A 3C-4D surface seismic and VSP program for a coalbed methane and CO_2 sequestration pilot, Red Deer, Alberta

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ABSTRACT

CREWES is embarking on a three-year program to develop and conduct a repeated seismic monitoring experiment at a site in Alberta that is proposed for coalbed methane (CBM) production, stimulated by CO_2 injection. The main objective is a proof-of-concept test for seismic-imaging technology to successfully monitor the motion of the subsurface gas plumes and assess whether time-lapse seismology can verify that the injected gases are truly sequestered. Secondary objectives are to test seismic imaging technology to monitor water withdrawal from the coal zone prior to CO_2 injection and methane production. The site is near Red Deer, Alberta, where coals of the Ardley Zone of the Lower Tertiary-Upper Cretaceous Scollard Formation are up to 8 m thick at a depth of approximately 290 m below surface. Based on numerical modelling, a surface seismic has been designed with a 400 m x 400 m patch, orthogonal source and receiver lines 40 m apart, with shot and receiver intervals of 10 m. A vertical seismic profile survey has also been designed, with 50 m source offsets to a maximum offset of 250 m.

INTRODUCTION

Coalbed methane (CBM) is predicted to be a significant energy resource in Alberta in the future and this project will assist in the optimization of production through seismic monitoring of coal seam dewatering, CO_2 injection, and methane production. In addition, time-lapse seismic surveys will play a crucial role in the verification of geological sequestration of greenhouse gases over extended periods of time. The verification of greenhouse gas sequestration (in this case CO_2) is critically important because the public must be assured that the gases have been removed permanently from the surface environment. Geological sequestration of CO_2 is attractive for Canada since a large percentage of our CO_2 emission comes from fixed-point sources such as power plants and petroleum processing facilities. If these emissions are captured and delivered to a sequestration site, they will not be released into the atmosphere. However, merely injecting gases into a reservoir does not guarantee that they will stay there. The gas could leak back to the surface or into valuable aquifers through a variety of mechanisms. Seismic imaging is a viable technology that can create detailed images that document the motion of the injected gas (Chadwick et al., 2000; Gibson et al., 2002).

Since atmospheric concentrations of greenhouse gases, predominantly CO_2 but also H_2S, CH_4, and other naturally occurring gases produced by burning fossil fuels, may be pollutants or correlated with global warming, technologies that reduce their release into the atmosphere are becoming increasingly important. CO_2 sequestration involves “the removal of CO_2 (or other gases), either directly from anthropogenic sources or from the atmosphere, and disposing of it either permanently or for geologically significant time periods” (Bachu, 2000a). Several methods of greenhouse gas sequestration are possible, including biological, oceanic, or subsurface (geological) sinks. Biological sequestration through biomass fixation requires 40-50 years for a large forest to absorb a significant amount of carbon (Bachu, 2000b). Oceanic fixation has environmental implications that are poorly understood and is limited to GHG sources near an ocean. Therefore, subsurface sinks are the most attractive option, using proven technology from the energy industry, and co-existing with other land uses such as agriculture or fishing industries (Bachu, 2000b; Herzog, 2002). Any suggested CO_2 removal strategy will need to provide a method of quantifying the amount of CO_2 initially sequestered, and monitor the system over time, ensuring no leakage back to the atmosphere (Chadwick et al., 2000). Geological sequestration of CO_2 involves pumping fluid CO_2 underground and trapping it in porous rocks, in the same manner that hydrocarbons are trapped. This is possible in depleted oil and gas reservoirs, coal beds, and high-salinity aquifers (Wawerski and Rudnicki, 1998; Law and Bachu, 1996). Injection of CO_2 into oil reservoirs is currently used as a method of enhanced oil recovery at a number of sites, such as the Weyburn oilfield in Saskatchewan, which injects CO_2 stripped from a coal gasification plant (Chadwick et al., 2000). Whereas depleted oilfields often retain significant residual oil saturation, closed depleted gas reservoirs may have primary recovery up to 95% of the original gas in place (Bachu, 2000b). CO_2 may be used to repressurize the reservoir to its original pressure. At present, geological sequestration of CO_2 in coal beds is the most attractive mitigation measure since it also contributes to the development of unconventional energy resources.

This seismic program is being undertaken near Red Deer, Alberta, in conjunction with Suncor, the CBM program operator, and Suncor's industry and government partners. Funding for the seismic studies has been obtained through a 3-year grant from the Natural Sciences and Engineering Research Council of Canada (NSERC), and initial one-year grant from the Alberta Energy Research Institute (AERI), along with anticipated modest cash and in-kind contributions from CREWES.

OBJECTIVES

In the proposed CBM experiment, it is anticipated that the bulk elastic properties of the coal zone will change with dewatering of the coals, and that additional changes in physical properties of the coal zone will also occur with CO_2 flooding. Changes, particularly in density and velocity, in turn affect the amplitude and traveltimes of reflected seismic waves. Thus, a baseline survey conducted prior to any CO_2 injection will be compared to a survey conducted after a set period of injection to monitor the effects of gas on the reservoir. The magnitude of the change in seismic properties is dependent on the elastic properties of the host sediments. Poorly consolidated rocks, rocks with open fractures, and rocks under low overburden pressure will be those with seismic properties most affected by injection or production (Wang, 1997).

