Acquiring and processing deep dual-well DAS walkaway VSP in an onshore desert environment

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https://doi.org/10.1190/tle42100676.1

Abstract

This study describes the first successful dual-well distributed acoustic sensing (DAS) vertical seismic profiling (VSP) walkaway acquisition in two 4 km deep wells in an onshore desert environment in the Middle East. A dual-fiber interrogator enabled efficient recording of high-channel-count walkaway VSP that was suitable for robust velocity model building and imaging. A good signal-to-noise ratio (S/N) was achieved due to three main factors. First, the fiber cable that was deployed outside the tubing provided good receiver coupling. Second, a gauge length of 24 m was used as a natural receiver array, boosting the S/N. Finally, 16 sweeps per shotpoint were performed using two vibrators in the source array. The selection of optimal acquisition parameters enabled on-tubing fibers to record high-quality seismic signals down to about 4 km. Each shot was recorded by two fibers deployed in wells that are 1.5 km apart. Even with high-quality casing cementation, DAS records exhibited reduced sensitivity/coupling in the shallower section, requiring low-pass filtering for robust first-break picking. The corridor stacks at the two wells show an excellent tie to the surface seismic and agree with the zero-offset VSP geophone corridor stack at one of the wells. A massive ensemble of first-arrival picks enabled multioffset traveltime inversion to reconstruct a reliable velocity profile, approaching the sonic log and overcoming the lower sensitivity of DAS measurement at higher well deviation angles. We used the inverted velocity model to migrate the upgoing reflection response at the two deep onshore wells. The results demonstrate the ability of the dual-well DAS recording to obtain a high-resolution VSP subsurface migrated section with an estimated vertical resolution of about 15 m of reflections down to about 4 km.

Introduction

Distributed acoustic sensing (DAS) technology is an inexpensive alternative to conventional vertical seismic profiling (VSP) wireline acquisitions (Zhan, 2020). DAS VSP is increasingly acquired and recognized as a feasible replacement for traditional geophone surveys (Yu et al., 2020). DAS utilizes optical fiber-optic cables as a sensing array to capture seismic signals. Whereas, conventional VSP surveys use three-component (3C) geophones. Cables are often installed inside wellbores, resulting in a large downhole seismic array for VSP imaging and monitoring (Yu et al., 2019). Downhole wireline geophones are conventionally spaced at 15 m, and the array's length is limited to a few hundred meters. They are typically moved several times to cover the entire well (Titov et al., 2022). However, once conveyed and installed, DAS cables can cover the entire well at once, with high channel densities and lower costs (Yu et al., 2019). Fiber-optic cables are often installed in wellbores to monitor the downhole pressure and temperature for production purposes (Fitzel et al., 2015). These preinstalled cables can also record VSP data sets in a nonintrusive borehole operation when supplemented with a seismic vibrator and optical recording equipment called an interrogator.

Numerous DAS VSP field tests have been conducted for subsurface imaging and monitoring by using various VSP acquisition geometries and cable conveyance methods such as on tubing, behind the casing, wireline, etc. (Hartog et al., 2014; Mateeva et al., 2014; Parker et al., 2014). Using fiber-optic cables that cover the entire well enables multiwell 3D VSP acquisition because there is no requirement to repeat the shots when moving the tool string (Mateeva et al., 2014). Surface and borehole seismic data quality is much more challenging in a desert environment due to scattering and attenuation in the complex near surface (Bakulin and Silvestrov, 2021). As a result, few case studies report VSP borehole seismic imaging in desert environments (Müller et al., 2010a, 2010b; Owusu et al., 2011). Three-dimensional surface seismic overcomes signal-to-noise ratio (S/N) challenges through significantly increased source and receiver density and field source and receiver arrays (Bakulin and Silvestrov, 2023). Increasing the density of VSP data is more challenging with geophone receivers and requires novel acquisition such as DAS. The DAS receiver is a natural array, averaging over the gauge length (GL) while still allowing dense receiver sampling (Bakulin et al., 2020). Müller et al. (2010a, 2010b) report 3D VSP in a desert environment with a 126-geophone array between the surface and 2000 m depth spaced at 15 m. Owusu et al. (2011) present offshore 3D VSP from Saudi Arabia, with a 100-level array stopping at 2000 m, using 15 m spacing. Both data sets reveal significant challenges associated with the desert environment and much less density of 3D VSP compared to surface seismic data. This study presents the first simultaneous dual-well DAS walkaway VSP in a desert environment in two 4 km deep wells, each instrumented with approximately 600 DAS levels spaced at 6.4 m. In addition, we reduced source sampling from the usual 25 m to 12.5 m to boost the acquisition density further. This was achieved without well intervention thanks to preinstalled fiber-optic cables on the production tubing. Data quality assessment, velocity model building, and reflection imaging are the main objectives of acquiring and processing this high-channel-count dual-well VSP survey.

