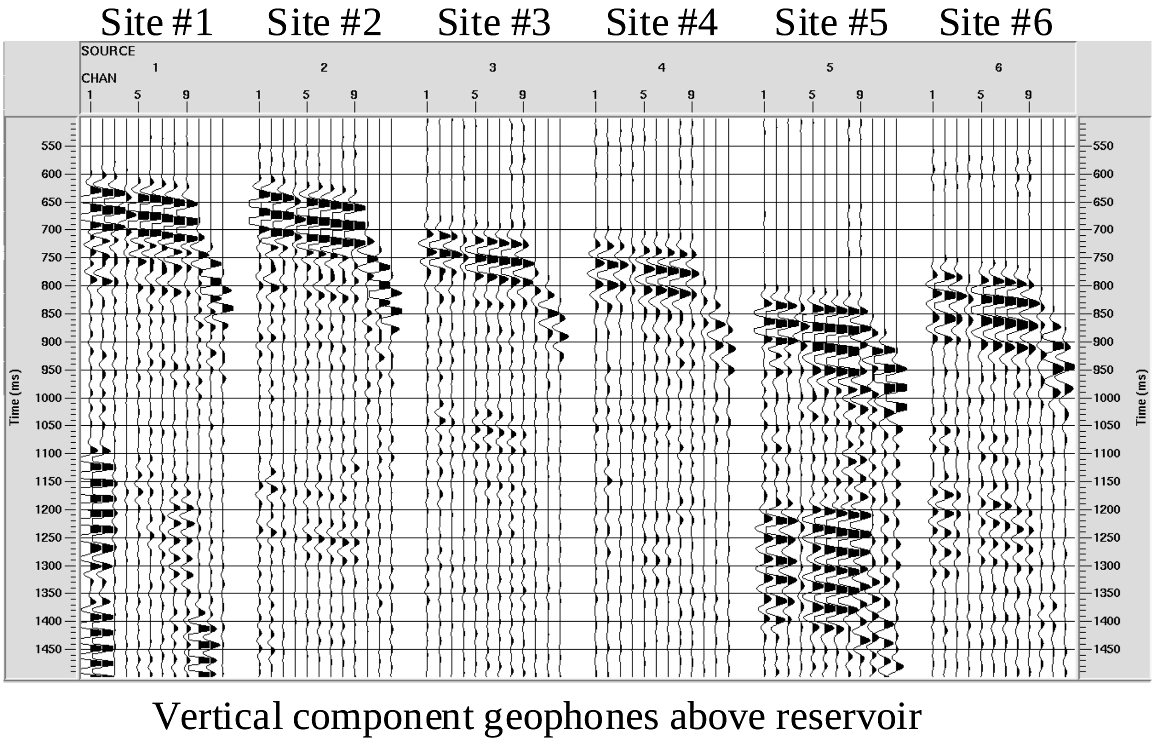


Figure 11 Data collected during the April 2008 seismic survey at the 6 HRTT locations showing good signal-to-noise.