Seismic images taken at various stages of the program will be compared to delineate the dewatered zone and to track the motion of the subsurface CO_2 plume. This comparison of seismic images from repeated seismic surveys is known as time-lapse imaging and is an emerging methodology for the monitoring of subsurface reservoirs. In addition to verification of sequestration, such monitoring may also enable the intelligent selection of additional injection and production wells to optimize CBM production. Cross-well seismic methods may also be used in later phases of the project if sufficient funds are available.

PROGRAM

Repeated surface 3C-3D reflection seismic and VSP surveys are proposed at the CBM site. Four program phases are planned:

Phase 1: Baseline multicomponent surface seismic survey and walkaway VSP. The objectives of these surveys are to image the Ardley Coal zone – to provide an accurate depth model of the coals in the survey area, and to detect lateral facies changes in the coals that may inhibit gasification. We also wish to evaluate converted-wave data for possible fracture mapping within the coals. Split shear-wave data has used by other researchers in coalbed methane projects (e.g. Thomsen et al., 1995). Joint inversion of both datasets will also be undertaken (Margrave et al., 2001). In addition, a limited number (~6) of geophones will be installed permanently in shallow observation wells to enable passive seismic monitoring to be undertaken.

Phase 2: Seismic imaging of the dewatered zone – to monitor the dewatering process and track lateral and vertical extent of dewatered zone.

Phase 3: Seismic imaging of the injected CO_2 plume – to monitor and track the plume within the coal zone and to optimize injection rates. Cross-well and in-seam seismic experiments may be included in this phase of the program, once the production wells have been drilled.

Phase 4: Seismic verification of CO_2 capture within the coals – to ensure that there is no significant leakage of CO_2 out of the coal zone, particularly into overlying strata that may yield pathways to the surface.

PROGRAM DESIGN

Phase 1

In this phase of the program, the baseline 3C-3D seismic survey will be undertaken at the chosen site, and the data fully processed. The development plan at the site is to have 3 drillholes, made up of 1 injection and 2 production wells. The plan proposed by Suncor is for the two producing wells to be each 200 m from the injector. Figure 1 shows a P-wave sonic log from an existing well near the survey site. The Ardley Coal zone is approximately 10 m thick and is at a depth of about 290 m and is characterized by low P-wave velocity (~2200 m/s) with respect to the host sediments, which have velocities of ~3000 m/s. No dipole sonic logs or density logs were available for this well. However, a discussion of the S-wave velocities and densities is given in a companion paper in this report (Richardson and Lawton, 2002).

For survey planning, the 10-34-38-28W4 sonic log was input into SYNTH, and P-P and P-S offset synthetic seismograms were generated. Since no shear sonic or density logs were available, Vp/Vs = 2 was assumed, and densities were assigned using Gardner's equation. Figures 2 and 3 shows a P-P offset synthetic seismogram plotted in time and in depth respectively. A maximum offset of 400 m was used, and the seismogram was created with an 80-Hz Ricker wavelet. The coal event is indicated by a high-amplitude trough-peak event at 0.25 s (Figure 2), with maximum incident angles of about 35 degrees at the farthest offset (incidence angles are shown as overlays on the offset gathers). There is slight evidence of NMO stretch at the far offset, so the maximum offset of 400 m is reasonable for survey design.

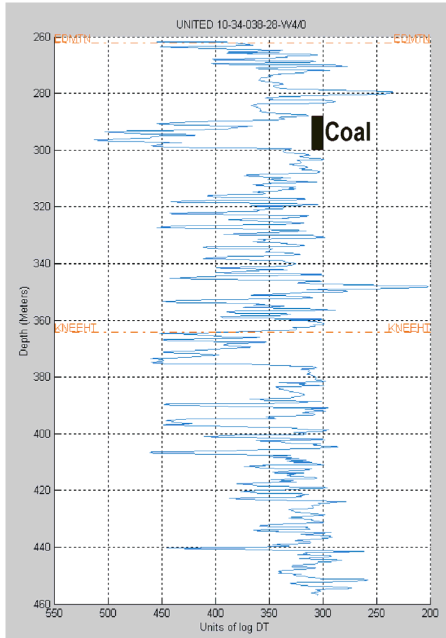

FIG. 1: Sonic log from 10-34-38-28W4

Figures 4 and 5 show P-S offset synthetic seismograms in time and in depth respectively. A 40-Hz Ricker wavelet was used to create the seismograms and the same maximum offset was the same as had been used for the P-P modelling (400 m). The P-S coal event is a tuned, trough-peak event, with the maximum amplitude occurring over the mid-offset range (200 to 300 m). At far offsets, there is some wavelet distortion probably related to the large incident angles at far offsets (in excess of 40 degrees).

Figure 6 shows a comparison of P-P and P-S synthetic seismograms, plotted in depth. Given the wavelets used in the modelling, the major reflection events can be correlated between the seismograms easily. In the actual data, some differences are to be expected as *Vp/Vs* changes with depth. Logs used by Richardson and Lawton (2002) show that *Vp/Vs* in coals can be as high as 2.4. However, the modelling presented in this paper is deemed to be appropriate for the design of the surface 3C-3D survey.

Figure 7 shows a template of the source and receiver lines for the proposed surface seismic survey, with details provided in Table 1. The total survey area is 400m x 400m.

