Overview of the Violet Grove CO_2 seismic monitoring project

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ABSTRACT

In March 2006, the baseline seismic program was completed at the Penn West CO_2 injection and monitoring pilot in west-central Alberta. The reservoir is the Cardium Formation in the Pembina field, and the reservoir depth at the pilot site is 1640 m. High-fold multicomponent seismic data were collected along three 2D lines (two parallel, one orthogonal) and from eight triaxial geophones that were cemented into an observation well at the site. All geophones were kept live for all shots of the program, and data quality was excellent. The surface seismic data were processed as individual 2D lines as well as a sparse 3D survey; the data from the downhole geophones were processed as walkaway vertical seismic profiles. The reservoir is a low-amplitude event on P-P and P-S sections and data volumes and shows little structure. Few passive seismic events were recorded in the first 6 months of monitoring. The first monitor survey is scheduled for January, 2006.

INTRODUCTION

The geological storage of CO_2 is a technically feasible way of making significant reductions in emissions of CO_2 into the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) first reported on geological storage in its Third Assessment Report (IPCC, 2001), and is currently undertaking a Special Report on CO_2 capture and storage, due for release in 2005. The International Energy Agency (IEA) has also completed several studies that discuss opportunities for CO_2 sequestration (e.g. IEA GHG, 2001). The WCSB has enormous potential for the geological storage of CO_2. Bachu and Shaw (2004) report that ~4 Gt of CO_2 could be stored in depleted oil and gas reservoirs in western Canada. In deep saline aquifers, the potential storage capacity is much greater, estimated to 4,000 Gt (Bachu and Adams, 2003). The total storage capacity is very large compared with Canada's annual CO_2 emissions (700 Mt in 2000). However, security of storage is a key issue, and monitoring and verification protocols are required to enable geological storage of CO_2 for accounting purposes related to emissions trading scenarios (Chalaturnyk and Gunter, 2004), as well as for acceptance by the general public. Theoretical and laboratory studies of changes in rock properties with CO_2 flooding predict that changes in seismic attributes should be observable in field seismic surveys (e.g., Wang et al., 1998; Sinartio, 2002). Time-lapse seismic surveys have been shown to be effective at mapping the CO_2 injection plume at the Sleipner CO_2 storage site in Norway (Skov et al., 2002; Arts et al., 2002) and at the Weyburn CO_2 injection project in southeastern Saskatchewan (White et al., 2004; Li, 2003; Davis et al., 2003). At both of these sites, P-wave amplitude and traveltime anomalies have identified the distribution of CO_2 in the reservoir.

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In order to properly map the movement of the CO_2 plume in the injection reservoir and to track possible leakage paths, three-dimensional (3D) seismic surveys are required. However, 3D surveys with close line spacing and small shot and receiver intervals are expensive, and surface seismic data may have insufficient bandwidth to resolve thin (< 20 m) injection zones. At the Penn West CO_2 – enhanced oil recovery project in Alberta, an innovative seismic monitoring strategy has been implemented involving a sparse, multicomponent surface seismic program integrated with active and passive monitoring using geophones permanently cemented into an observation well. The surface seismic program provides 3D subsurface coverage of the pilot site whilst data from the downhole geophones provide high-resolution images around the observation well. The downhole geophone installation will be used for passive monitoring of CO_2 injection between active-source seismic surveys. The Penn West baseline survey was completed in March 2005 and passive monitoring has been undertaken for 5 months. The first monitor survey is scheduled for January, 2006.

LOCATION AND PROGRAM

The Penn West pilot is located in the Pembina Oil Field in west-central Alberta (Twp 48, R8-9 W5M). The primary purpose of the CO_2 injection program is for enhanced oil recovery from the field, with a secondary objective of evaluating this depleted reservoir for the geological storage of CO_2. The reservoir in this field is the Upper Cretaceous Cardium Formation which occurs at a depth of approximately 1650 m below ground surface. The Cardium Formation is made up of sandstone sheets and a thin conglomerate layer sandwiched between thick black marine shales of the Blackstone Formation (below) and the Wapiabi Formation (above). The total thickness of the Cardium Formation at the site is approximately 20 m.

Surface access at the site is limited due to swamps and tree cover. The surface seismic program consisted of two parallel, multicomponent 2D lines, 400 m apart and oriented east-west, and one orthogonal multicomponent 2D north-south line, intersecting near the CO_2 injector wells. These three lines were 3 km long in order to yield a good distribution of source-receiver offsets at the injection pad. Two additional short north-south receiver lines were also included to provide added seismic coverage around the injection zone. A detailed map showing wells, seismic lines, and surface culture is shown in Figure 1.

SURFACE SEISMIC PROGRAM

Data acquisition

The seismic program was coordinated by OutSource Seismic Consultants Ltd and data acquisition by undertaken by Veritas Geoservices Ltd on March 15, 2005. Some limited line clearing was required for setbacks from pipelines and infrastructure, and a helicopter was used for distribution of the seismic acquisition equipment along the lines. Acquisition parameters for the survey are summarised in Table 1.

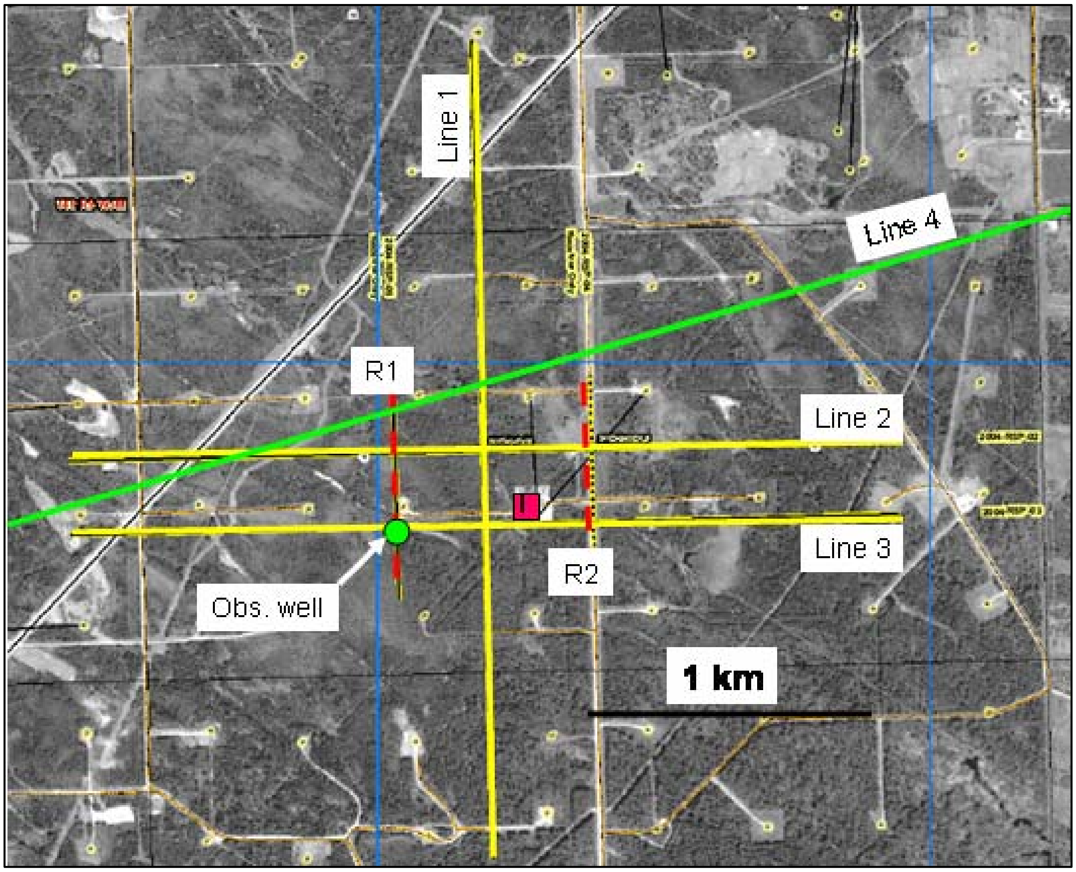

FIG. 1. Map showing Penn West CO_2 injection site. Multicomponent seismic lines (Lines 1, 2, 3) are shown in yellow , and receivers-only lines are shown in red R2, R2). A regional seismic line (Line 4) is shown is green. The observation (VSP) well is shown by the filled green circle, and the CO_2 injection pad is indicated by the red square.

Table 1. Acquisition parameters for the Penn West CO_2 seismic monitoring program

Acquisition parameter	**Value**
Source spacing	40 m
Source type	Dynamite
Source depth	15 to 18 m
Receiver spacing	20 m
Receiver type	Sercel DSU 3C
Instruments	Sercel 408 XL
Sample interval	1 ms

A total of 12.8 km of lines were occupied by receivers, and 9.0 km with shots. The total program consisted of 323 source points and 643 receiver points. All lines were kept live for all shots. Figure 2 shows an example of seismic equipment laid out along Line 1.

