Seismic monitoring with continuous seismic sources

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ABSTRACT

The Containment and Monitoring Institute has established a Field Research Station southwest of Brooks, Alberta which will be used to study how injected carbon dioxide behaves in the subsurface, as well as to test various measurement, monitoring and verification technologies to determine their applicability for use in monitoring subsurface fluid injection projects. One technology of interest that will be tested is the use of permanent, or continuous, seismic sources.

A synthetic source function representing the sweep of a continuous seismic source was created and used to generate synthetic shot records. Additionally, a correlation routine was developed to handle multiple shot records, each originating from an individual sweep, and then remove the sweep overprint and suppress noise. Two potential correlation and stacking workflows were tested, and were found to produce comparable results. However, stacking recorded data to suppress noise before correlating with the source function produced a final shot record up to 10% faster than correlating before stacking.

To serve as a baseline dataset against which to compare data acquired using a continuous seismic source, a 2D seismic line, acquired in May 2017, was processed. A similar processing flow will be developed and semi-automated for use with continuous source data. Field work is ongoing at the Field Research Station, and includes the installation and testing of permanent sources. Based on raytracing and analysis of offset-dependent synthetic seismograms, an offset of 110 metres between the continuous seismic source and the VSP recording well will give an optimal combination of spatial coverage and angle content in recorded seismic data.

INTRODUCTION

Near Brooks, Alberta, the Containment and Monitoring Institute (CaMI) has established a Field Research Station (FRS), where various measurement, monitoring, and verification (MMV) technologies will be implemented and tested to assess their viability in the monitoring of carbon capture and sequestration (CCS) projects. The FRS is located approximately 190 km southeast of Calgary, Alberta and approximately 25 km southwest of Brooks, Alberta (FIG. 1). At the centre of the FRS is the injection well 10-22-017-16W4, drilled in 2015 (FIG. 2).

At the FRS, several geophysical monitoring technologies have been used, including 3D multicomponent (3C) surface seismic, walkaway and walkaround vertical seismic profiles (VSPs), straight and helically-wound fibre optic cables, surface tiltmeters, and a full suite of geologic well logs. Small amounts of carbon dioxide, approximately 600 tonnes per year, will be injected over a period of five years to study the storage potential of the reservoir, as well as assess the suitability of the various MMV technologies for use in CCS and other fluid injection projects, such as for steam chamber monitoring projects and waterfloods for enhanced recovery.

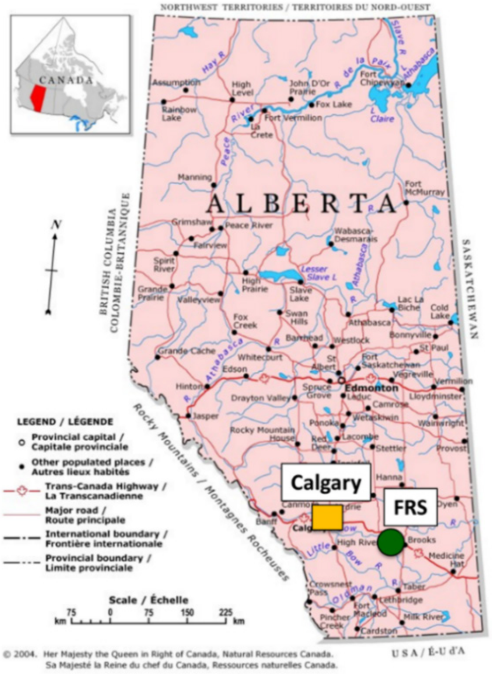

FIG. 1: Location of the Field Research Station (FRS) in Alberta, Canada (Lawton et al., 2016).

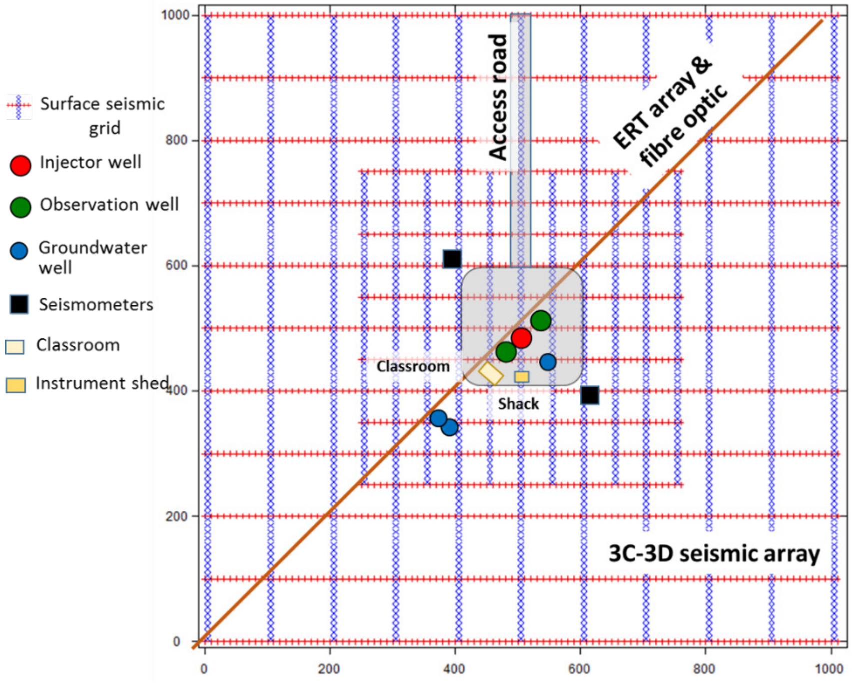

FIG. 2: Schematic of the FRS site (Lawton et al., 2016).