To properly assess this field experiment, we compared the results with legacy conventional geophone VSP and sonic data available in one of the wells. We also fully utilized the large ensemble of traveltime picks from the dense walkaway data set

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to invert for an accurate laterally homogenous velocity model. The inverted velocity model was then used to migrate the upgoing reflection data (recorded simultaneously at the two wells) to obtain a wide-aperture migrated image, achieving a vertical resolution power of thin layers at these two deep exploratory wells.

Dual-well DAS VSP data acquisition in deep wells

We utilized preinstalled fiber cables in two adjacent deep wells in a desert environment as receiver arrays to conduct the VSP survey. A dual-fiber interrogator recorded data simultaneously in two wells, enabling densely sampled acquisition of dual-well walkaway VSP data. As a result, this saved the substantial cost of acquiring two separate walkway lines (one for each well). The two wells are separated by about 1.5 km (Figure 1a), each with a total depth of about 4 km. Both wells are equipped with preinstalled fiber-optic cables clamped outside the production tubing. The recording was performed in a nonflowing condition. Furthermore, one of the wells was chosen based on the availability of a high-quality zero-offset VSP geophone data set that extends throughout the entire well, reaching as shallow as 30 m from the surface.

On the source side, an array of two vibrators (Figure 1c) performs 16 sweeps over 24 s at each shot location. Spacing is 12.5 m along the shot line (Figure 1a). The large number of sweeps per vibrator point (VP) was designed to enable a decimation study of the final results versus the number of sweeps reported in future studies. With multiple sweeps, average productivity was about eight VPs per hour. Approximately 39 hours were needed to complete the shooting of the profile, consisting of 293 VPs covering a 4 km line (Figure 1a). Typically, walkaway VSP lines are acquired with three sweeps per shot location due to higher sensitivity of the geophones. Thus, a shotpoint productivity would be about 28