FIG. 2. Seismic recording equipment along Line 1.

Figures 3 and 4 show a Sercel 3C DSU geophone unit before and after deployment. Considerable care is required in laying out this equipment. The unit is planted in the ground on a spike in an augured hole and is oriented towards magnetic north and is also leveled.

FIG. 3. Veritas Sercel DSU 3C unit prior to deployment (with CREWES rep. Dr. Zoulin Chen)

FIG. 4. Sercel DSU 3C unit after deployment

In order to minimize noise from wind and the nearby highway 620, data recording was undertaken during the evening. Conditions were ideal with calm winds and occasional light snow. Recording commenced at 7 pm in March 19 and was completed at approximately 11 pm the same evening. University of Calgary representatives (Lawton, Bertram, Gallant, Chen and Coueslan) were on site during data acquisition. Data quality is excellent.

Data processing

The surface seismic data were processed by Veritas Geoservices Ltd during the spring of 2005. Lines 1 through 3 were initially processed as individual 2D lines. In addition to these lines, recorded for this program, Penn West donated the processing of Line 4, which was an older, 7 km long regional line that cuts diagonally across the northern side of the injection site (location shown by the green line in Figure 1). This line will be used in the development of a regional geological model of the injection site in Phase 2 of this monitoring project.

The processing flow used for data processing is listed in Table 2.

Table 2. Data processing flow and parameters

Processing parameters
Reformat
Geometry assignment
Tilt correction to vertical
Ground roll attenuation – polarization filter
Trace edits (manual)
Amplitude recovery (exponent = 2.2)
Minimum phase deconvolution (60 ms operator length; 0.1% prewhitening)
Tomographic structure statics (datum 910 m; replacement velocity 2500 m/s)
Trace gather
Velocity analysis
Surface consistent residuals statics
Spectral whitening (5 – 160 Hz)
Mute and final trim statics
Surface consistent scaling
CDP stack
F-X noise attenuation
Poststack Kirchhoff migration (100% stacking velocities)
Bandpass filter (5-10-100-120 Hz)
Scaling (mean, 500 ms window)

The final, processed sections for Lines 1 through 4 are displayed in Figures 5 through 8 respectively. The intersection of Line 1 ties very well with Lines 2 and 3.