Table 1: Design for 3C-3D surface seismic survey

Source Parameters (N-S)		**Receiver Parameters (E-W)**	
Source line spacing	40 m	**Receiver line spacing**	40 m
Source spacing	10 m	**Receiver spacing**	10 m
# sources/line	41	**# 3C receivers/line**	41
Total number of sourcepoints	451	**Total number of receivers**	451

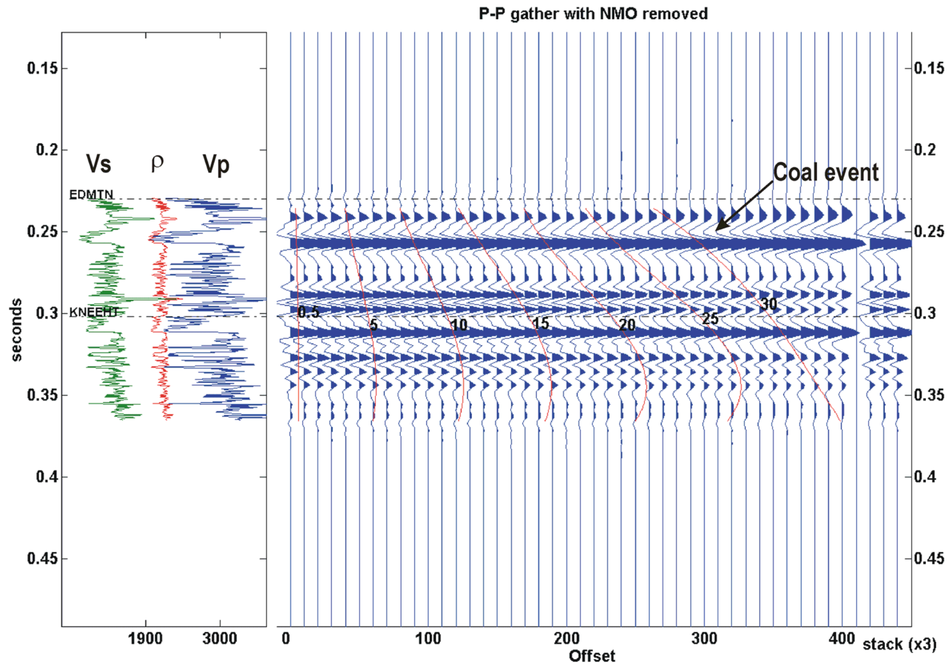

FIG. 2: P-P offset synthetic seismogram (time) based on the 10-34-38-28W4 sonic log. Offsets 0 to 400 m; 80 Hz Ricker wavelet. Last 3 traces are stacked from the gather. Overlay shows incidence angles.

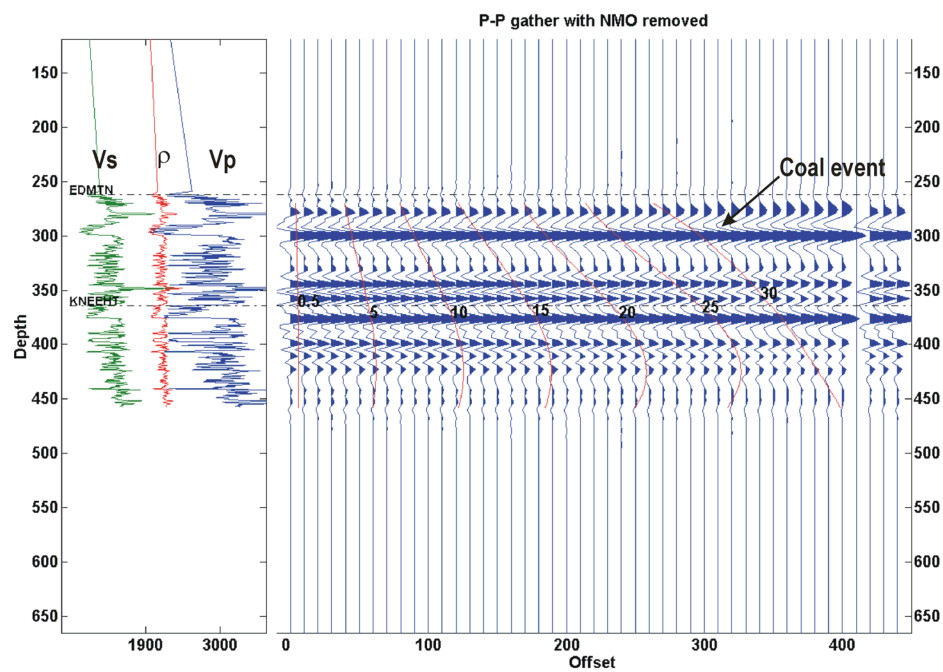

FIG 3: P-P offset synthetic seismogram (depth) based on the 10-34-38-28W4 sonic log. Offsets 0 to 400 m; 80-Hz Ricker wavelet. Last 3 traces are stacked from the gather. Overlay shows incidence angles.

