Velocity calibration for microseismic monitoring at the Newell County carbon storage facility using SADAR compact phased arrays

Jian Zhang[1], Paul A. Nyffenegger[1], Kevin D. Hutchenson[1], Elige B. Grant[1], Jason Jennings[1], Derek Quigley[1], Mark A. Tinker[1], Mike Dahl[2], David Grindell[2], Marie Macquet[3], and Don C. Lawton[3,4]

[1]Quantum Technology Sciences, Inc. (Quantum); [2]Geospace Technologies Canada, Inc.; [3]Carbon Management Canada (CMC); [4]University of Calgary

Summary

Passive monitoring of microseismic and induced seismicity continues serving as a necessary tool for industrial geologic applications including geologic carbon storage. A critical step in determining accurate event locations for passive monitoring is velocity model calibration, which often faces great challenges for surface/near-surface monitoring due to poor signal-to-noise ratio (SNR) of the calibration events at depth. In this paper we present velocity model calibration results using a deep ground truth event in addition to several hammer strikes at the surface with data recorded by a sparse network of compact volumetric phased arrays (SADAR arrays) installed at the Newell County carbon storage facility. Although seismic signals of the deep event cannot be seen from the surface geophone network deployed at the Newell County facility, the SADAR arrays show a clear advantage of SNR gain allowing the ground truth event signals to be detected with SNR adequate for identifying the phase arrivals picked for calibrating the velocity model.

Introduction

Passive seismic monitoring technologies are being tested at the Newell County facility CO_2 storage test site in southern Alberta, Canada, constructed and operated by the Containment and Monitoring Institute (Macquet *et al*., 2022). Small volumes of CO_2 (~15-20 tonnes/year) are injected into the reservoir formed by the Basal Belly River Sandstone (BBRS) formation at 300 m depth (Lawton *et al*., 2019). Permanent seismic instrumentation (Figure 1) includes a surface network of 28 three-component geophones buried at 1m depth and a downhole array of 24 three-component geophones extending to reservoir injection zone depth (Macquet and Lawton, 2019). The latest addition is a sparse network of four compact phased Seismic and Acoustic Detection And Ranging (SADAR) arrays that Quantum Technology Sciences Inc. (Quantum) developed and installed (Nyffenegger *et al.*, 2022, Zhang *et al.*, 2023). The SADAR system takes advantage of the three-dimensional array response and spatially coherent processing (beamforming) that can optimally increase signal SNR and thereby reduce the uncertainty in determining phase arrival times. Zhang *et al*. (2022) and Zhang *et al*. (2023) have demonstrated that coherent processing of SADAR arrays achieves SNR gains up to ~20dB and location errors down to 10m.

Monitoring a reservoir at depth with surface/near-surface observations requires a velocity model to be well resolved. Creating a calibrated velocity model and validating event location solutions using ground truth events plays an important role for achieving location confidence for microseismic monitoring. The fundamental method to improve a velocity model using a ground truth event is to manually pick the phase arrivals and reduce the difference between the picked and modeled times across the network by adjusting the velocity model. Unlike surface ground truth events that are easier to be detected and picked, using calibration events at reservoir depth often faces a great challenge in the signal quality recorded by surface sensor networks. High SNR signal records with clear phase onsets are always preferred.

In this work we start with velocity model improvements using several hammer strikes at the surface observed with SADAR arrays, then follow up with a calibration for the velocities at depth by using a deep well swabbing event that can be confirmed by the downhole observations but on surface can only be detected and picked across the SADAR network.

