A time-lapse multi-offset, multi-azimuth VSP acquired as a candidate for low-cost monitoring of CO_2 injection and storage

Kris Innanen, Kevin Hall and Don Lawton

ABSTRACT

In August 2022, CREWES returned to the field to carry out a monitoring version of the 2018 multi-offset/azimuth VSP survey referred to as the Snowflake. The purpose is to add to the datasets which enable research into CO_2 injection/storage monitoring (through, e.g., FWI methods), side-by-side comparisons of standard geophone and accelerometer sensors with both straight and helical wound fiber, and (now), enable research into methods for time lapse analysis, whether involving FWI or other methodologies. Partners Echo Seismic and HDSC worked with University of Calgary/CREWES researchers to acquire a data set designed to maximize repeatability while adding several new dimensions. For instance, two of the VSP azimuths were re-shot with low-dwell as opposed to linear sweeps. Observing differences in effectiveness in waveform and standard analysis methods between these two sweep types is expected to shed significant light on optimal monitoring. This globally unique dataset, coupled with its baseline 2018 counterpart, is expected to support years of groundbreaking research.

INTRODUCTION

Reliable, low-cost, and long-term geophysical monitoring of CO_2 injection and storage, as an element of measurement, monitoring and validation (MMV), is a critical enabling technology for the transition to a carbon-neutral economy. Active source applied seismology, being the only geophysical technology capable of producing 3D, volumetric geological models on the 1 km scale, with 10 m resolution, stands alone as a monitoring tool, and is a natural candidate to address MMV. However, a "standard" 4D seismic program, monitoring a geological volume over the multiple decades of a CO_2 project, must generally exceed any practical cost limitation. Furthermore, an adequate characterization of the CO_2 plume, including its detailed spatial extent and physical state, requires high spatial resolution, and a range of choosable parameterizations. Assemblages of seismic methodologies which (at least in principle) keep costs low, while simultaneously making maximal use of the information content of the data, are therefore sought. Because these two desirable features of a data acquisition and analysis method are generally under tension with each other, the goal is to achieve a balance.

Experience suggests that an acquisition/inversion combination including vertical seismic profile (VSP) data, produced from distributed acoustic sensing (DAS) instrumentation, and inverted using a properly-formulated full waveform inversion (FWI) method, holds promise in the above sense. In CO_2 settings the presence of one or more boreholes can often be assumed, making the VSP a natural sensing mode; meanwhile, instrumenting boreholes with fiberoptic cable, either behind casing or downhole, is becoming standard procedure, and tends to introduce few/minor additional costs. Furthermore, DAS surveys involve little interruption of any other production or injection process. FWI (Virieux and Operto, 2009), meanwhile, though immature as a high-resolution, multiparameter reservoir characterization tool, interrogates seismic data sample-by-sample, in the context of any desired wave physics model (Keating and Innanen, 2020), can be formulated to accommodate DAS data (Eaid et al., 2020), and can be merged with, or support, most rock-physics models deemed appropriate for the geomechanics/chemistry relevant to a CO_2 program (Hu et al., 2021b,a). The VSP-DAS-FWI technology combination is, for these reasons, a serious candidate approach to be examined for efficacy.

FIG. 1. Operating the OptaSense ODH4 in the CaMI-FRS Trailer.