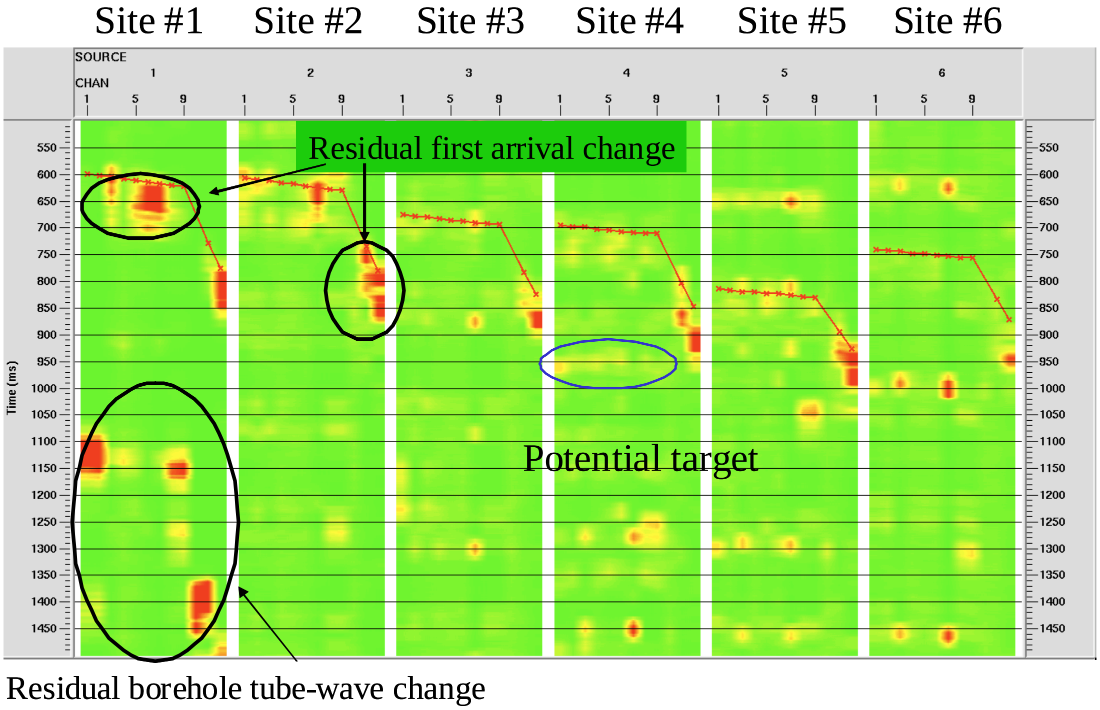


Figure 12. Time lapse change between the April, 2008 and May, 2008 HRTT measurements. Red indicates more variance between data sets. Large variance at first arrival times indicates that better normalization of first arrival energy is required for evaluating the small changes expected from reflections in the reservoir horizon (such as the indicated potential target).

The testing of seismic sources for active source experiments had two main conclusions, explosive sources would be best and the reservoir level sensors had too low sensitivity to surface source to allow analysis. Therefore the active source analysis has focused on analysis of reflected energy from below the Waarre C reservoir zone. This data is shown in schematic form in Figure 13, where the seismic raypath travels through the reservoir twice, going down and coming back up. This reflected energy is recorded on the sensors in the Paaratte formation, as well as on the microseismic monitoring sensors just above the Waarre C. Potential changes in reservoir reflections need to have larger change than the residual change in the first arrival energy, since the first arrivals do not pass through the reservoir.

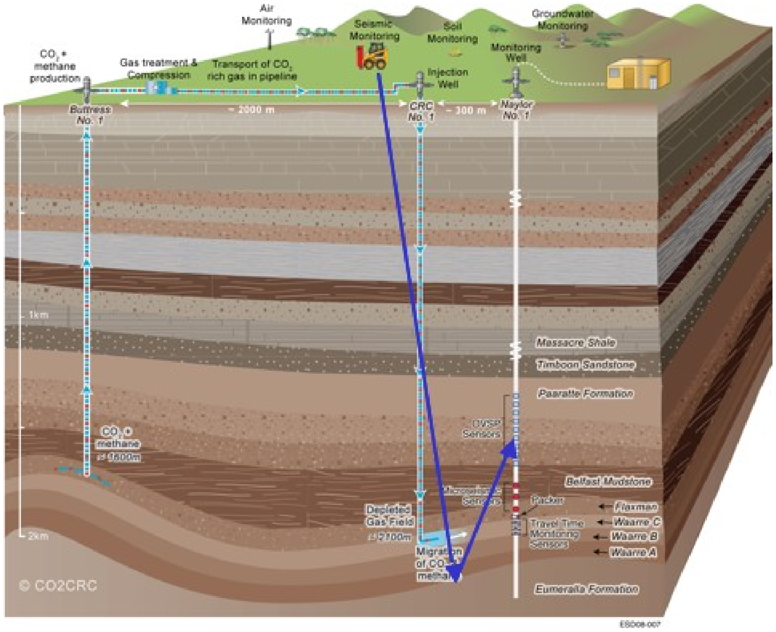


Figure 13. Otway site, including seismic sensors in Naylor-1 borehole, with example active source raypath shown in blue.

The Otway site is a difficult problem for seismic monitoring for two main reasons, the near surface has large seasonal changes and the expected seismic response from CO_2 displacing CH_4 is minimal. A processing flow has been developed to minimize the near surface changes. This analysis includes minimizing travel time and amplitude changes in the first arriving waves. These first arrivals have passed through the near surface, but not through the reservoir, therefore they can be used to minimize those effects related to shallow material. Figure 14 shows a comparison of data from April 2008 (at the beginning of injection) and May 2008 (one month after injection).