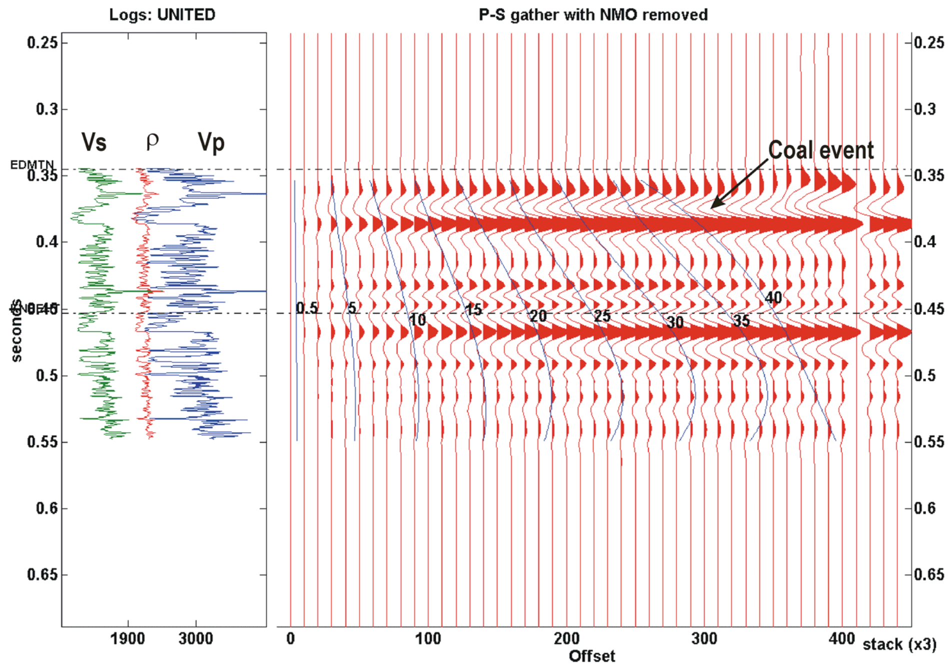

FIG. 4: P-S offset synthetic seismogram (time) based on the 10-34-38-28W4 sonic log. Offsets 0 to 400 m; 40-Hz Ricker wavelet. Last 3 traces are stacked from the gather. Overlay shows incidence angles.

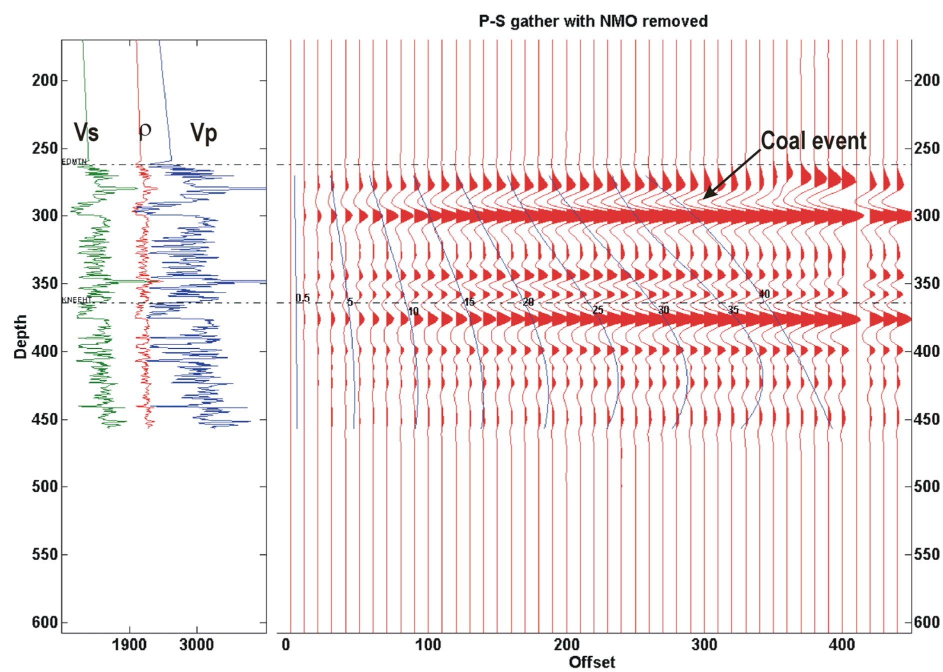

FIG. 5: P-S offset synthetic seismogram (depth) based on the 10-34-38-28W4 sonic log. Offsets 0 to 400 m; 40 Hz Ricker wavelet. Last 3 traces are stacked from the gather. Overlay shows incidence angles.

Phase 1 of the 3C-3D surface seismic program will be undertaken after the injector well has been drilled (Figure 7), and if subsequent permeability tests are favourable for CBM production. A vibrator source will be used for the survey due to environmental restrictions. Up to 6 three-component geophones will be permanently installed at shallow depths around the well pad, in order to calibrate repeatability between successive surveys and also for possible passive monitoring experiments.

A walkaway vertical seismic profile (VSP) will also be undertaken during Phase 1, with 5 source offsets at 50-m intervals from the well. The purpose is to tie the seismic data to depth, to maximize reflection bandwidth for optimum inversion to elastic parameters of the coal zone, and for attenuation measurements. For the VSP, a 3-component geophone tool will be used, with a 5 m receiver interval for the zero-offset source location, and a 15-m receiver interval for the offset source locations. The receiver aperture will be from total depth (~310 m) to as shallow as possible. The VSP will be run in the well after casing has been set.