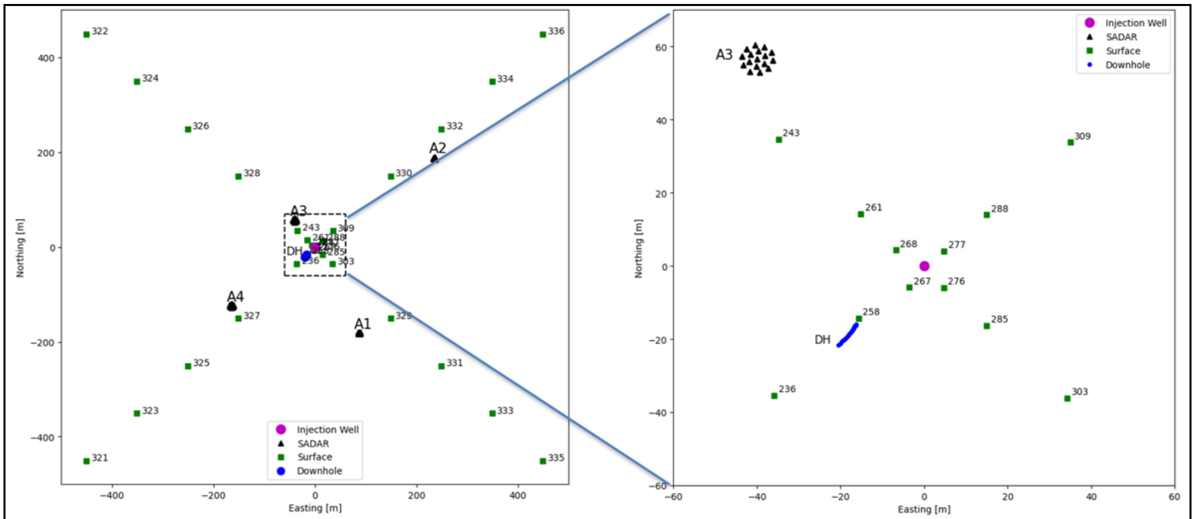

Figure 1: (left) Map view of the seismic monitoring networks centered at the injection well (magenta dot at center), and showing the locations of the SADAR arrays (A1—A4, black triangles), the surface network (green squares), and the downhole array (blue dots). (right) Zoomed-in map view of the area close to the injection well.

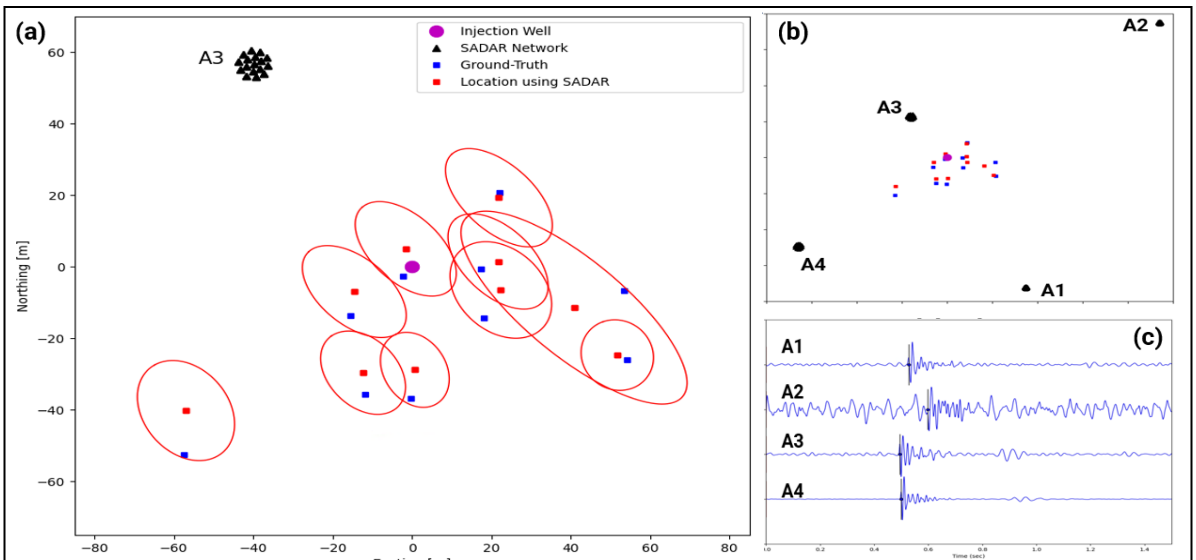

Figure 2: (a) Locations and error ellipses of surface ground-truth events (hammer strikes) in red, after the first-fold calibration using P arrivals detected and picked from SADAR beamformed data. The ground-truth locations are shown in blue; (b) Zoom-out view showing the SADAR network locations (A1—A4); (c) Example SADAR beam signals of one hammering strike.

Calibration: Surface hammer strikes

The first round of calibration focuses on the shallow velocity structure using the hammer strikes made on the surface at known locations (Figure 2). Ten calibration strikes were clearly detected and confidently picked using the SADAR beamformed data with picking errors typically less than 2ms. It can be seen in Figure 2 that the location errors are less than 15m after locating the events using the adjusted velocity model.