The VSP-DAS-FWI monitoring mode and its efficacy remains in the research sphere for a number of reasons, spanning acquisition, inverse theory, and computational issues. DAS is a rapidly-growing seismic acquisition mode, and successful reports of inversion of DAS measurements are gradually growing in number in the literature (e.g., Egorov et al., 2018). However, a self-consistent treatment of DAS amplitude and phase information requires modelling and processing which accommodates unique noise, directionality and strain-rate projections (**?**), as well as registration and calibration, and accommodation of fixed or variable gauge lengths and channel spacings (Hall et al., 2021). Meanwhile, FWI algorithms must be designed to self-consistently accommodate DAS data, and any other measurements, which means multidimensional and elastic simulations are generally not optional. Furthermore, sampling operators must be properly designed (Eaid et al., 2020), and data inputs with generally different noise types and amplitudes accommodated. This may or may not include acquisition efforts made to partially sense multiple components of strain-rate, beyond the essentially 1C measurement a fiber channel provides (Hall and Innanen, 2022). The sensing environment itself also introduces challenges for FWI whose solutions remain in the research sphere. For instance, the difficulties of seismic inversion in the presence of a complex, low-velocity near surface can be mitigated with VSP data, but, experience shows that attempts to match waveform data at depth by directly modeling the near surface produces models with little interpretability. The question of whether DAS data can, in isolation, provide the data needed to produce adequate FWI models characterizing the CO_2 injection process and/or plume, or whether full or partial broadband multicomponent sensing must occur alongside, is also completely open. Thus, to usefully examine VSP-DAS-FWI as a CO_2 monitoring paradigm, experimentation should simultaneously involve complete broadband multicomponent sensing alongside DAS, and the FWI formulation should accommodate both types of data in a flexibly (i.e., weighted) combination. Finally, the testing should be carried out in a time-lapse setting, ideally involving a real CO_2 injection environment, with extensive "ground truth" information available, so that time-variability of FWI models in the vicinity of a VSP borehole can be assessed.

FIG. 2. HDVSP tool laid out prior to borehole deployment. Foreground: OBS2 well, HDVSP trailer, downhole tool; background: crane.

As detailed by Hall et al. (2019), in 2018, University of Calgary/CREWES researchers (partnering with High Definition VSP, Fotech, and INOVA) carried out a baseline VSP-DAS dataset, involving roughly 500 source points at multiple offsets and azimuths, and both broadband accelerometers and DAS sensors extending from surface to injection depth, acquired in collaboration with the Containment and Monitoring Institute (CaMI), part of Carbon Management Canada (CMC), at the Field Research Station (CaMI.FRS) in Newell County AB. This experiment, which intensively characterized the injection environment from surface to the injection formation, a sandstone formation at roughly 330m depth, occurred prior to any injection of CO_2 and thus has acted as a baseline dataset well-suited to examine the VSP-DAS-FWI assemblage. A FWI formulation was introduced (Eaid et al., 2020) from which elastic models were derived with a tune-able balance of accelerometer and DAS data as input. This permits any decreased efficacy associated with the replacement of multicomponent data with the less-expensive but fundamentally 1C DAS data to be identified. The formulation incorporates data from accelerometers, geophones, and fibers of any desired geometry, regularization terms which penalize multidimensional geological structures, and the replacement of the near surface with subsurface wavefield values, as a means of avoiding direct updating of poorly-constrained, spatially complex and low velocity regions of the model.

Meanwhile, injection commenced at the CaMI-FRS, and by 2022 55 tonnes of CO_2 have been injected into the Basal Belly River Sandstone formation (Kolkmann-Quinn, personal communcation). Motivated by this, in August 2022, a monitoring version of the multi-azimuth/multi-offset experiment was undertaken by the CREWES project and several partners. The identical acquisition geometry and basic instrumentation, were maximally reproduced (within some limits to be discussed herein).

The purpose of this report is to give an overview of the equipment and the survey, and provide an initial look at the data, and to point towards research expected to jump into high gear in 2023 with these data registered and pre-processed.

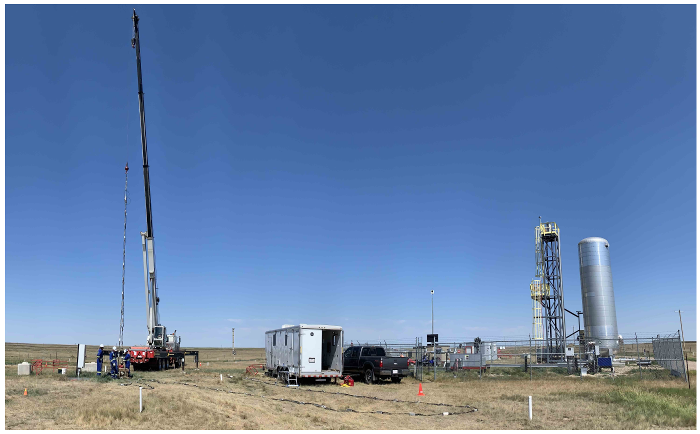

FIG. 3. Crane deployment of HDVSP 3C accelerometer tool.