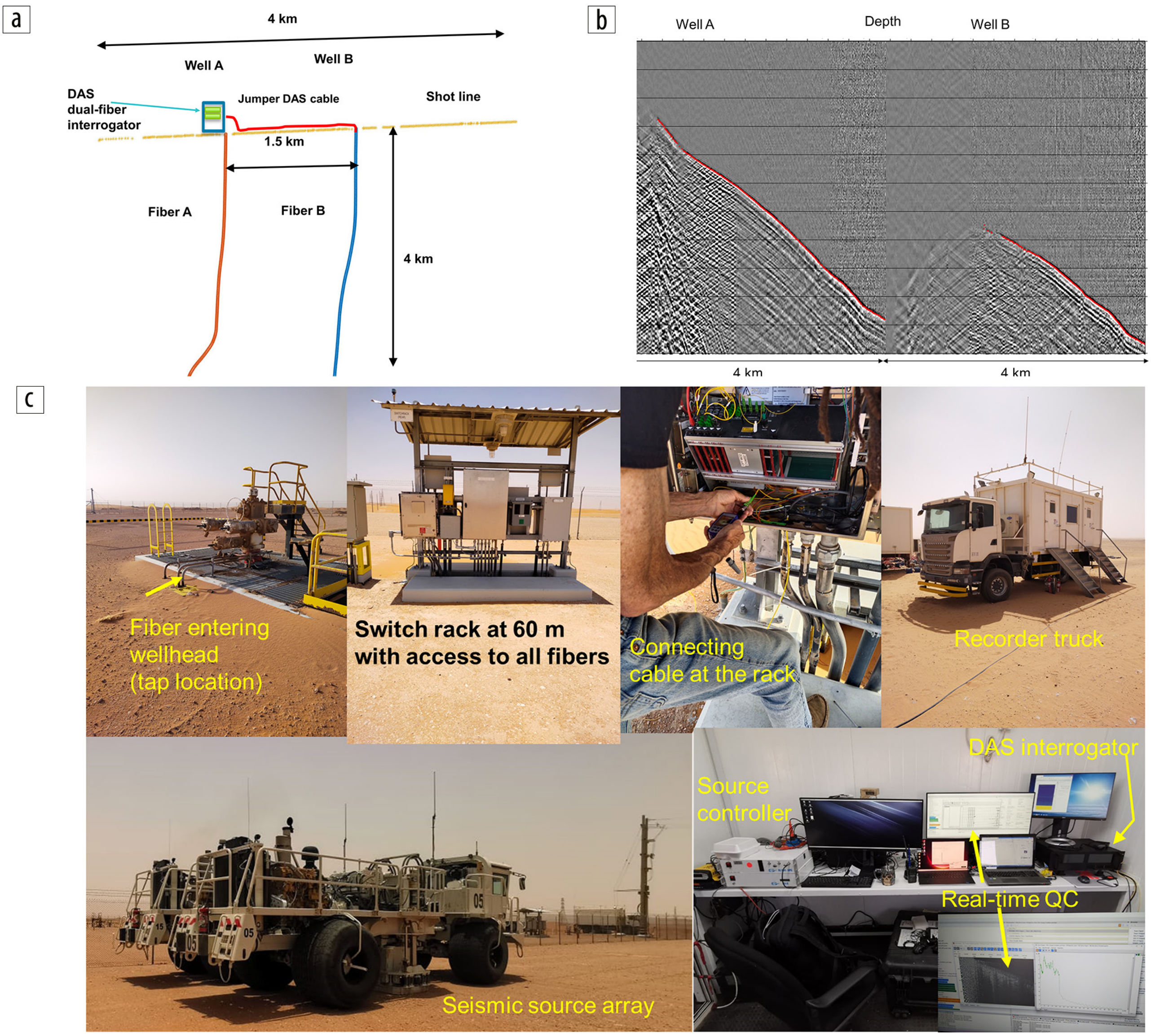

Figure 1. Dual-well DAS VSP acquisition layout and data. (a) The acquisition geometry with sources denoted by the yellow crosses. The red and blue dots represent the receiver points at wells A and B, respectively. (b) Typical common-shot gathers recorded simultaneously at the two wells show high-fidelity DAS data at near (well A) and far offsets (well B) down to 4 km depth. (c) Field photos showing the wellhead, switch rack with a fiber connection, recorder truck, seismic source array, and recording room equipment.

VPs per hour for conventional walkway VSP data in an analogous acquisition. If we have a standard 80-level geophone array with 15 m spacing, it will need to be relocated at least three times within a single well to effectively cover the majority of a 4 km well. This requires multiple reshoots of the same line. Therefore, repeating the same dual-well experiment with conventional VSP acquisition would take at least 62 hours of shooting time (with only three sweeps), compared to about 39 hours using the simultaneous dual-well DAS VSP acquisition (with 16 sweeps). Wireline VSP would need additional time to perform the well intervention and move the tools. Finally, significant rig time would also be consumed. The 16 sweeps delivered robust S/N of the recorded wavefields at the two wells at deeper levels, especially for large offsets away from the wells.

