Squid: An innovative, new ground-coupled electric seismic source for semi-continuous seismic monitoring

Don Lawton[1,3], Trent Hunter[2], Brendan Kolkman-Quinn[3], Malcolm Bertram[1], Greg Maidment[1]

[1]CMC Research Institutes Inc, [2]3P Technologies Inc., [3]CREWES, University of Calgary

ABSTRACT

A new seismic source has been tested at the Containment and Monitoring Institute Field Research Station (CaMI.FRS) in Newell County, Alberta. The 'Squid' source is a patent pending surface source leveraging the dynamics of an atmospheric plasma discharge in a water filled reactor. It has been developed by 3P Technologies Inc in Calgary, Alberta.

At CaMI.FRS the source was coupled to the ground by bolting it to a thick steel plate at the top of a helical pile that had been screwed into the ground to a depth of 24.7 m. The Squid source triggered a Geode seismic system that recorded vertical seismic profile data from 24 3-component geophones in an observation well over a depth range from 191 m to 306 m below surface, with a geophone interval of 5 m. Source offset from the VSP well was 62 m. Good quality data were acquired with a single shot (3.6 kJ energy). The SNR improved significantly after a 50-shot stack. Processed data exhibit a frequency band from 10 to 180 Hz and compared favourably with VSP data collected in the same well with an Envirovibe source located beside the Squid pedestal. Comparison of the travel times of the downward propagating wavefield for both sources indicate that the Squid source is coupling to the subsurface bedrock through the base of the pedestal.

INTRODUCTION

In seismic monitoring for CCS projects we have 3 main challenges - repeatability, resolution and how often we repeat the surveys. Some aspects of repeatability with our Envirovibe source in time-lapse surveys at the Containment and Monitoring Institute Field Research Station (CaMI.FRS) in Newell County, Alberta, is discussed by Kolkman-Quinn et al. (2020). Also, conventional 4D surveys, such as with vibratory or dynamite sources are costly to undertake frequently and recently interest has been developing in permanent reservoir monitoring including active source surveys to better track transient changes that might occur in the reservoir. Surface orbital vibrators mounted on concrete foundations have been developed with good results shown from Otway (Australia) and EEERC in North Dakota (US). However, like any surface source, vertical resolution in seismic images is challenged by source-side signal attenuation through the weathering layer and seasonal changes in the near surface that may impact repeatability (Henley and Lawton, 2020).

The Field Research Station (FRS) is located approximately 200 km southeast of Calgary in the Newell County. It is focused on the development of new continuous and discrete subsurface and surface measurement, monitoring and verification (MMV) technologies related to carbon capture and storage (CCS) and other containment and conformance requirements, including CO_2 EOR (enhanced oil recovery) for monitoring CO_2 sweep efficacy. Research is conducted at the 1 km x 1 km globally-unique facility with a comprehensive range of leading-edge geophysical methodologies implemented for characterizing the subsurface and tracking injected CO_2.

PEDESTAL MOUNTED SURFACE SOURCES

At CaMI.FRS we have been testing mounting permanent sources on large helical screw piles (pedestals) that are screwed into the ground into bedrock below the weathering layer (Spackman and Lawton, 2019). These are fixed source locations for continuous or semi-continuous seismic monitoring. The source types are GPUSA orbital vibrators and a new 'Squid' impulsive source that has been developed by 3P Technologies in Calgary, Alberta, Canada. A schematic diagram of these various seismic sources is shown in Figure 1. The red circles shown at the base of the pedestal for the GPUSA and Squid sources indicate how the source energy is inferred to be coupled into the bedrock.