EQUIPMENT

In this section we summarize the equipment used in the 2022 experiment. Sensors were chosen to optimize the bandwidth of recording, to enable FWI, and also to simultaneously support continuing investigations into the capability of DAS and standard phones. Table contains a summary of the recording systems involved in 2018 and 2022. Although pains were taken to maximize repeatability, recording options have evolved since 2018. This is reflected in the vendor and sensor differences.

Recorders	Comments	Year	Operator
Fotech	2/3m TS, 5m GL, continuous	2018	Fotech
OptaSense ODH4	1m TS, 7m GL, continuous	2022	CREWES
INOVA Scorpion	Downhole, triggered	2018, 2022	HDSC
INOVA (Aram) Aries	GPS timing, Line 13 (Surface)	2022	CREWES
Geometrics Geode	Downhole, triggered	2018, 2022	CMC/CREWES
INOVA Hawk	Surface phones, continuous	2018, 2022	CMC

Table 1. Recording system details. TS: trace spacing; GL: gauge length.

Side by side comparisons of sensors/receivers are also enabled by this experiment, both in the 2018 and 2022 surveys. The permanent borehole geophones (Geospace 3C) and the HDVSP borehole accelerometers (INOVA Vectorseis) sensors are identical from baseline to monitoring (with repeatability of the HDVSP tool position not being precisely ensured), as are the fiberoptic cables, so on balance repeatability is expected to be excellent on the sensor side. Table summarizes receivers.

Finally, Table summarizes sources between 2018 and 2022. Here some differences both in vendor/source, source signature, and source positioning must be expected to be present, though significant mitigation by careful deployment was possible and we believe effective. The heavy vibroseis source differed: in 2018 the INOVA Univib (courtesy INOVA Geophysical) was employed, in contrast to 2022 when the INOVA AHV-IV was employed (courtesy Echo Seismic). Both vibes have comparable source signatures, but preferred sweeps have some differences (see Table). In 2022 some trials with the IVI EnviroVib (courtesy University of Calgary) and an experimental propane hammer (courtesy

FIG. 4. INOVA AHV-IV vibroseis source (owner: Echo Seismic).

Receivers	Comments	Year	Operator
INOVA VectorSeis	1m S, OBS2, surface-TD	2018, 2022	HDSC
Geospace GS32CT 3C	10Hz, 5m S, OBS2, 195-310m	2018, 2022	CMC
SM-7 3C	10Hz, 10m S, Line 13 (Surface)	2018, 2022	CMC
Straight fibre, permanent	OBS1, OBS2, Trench, Pretzel	2018, 2022	CMC
Helical fibre, permanent	30° pitch, OBS1, OBS2, Trench, Pretzel	2018, 2022	CMC

Table 2. Receiver details. S: spacing; TD: total well depth; OBS1: observation well 1 (geophysics well); OBS2: observation well 2 (geochemistry well).

Echo Seismic) also took place.

Sources	Comments	Year	Operator
INOVA Univib	1-150Hz 16s LS, 3s L, 0.25/0.25s T, 2 SV	2018	INOVA
INOVA AHV-4	2-150Hz 20s LS, 3s L, 0.5/0.25s T, 2 SV, L 1-13	2022	Echo Seismic
INOVA AHV-4	2-160Hz 24s LD, 3s L, 0.5/0.25s T, 2 SV, L 7,13	2022	Echo Seismic
IVI EnviroVib	10-150Hz 16s LS, 3s L, 0.25/0.25s T, 2 SV, L 7,13	2022	CREWES
Propane Hammer	10 hits per source point, L 13	2022	Echo Seismic

Table 3. Source details. LS: linear sweep; LD: low-dwell sweep (2-10Hz over 5s, followed by 6-160Hz over 19s); L: listen time; T: start/end taper; SV: sweeps per vibe point; L: line numbers shot.