At the FRS, carbon dioxide will be stored on site (FIG. 3) before being pressurized and injected into the Basal Belly River Formation at a depth of approximately 300 metres. The Basal Belly River Formation in this area is known to be composed of shoreface sands, and is overlain by silts and coals from a proximal coastal plain environment. The Basal Belly River sands near the injection site are up to 10 metres thick. Additionally, through previous analysis of gamma ray well logs and lithology logs, it was determined that the siltstones and mudstones overlying the Basal Belly River sands will act as excellent sealing units for injected CO_2 (Isaac and Lawton, 2014a).

FIG. 3: injector well 10-22-017-16W4 (left, in red) and CO_2 storage tank (right).

CONTINUOUS SEISMIC SOURCES

To determine how subsurface reservoirs change over time due to some stimulus, time-lapse seismic surveying is a tool that is of immense interest. Time-lapse surveying allows interpreters to identify four-dimensional changes in the interval of interest. Typical seismic surveys produce a snapshot of the subsurface at a single point in time, and surveys are repeated to track how the subsurface is changing. There are two issues faced by time-lapse surveying: the time interval between surveys, and the survey repeatability. Both issues can be resolved by utilizing permanent seismic sources.

Permanent or continuous seismic sources reduce the time between each monitor survey in time-lapse seismic surveying effectively to zero, as these sources will continually propagate seismic waves into the subsurface and permanent receiver arrays will continually record the Earth's response. Survey repeatability refers to how the source and receiver locations, source type, and other acquisition parameters may change between surveys. As the same permanent source and receiver geometry is continually used, the survey repeatability is excellent.

Continuous seismic sources, also known as orbital vibrators, may be installed on the surface, buried in the near surface, or installed in a borehole, and operate by rotating an eccentric mass around an axis over a sweep of frequencies up to 200 Hz, with each sweep lasting 20-30 seconds. "Orbital vibrator" is an apt name for this type of source, as these sources can be thought of as conceptually equivalent to several Vibroseis sweeps run consecutively, while the mass "orbits" around the axle. Seismic waves are generated by continuous sources due to the coupling between the axle around which the mass rotates and the ground. Consider a typical laundry washing machine with clothes inside. As the washing machine is run, the wet clothes tend to bunch up into a single mass and are pressed against the outer wall of the rotating drum. This unbalanced mass exerts a force on the axle of the washing machine, causing the entire machine to vibrate. This scenario is conceptually very similar to how continuous seismic sources operate, except the source is fixed to the Earth, causing vibrations (seismic waves) to propagate through the subsurface.

The centre of mass of the rotating eccentric wedge causes a radial particle displacement $\boldsymbol{u}$ at the point of contact between the axle and the Earth. For a surface orbital vibrator (SOV), where the axle is parallel to the surface of the Earth, the vertical and horizontal components of the particle displacement can be described by the angle between the line connecting the axis of rotation and the centre of mass, and an arbitrary non-rotation axis (FIG. 4).

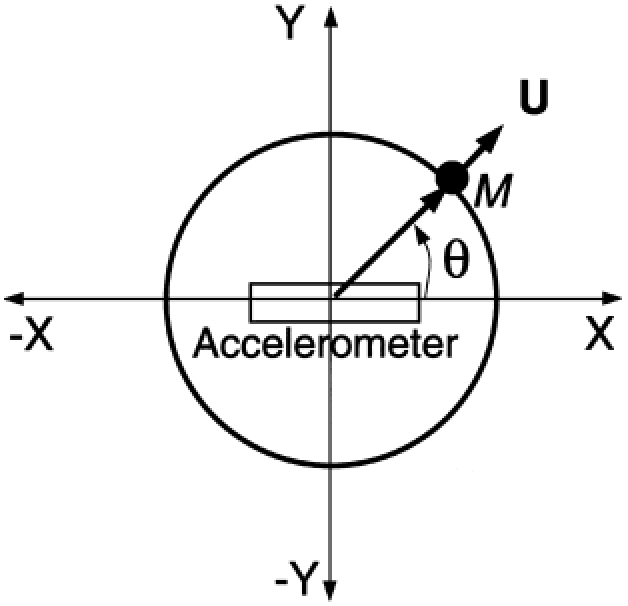

FIG. 4: Schematic of orbital vibrator showing particle displacement relative to an arbitrary coordinate system (Daley and Cox, 2001).