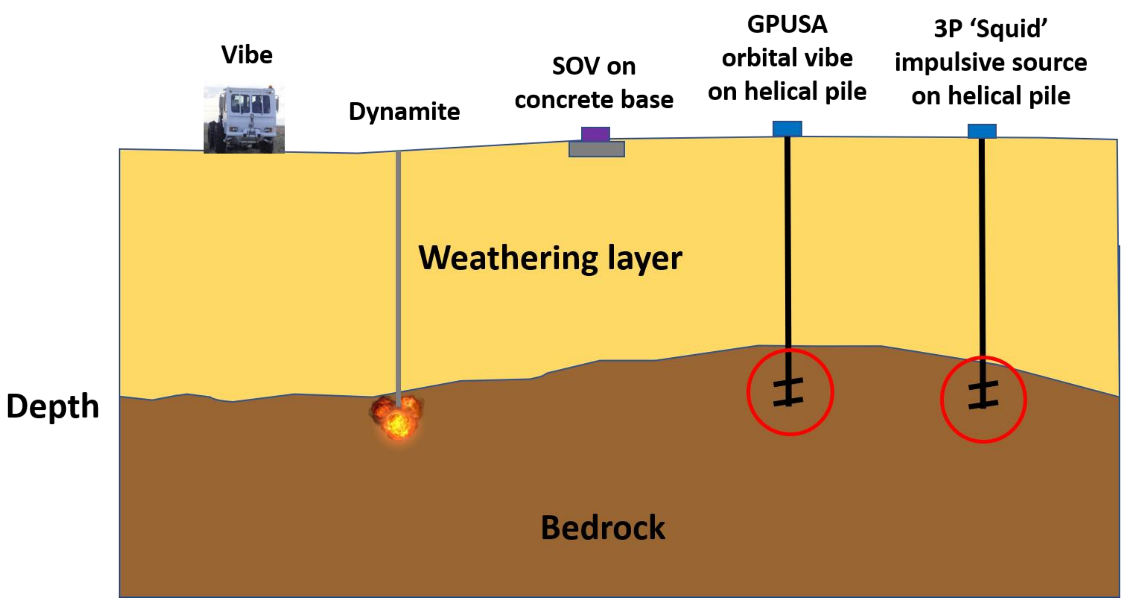

FIG. 1: Surface seismic sources. Shown at the left are conventional seismic sources (vibratory and dynamite). The remainder are types of permanent seismic sources. In the centre is a surface orbital vibe (SOV) mounted on a concrete foundation. On the right hand side are shown the GPUSA and Squid sources mounted on helical piles (pedestals).

The pedestals shown schematically in Figure 1 are made of heavy-duty piping with helical flutes at the base of the lowest section (Figure 2). Each section is about 3 m in length and can either be bolted or screwed together as the pedestal is screwed into the ground. At the FRS was have installed and tested pedestals in the southwest corner of the lease (Figure 3) where we can mount surface sources and record fixed offset VSP data into borehole geophones in Observation well 2 and also DAS fibre in both observation wells for imaging the injected CO_2 plume around the injection well. In this paper we will show data recorded on the downhole geophones in Observation well 2. These geophones extend from 191 m to 306 m below surface, at 5 m intervals. In the near future, we plan to record data with the pedestal sources into the DAS fibre in both Observations wells.

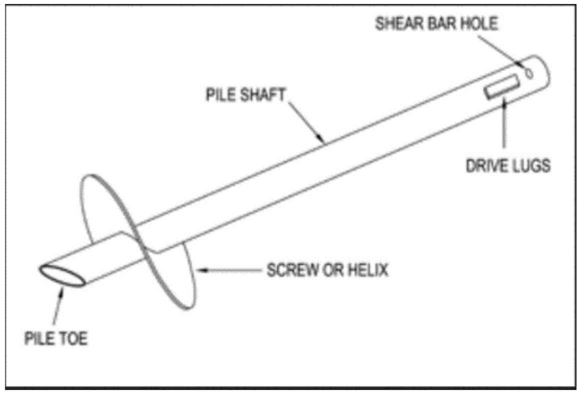

FIG. 2. Schematic diagram of a helical screw pile. The basal units has screw-like flutes welded near the base; the pile can be extended by adding shafts as the pile is screwed into the ground.