GL, the fiber length over which the recorded signal is optically averaged (Dean et al., 2017; Hartog, 2017), is a critical parameter in DAS acquisition. A larger GL leads to a higher S/N. However, when exceeding half of the dominant wavelength, averaging leads to destructive interference, reducing the signal (Dean et al., 2017). To meet this requirement and maximize the S/N, we set the GL to 24 m in this experiment to reveal the signal at 4 km depth. The aim is to overcome the low S/N of the recorded borehole seismic data that is often noted in deep exploration wells in desert environments. We set the receiver spacing to 6.4 m, aiming for a higher resolution of deeper subsurface information. Such dense sampling also enables robust signal processing steps (e.g., wavefield separation and first-break picking) and minimizes spatial aliasing.

Figure 1a summarizes the geometry of the simultaneous dual-well acquisition, with the red dots denoting shotpoints and the yellow dots representing the receiver stations along the DAS cables. The two deep wells are nearly vertical, with well A showing higher deviation angles of up to 26° at deeper levels. A jumper cable of 3 km was used to connect well B to the interrogator near well A. In summary, the data set resulted in

- 1276 DAS receivers at 6.4 m (both wells);
- 293 VPs with 12.5 m spacing;
- 373,868 traces after stacking 16 sweeps per VP (16× larger data set with individual sweeps recorded for the future decimation study).

This data set is an order of magnitude larger than conventional geophone walkaway VSP acquisition with similar geometries. Figure 1c visualizes essential acquisition equipment and the fiber-optic switch rack to which fiber was connected.

DAS VSP data processing and analysis

In this section, we present and discuss the initial results of the recently acquired dual-well DAS VSP data set. Figure 1b shows common-shot gathers simultaneously recorded in two wells with a VP close to well A. As a result, the left side represents a typical near-offset gather for well A, whereas the right side depicts a far-offset gather for well B. Because the interrogator was placed near well A, we used a jumper extension cable of 3 km to connect it to well B. Consequently, the estimated S/N is about 5 dB lower in well B than in well A when comparing shot records with similar offsets from the wells. This number is supported by optical time-domain reflectometer measurements, revealing a significant existing optical reflector with a loss near well B in addition to average cable attenuation. We also noted an intense noise in 500–700 m that could be attributed to reduced coupling between the on-tubing DAS cable and the formation. This prompted us to calculate the apparent velocity in the zero-offset VSP (ZVSP) DAS gather within the initial 500 m, leveraging the slope of the arrivals. Our computation yielded an approximate value of 5300 m/s, closely resembling the P-wave velocity within the steel that constitutes the production tubing. Consequently, we deduced that inadequate coupling with the formation existed, preventing precise measurement of the actual formation velocities.

We applied a processing workflow tailored for DAS VSP data. Successful DAS VSP processing requires an accurate depth assignment of the DAS channels. Therefore, we conducted a tap test at the entry point approximately 1 m from the wellhead (Figure 1c). Figure 2 shows the tap test results, identifying channels 23 and 484 as the first traces (ground level) at wells A and B, respectively.

First-break picking was challenging, especially in the shallow section of well A (Figure 3). However, low-pass filtering up to 30 Hz enhances the first-arrival waveforms, as shown in Figure 3a. In addition, filtered data enable robust first-break picks, marked by the red circle, not achievable with the full bandwidth data (Figure 3b).

Upgoing and downgoing wavefield separation is limited to a few methods (e.g., frequency-wavenumber and median filtering) because the recorded DAS VSP data are a single-component strain measurement along the fiber (Sayed et al., 2020). We