This angle is equal to the product of the frequency, ω, and the time, t. Therefore, assuming the rotation axis is parallel to the ground, the horizontal and vertical components are described in Cartesian coordinates for the clockwise rotation direction by

$$u_{cwx} = A\cos(\omega t) \tag{1A}$$

$$u_{cwy} = A\sin(\omega t) \tag{1B}$$

and for the counterclockwise rotation direction by

$$u_{ccwx} = A\cos(-\omega t) = A\cos(\omega t) \tag{2A}$$

$$u_{ccwy} = A\sin(-\omega t) = -A\sin(\omega t) \tag{2B}$$

where A is the amplitude of the particle displacement u (Daley and Cox, 2001).

After each sweep, the rotation direction can be reversed between clockwise and counterclockwise, thus a component of the recorded data, depending on the rotation axis orientation, can be cancelled by taking the sum or difference of the clockwise and counterclockwise recordings. The consecutive clockwise and counterclockwise sweeps are representative of one "shot" in conventional seismic acquisition terms. For example, by taking the difference of clockwise and counterclockwise data

$$\begin{gathered} u_x = u_{cwx} - u_{ccwx} \\ u_x = A\cos(\omega t) - A\cos(\omega t) \\ u_x = 0 \end{gathered} \tag{3}$$

gives an expression for the horizontal component, and

$$\begin{gathered} u_y = u_{cwy} - u_{ccwy} \\ u_y = A\sin(\omega t) + A\sin(\omega t) \\ u_y = 2A\sin(\omega t) \end{gathered} \tag{4}$$

yields the vertical component. Thus, by taking the difference between the two recorded datasets, we have cancelled the horizontal component of the data while simultaneously boosting the vertical component.

MODELING OF CONTINUOUS SOURCE DATA

To reasonably model the data created by an orbital vibrator seismic source, source functions representing the sweep signature were created. The sweep signatures were assumed to have a linear dependence on frequency and time, and were this simple to create using Equation (4). Only the vertical component of the recorded wavefield was modeled. The maximum frequency achieved by the sweep was 50 Hz and the sweep lasted 20 seconds. A cosine taper of 5 seconds was applied to the start and end of the sweep. The model used to create the synthetic data was a two-dimensional model representing the P-wave velocities of the subsurface at the FRS (FIG. 5).

Synthetic shot records were created using a finite difference approximation to the wave equation, where the source function is inserted at every time step. The approximation was allowed to run for twice the length of the sweep to allow the source function to propagate fully through the velocity model. This can be considered to be the "listen time" between sweeps. It was found that the synthetic shot records recorded using the orbital vibrator sweep signature contained a strong overprint of the sweep which needed to be removed through cross-correlation with the sweep signature to produce interpretable results. On the correlated shot records near zero offset, a strong series of events are observed throughout the length of the section. It is speculated that these events are a consequence of how the source function is propagated through the velocity model, and potentially produce a strong correlation with the sweep signature. This "correlation artifact" can be subsequently removed by producing a correlated shot record from a constant velocity model, then computing the difference between the layered model shot record and the constant velocity shot record.

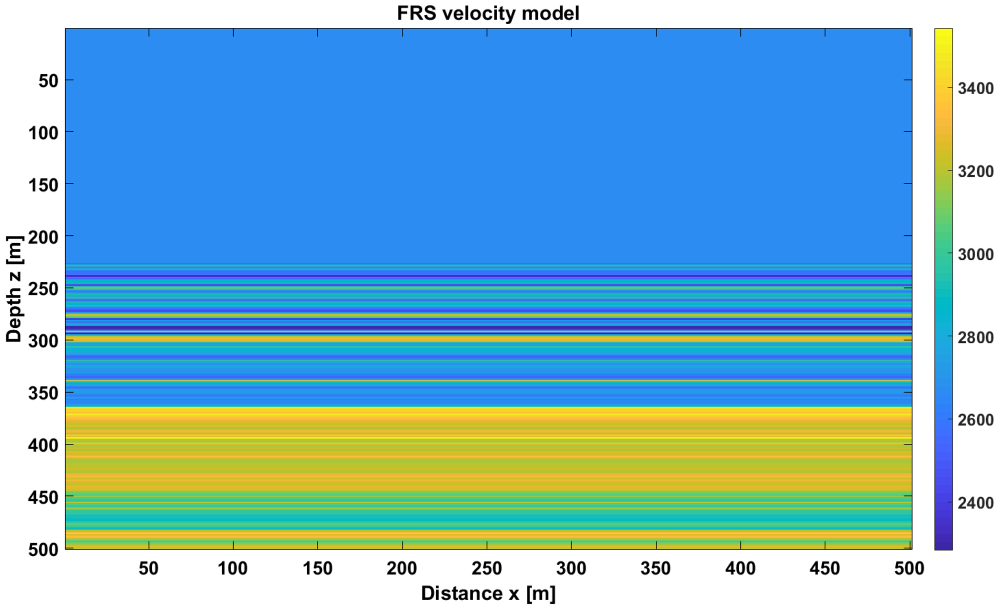

FIG. 5: P-wave velocity model for the FRS (Courtesy M. Macquet, 2017).