Figures 8 and 9 show the P-P and P-S fold derived from the surface seismic survey, with offsets limited to 400 m. The P-S fold (Figure 9) has been computed at a depth of 290 m, which corresponds approximately with the top of the coal zone. In both P-P and P-S imaging, subsurface fold is at least 45 over the area that encompasses the injection and proposed production wells. P-P and P-S minimum offset distributions are shown in Figures 10 and 11 respectively, with the P-S minimum offset distribution (Figure 11) having a slightly greater spread than the P-P minimum offset distribution (Figure 10). However, this is not a significant issue as the P-S amplitudes at source-receiver offsets of less than 90 m are predicted to be low relative to those at mid-offsets (Figures 4, 5). Figures 12 and 13 show the maximum offset distributions for the P-P and P-S case respectively. The distribution is excellent for P-S imaging (Figure 13) and acceptable for P-P imaging (Figure 12).

Phase 2

Phase 2 surveys are planned when dewatering has been completed and methane production has started. A time-lapse seismic response is predicted due to methane saturation within the cleats as pressure is reduced. At this time, it is anticipated that one or both production wells will be drilled. If funding is available, then cross-well (including in-seam) surveys will also be included in the Phase 2 programs.

Phase 3

Phase 3 surveys will be undertaken after an initial period (probably several months) of CO_2 injection, with the purpose to determine whether the extent of the CO_2 plume can be monitored from surface and/or borehole seismic surveys.

Phase 4

The final time-lapse survey program is planned after CO_2 breakthrough at the production wells. At this time, the coal zone between the injection and production wells will be saturated with a CO_2-CH_4 mixture.

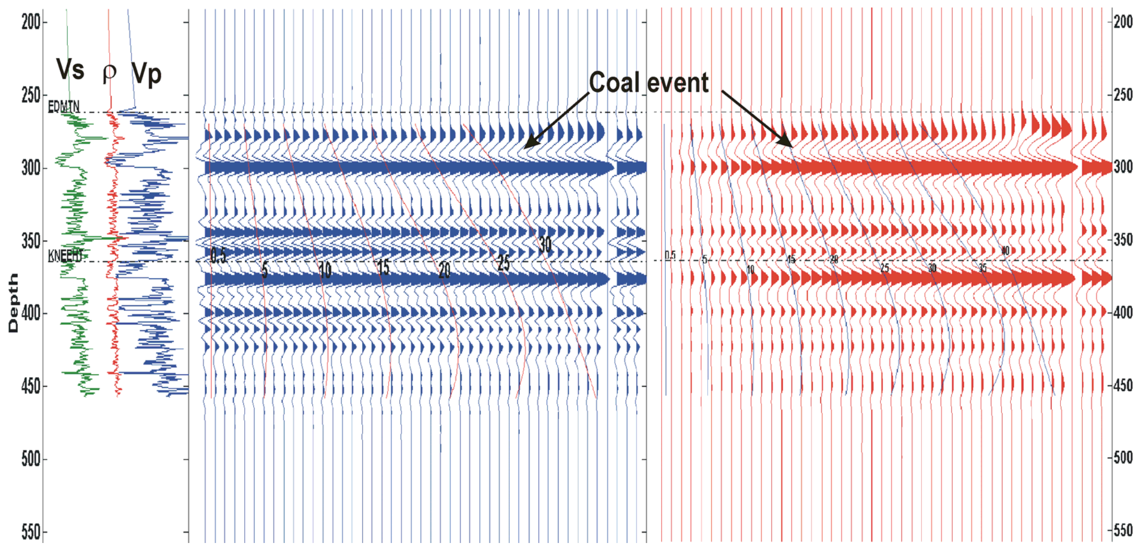

FIG. 6: Comparison of P-P and P-S offset synthetic seismograms displayed in depth. Left is P-P (80-Hz Ricker wavelet); right is P-S (40-Hz Ricker wavelet). Overlays show incidence angles.