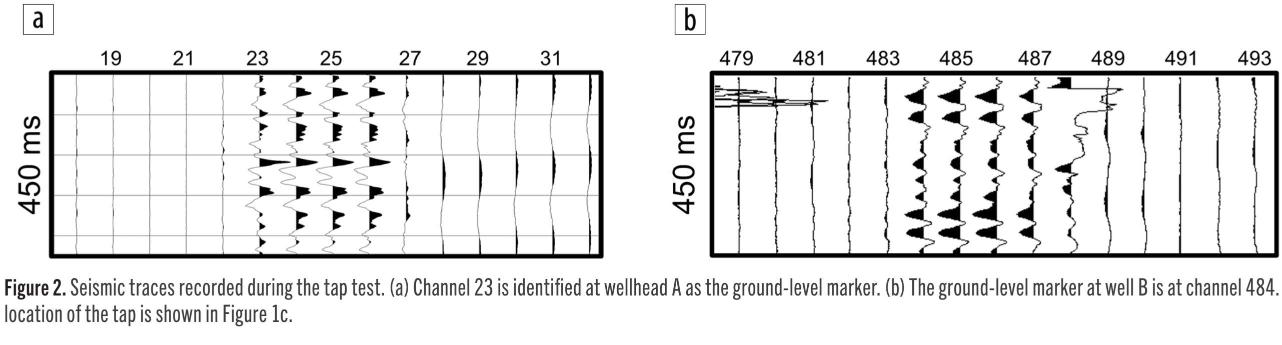

Figure 2. Seismic traces recorded during the tap test. (a) Channel 23 is identified at wellhead A as the ground-level marker. (b) The ground-level marker at well B is at channel 484. The location of the tap is shown in Figure 1c.

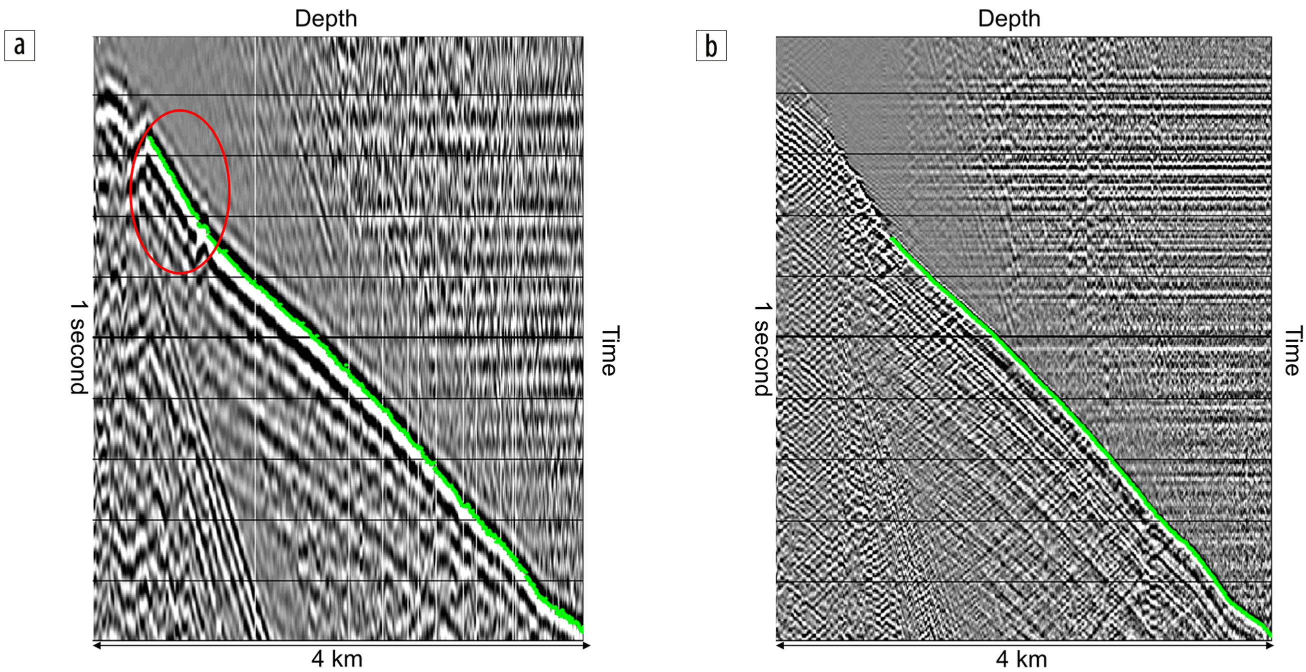

Figure 3. Effect of low-pass filtering on picking. (a) The low-frequency filtered data extend the picks to as shallow as 500 m depth (denoted by the red circle) compared with (b) the full bandwidth data.