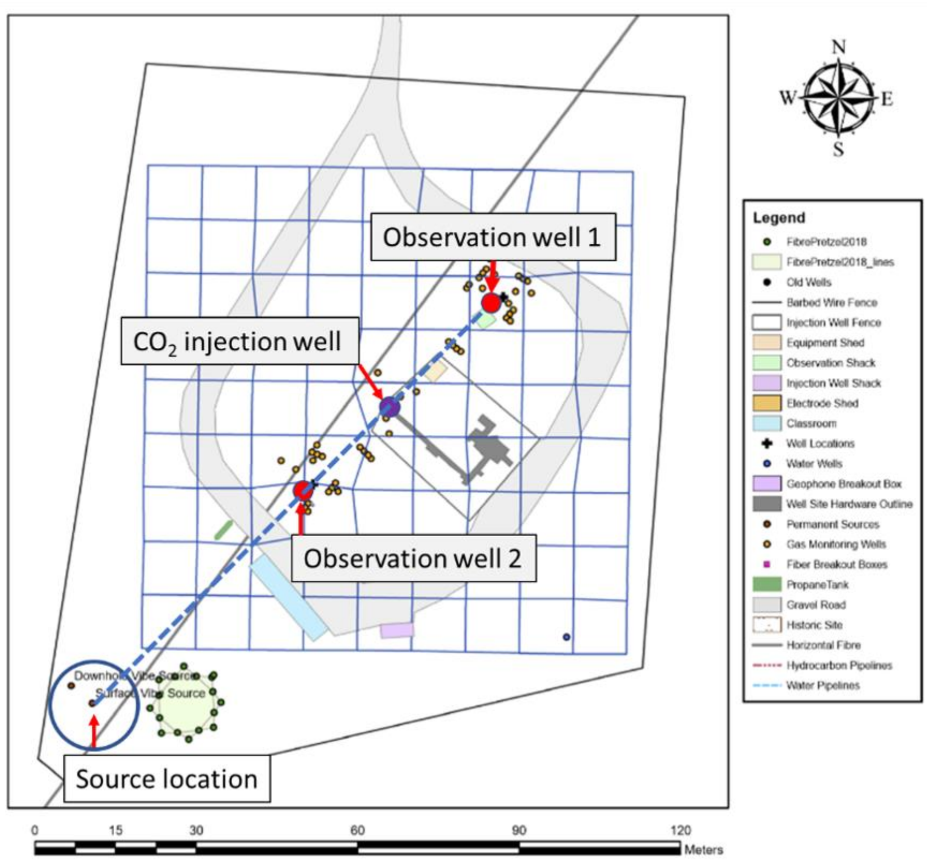

FIG. 3. Layout of the CaMI.FRS field site. Injection well is shown in blue and the observation wells are shown in red. The helical pile location is near the southwest corner of the lease.

Figure 4a is a picture of a pedestal being installed at the site and Figure 4b shows the pedestal nearly fully installed, with a 2.54 cm thick steel plate mounted at the top of the pedestal onto which the source is bolted. Figure 5 shows 2 of the GPUSA permanent sources, with the larger orange source bolted onto the top of the pedestal. These sources contain counter-rotating masses that can spin up and down over a prescribed, controlled sweep. The orange devises can rotate up to a maximum frequency of 100 Hz, whereas the smaller source (aluminum canister shown in Figure 5a) has a maximum spin frequency of 200 Hz. An example of a correlated VSP record with these sources is shown in Figure 5b. Clear down-going first arrival P-waves are evident, along with downward propagating reverberations and a number of upgoing reflections, marked by arrows. The data are quite ringy due to the amplitude spectrum of the source sweep (Spackman and Lawton, 2019).

FIG. 4. (a) helical pile being installed at CaMI.FRS and (b) pile installed to a depth of 24.7 m with steel plate mounted on top of the pedestal (almost fully installed).

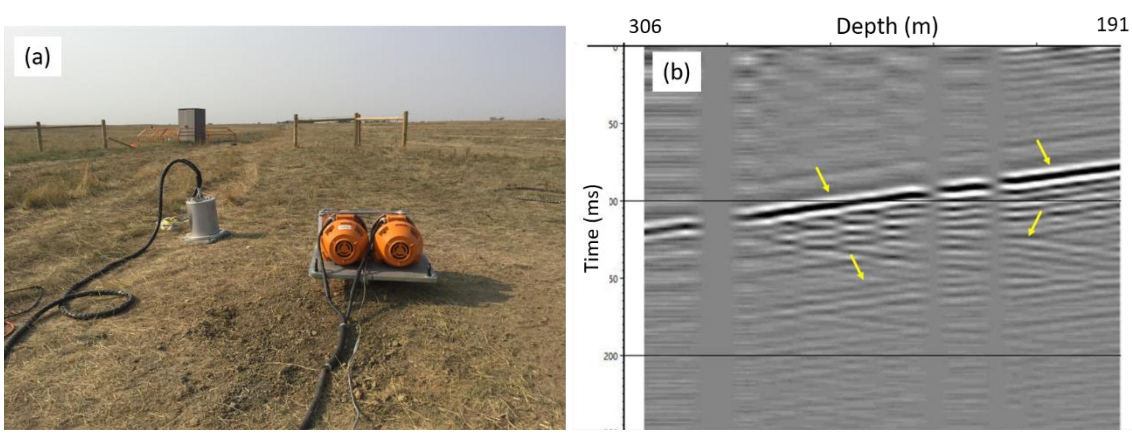

FIG. 5. (a) GPUSA linear vibes at site and (b) correlated VSP shot gather from the smaller of the GPUSA sources.

SQUID SEISMIC SOURCE

Data acquisition

The 'Squid' source is a patent pending surface source leveraging the dynamics of an atmospheric plasma discharge in a water filled reactor. The reactor is configured to convert the internal acoustic dynamics into a high-power vertical force output. The system is a fully electric, single channel, low discharge energy, fast repeating impulse generator that can be grid, generator or solar powered. Figure 6 is a schematic diagram of the Squid source. It consists of 3 components, namely a pulse network with associated electronics, a large capacitive storage chamber and a plasma reactor chamber. The energy is generated by a fluid phase change in the reactor and Figure 7 show frames from a high-speed camera movie showing a single discharge. Within 2 μsec of the trigger, a 260 MPa pressure pulse is initiated at 70k degrees Kelvin and in this example, the peak volume of the resultant phase change is ~1 litre and occurs withing 100 msec of the discharge. Indicated peak output power is over 100 MWatts and the total duration of the impulse is less than 250 msec. A base was fabricated by 3P Technologies Inc to enable the source to be bolted on to the top of the pedestal at CaMI.FRS.