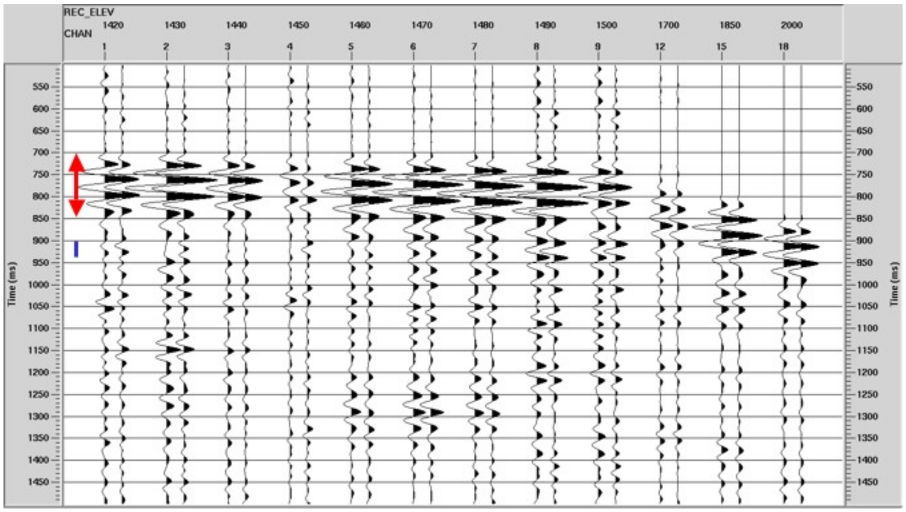


Figure 14 Comparison of recordings on 12 vertical geophones for data from source site 4 in April (left) and May (right), 2008. The red arrow indicates the time window used for first arrival normalization (slightly shifted for each pair), and the blue line indicates the length of the time window used for "moving window" analysis.

The time-lapse analysis includes the following processes:
1) Remove/minimize time change from near surface (including shot variation) using crosscorrelation of first arrival energy (150 ms time window);
2) Remove/minimize near surface amplitude change with normalization based on first arrival rms amplitude (50 ms time window);
3) Calculate change in later arrivals (coda) using moving window correlation/variance analysis (25 ms time window, 0.125 ms interval), Variance = $\sum 0.5 (a_i - b_i)^2$
4) Test window lengths for normalization and analysis

At the time of the May seismic acquisition, about 5200 tonnes of CO_2 had been injected. This is too small an amount to be expected to be seismically 'visible', but this data can be used to assess detectability limits. The first arrival times show a good repeatability (about 2 ms), but there had been little seasonal ground water change between these two data sets. Figure 15 shows the amplitude variance for each of the 6 source sites. There is still residual change seen in the first arrivals and in borehole tube-wave energy. Figure 16 shows the moving window time shift data, which, as expected, does not have an observable (i.e. consistent) time shift associated with the Waarre C reservoir.

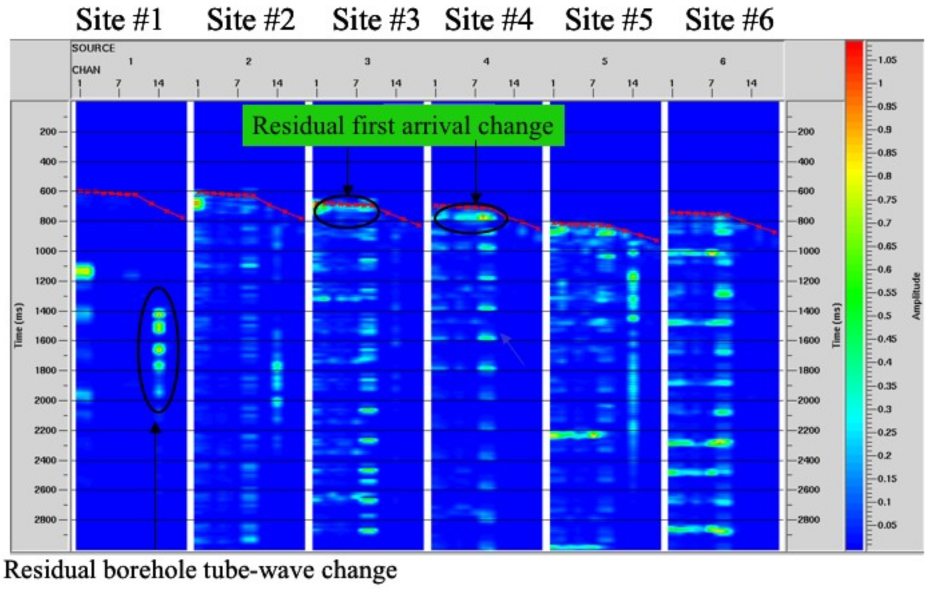


Figure 15 Time lapse amplitude variance between April and May 2008 data sets with larger change in green to yellow.