Calibration: A deep well-swabbing event

A well-swabbing operation generated a deep impulsive source (Figure 3, left) successfully detected across the downhole array (Figure 3, right) and the SADAR network (Figure 4). The SADAR data suggest this event has a moment magnitude of -1.6. The move-out observed across the downhole tools clearly confirms that the event is located below the downhole tools.

By using the precise picks (with picking errors less than 2ms) derived from the SADAR beamformed data, the difference between the picked and modeled arrival times is minimized with one solution of increasing the velocities below 150m by 20% (Figure 5). The updated and calibrated velocity model resolves the event location as shown in Figure 6, with the ground truth location within the location solution uncertainty ellipse (semi-major axis length of 27m, semi-minor axis length of 16m, and depth error of 55m).

The surface network that includes 28 stations covering a larger range would allow additional phase arrival constrains for calibrating the velocity model. However, we found that the event signals are undetectable over the surface network (Figure 7). In comparison, the phase arrivals on the optimal beam for the arrays can be clearly observed.

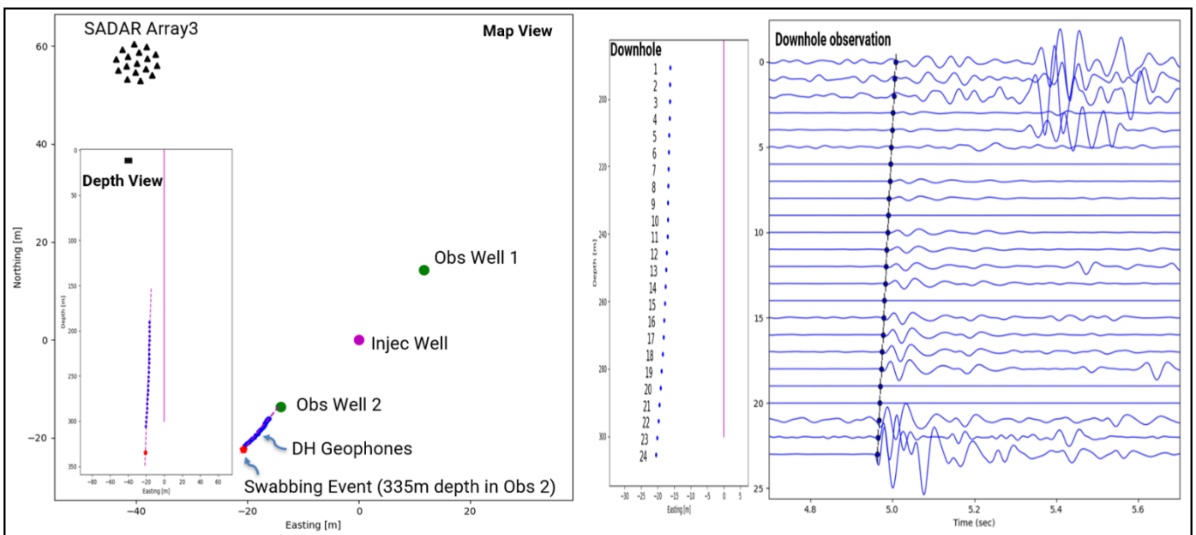

Figure 3: (left) Map view showing a downhole network installed in Observation well 2 and the swabbing event at the bottom of the well 2. The insert shows the depth east-west cross-section; (right) arrivals of the swabbing event observed at the downhole tools. Traces from the top to the bottom match the tool station number from the top to the bottom on the center plot to the left of the time record. Black ticks mark the calculated arrival time for the downhole array.