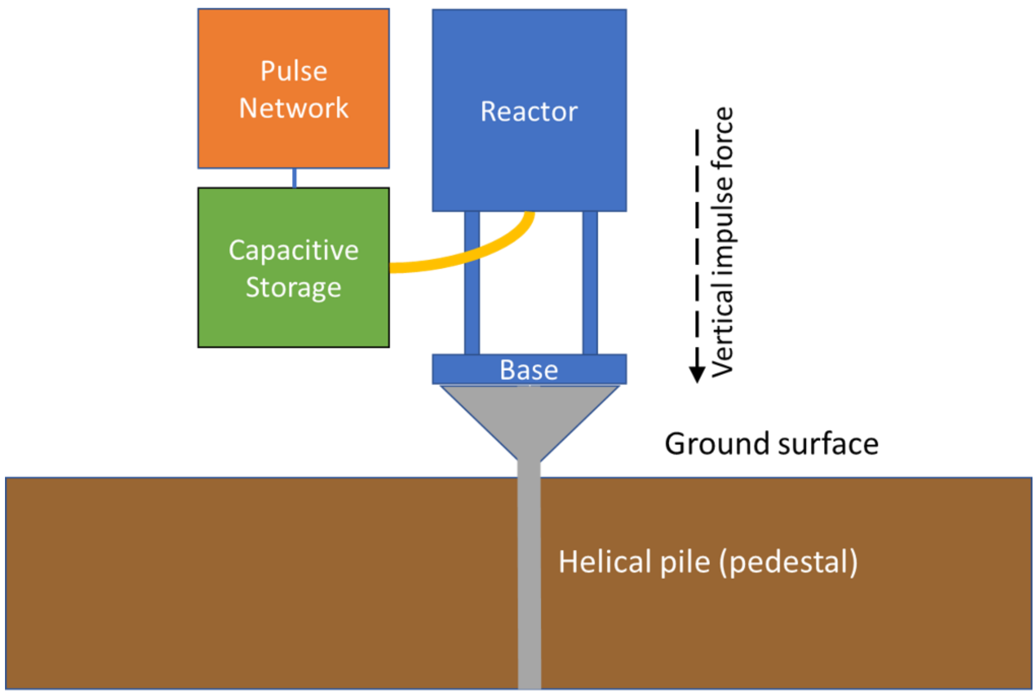

FIG. 6. Schematic of 3P Technology's Squid seismic source set up on a helical pile at CaMI.FRS

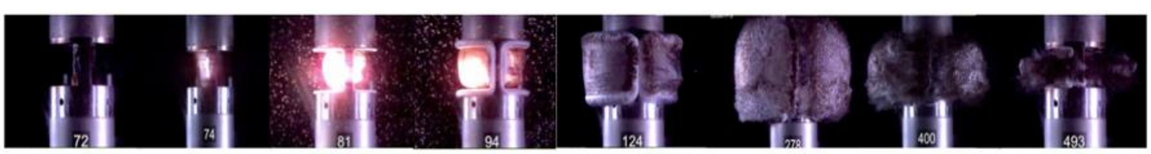

FIG. 7. High speed camera pictures of a duty cycle of the Squid source in the reactor chamber. The energy is generated by a fluid phase change in the reactor. Total duration is 250 ms.

Figure 8 shows a photo of the field set up with Trent Hunter for Phase 1 of the Squid tests (partly redacted for proprietary reasons). For this test, we also set out a small spread of surface geophones between the source and Observation Well #2 (62 m offset). Figure 9 shows data from a single source pop at an energy level of 3.6 kJ. The surface spread is on the left panel and the 3-components of the downhole geophones are shown as H1, H2 and Z from left to right. Energy on the horizontal components is weak because the source offset from the well is only 62 m. The down-going P-wave arrivals are seen clearly on the Z component and up-going reflections are visible in the raw data. Note that the first energy arrival on the Z component is a peak, suggesting that the initial coda is a rarefaction, not a compression. We were pleased with the data recorded with this initial test. The source can be repeated at regular time intervals, typically around 10 seconds. Figure 10 shows the data from a stack of 50 pops from the source, with clearly higher S/N than the single pop. The surface spread shows both refracted and surface waves being recorded. More energy is visible now on the horizontal components but again the dominant energy is seen on the vertical channel (Z component) and up-going reflection are also visible in this display.

FIG. 8. Trent Hunter from 3P Technologies with the Phase 1 test setup of the Squid source at CaMI.FRS. Observation well #2 (VSP recording) is just beyond the left end of the office trailer. Offset from source to well is 62 m.