SURVEY

The survey consists of thirteen source lines of approximately one kilometer length centered on the geophysics well (OBS2), where line numbers begin with the east-west line 1 and increment with counter-clockwise line rotation up to line 12 (Figure 5). Line 13 is parallel to permanent horizontally trenched straight and helically wound fibre. Nominal VP spacing is 10 m along lines 1,4,7,10 and 13, and 60 m along lines 2,3,5,6,8,9,11, and 12. Table one summarizes differences between the 2018 and 2022 surveys.

Four of the 2018 VP were not re-acquired in 2022, VP 1149 (wellsite hardware), 1197 (fence), 4151 (wellsite hardware) and 7157 (fence). Portions of Line 13 were acquired as part of a simultaneous Vibe experiment in 2018, but data was not recorded on accelerome-

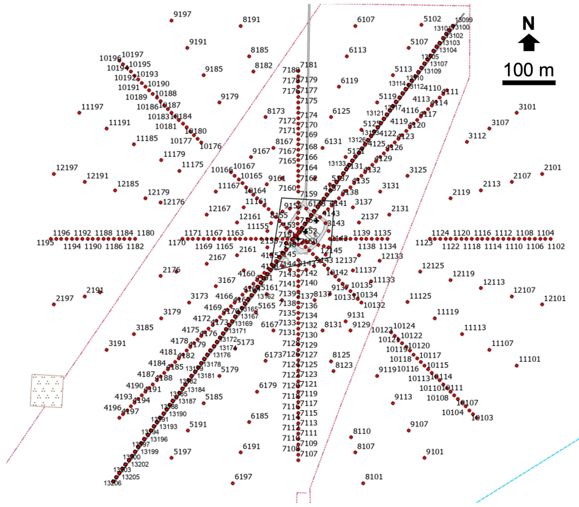

FIG. 5. Multi-offset, multi-azimuth source positions (referred to here as VP = vibe points).

ters or downhole fibre (Hall et al., 2018). In 2022, All of Line 13 was acquired as part of Snowflake2 and was recorded on all receivers.

Field operations

Setup began on August 14 with Echo Seismic, High Definition Seismic Corporation (HDSC) and CREWES on site. Stampede Crane and HDSC inserted HDSC's downhole VectorSeis tool into OBS2. CREWES set up and tested the OptaSense ODH4 DAS interrogator on the facilities 5 km fibre loop, with the pretzel multi-component fibre sensor plugged into the end. A 40 m fibre patch cable was added between the interrogator and the fibre loop to mitigate high amplitude noise observed on helical fibre in OBS, closest to the interrogator. The Geometrics Geodes for the downhole geophones, were swapped from CMC standard continuous recording mode to triggered recording mode.

On August 15, we began production shooting on Line 13 with the AHV-4 vibe (2-150 Hz linear sweep) and the Aries recorder plus Verif-i GPS timing, as the Scorpion recorder (downhole accelerometers) was offline. Data were recorded on fibre, downhole and surface geophones. Following completion of Line 13, the Verif-i was moved to the Scorpion recorder, and production shooting on Lines 1-12 continued with the AHV-4 and all receivers. The Aries recorder was online and monitoring but was not recording any seismic data or GPS times for the remainder of the survey. Lines 7 and 13 were then re-acquired with the AHV-4 with a 2-160 Hz low-dwell sweep. Lines 7 and 13 were then re-acquired with the EnviroVibe using a 10-150 Hz linear sweep. During EnviroVibe acquisition, Line 13 was simultaneously acquired with a Propane-hammer source (Table).