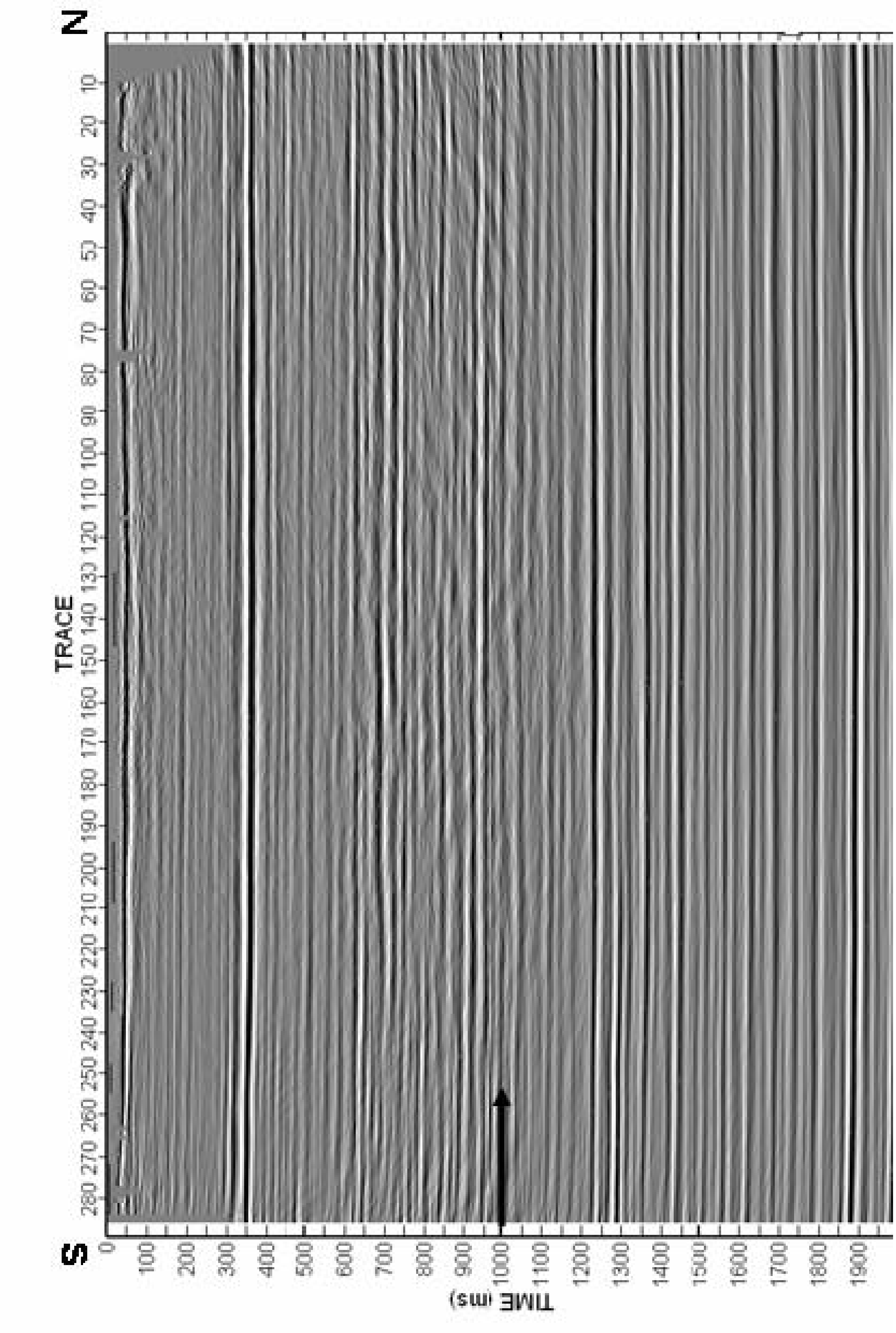

FIG. 5. Final P-P section, Line 1. The Cardium Fm is identified by the arrow

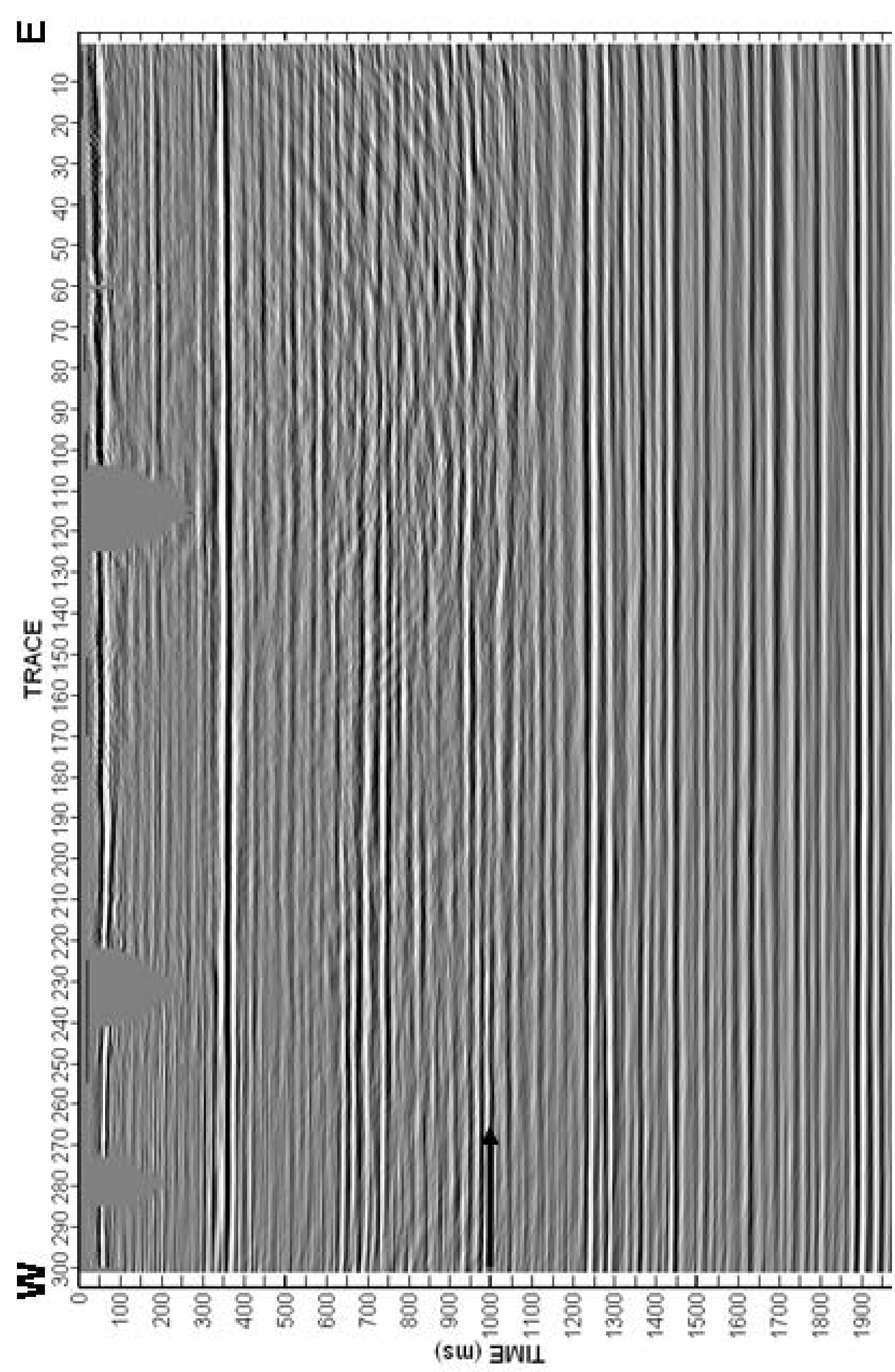

FIG. 6. Final P-P section, Line 2. The Cardium Fm is identified by the arrow

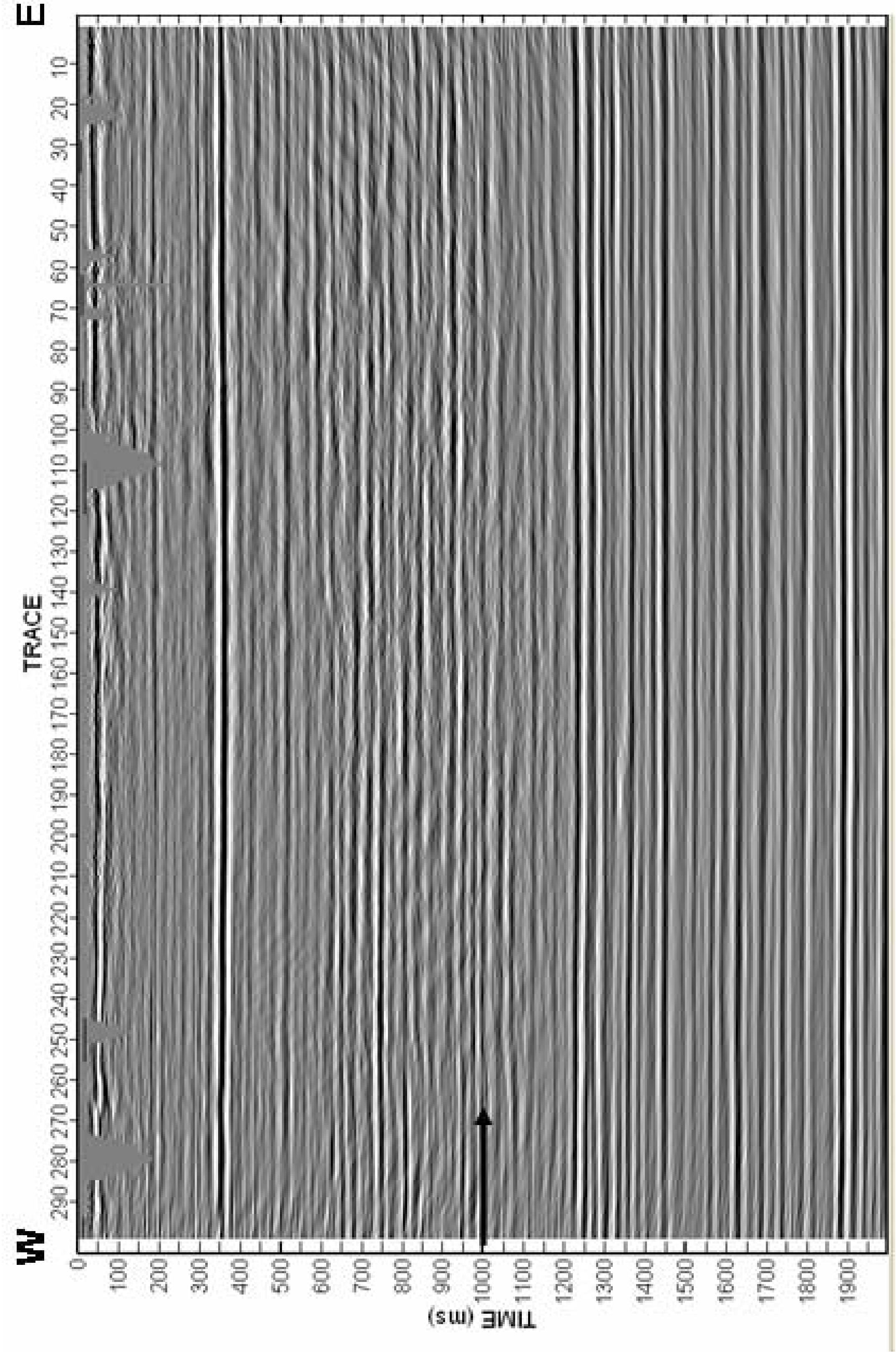

FIG. 7. Final P-P section, Line 3. The Cardium Fm is identified by the arrow

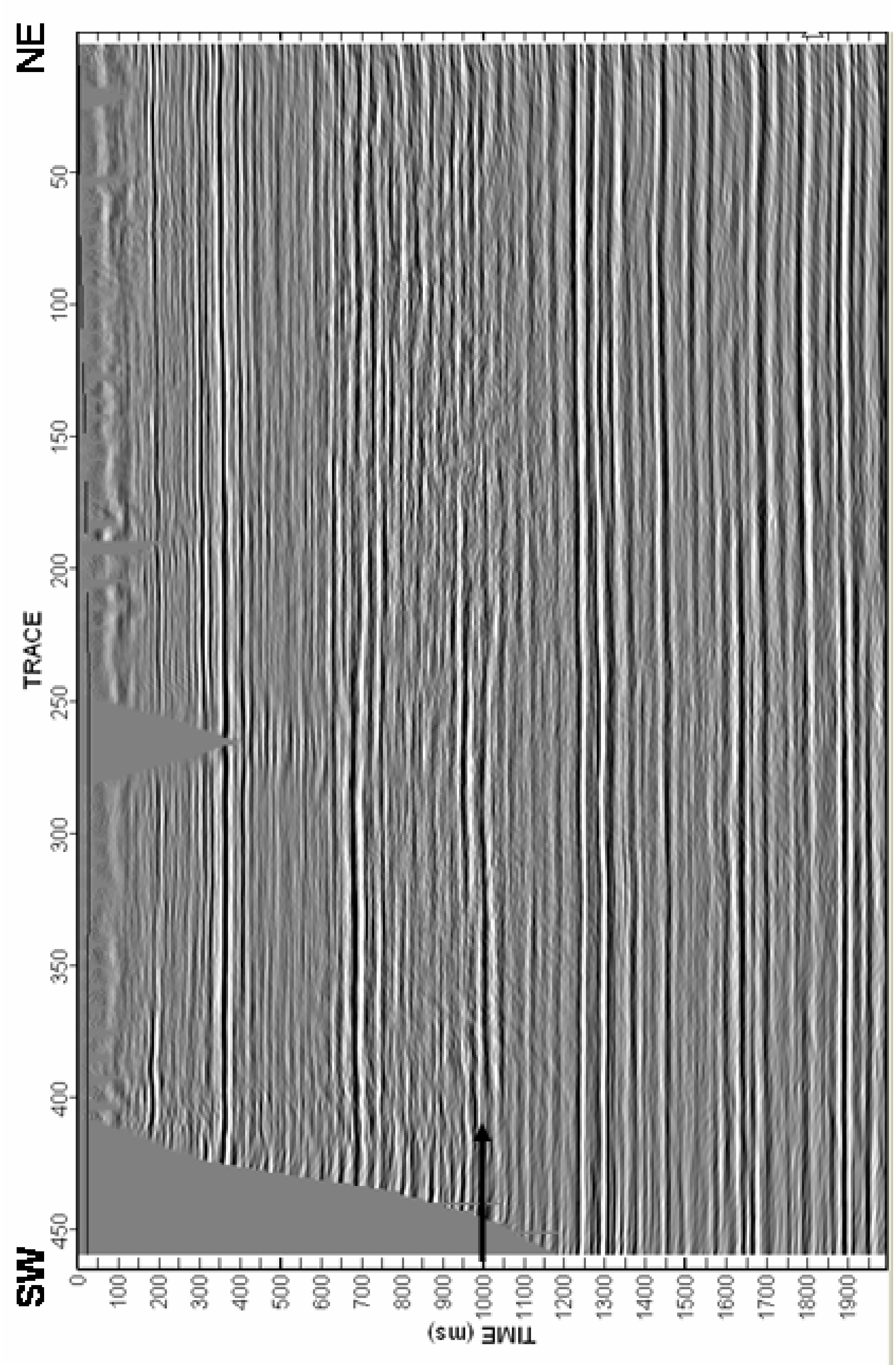

FIG. 8. Final P-P section, Line 4. The Cardium Fm is identified by the arrow

Line 4 (Figure 8) is the regional section and is about 7 km long, whereas the sections in Figures 5 through 7 are each 3 km long. In each section, the level of the Cardium Formation is identified. Amplitudes of the Cardium reflection are quite low and amplitude anomalies after CO_2 injection should be identifiable in the later monitor surveys. In subsequent monitor surveys, the high-amplitude, continuous reflections below 1.2 s should also exhibit traveltime anomalies below the reservoir after CO_2 injection due to lowering of the seismic velocity through the Cardium Formation with partial CO_2 saturation.