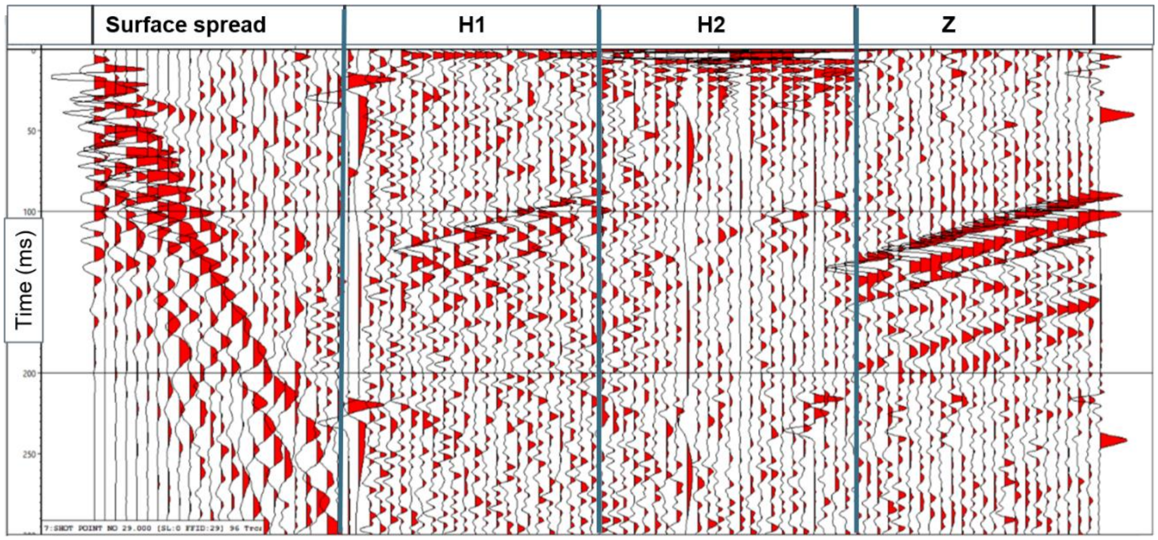

FIG. 9. Single pop record from Squid source mounted on the helical pile. Surface refraction spread (left), then 3 components (H1, H2 and Z) of the downhole geophones over a depth range of 191 to 306 m.

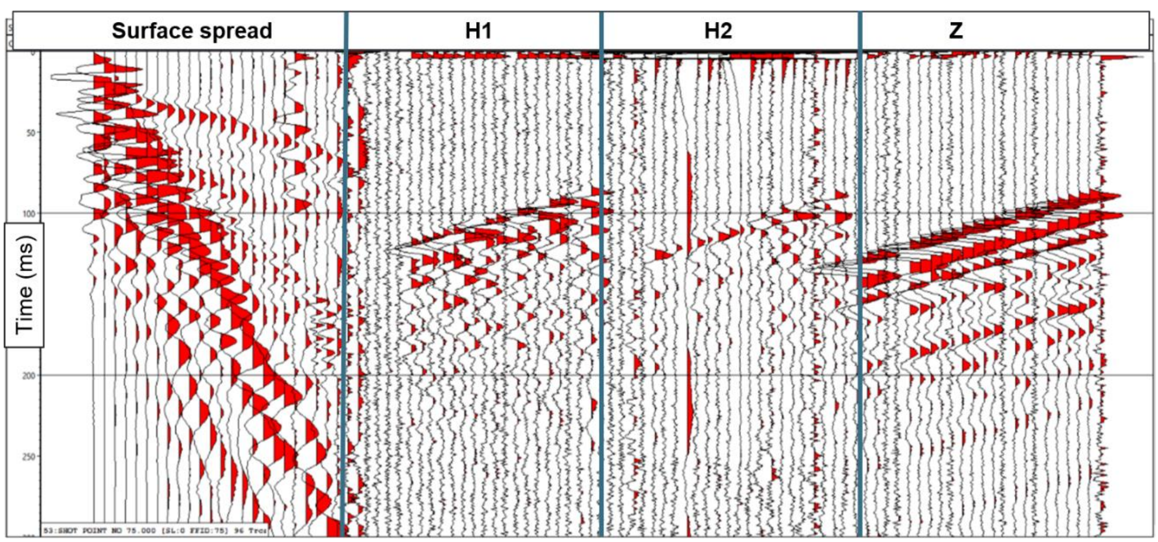

FIG. 10. Stacked record of 50 pops from Squid source mounted on the helical pile. Surface refraction spread (left), then 3 components (H1, H2 and Z) of the downhole geophones over a depth range of 191 to 306 m.