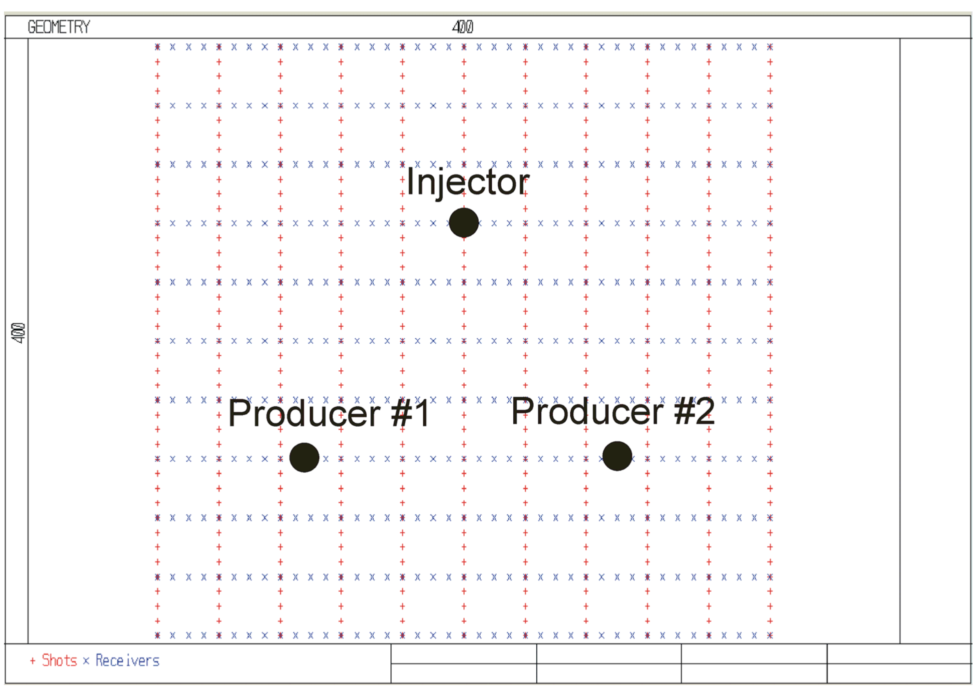

FIG. 7: Surface source and receiver geometry for planned 3C-3D surface seismic survey to monitor enhanced coalbed methane production, stimulated with CO_2 injection.

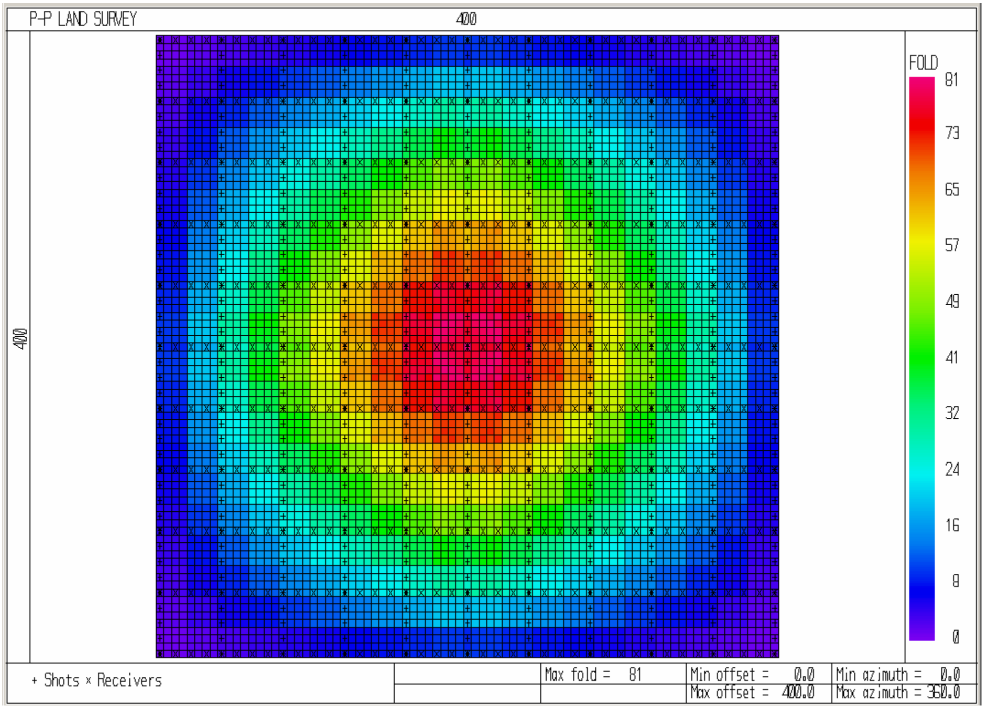

FIG. 8: P-P fold, coalbed methane 3C-3D seismic survey. Offsets up to 400 m.

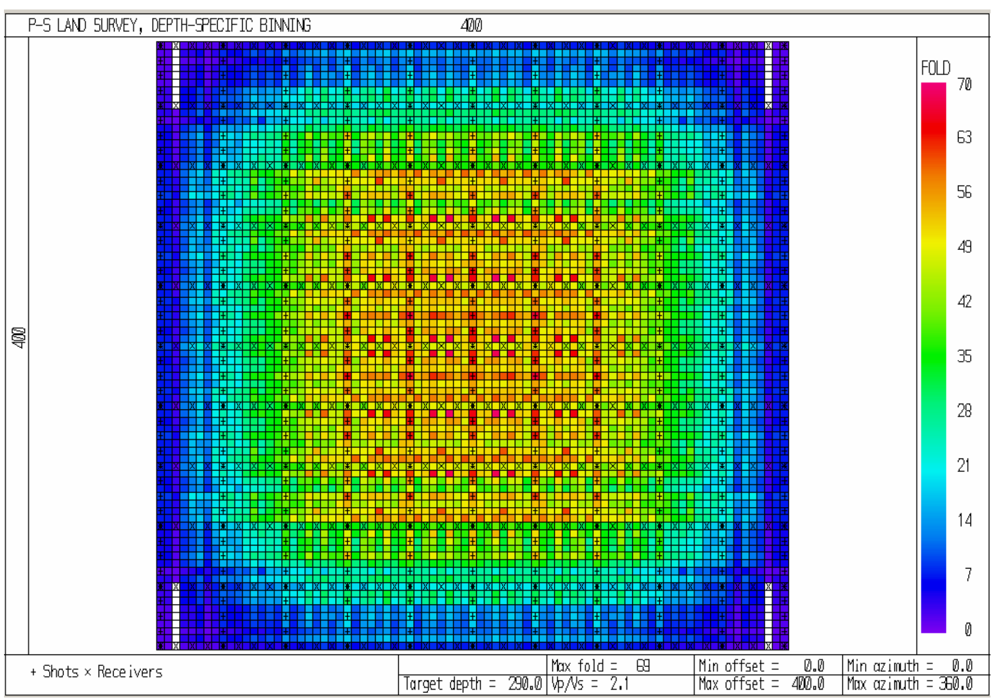

FIG. 9: Depth-specific P-S fold, coalbed methane 3C-3D seismic survey. Vp/Vs = 2.1 and depth = 290 m. Offsets up to 400 m.