Two potential workflows were analyzed to determine the most effective correlation routine for continuous source data: one where correlation with the source waveform was performed for each sweep, then followed by stacking, and one where the shot records from each sweep were stacked and then correlated with the source waveform to remove the sweep overprint. While each workflow produced acceptable results, albeit with a strong correlation artifact present in each record (FIG. 6 and FIG. 7), stacking shot records to suppress noise before correlating with the source waveform was more efficient, running up to 10% faster than the alternative workflow.

SEISMIC DATA PROCESSING

To serve as a baseline against which to compare seismic data acquired with continuous sources, a 2D seismic line was acquired in May 2017 and subsequently processed in October 2017. The most challenging aspect of processing this dataset was the importance of enhancing shallow reflectors, with the target interval between approximately 200 and 300 ms. Similar methods and parameters from previous seismic data processing of data from the FRS were used (Isaac and Lawton, 2014b). The processing flow applied to this dataset is outlined in FIG. 8 below. It follows a conventional approach for data acquired in the Alberta Plains, where reflectors are predicted to have very little dip. To enhance shallow reflectors, a prestack median spatial filter was applied, in addition to poststack Gabor deconvolution. The ProMax software package was used to process the data, and various algorithms were tested in anticipation of application to continuous source data yet to be acquired. The final processed section is shown in FIG. 9.

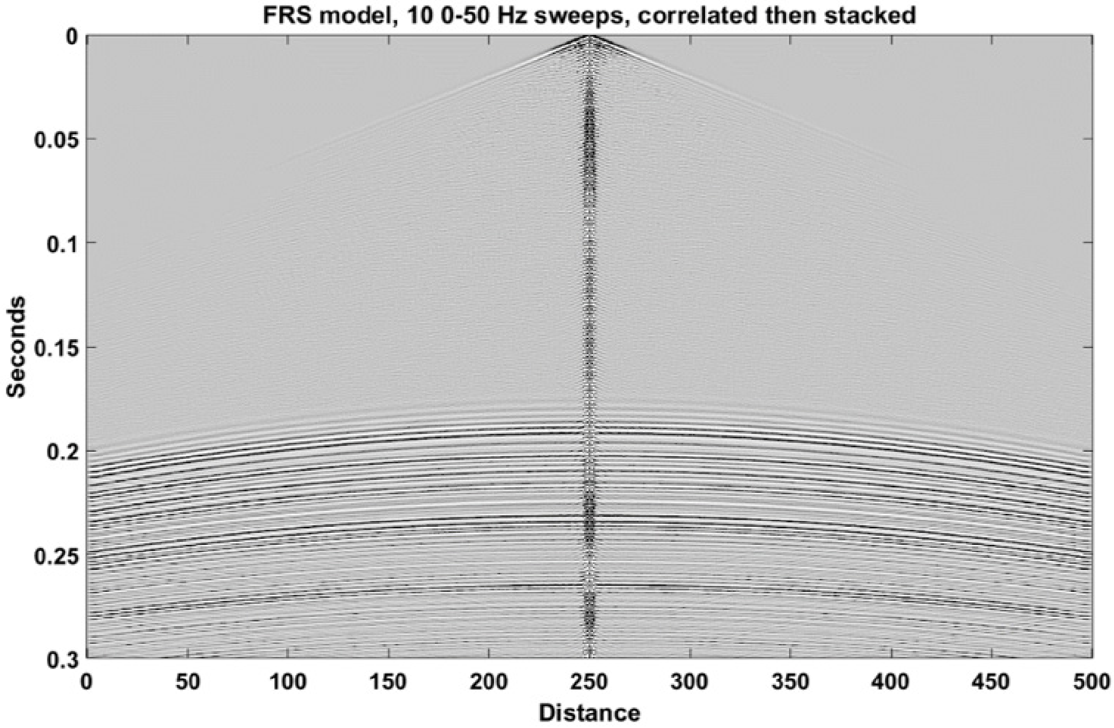

FIG. 6: shot record stack generated by correlating individual shot records to the source function, then stacking.