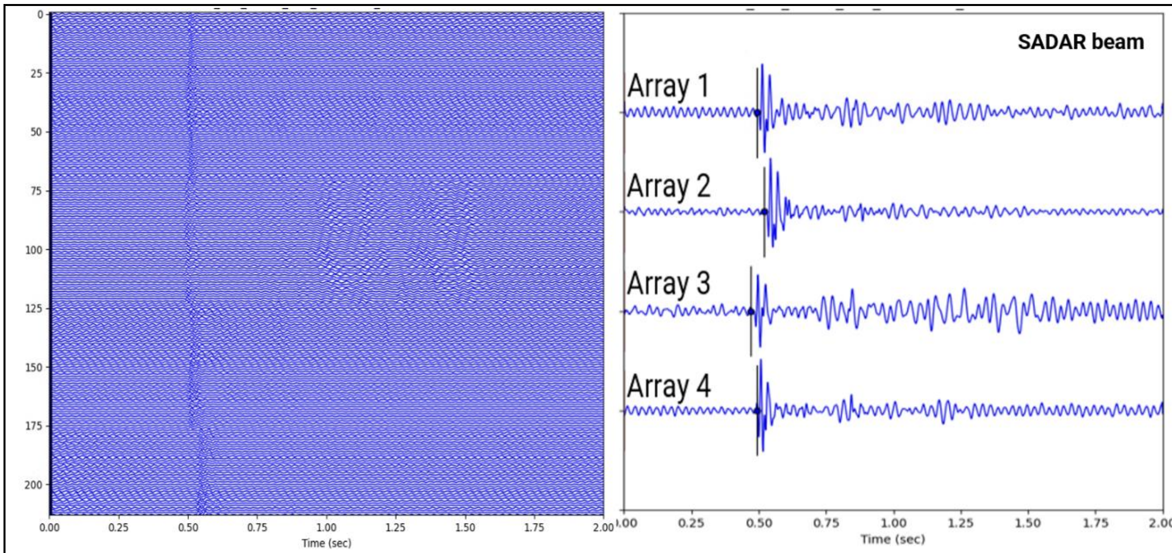

Figure 4: (left) Signals across all individual channels of the SADAR arrays; (right) optimal beam signals for network of four SADAR arrays.

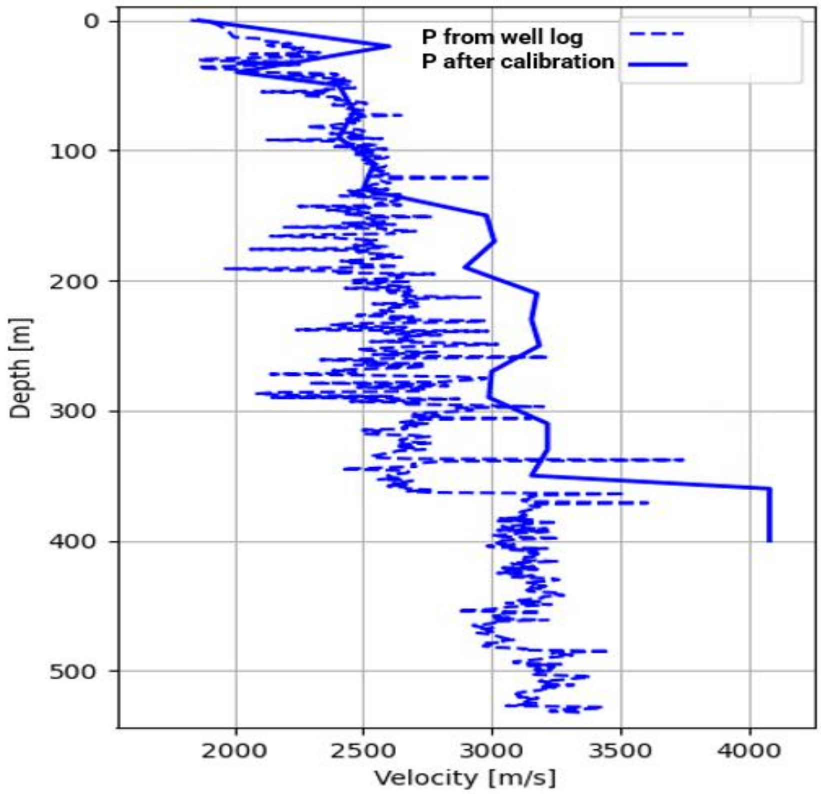

Figure 5: Calibrated velocity model compared with the initial model from the well logs.