Multicomponent data were recorded along the 3 lines in the Penn West survey. This enabled mode-converted P-S data to be recorded in addition to conventional P-P data. P-S data provides additional information about lithology and pore fluids (e.g. Stewart, et al., 2001) that might be very useful in monitoring CO_2 injection. Processing of P-S data is similar to that for P-P data (Table 2) except that common-conversion point (CCP) binning is undertaken instead of the common midpoint (CMP) binning used for conventional P-P data. This is due to asymmetric P-S raypaths. Figures 9 through 11 show displays of processed P-S data for Lines 1 through 3 of the PennWest baseline survey. Data quality is reasonably good and will enable innovative joint P-P and P-S interpretation to be undertaken.

3D seismic volume

Since the seismic program was recorded with all of the receiver lines live for all shots, 3D imaging of the reservoir zone around the injection pad was possible. An example of data from the 3D P-P volume is shown in Figure 11. Data quality is high and it is anticipated that the CO_2 injection plume will be able to be mapped by differencing the monitor surveys from the baseline survey. A time-slice from the 3D P-P volume that cuts through the Cardium Formation reflection time is shown in Figure 12, with positions of the bottom-hole locations of the injector wells indicated. Amplitude anomalies are evident in the time-slice but there appears to be no acquisition footprint in the data arising from the sparse line spacing in the survey. The P-S data were also processed into a 3D volume.

Interpretation of the 3D P-P and P-S data volumes, and the detailed 2D lines will be undertaken by M.Sc. student Fuju Chen during the Fall semester. This work includes the following analyses:

- P-P horizon mapping
- P-S horizon mapping
- P-P and P-S registration and extraction of interval Vp/Vs across the survey area
- Amplitude versus offset analysis for reservoir characterization
- Joint inversion of the P-P and P-S volumes for rock properties.

This work will prepare the appropriate processing flows for analysis and interpretation of the monitor surveys.