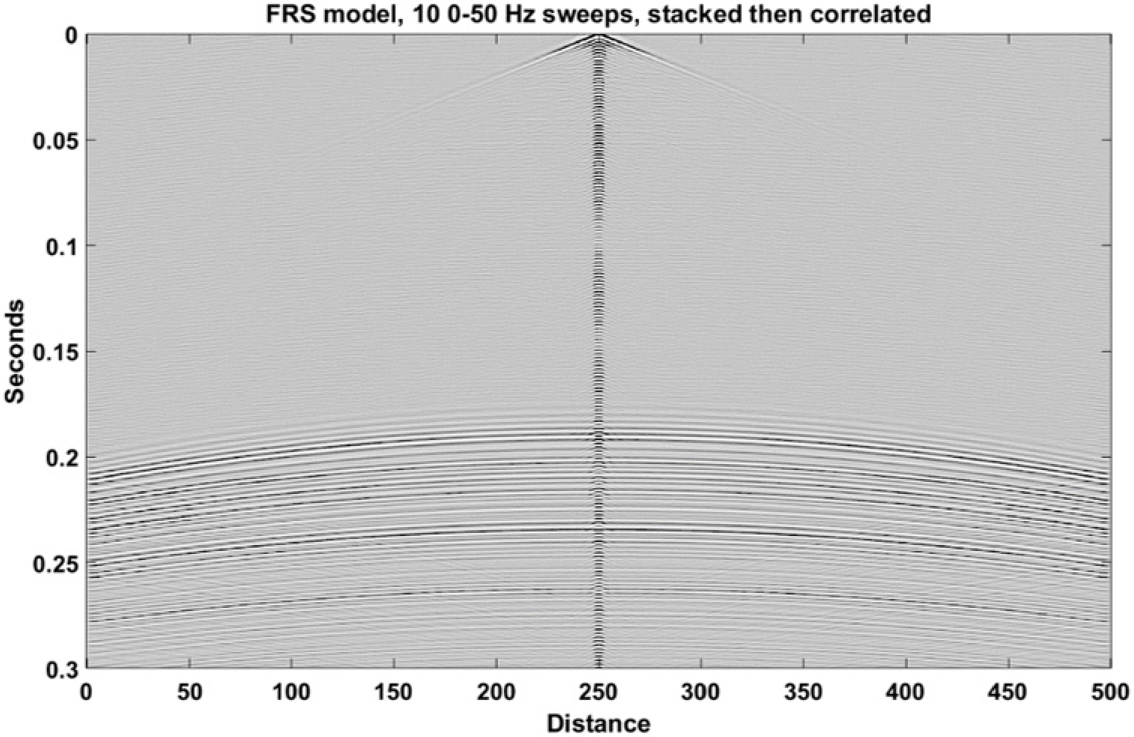

FIG. 7: shot record stack generated by stacking individual shot records before correlating the stack with the source function.

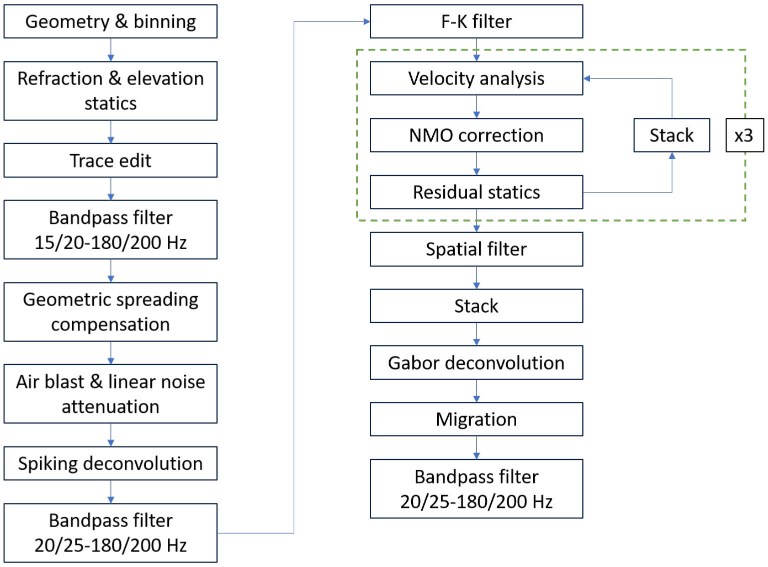

FIG. 8: processing flow applied to 2D seismic data acquired at the FRS in May 2017.

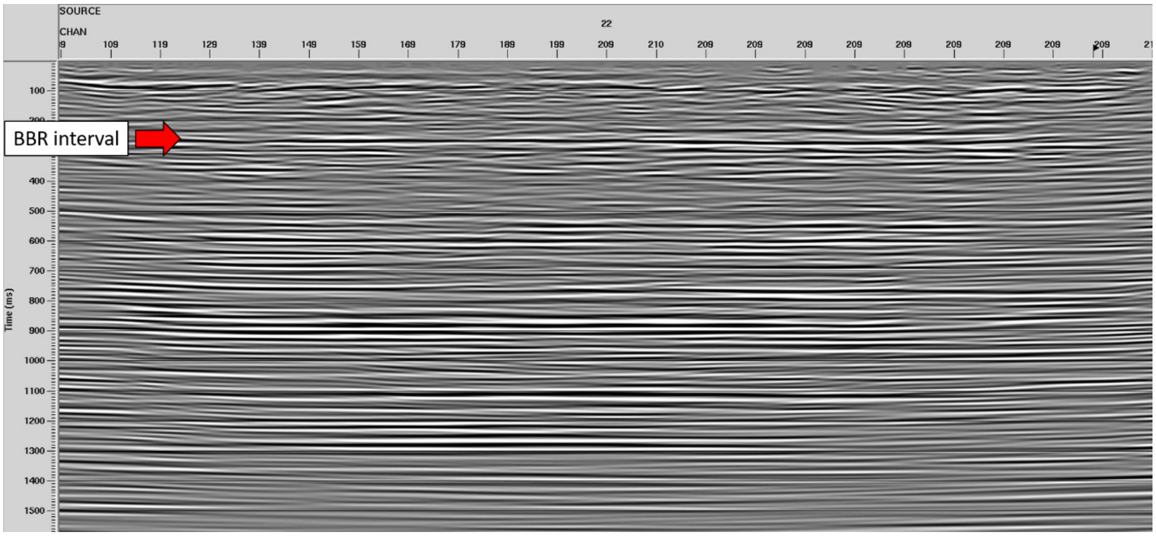

FIG. 9: processed 2D seismic data acquired at the FRS with the Basal Belly River injection interval identified on the section.