Production shooting was completed on August 18, and the crane arrived back on site to remove the VectorSeis tool from OBS2. Line 13 was re-acquired Aug 18-21 using the Aries recorder with a cabled 3C spread of SM7 geophones and the EnviroVibe as part of the GOPH 549 geophysics field school. Visitors during acquisition included CNRL on Tuesday Aug 16, and Cenovus, ConocoPhillips, and representatives from the University of

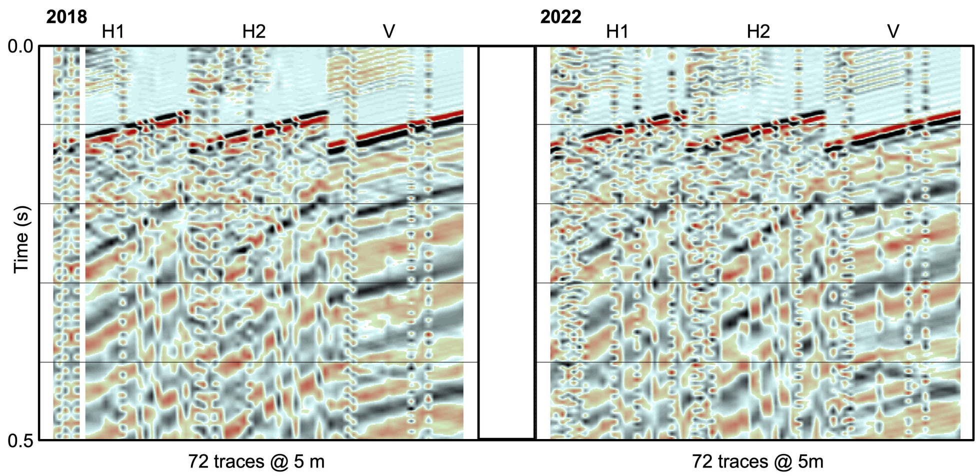

FIG. 6. Shot records: data from permanent 3C geophones behind casing in OBS2. Left panel: 2018; right panel: 2022.

Calgary's Faculty of Science the following day.

INITIAL LOOK AT THE DATA

This section contains data comparisons of 2018 and 2022 data for VP 7158 for the downhole geophones, downhole accelerometers, and data from the fibre loop. All data are shown with a 100 ms AGC and no other processing. Figure 6 shows a comparison of 2018/2022 downhole geophone field data. The 2018 data have been bulk-shifted -20 ms for this figure, where the bulk-shift was determined by visual inspection. While the vertical component looks similar in terms of data quality, there are more dead channels observed on the horizontal components of the 2022 data. In 2018 we waited for the Geode system to download full uncorrelated gathers for each sweep at each VP, but in 2022 we did not. The results is 2 vertical-fold for each 2018 VP, and 1 vertical-fold for each 2022 VP. However, the 2022 data are from a bigger Vibe running a longer sweep, so the source effort is greater.

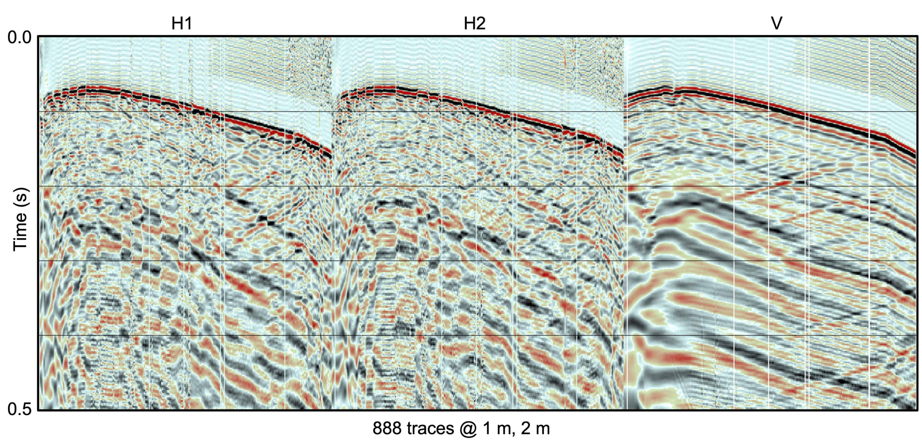

FIG. 7. Example shot records: data from HDVSP 3C accelerometer phones in OBS2 for offset source. Baseline (2018).