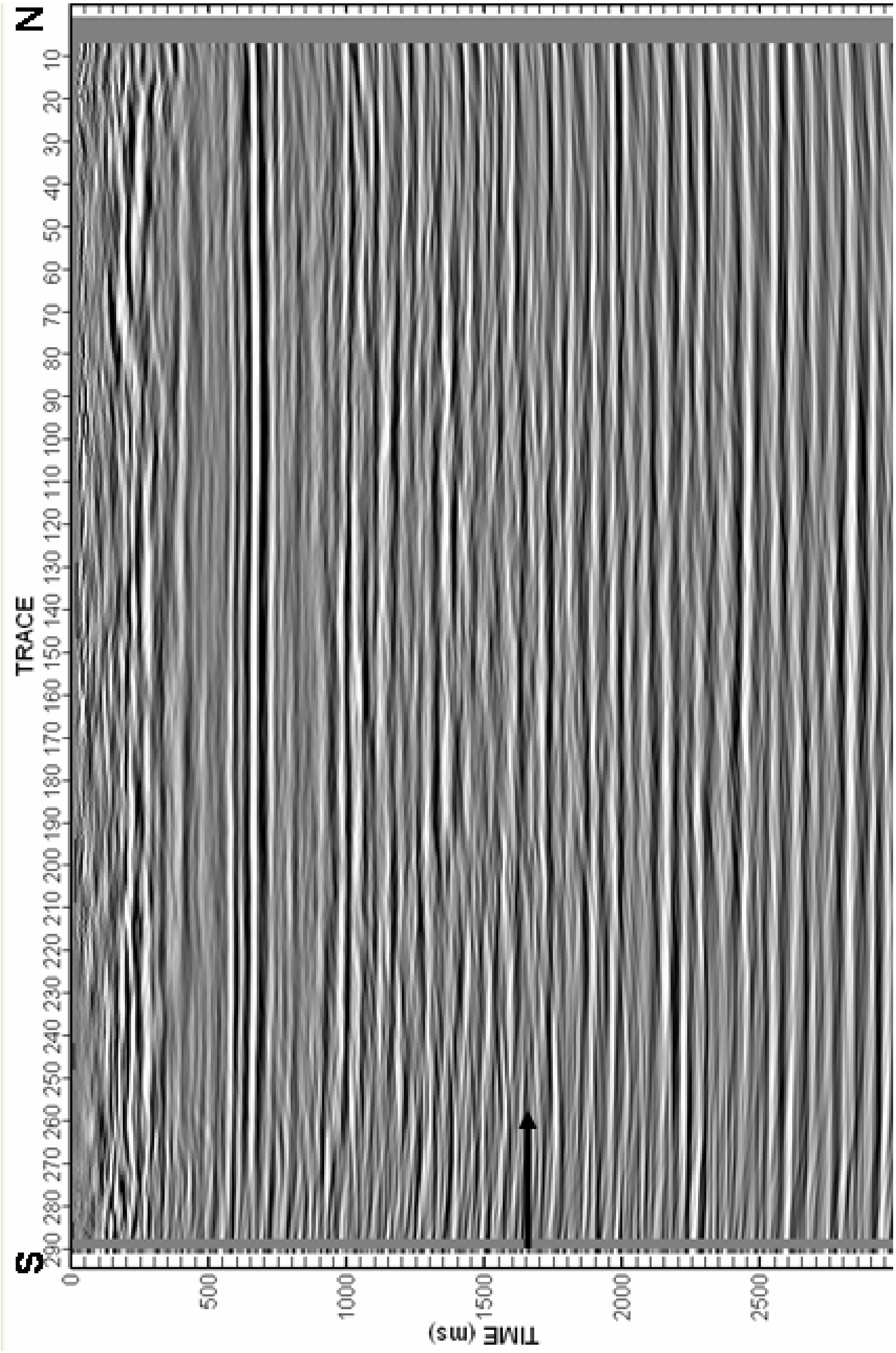

FIG. 9. Final P-S section, Line 1. The Cardium Fm is identified by the arrow

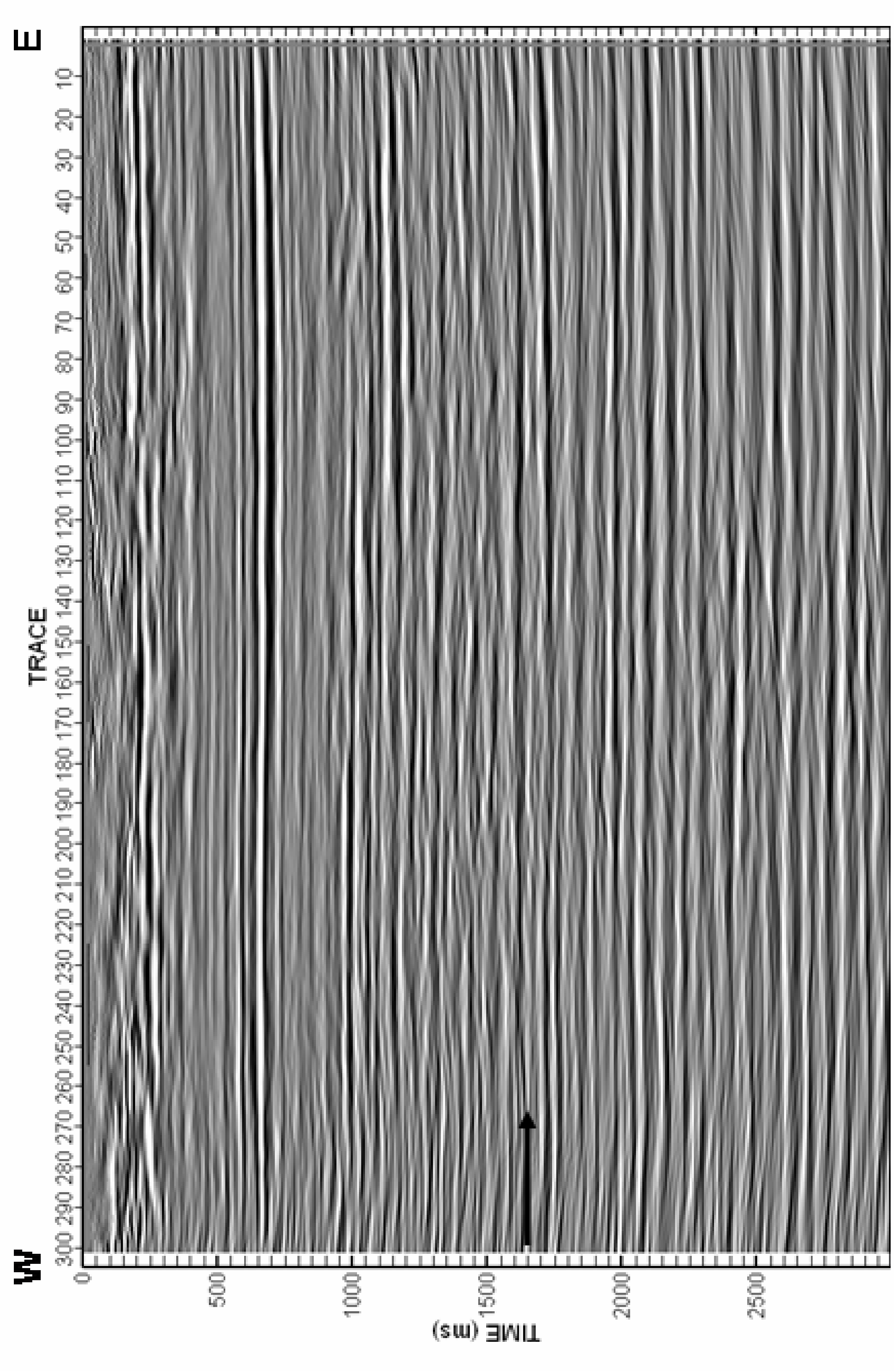

FIG. 10. Final P-S section, Line 2. The Cardium Fm is identified by the arrow

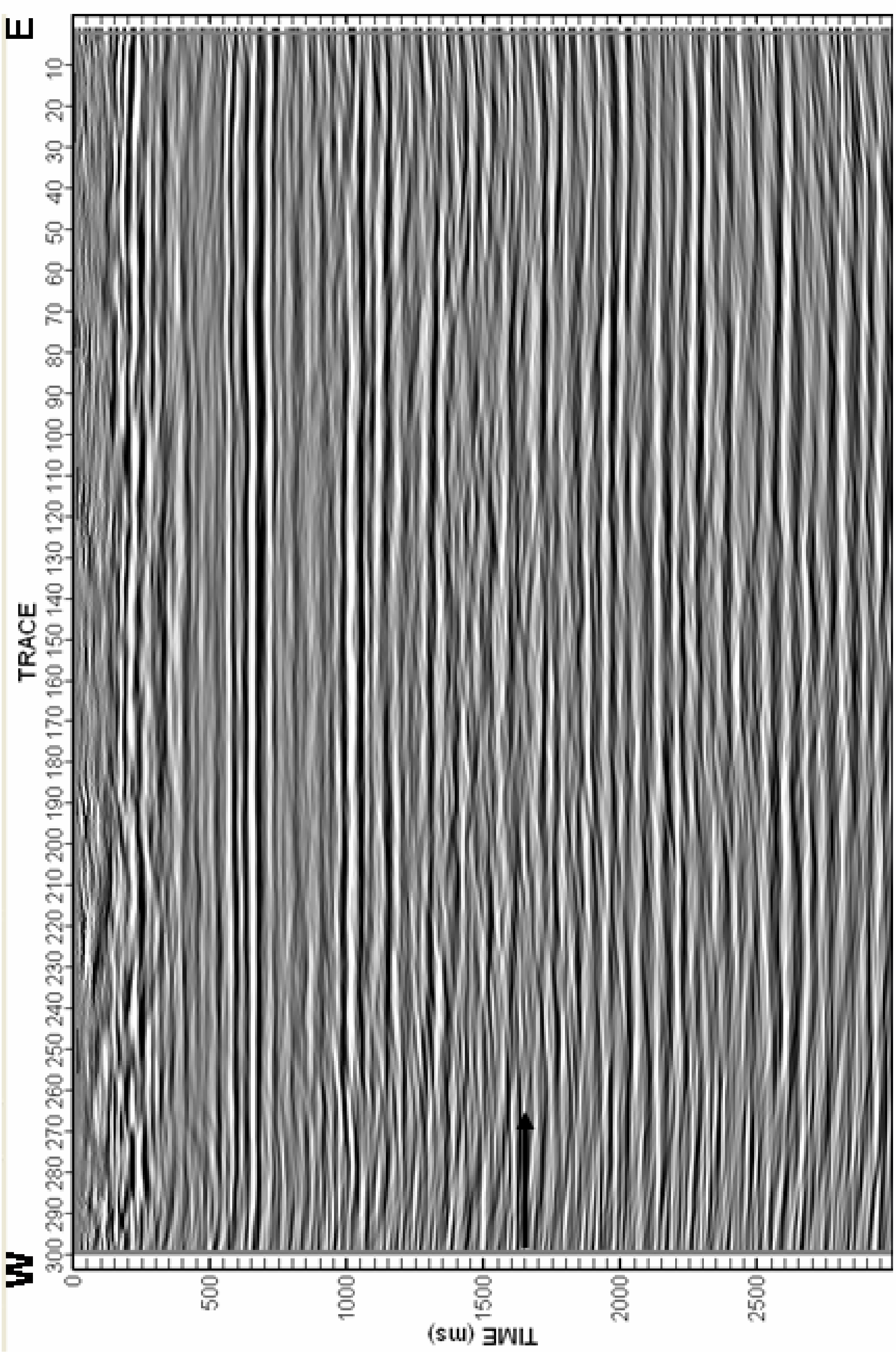

FIG. 11. Final P-S section, Line 3. The Cardium Fm is identified by the arrow

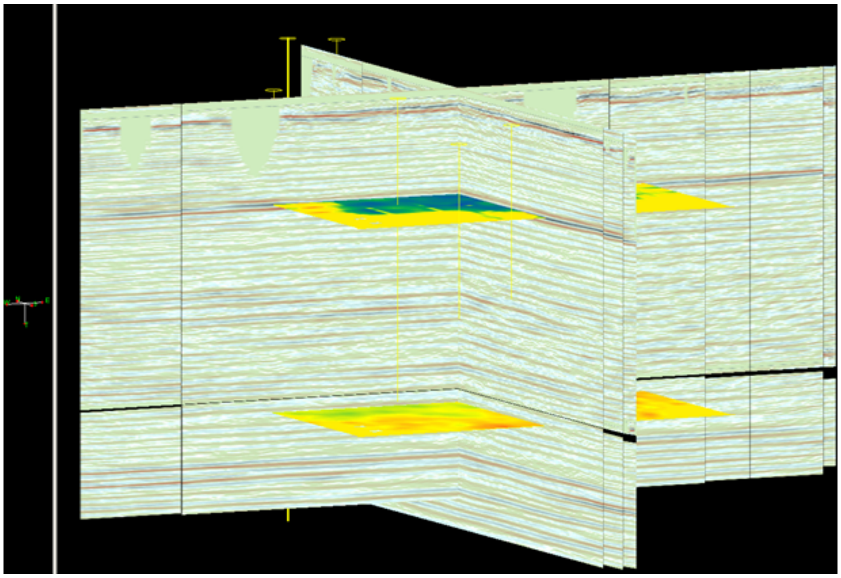

FIG. 12. Slices from the P-wave volume imaged across the injection pad. The lower time slice correlates with the Cardium Formation.

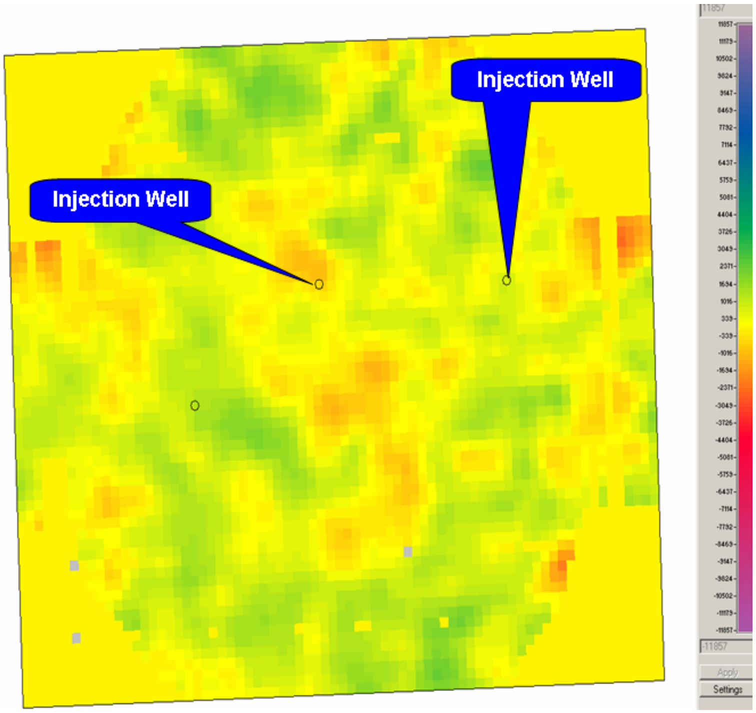

FIG. 13. Time-slice from the 3D P-wave volume that correlates with the Cardium Formation. Locations of the injector wells are indicated.