FIELD WORK AT THE FRS

Field work at the FRS continues through the autumn of 2017, with the installation and testing of continuous seismic sources in early November. Of utmost importance for monitoring with continuous sources is the careful placement of the source at the surface. Unlike with dynamite surveys, where multiple source points are easily achieved, or with Vibroseis, where the source is mobile, surface orbital vibrators are cemented at the surface.

The primary target that will be imaged using the permanent source is the Basal Belly River at a depth of approximately 292 metres in the injection well 10-22 (Isaac and Lawton, 2014a). This reservoir will be targeted with a vertical seismic profile (VSP), recorded using a distributed acoustic sensing (DAS) fibre optic cable in observation well #1. DAS cables have also been installed in observation well #2, however investigations into the placement of the continuous source were done with observation well #1 as the location of receivers. The continuous source will be installed along an azimuth passing through the injection well and observation well #1 (FIG. 10). Conveniently, this azimuth also passes through observation well #2. Observation well #1 is located approximately 30 metres northeast of the injector, which is in turn approximately 20 metres northeast of observation well #2.

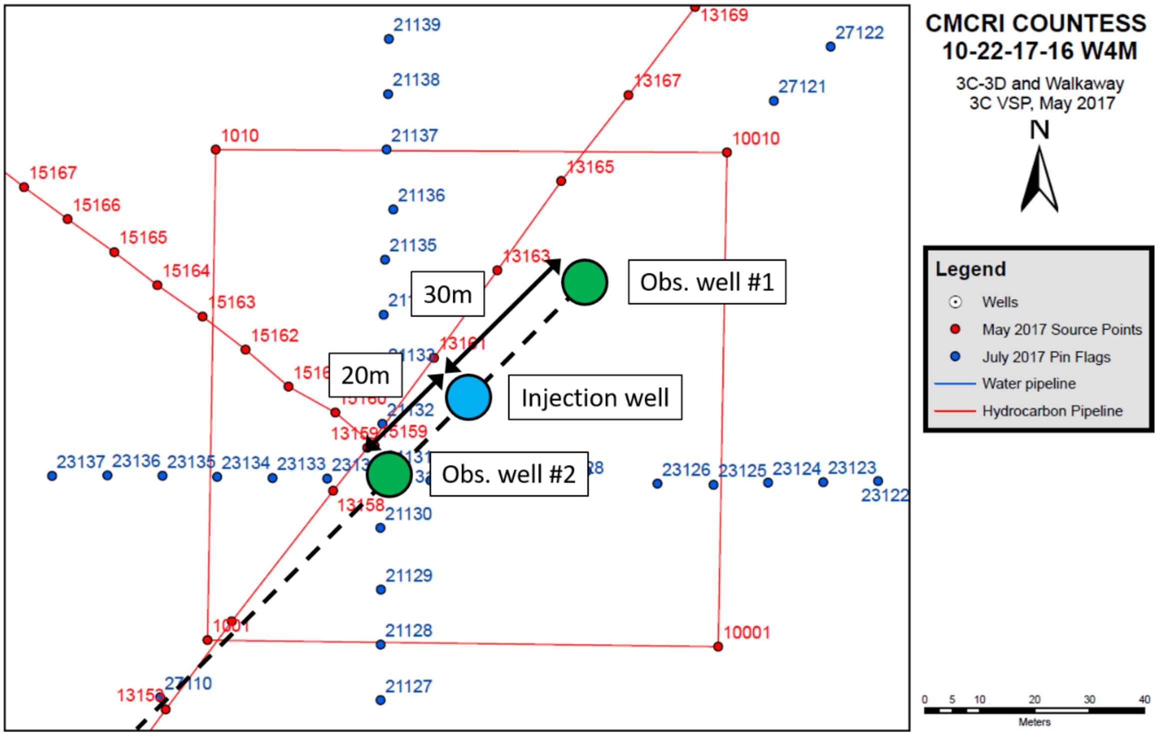

FIG. 10: FRS schematic showing locations of both observation wells, the injection well, and shot points for an earlier seismic program. The azimuth along which the continuous source will be placed is represented by the black dashed line.