Figures 7 and 8 show a comparison of the downhole accelerometer data. In both data sets, the trace spacing is 1m at the top of OBS2 (left side in the figures), and 2 m at the bottom. The downhole tool is formed by interleaving cables with receivers at a 2 m interval, and for both surveys one set of cables failed after installation in the well. In 2018 we lost contact with 30 receivers I the deeper part of the borehole, and in 2022 it was 93 receivers (Note break in slope on right-hand side of each component plotted in Figures 7 and 8 due to the transition from 1 m to 2 m trace spacing). We did not have the time or the budget to pull the string out of the well for troubleshooting either year.

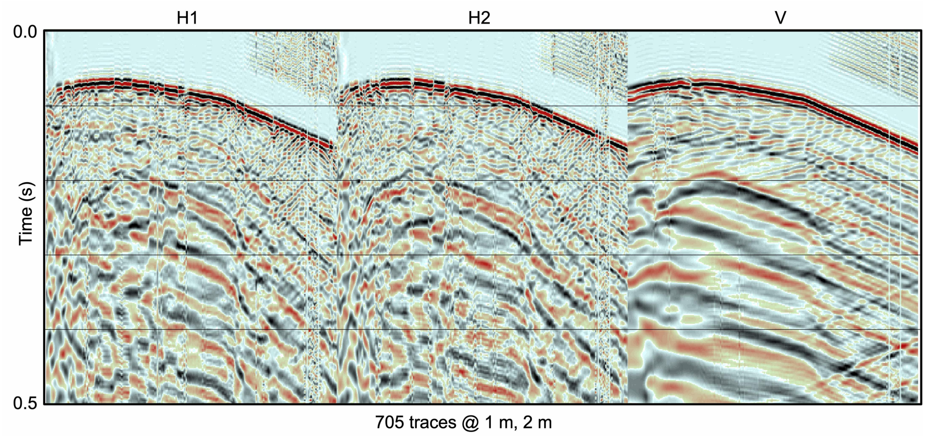

FIG. 8. Example shot records: data from HDVSP 3C accelerometer phones in OBS2 for offset source. Monitoring (2022).

Figures 9a-b show a comparison of DAS data recorded in 2018 and 2022. Plots shown in the figure have been arbitrarily stretched and squeezed to attempt to line them up in time and space. This is required because time-zero appears to be different, and the two interrogators that were used output data with different trace spacings. Additionally, the data appear to be opposite polarity. The data in Figure 5 have been arbitrarily polarity reversed to better match the appearance of the data shown in Figure 6. Our experimental multi-component fibre sensor (the Pretzel) did not exist at the time of the 2018 Snowflake survey, but we recorded data on it for every VP of the Snowflake 2 survey (see Hall and Innanen, 2022). The DAS data are generally comparable, but the 2022 OptaSense data appear to have a better signal-to-noise ratio, and a more clearly defined up-going wavefield. Since we changed the interrogator, the vibe, and the sweep, it is difficult to say precisely what may account for the improvement in data quality.