VERTICAL SEISMIC PROFILE

Prior to the surface seismic program, 8 three-component geophones were permanently cemented into an observation well at the pilot site. The location of the observation well is shown in Figure 1, and it is close to Line 3 of the surface seismic survey. The geophones were placed at ~20 m intervals from a depth of 1497 m to 1640 m; the deepest geophone is located in the Cardium Formation so that the vertical seismic profile (VSP) array can be monitored between time-lapse active-source seismic programs. All shots of the baseline seismic program were recorded by the downhole array and are being processed and analyzed as 2D walkaway surveys and as a sparse 3D VSP. Processing is being undertaken by M.Sc student Marcia Coueslan at the offices of Schlumberger Canada in Calgary. Figure 14 shows a picture of seismic acquisition equipment recording data from the downhole array.

FIG. 14: Seismic data acquisition with downhole geophone array

Data quality in the downhole geophone array is outstanding, with high vector fidelity and good bandwidth data being recorded. An example of raw data, with agc applied for display, is shown in Figure 15. Processing of the VSP data consists of rotation of the horizontal components into the source-receiver plane, separation of the data into upgoing and downgoing P-wave and S-wave wavefields, deconvolution based on the signature of the downgoing wavefield, stack and migration to create time and depth images. Since only 8 receivers were placed in the well, the image of reflected events is primarily from below the Cardium Formation. Examples of the P-wave stacked section from Line 3 of the program is shown in Figure 16. The data from the offset VSP processing has been spliced into the image derived from the surface seismic data. It is expected that differencing between monitor and baseline surveys will map transit time anomalies through the reservoir after CO_2 is injected into it.

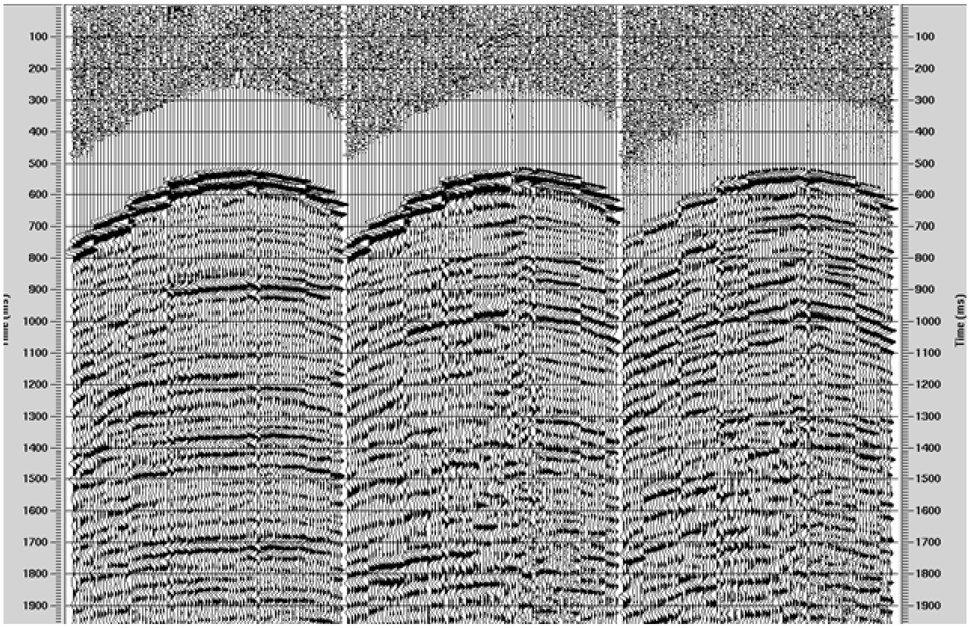

FIG. 15. Example of raw VSP data from the deepest geophone in the observation well. From left to right the panels show the Z, X and Y components for all shots from Line 3.

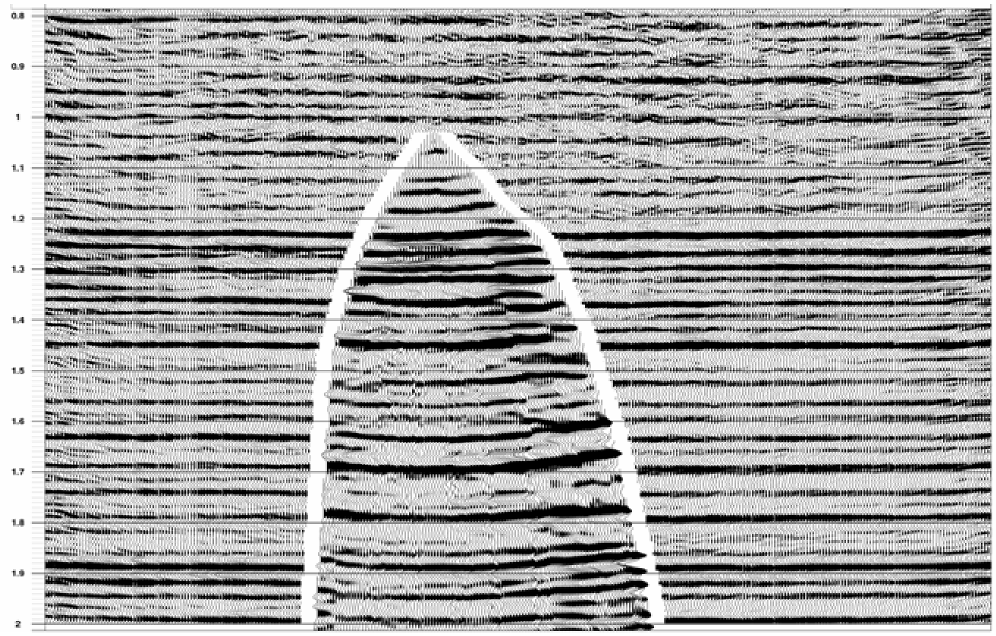

FIG. 16. Stacked offset VSP section spliced into the surface seismic data from Line 3.

The VSP data shown in Figure 16 have greater bandwidth than the surface seismic data, and reflections close to the base of the well also have higher amplitudes and greater coherency. The processing and interpretation of the VSP data will continue through the Fall of 2005 and processing flows established will be used for data recorded during the monitor surveys scheduled for early 2006.

PASSIVE SEISMIC PROGRAM

The passive seismic technique for mapping subsurface changes has been applied in many field sites. Reservoir extraction actives, such as oil and gas production, and injection activities, such as steam or water flooding are known to change the stress in and about the reservoir. At depth, changes in stress can cause shear fracturing, which generates microseismicity. Using the technique of continuous seismic recording from an array of subsurface sensors, one can hope to record the microseismic events, and detect the arrival times of their P- and S- wave, and ultimately locate the hypocentres of the source in three dimensions. Mapping the hypocentre locations relative to changes in time provides insight into the physical processes at work within the reservoir.

Data acquisition

A set of eight 3-component geophone sondes were installed in the monitoring well. These sondes are sensitive to ground motion and have axis directed along the borehole (Z) and two axes perpendicular to the hole (X, Y). Output signals from the sondes travel along two multiconductor cables to the surface where they are recorded by a seismic data recorder. This recorder, manufactured by Terrascience Systems Ltd is a Terrascience Acquisition Recorder (TAR). It is capable of recording 24 channels with 24-bit resolution at sample rates up to 3750 samples per second. The TAR does not have any onboard storage. Instead, it relies on a Windows computer, connected by an Ethernet network, to process and store the data as it is acquired. This computer is charged with analyzing all the data for the occurrence of microseisms in real time. Whenever a microseism-like pattern is visible in the data, the PC saves a snapshot of the data to a disk file. These files contain the period before, during, and after a potential microseismic event.

Data storage is provided by a series of removable hard drives connected to the seismic acquisition PC. Over 240 GB of data have been acquired to date, and the removable drives have proven an efficient way to retrieve the data. Although data are stored in a Terrascience-proprietary format, the company has as supplied software for viewing and exporting this data to other formats. Terrascience has also released the file format information, allowing us to write programs which read directly from these files.

Event detection is performed using the STA/LTA algorithm. The STA/LTA algorithm first computes the average signal amplitude within two moving windows (one short, one long) and then divides the short term average by the long term average. The resulting ratio is a measure of the signal’s relative increase in strength. When the ratio reaches a threshold value, the instrument’s data capture mechanism is triggered, and a file containing a snapshot of data is recorded to disk. The STA/LTA algorithm is relatively robust, and has many years of use in the field of earthquake detection. The Terrascience implementation of STA/LTA allows one to specify the window lengths (short and long) as well as the threshold ratio required to trigger the instruments. Since individual channels may exceed the STA/LTA threshold due to noise spikes, it is advantageous to add additional criteria to the event detection system. One can instruct the TAR system to disregard cases when the total number of triggered channels or triggered sensors is less than some amount within a time window. At the Penn West site, TAR requires triggers on three or more channels within 100ms before an event is captured. This greatly reduces the number of false event determinations. Additionally, channels which are frequently noisy have been excluded from the event detection algorithm as a way to prevent unwanted event files.