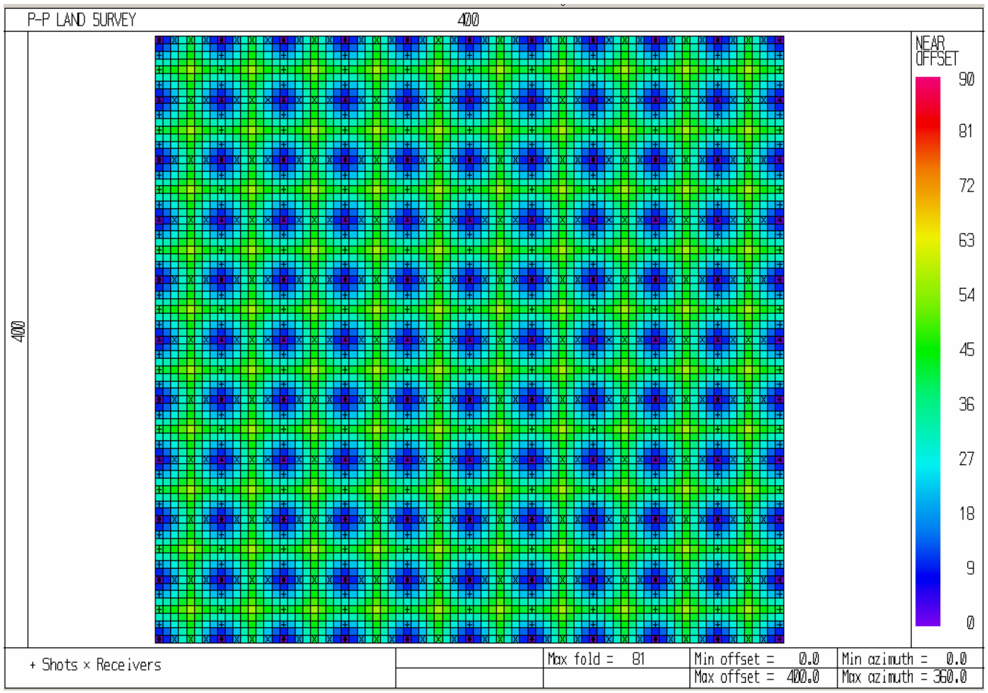

FIG. 10. P-P minimum offset distribution, coalbed methane 3C-3D seismic survey.

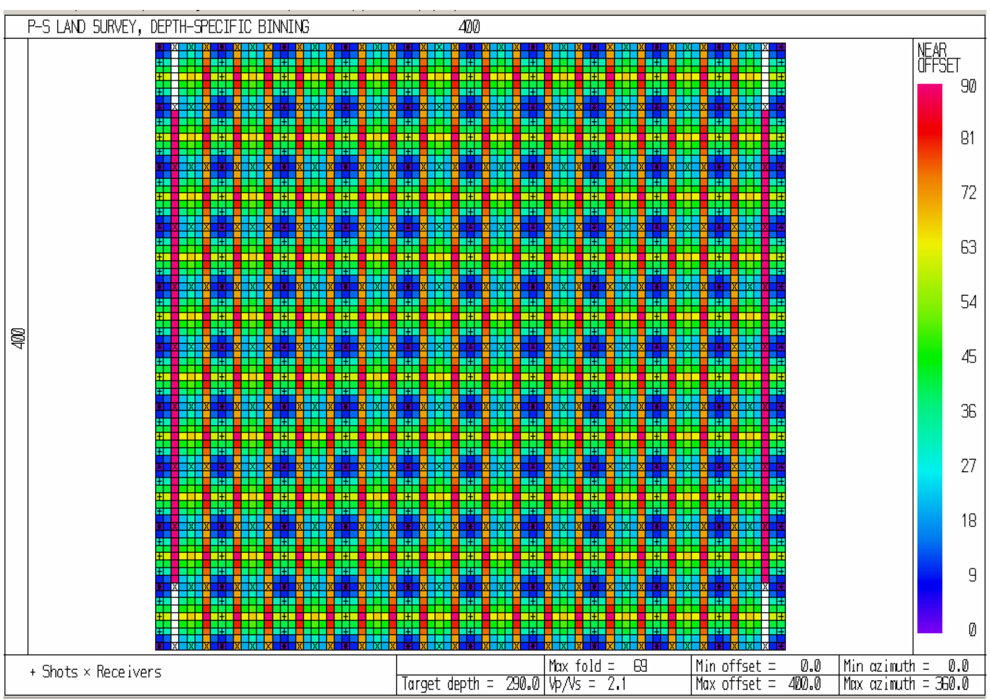

FIG. 11: P-S minimum offset distribution, coalbed methane 3C-3D seismic survey.