While the primary objective is to image the BBR in observation well #1, future studies will compare data recorded in each of the observation wells. To determine the offset between observation well #1 and the location of the permanent source, raytracing through the FRS velocity model was performed (FIG. 11). To simulate DAS fibre in the observation well, receivers were placed at 1 metre intervals in the well. The first receiver depth was placed at a depth of 50 metres. This was done to simulate that data cannot be reliably acquired in the uppermost part of the well. Two important factors were considered in the determination of the permanent source offset:

1. Maximizing the horizontal area around the injector that will be imaged; and,
2. Maximizing the range of incidence angles to capture any potential amplitude-versus-offset/amplitude-versus-angle (AVO/AVA) effects.

From the raytracing performed, it was found the maximum possible offset was approximately 450 metres. Offsets beyond this distance were found to produce critically refracted rays.

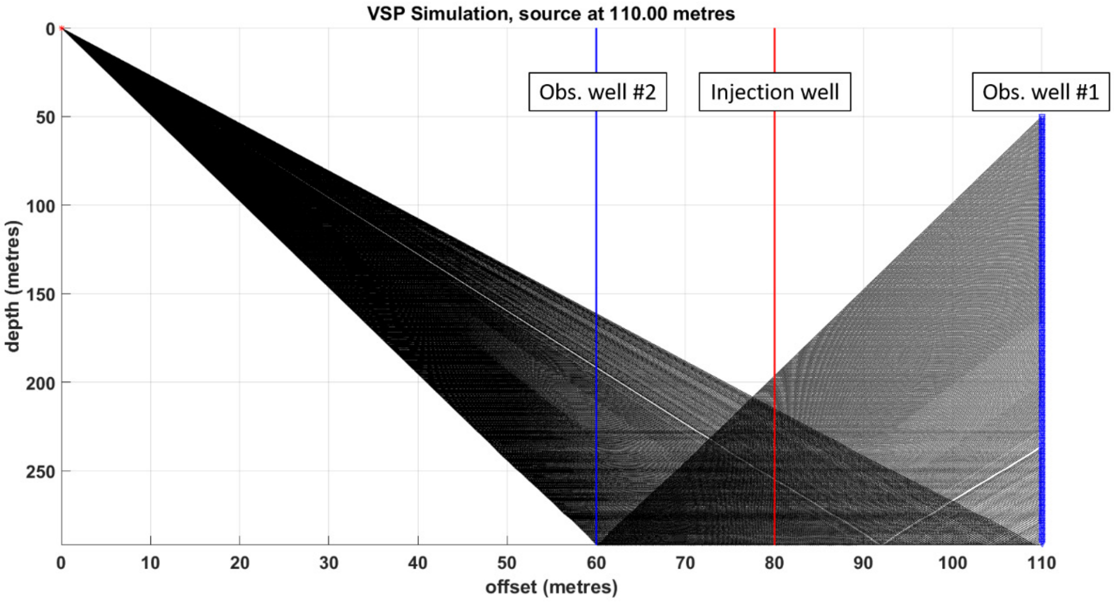

FIG. 11: VSP raytracing through the FRS velocity model using a source-receiver offset of 110 metres.

An offset of 110 metres between observation well #1 and the continuous source adequate coverage of the horizontal area around the injection well, and will allow the zone with the highest saturation of injected CO_2 (Macquet et al., 2016) to be imaged by the continuous source.

In addition to optimizing the horizontal area imaged by the continuous source, the impact of the offset on potential AVO/AVA responses was investigated. The range of incidence angles at the Basal Belly River was computed for each offset analysed during raytracing. For the simulation in FIG. 9, incidence angles ranged from approximately 13 to 25 degrees (FIG. 12). This angle range was then used to generate angle-dependent offset synthetic seismograms from recorded well logs. The synthetics generated displayed a typical Class I AVO response for the reflector of interest over the angle range (FIG. 13), with the seismic amplitude decreasing as the incidence angle increased. A fluid replacement algorithm was then applied to the original well logs in the Hampson-Russell software package to simulate 100% CO_2 saturation, and the synthetics were subsequently recalculated. No significant change in the class of the AVO response was observed; however, seismic amplitudes at all incidence angles were reduced in the case of 100% CO_2 saturation.

Mateeva et al. (2012) characterize the seismic amplitude recorded by a single-component (i.e. straight) DAS fibre to vary with the square of the cosine of the angle between the incident ray and the fibre. Thus, the amplitudes of the BBR reflector recorded in observation well #1 with a 110 metre source-receiver offset will be scaled by approximately 82% to 96%. In observation well #2, a combination of straight and helical DAS fibre, as well as geophones, will be used to record continuous VSP data. Performing the same raytracing and calculations for amplitude scaling, it was found that amplitudes recorded in the straight DAS fibre will be scaled by approximately 94% to 98%. This is caused by the short offset, which results in sub-vertical raypaths and incidence angles of less than 15 degrees. This amplitude scaling could be potentially confirmed by comparing with data recorded in helical DAS fibre and geophones.