The amplitude spectra of the Z component raw data shown in Figure 10 are displayed in Figure 11, showing frequency content from 10 to nearly 200 Hz, with a peak frequency between 75 to 85 Hz. Previous surveys with the surface sources at the site have peak frequencies of about 50 Hz. Figure 12 displays a record from the Envirovibe source located beside the pedestal and this can be compared with the Squid record in Figure 10. The Envirovibe has higher energy output than the Squid (based on visual S/N) but the dominant frequency is lower for the Envirovibe data. Note also that the first arrivals for the Envirovibe Z-component data are opposite in polarity and later in time compared with those for the Squid data. We interpret the decrease in arrival time and the increase in spectral bandwidth of the Squid data compared to the Envirovibe data to be due to energy coupling from the source into the bedrock at the base of the pedestal.

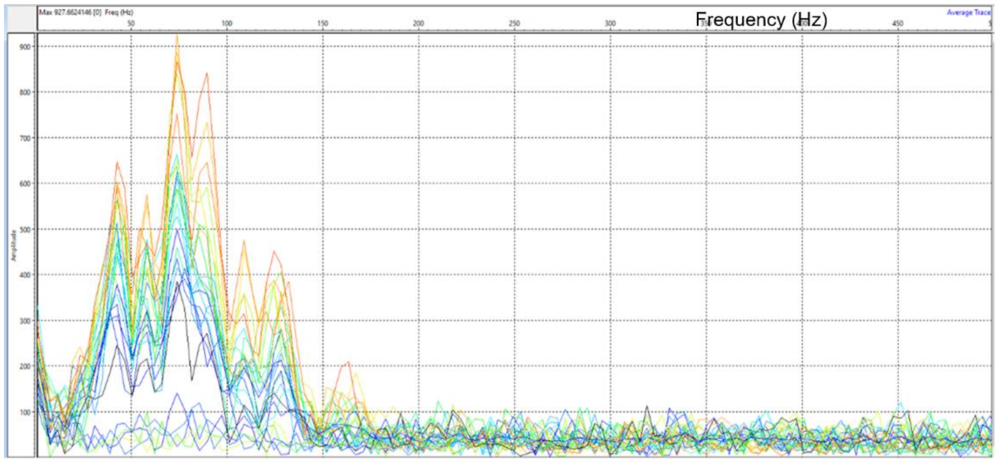

FIG. 11. Amplitude spectra of the Z-component data shown in Figure 10.

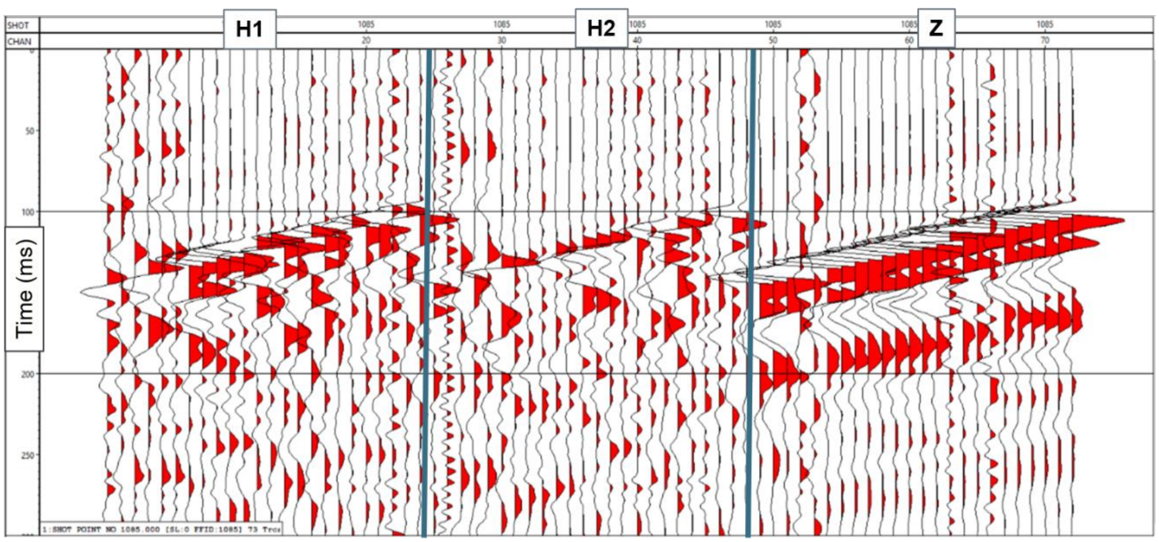

FIG. 12. VSP record obtained with an Envirovibe source. Sweep was 10-150 Hz over 16 seconds.