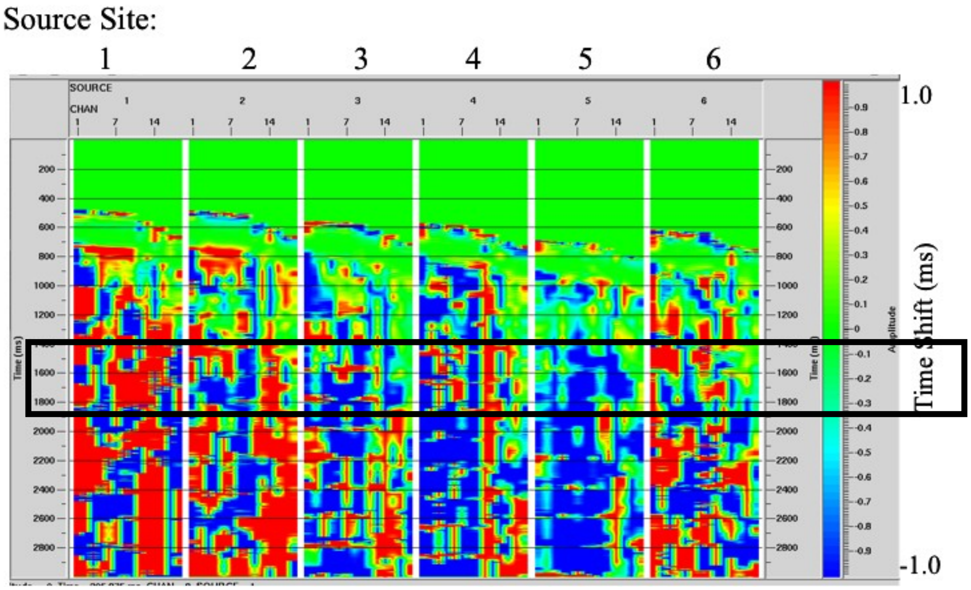
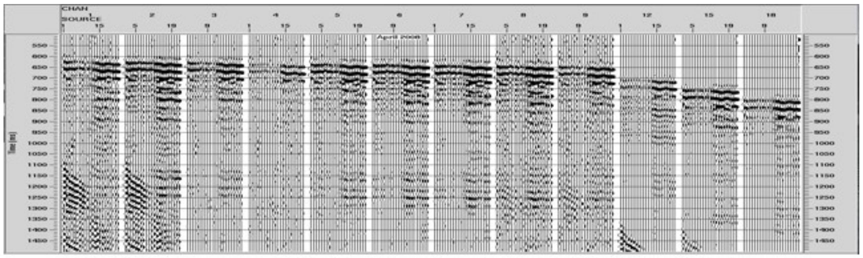


Figure 16 Time-lapse time shift in a moving window for each of 6 source sites. The target time window is inside the black rectangle. The time shift is inconsistent in this window. While no effect from the injected CO2 was expected to be seen at this time, a decrease in travel time (green to blue colors) is predicted for CO2 displacing CH4.

In addition to the 6 travel time monitoring sites, a ‘walkaway’ survey was run with source points about every 10 m between Naylor-1 and CRC-1 boreholes. This data, shown in Figure 17, has also been analyzed for amplitude and travel time changes. Again the result shows no detectable change, as expected after only 1 month of injection, but the resolution or detectability can be assessed with this data.