Physical layout

The microseismic monitoring equipment is located in a shack beside the observation well (Figure 17).

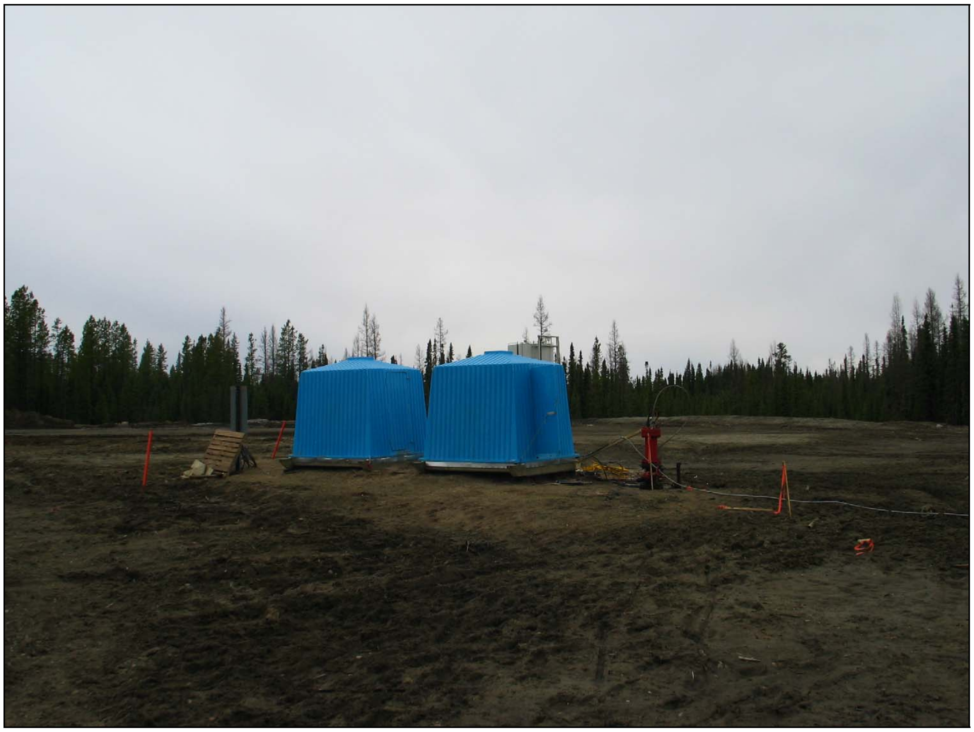

FIG. 17. Passive seismic monitoring instrumentation shack (right).

The geophone sondes are connected to the surface instrumentation via two multi-conductor cables which terminate within the monitoring shack. Figure 18 shows a picture of the recording instrumentation in the monitoring shack.

FIG. 18. The passive seismic recorder and associated equipment. The top shelf houses a cellular phone modem and antenna (now moved to an external mount) and the TAR unit. Two two yellow cables entering the TAR from the right are the signal cables coming from the sondes. The lower shelves house a PC system used to analyse and record the microseismic data.

Data Communications

In order to ensure continued operation of the seismic recorder, and to view and obtain mid-term results, we elected to install a modem to provide network access to the seismic monitoring system. Because the monitoring shack is far from any communication lines, the only option for inexpensive data access was to use a modem which communicates wirelessly via the cellular phone system. A Cypress Systems Chameleon CT-110 wireless modem was purchased, and a small antenna was installed on the roof of the shack. This modem provided very slow access to the passive seismic monitoring computer.

Although the slow data access was suboptimal, a reliable connection would have been very beneficial to the project. Unfortunately, this particular Chameleon modem proved ill-suited for the task due to its inability to keep a network connection operating. The loss of data connectivity for weeks at a time made it very difficult to monitor the recording system. Although the passive seismic system continued to operate in the absence of external influences, we believe that many of the acquisition parameters could have been adjusted better (and more frequently) had the modem been fully operations.

Results

There have been only a few events located in the dataset which appear to contain seismic data. Based on the code length, some events contain nearby seismicicity (Figure 19) while others originate several hundred (or thousand) kilometers away (Figure 20). These two cases indicate that the majority of geophone elements are operational.

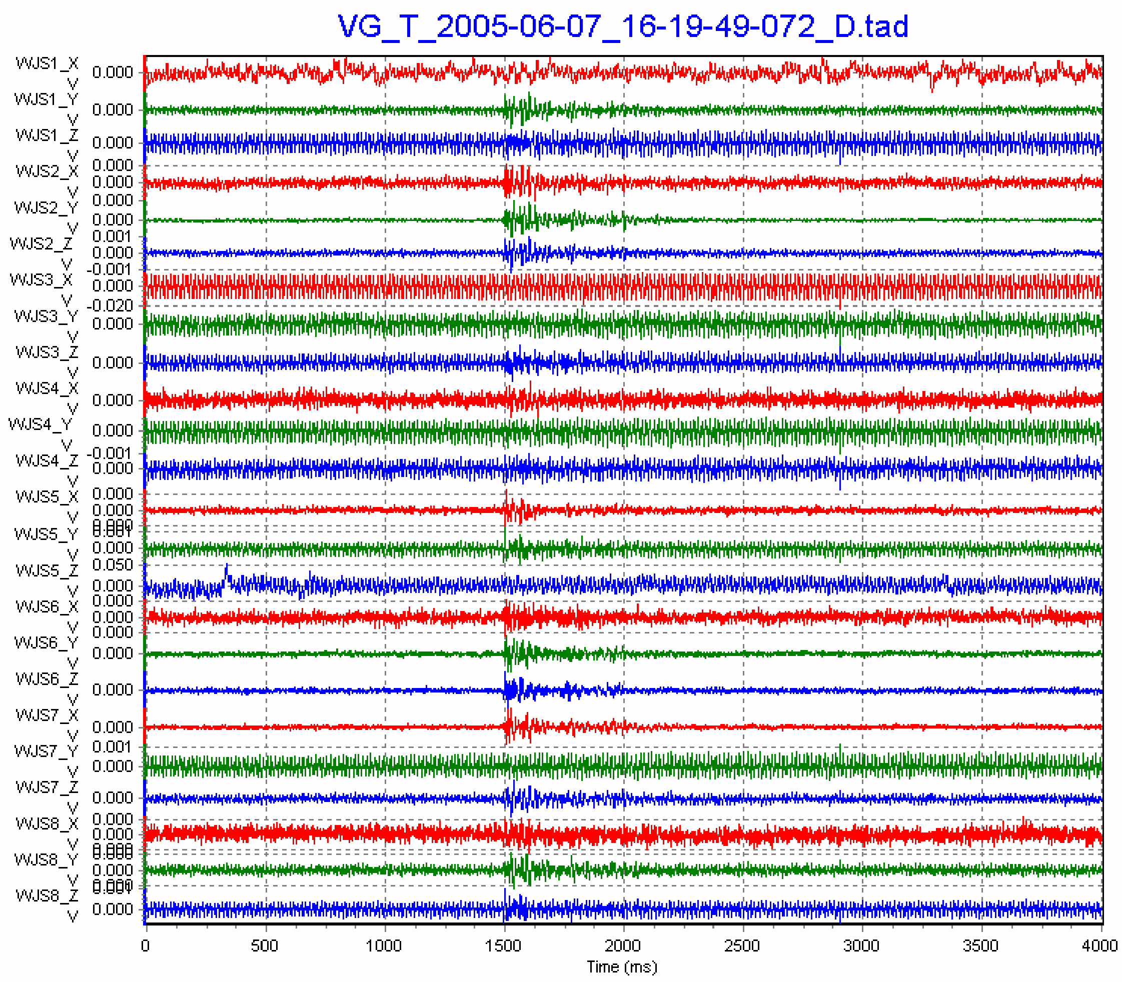

FIG. 19. A seismic event from June 7th, 2005. This event is one of the few events which illustrates nearby seismicity.