Data processing

A 2-10-180-200 Hz ormsby bandpass filter was initially applied to the raw data to remove very high frequency noise and DC bias. This noise is likely visible only due to the lower signal strength of the Squid data compared to the Envirovibe data. This filter was not intended to otherwise alter the spectrum, or taper frequencies containing low SNR above 150 Hz. Next, first breaks were picked on the prominent peak of the first arrivals for the Squid data, and the prominent trough for the Envirovibe data. The separation of the down-going and up-going wavefields was achieved by use of median filter. For previous Envirovibe datasets, using a 5-trace median filter for down-going wavefield separation had been found to produce slightly better results than using an f-k filter. In more detail, the shot gathers were flattened by shifting the first breaks to 100 ms. Mean scaling was applied to a 20 ms window around the first arrivals to correct for spherical divergence and transmission losses. The median filter was then applied, removing the up-going wavefield through destructive interference. The resulting down-going wavefield was then subtracted from the original flattened gather, yielding the up-going P-wavefield along with some minimal upgoing SV amplitude and noise. The up-going P-wavefield was then further isolated using an f-k filter. Rather than applying the f-k filter directly, the up-going P-arrival was first removed from the data with the resulting gather consisting of noise and SV amplitudes. That noise gather was then subtracted from the original data, leaving a de-noised up-going wavefield. Figure 13 shows the up-going wavefields for the Squid and Envirovibe data with and without application of the f-k filter. The higher frequency content of the Squid data is apparent in Figure 13 but note that identifying the same reflection events on the Envirovibe data is somewhat difficult due to the opposite polarity of the Squid data.

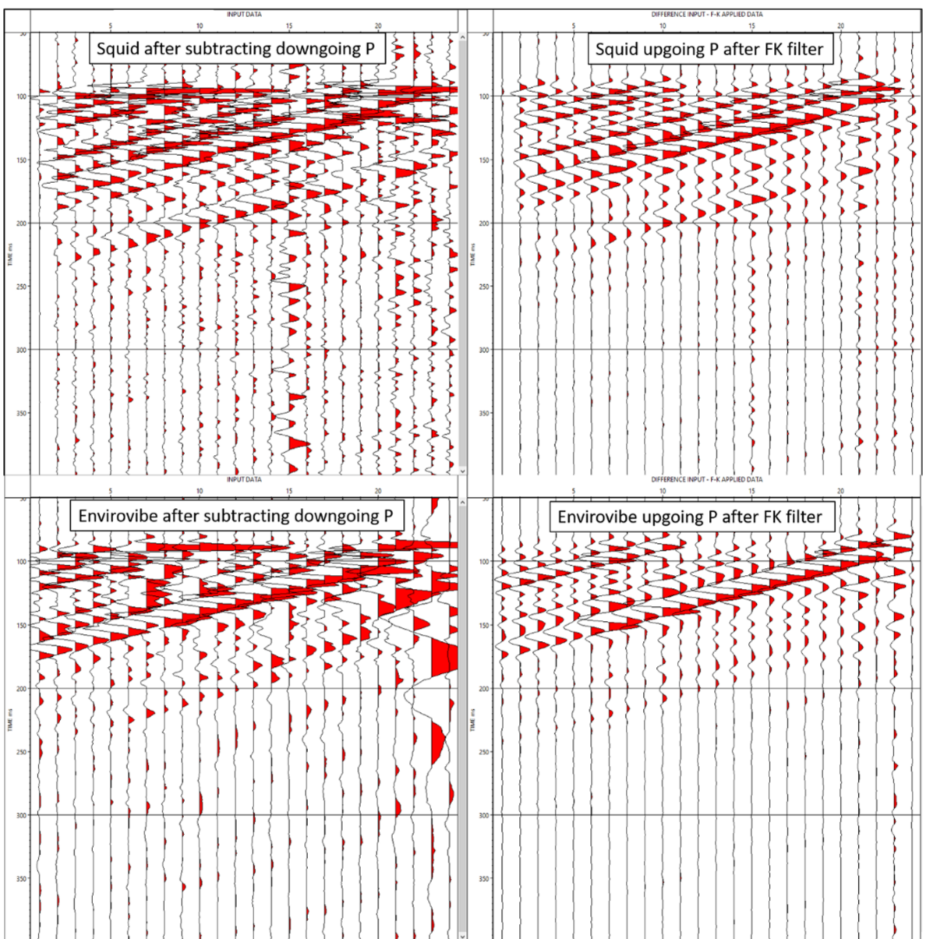

FIG. 13. Up-going separated wavefields for Squid (upper) and Envirovibe sources (lower). After median filter process (left) followed by an f-k filter (right).

Figure 14 shows processed pre-stack gathers converted to two-way-time, along with the full stack. Since the source-well offset was only 62 m, normal-move-out was minimal and an NMO correction was not made. Also, the polarity of the Squid data was reversed for easier comparison with the Envirovibe data. Figure 15 shows the stacked gathers, time-shifted for easier comparison. The higher frequency content of the squid data is most apparent at ~250ms, versus ~275ms on the Envirovibe data, just prior to the high-amplitude peak corresponding to the injection interval. The low amplitude peak in the squid data cannot be fully resolved in the vibe data. This improvement in vertical resolution may benefit interpretation of the reservoir interval. Note the original ~13ms time-delay between data records has been doubled after two-way-time (TWT) conversion. Again, this time difference indicates that the Squid energy is essentially originating from the base of the pedestal.