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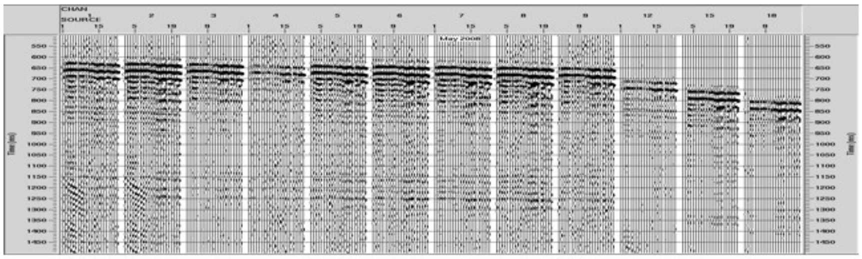

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Figure 17 Walkaway type seismic survey data for the 12 vertical geophones in Naylor-1 well. Data will be processed and analized for time-lapse changes.

The time-lapse data from April and May 2008 was analized for the RMS time shift in three windows representing ‘background noise’. The levels measured in the field data can be compared to the expected change due to CO_2, and compared to an estimate of best expected precision. The best expected precision is calculated based on the Cramer-Rao bound of delay time (Silver et al., 2007). Figure 19 shows this comparison. About half of the data points exceed the estimated change, meaning these data are too noisy to allow detection. The data points below this level indicate detection is possible, but will require repeatability as good or better than the April/May data sets.

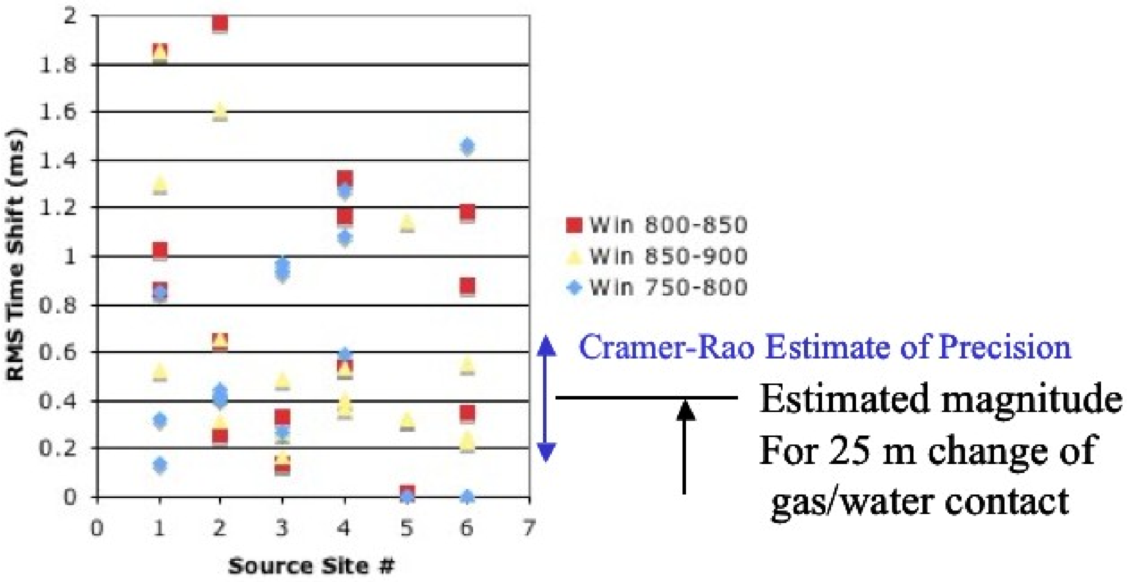

Figure 19 The RMS time-shift between April and May data sets for 3 time windows representing typical 'noise' levels and for the 6 monitoring sites. Also shown is the estimated magnitude of time shift for a 25 m change in the gas/water contact (the maximum expected at Naylor-1) and the estimated theoretical precision of the Cramer-Rao bound.

In Nov 2008 the first 'post-injection' seismic data was collected (previous survey from May 2008 was only a month after beginning injection). Unfortunately, the initial analysis indicates that the data repeatability is not sufficient to allow detection of the CO2 induced response. The previous analysis indicated the repeatability from April 2008 to May 2008 was only marginally sufficient, now the November 2008 indicates a much larger variation (about 6 ms in April-to-Nov. time shift vs 1-2 ms shift for April-to-May). The calculated residual time shifts in a moving window for the high-resolution (HR) source points has scatter in the data (from 2 to -2 ms shift) which overwhelms an expected change of about 0.4 ms). Similarly, Figure 20 shows the amplitude change, also in a moving window. For amplitude, the residual change in the direct first arrival is again larger than any later arrival which has traveled through the CO2 reservoir zone. This means that changes in the seismic 'coda' can not be attributed to the CO2 injection. This analysis has been completed for the HR source points and the walkaway data.