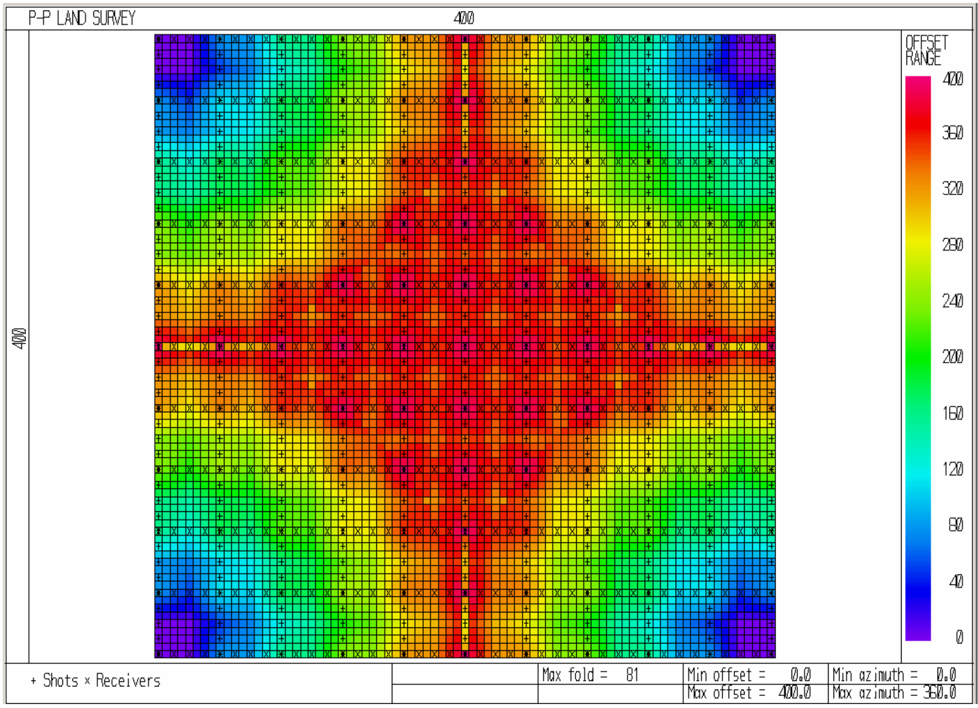

FIG. 12: P-P maximum offset distribution, coalbed methane 3C-3D seismic survey.

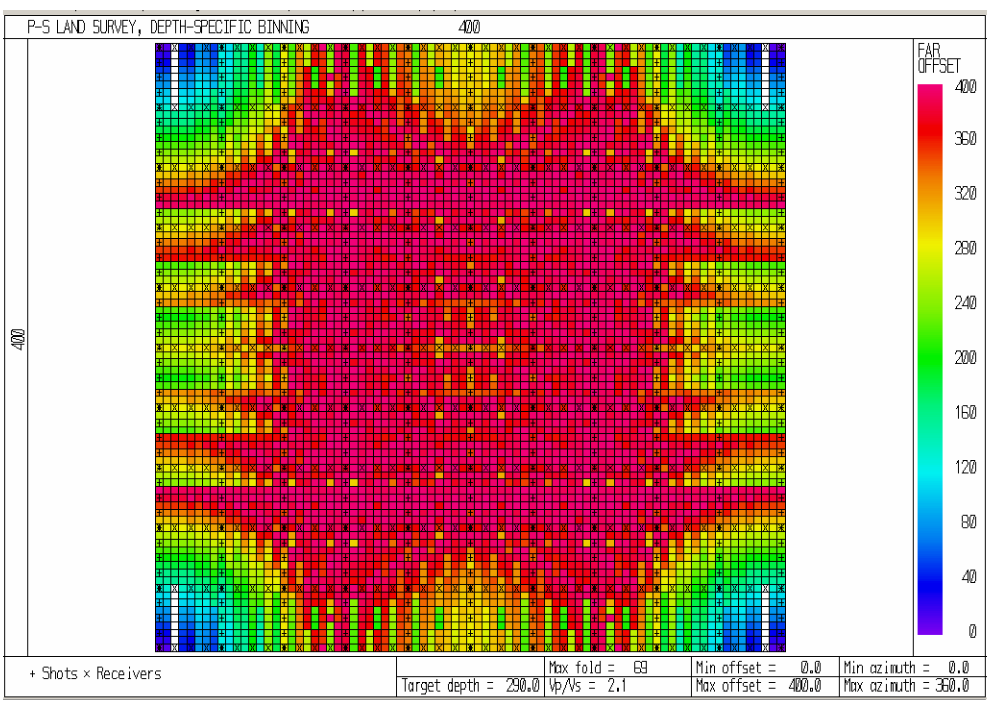

FIG. 13: P-S maximum offset distribution, coalbed methane 3C-3D seismic survey.

CONCLUSIONS

To our knowledge, the planned 3C-3D surface seismic survey will be the first undertaken in Canada to monitor coalbed methane production, enhanced by CO_2 stimulation. The survey design has been based on offset-synthetic seismograms and depth-specific converted-wave modelling using realistic properties based on logs from nearby and regional wells. The program has significant potential for development of this unconventional resource. It also has advantages through production of clean energy and mitigation of greenhouse gas emissions.

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