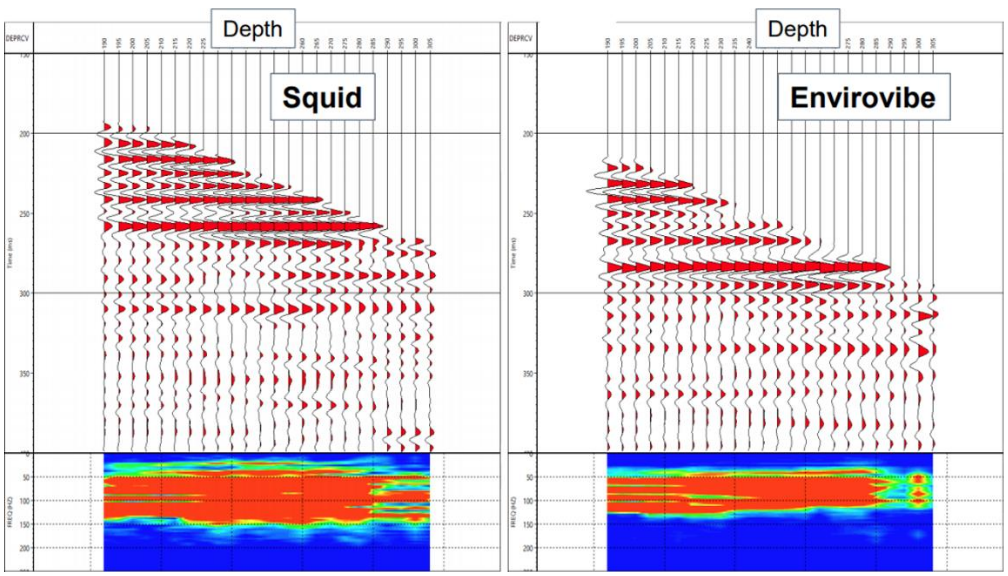

FIG. 14. Prestack gathers from Squid (left) and Envirovibe (right) sources. The Squid data are earlier in time, indicating that the source energy is coupling to the ground into the bedrock at the base of the pedestal. The Squid data is also broader band than the Envirovibe data, as shown by the amplitude spectra images below each gather. Times are 2-way times.

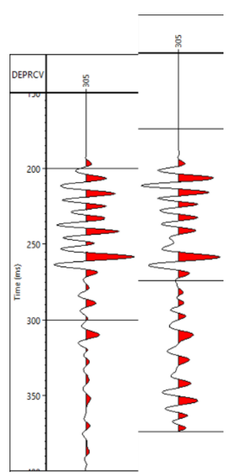

FIG 15. Aligned VSP stacked traces from the Squid source (left) and the Envirovibe (right).

DISCUSSION AND CONCLUSIONS

This project has shown encouraging results for VSP seismic data collected with a new seismic source – the Squid. In addition to the characteristics of the source, we have determined that with the source mounted on the top of a helical pile, the source energy is being transferred into the earth primarily through the base of the pile which was anchored in bedrock below the weathering layer, at a depth of 24.7 m. This conclusion is drawn by one-way first arrival times at the geophone array in Observation Well #2 being ~13 ms earlier than the first arrival times from an Envirovibe source located beside the pedestal. In addition, excellent data bandwidth was achieved with this new source, with peak frequency of 70 – 85 Hz and bandwidth from 10 – 180 Hz. The high dominate frequency yields higher resolution data than that acquired with the Envirovibe source. This is important for monitoring subtle time-lapse changes in the reservoir of interest at a depth of 300 m, into which CO_2 is being injected.

ACKNOWLEDGEMENTS

We thank the sponsors of CREWES for continued support. This work was funded by CREWES industrial sponsors, NSERC (Natural Science and Engineering Research Council of Canada) through the grants CRDPJ 461179-13 and CRDPJ 543578-19. We also thank CaMI.FRS JIP members and 3P Technologies Inc for their support for this project. The authors also acknowledge financial support from the University of Calgary's Canada First Research Excellence Fund program: The Global Research Initiative in Sustainable Low-Carbon Unconventional Resources. We also thank Schlumberger for Vista software licenses for processing the VSP data collected during this project.

REFERENCES

David C. Henley and Donald C. Lawton, *in press*, Time-lapse detection using raypath interferometry. Geophysics.

Brendan Kolkman-Quinn and Don C. Lawton, 2020, Time-lapse VSP results from the CaMI Field Research Station. CREWES Research Report 34, 35.

Tyler W. Spackman, Donald C., Lawton and Malcolm B. Bertram, 2019, Seismic data acquired with a novel, permanently-installed borehole seismic source. SEG Annual General Meeting. https://doi.org/10.1190/segam2019-3214836.1