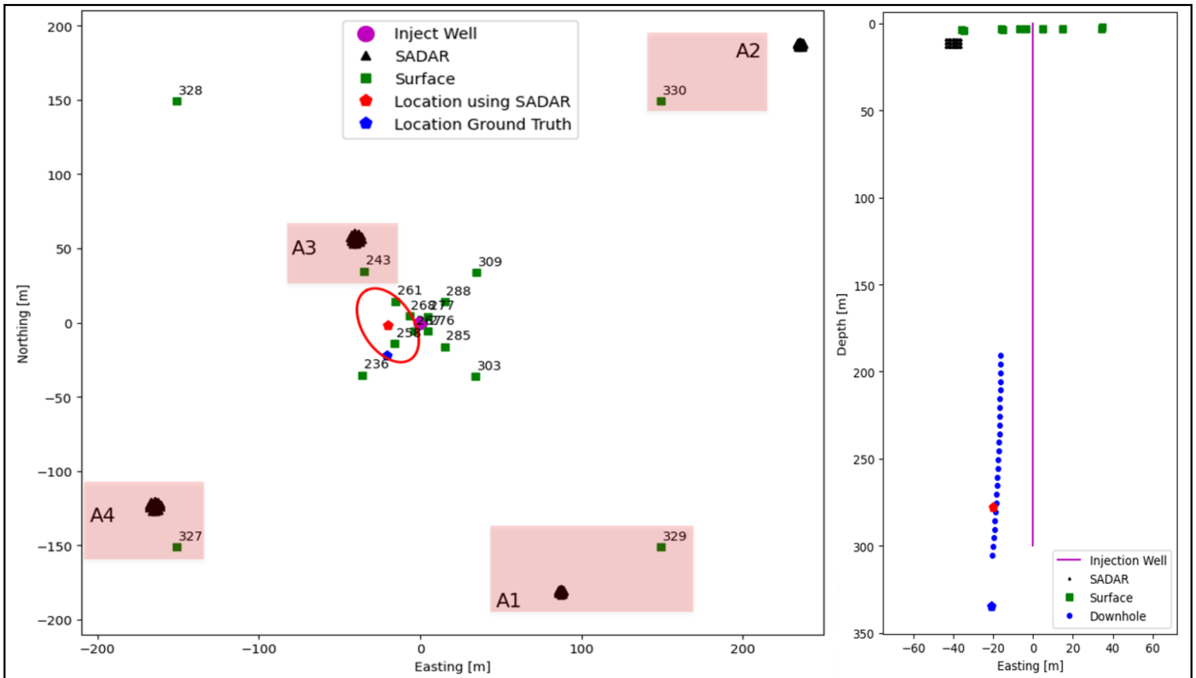

Figure 6: (left) Map view of the SADAR arrays (black trangles), the surface network (green squares), the estimated event location and error ellipses after velocity model calibration (red star). The ground truth location is shown as the blue star; (right) depth view showing the estimated event location from the calibrated velocity model (red star) compared with the ground truth location (blue star).