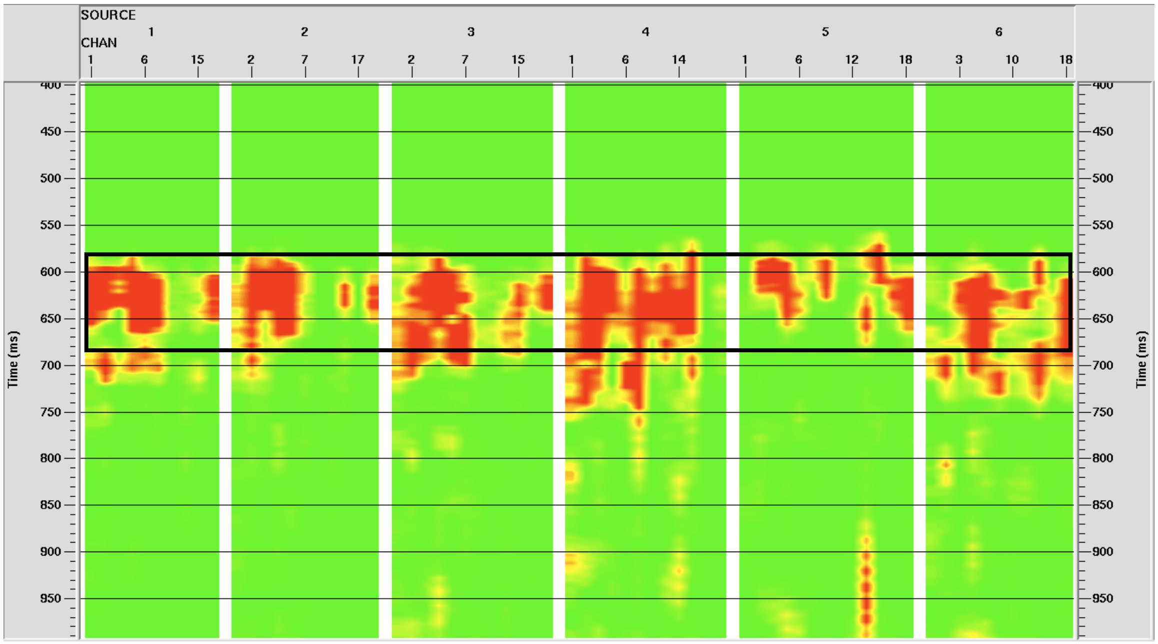

Figure 20 Calculated residual amplitude change for Nov. 2008 survey. The residual change in the first arrival window (approximately indicated by black box) is larger than later changes, meaning that data repeatability is not sufficient to allow detection of CO2 induced changes in later arrivals.

Summary and Conclusions:

A multipurpose monitoring instrumentation package was installed in the Naylor-1 well. As part of this package, seismic sensors were installed with two planned uses, microseismic monitoring and active source monitoring. Initial testing showed that the seismic sensors had some electrical noise problem (with some leakage to ground observed) and also poor coupling to the borehole. This is probably a problem with the bow spring clamps which were a unique design for this sucker rod deployment. Additionally, the sensors below the packer, in the reservoir, are not responding to active source signals (despite observation of perf shots during perforation of the injection well, CRC-1.

For the microseismic monitoring, Event detection began on Jan 29, 2008 with Very few events observed, most triggers are electrical noise. Continuous (24x7) recording was completed for ~1 month during initial injection with no evidence of missed events, so the system was returned to triggered recording. Adjusting trigger parameters to minimize ‘false’ triggers was part of the first few months monitoring. Currently there are about 2 trigger/day; ~2 true events/week. This lack of activity, and the very small size of the events shows there is no evidence of fault activity.

The active source monitoring had early work on choosing an appropriate source, limited by the poor coupling (requiring high source signal). The conclusion was to use an explosive source. The problems with sensors in reservoir required use of reflection/coda

analysis which further limited the signal/noise ratio. The data to date indicates that the sensitivity to Waarre CO_2 is not sufficient for detection. This is compounded by the expected very small seismic response for CO2 displacing CH4 in a reservoir.
The monitoring data can still be used for leakage monitoring in the shallower saline zones, and surveys are planned to be repeated.

Acknowledgment

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