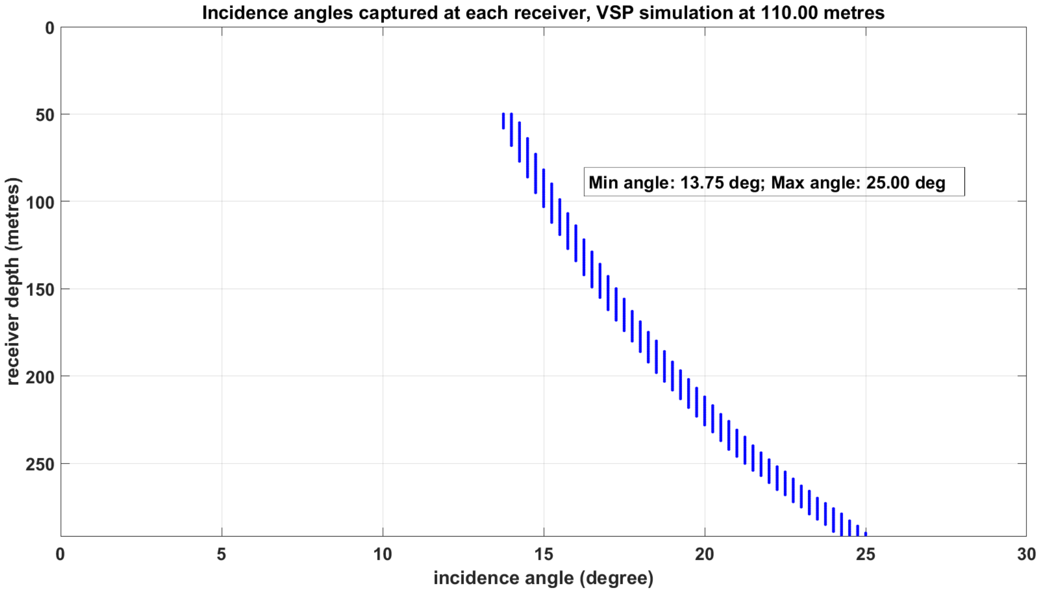

FIG. 12: incidence angles at the Basal Belly River and the receiver depth they are captured by for a VSP simulation with the source at 110 m offset.

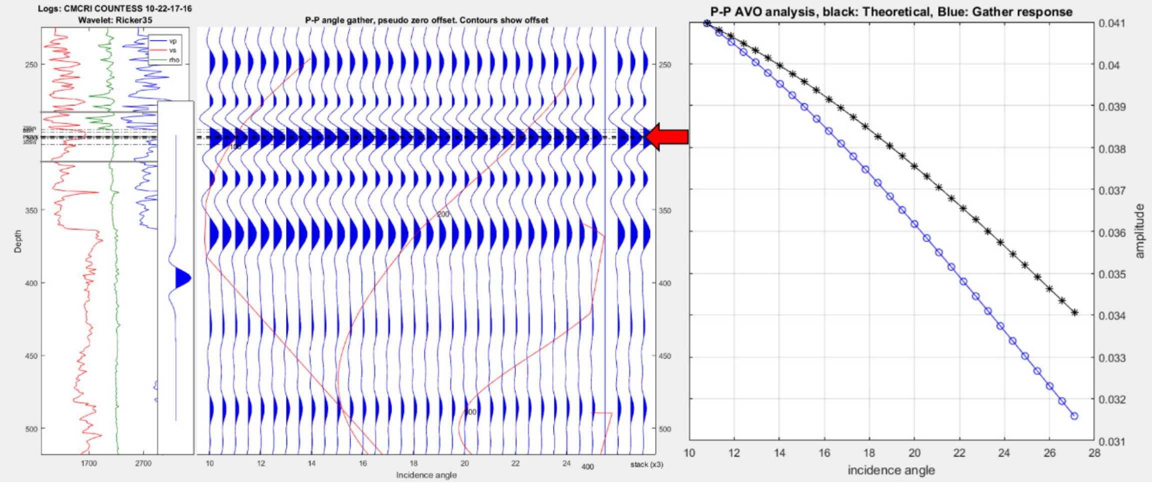

FIG. 13: (left) offset-dependent synthetic seismogram for the injection well, Basal Belly River identified with arrow; (right) seismic amplitude versus incidence angle at the BBR.

CONCLUSIONS

Continuous seismic sources are one of the many technologies being tested at the CaMI.FRS, and are extremely important for the study of geophysical monitoring tools in carbon storage projects. By rotating an eccentric mass around an axle at a known frequency, the vibrations caused by a continuous source can be modelled using a sinusoidal function, and are conceptually analogous to Vibroseis sweeps. Similar to Vibroseis acquisition and processing, continuous source data should be handled by stacking each shot record to suppress noise, then correlating with the source function. Additionally, a baseline seismic data processing flow was developed, and will be tested on and modified for, data acquired using continuous sources. Field work is ongoing at the FRS, with continuous sources installed and tested in November 2017. An offset of 110 metres between observation well #1 and the continuous source will provide adequate spatial coverage of the injected CO_2 plume, and will yield incidence angles up to approximately 25 degrees, which may help in identifying potential AVO/AVA effects as CO_2 is injected.

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