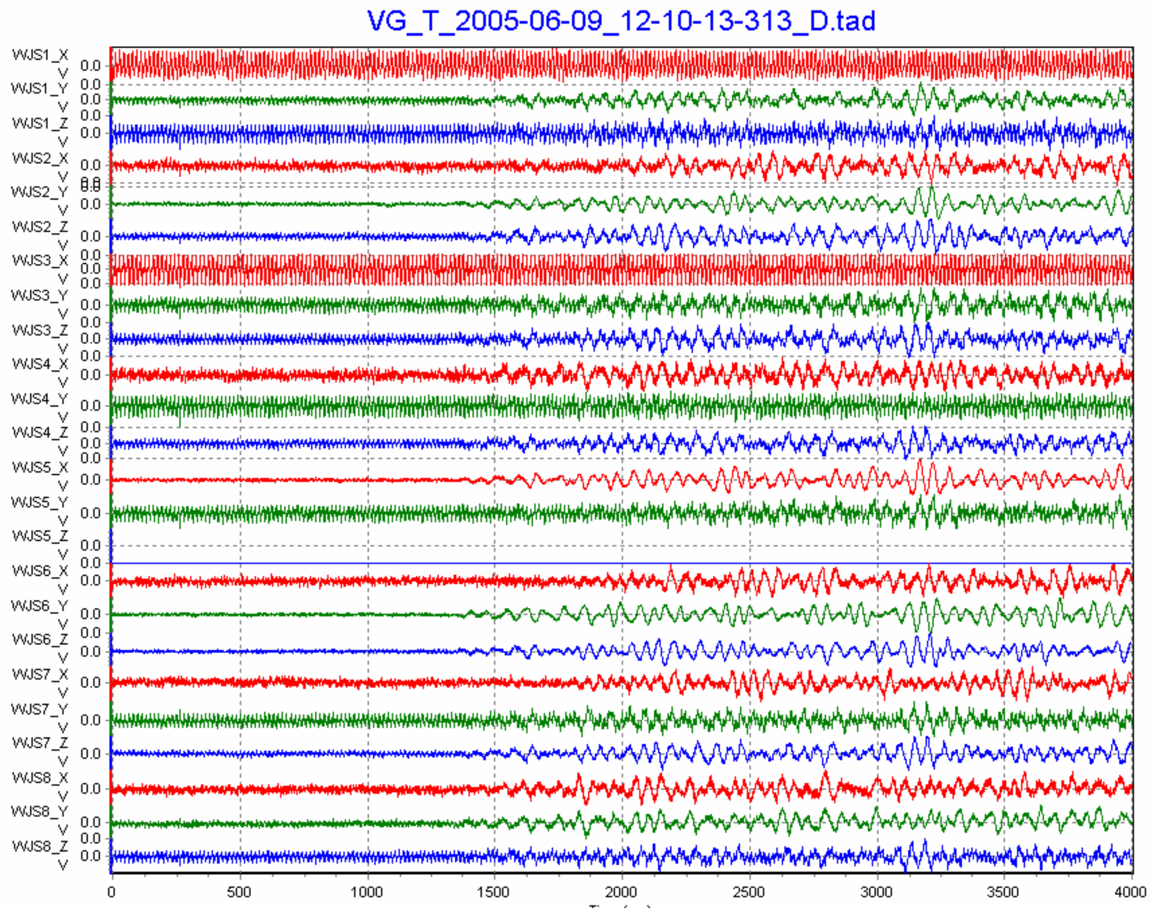

FIG. 20. A teleseismic event is detected and recorded by the passive seismic monitoring system. Events of this nature show that the seismic monitoring system is largely functional. Two channels (WJS1_X and WJS3_X) show large amounts of 60 Hz noise.

The geophone sondes are unpowered, and the geophone signals must travel from depth to the surface without any signal enhancement of conditioning. Since the signals travel a great distance at low amplitudes, there is ample opportunity for the ingress of noise into the recordings. Based on preliminary data, we see an abundance of noise on the signal coming from the sondes (Figure 21). Two channels are saturated with 60 Hz electrical noise, probably a result of one of the two differential lines having been severed or shorted to the drill pipe. The remaining channels contain intermittent noise which is often bursty in nature. We have seen very little microseismicity. Since we do not know how much microseismicity to expect, it is difficult to draw conclusions about the suitability of the equipment for thus purpose. A complicating factor is the likelihood that the geophone cable suffered damage as a result of well calming operations during the cementing process. Our initial review of the data shows that STA/LTA algorithm is poorly equipped to distinguish between microseismic events and bursty electrical noise – particularly when the noise appears coincidentally on multiple channels. Small changes to the event detection parameters make a large difference in the system's sensitivity. In some cases, the sensitivity was much too high, and hundreds of thousands of event files were captured in a matter of days. Difficulties with remote communications made it difficult to iteratively-adjust the event detection parameters. As a result, a large amount of work will be required to thin the existing dataset and extract only those event files which contain microseismic activity.

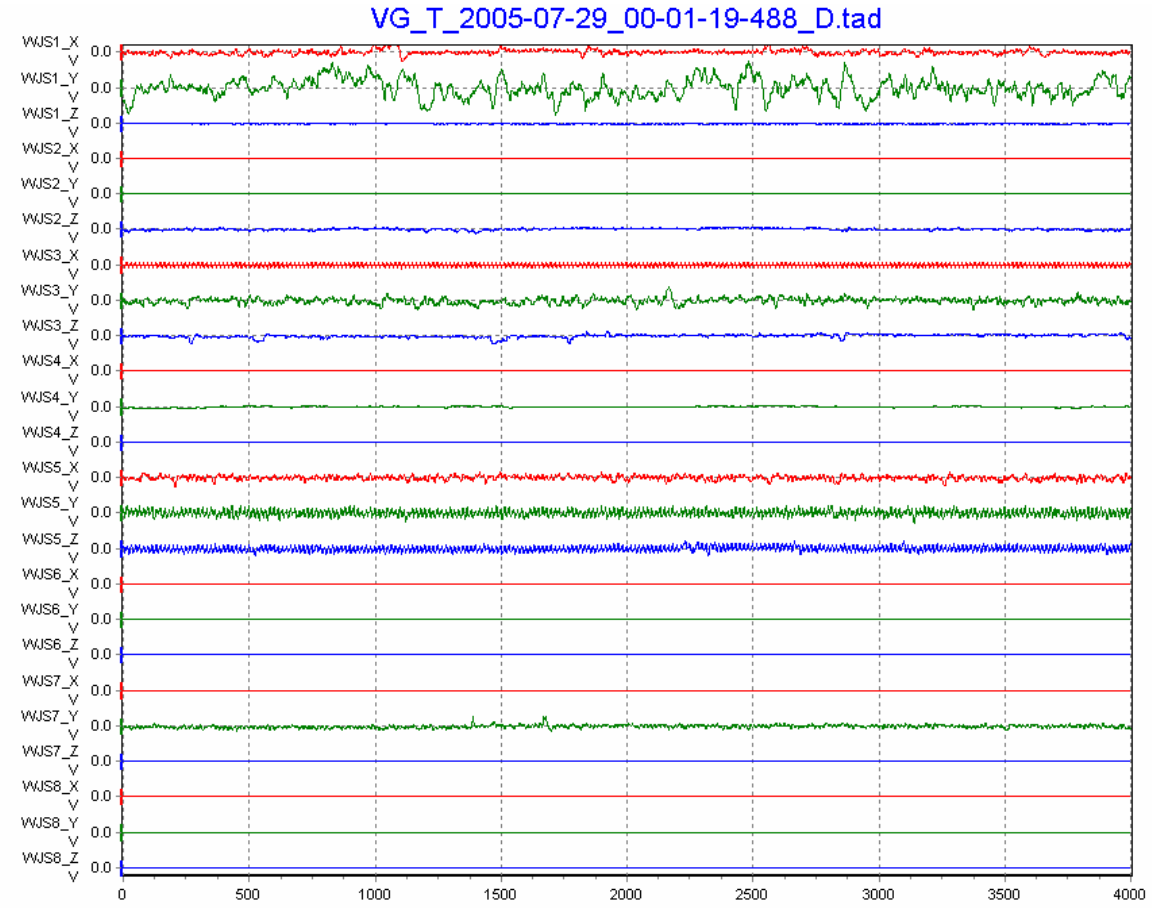

FIG. 21. Typical electrical noise record. This record was plotted with equal trace gain applied to all traces.

DISCUSSION

For the majority of the early study period, the event detection configuration for the seismic recorder was set to an overly sensitive setting. Over half a million event files were recorded between April and September 2005. A cursory examination of these event files shows that they are largely full of electrical noise. Only a handful of microseismic events have so far been extracted from the dataset. Due to the size of the dataset, an automated method for locating microseismic events in the dataset is being developed. Although the overwhelming number of noise files does present a problem, we are hopeful that if any microseismicity occurred, the event detection parameters were set in such a way that the event would have been recorded. We hope that future analysis of the dataset will indicate whether or not the CO2 injection induced microseismicity.

SUMMARY

The baseline seismic program at the Penn West CO2 –EOR site has been successfully accomplished. High quality seismic data from both the surface seismic program and the downhole geophone array have been acquired and processed. Passive seismic monitoring with the downhole array has also been recorded although not a lot of seismicity has been observed.

Additional processing and interpretation of the surface seismic and VSP data will be undertaken through the Fall and early winter of 2005/2006 and we anticipate recording the first monitor seismic survey in January, 2006.

ACKNOWLEDGEMENTS

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