CONCLUSIONS

In August 2022, CREWES returned to the field to carry out a monitoring version of the 2018 multi-offset/azimuth VSP survey referred to as the Snowflake. The purpose is to add to the datasets which enable research into CO_2 injection/storage monitoring (through, e.g., FWI methods), side-by-side comparisons of standard geophone and accelerometer sensors with both straight and helical wound fiber, and (now), enable research into methods for time lapse analysis, whether involving FWI or other methodologies. Partners Echo Seismic and HDSC worked with University of Calgary/CREWES researchers to acquire a data set designed to maximize repeatability while adding several new dimensions. For instance, two of the VSP azimuths were re-shot with low-dwell as opposed to linear sweeps. Observing differences in effectiveness in waveform and standard analysis methods between these two sweep types is expected to shed significant light on optimal monitoring. This globally

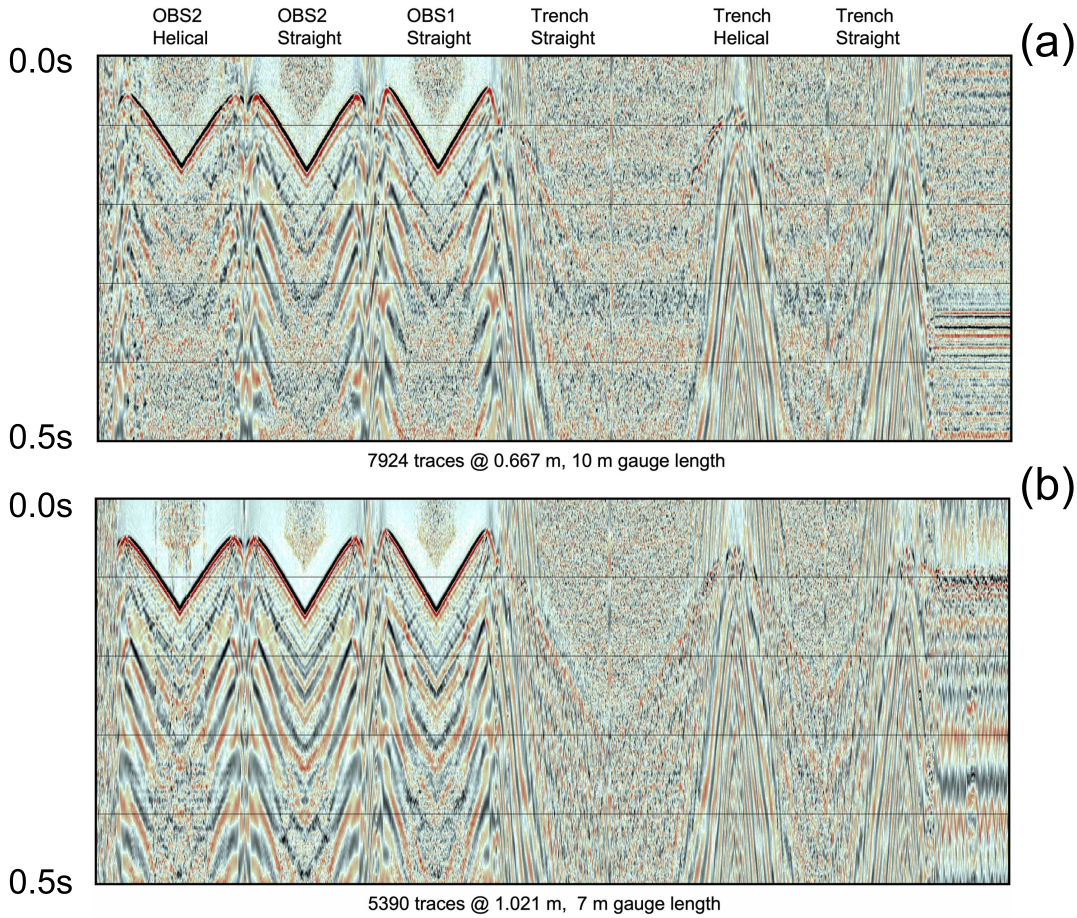

FIG. 9. Comparison of example DAS data records. (a) 2018 (Fotech interrogator); (b) 2022 (OptaSense interrogator).

unique dataset, coupled with its baseline 2018 counterpart, is expected to support years of groundbreaking research.

ACKNOWLEDGEMENTS

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