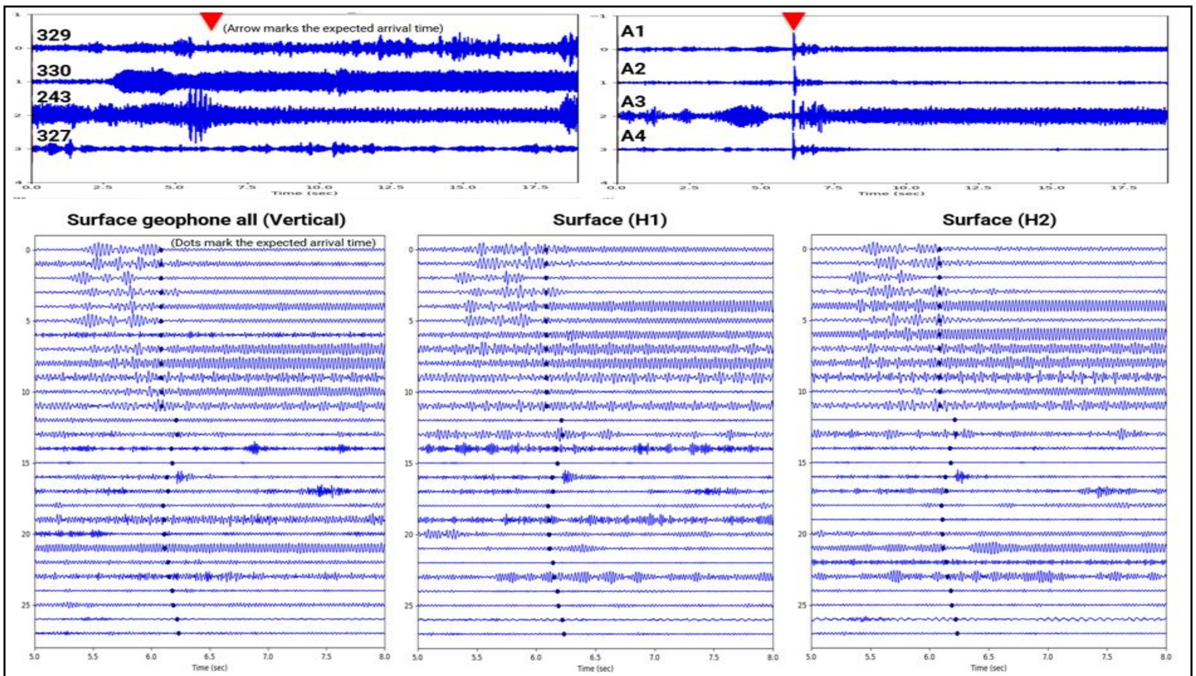

Figure 7: (top) Comparison of the observations from the SADAR network (A1—A4) versus the nearby surface network stations (see Figure 6) for the deep swabbing event. (bottom) Recorded three-component traces across all surface network stations, with black dots marking the expected arrival time of the deep swabbing event.

Discussion

Given that only *P* arrivals can be confirmed and picked from the data, we focus on a simple layered isotropic velocity model that can explain the observations. In addition, we do not expect to resolve an accurate velocity model across all depths considering we have only one deep ground truth event available at one sampling depth and location. Therefore, the model we derived may be just one of multiple velocity model solutions that well-fit the observations. For any potential deep events, the calibrated model would only provide location confidence for those events close to the calibration event. The actual geologic velocity structure may also involve azimuthal anisotropy potentially explaining the difference between the calibrated velocity model and the initial model derived from the well log measurements. It would be necessary to invert for more complex velocity models using additional calibration events and/or a larger network coverage.

Conclusion

Significant SNR gain obtained using beamformed data acquired with Quantum's SADAR arrays enables detection and precise phase arrival picking of a ground truth event at the reservoir depth critical for velocity model calibration and validation at the Newell County facility. Our results suggest the *P*-wave velocity structure at the Newell County facility injection site may be up to 20% higher at reservoir depths compared to the model built from the well logs.

Acknowledgements

Quantum Technology Sciences, Inc., is a wholly owned subsidiary of Geospace Technologies Corporation, Inc. We acknowledge Carbon Management Canada (CMC) for providing access to the Newell County facility to enable installation of the SADAR system, and for sharing the data from the surface and downhole networks. The Newell County facility is supported by funding from the Global Research Initiative at the University of Calgary from the Canada First Research Excellence Fund and from the Containment and Monitoring Institute Joint Industry Project. CMC is also acknowledged for providing operational data from the site.

References

Lawton, D. C., J. Dongas, K. Osadetz, A. Saeedfar, and M. Macquet, 2019, Chapter 16: Development and analysis of a geostatic model for shallow CO_2 injection at the Field Research Station, Southern Alberta, Canada: *in* T. Davis, M. Landro, and M. Wilson, eds., Geophysics and Geosequestration: Cambridge University Press, 280-296, DOI 10.1017/9781316480724.017.

Macquet, M., D. Lawton, K. Osadetz, G. Maidment, M. Bertram, K. Hall, B. Kolkman-Quinn, J. Monsegny Parra, F. Race, G. Savard, Y. Wang, 2022, Overview of Carbon Management Canada's pilot-scale CO2 injection site for developing and testing monitoring technologies for carbon capture and storage, and methane detection: Recorder Focus Article, **47**, No. 01, April 2022.

Macquet, M. and D.C. Lawton, 2019, Exploring continuous seismic data for monitoring CO_2 injection at the CaMI Field Research Station, Alberta, Canada: SEG Technical Program Expanded Abstracts, 4913-4917.

Nyffenegger, P. A., M. A. Tinker, J. Zhang, E. B. Grant, K. D. Hutchenson, and D. C. Lawton, 2022, Compact phased arrays for microseismic monitoring: First Break, **40**, 69-74.

Zhang, J., E.B. Grant, P.A. Nyffenegger, M.A. Tinker, K.D. Hutchenson, and D.C. Lawton, 2022, Seismic monitoring using compact phased arrays: CO_2 sequestration monitoring: Second International Meeting for Applied Geoscience & Energy. August 2022, 483-487.

Zhang, J., K.D. Hutchenson, P.A. Nyffenegger, E.B. Grant, J. Jennings, M.A. Tinker, M. Macquet, and D.C. Lawton, 2023, Performance comparison of compact phased arrays and traditional seismic networks for microseismic monitoring at a CO2 sequestration test site: The Leading Edge, forthcoming.