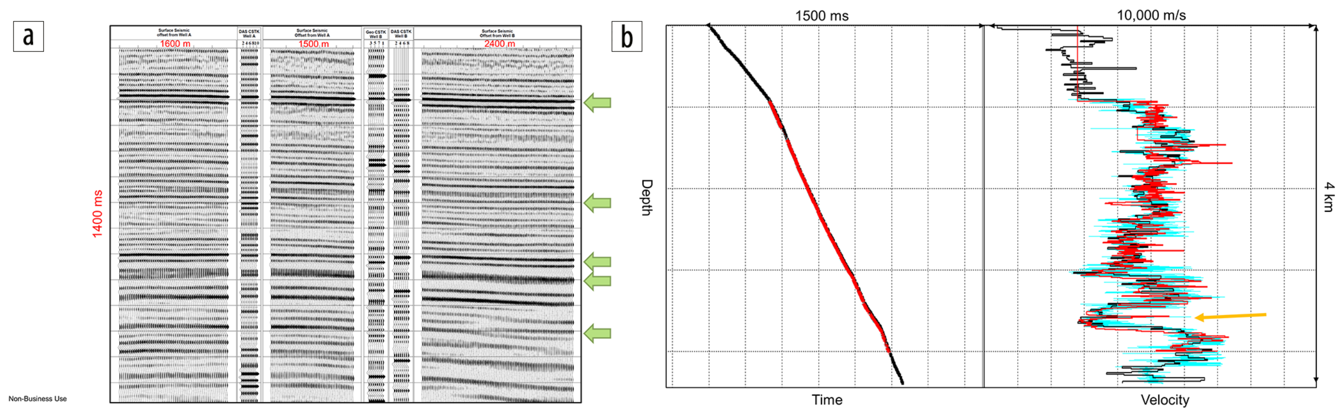

Figure 4. (a) The corridor stacks at wells A and B strongly correlate with the surface seismic section between and away from the wells. The DAS corridor stack also ties with the geophone one at well A. (b) The DAS ZVSP velocity profile (red curve) at well B remarkably agrees with the P-wave sonic log (light blue curve) and the geophone-derived wavespeed profile (black curve). The yellow arrow denotes a streak of thin high-velocity layer outlined by DAS.

obtained a corridor stack from DAS ZVSP data at well A, as plotted in Figure 4a. The corridor stack closely resembles the one obtained from conventional ZVSP geophone data. In addition, we performed seismic-to-well calibration, which yielded a great tie to both corridor stacks obtained from the DAS ZVSP data in wells A and B over a two-way time window of 1400 ms (Figure 4b). The correlation factor between the DAS corridor stack at well A and the surface seismic is 56% with a phase shift of −96°.

Similarly, although the DAS corridor at well B suffers from low S/N, it shows a remarkable 53% correlation with a phase shift of about −63°. The geophone at well A also ties with the surface seismic, with a correlation factor of 66% and an 81° phase shift. The green arrows in Figure 4a show the key horizons with the highest continuity across the section.

The first-arrival traveltime picks from DAS ZVSP data at well B yield a high-resolution P-wave velocity profile, as shown in Figure 4b. The red curve represents the velocity profile from ZVSP DAS data. The velocity obtained from the sonic log is in light blue. The black curve represents the legacy profile reconstructed using the geophone ZVSP data. There is a high similarity between the velocity profile obtained from DAS and geophone ZVSP data. Both profiles accurately follow trends revealed by the sonic log. In addition, a thin high-velocity layer was captured by the DAS measurement (yellow arrow in Figure 4b). The sonic logging confirms the presence of this streak, and it was not delineated accurately by the legacy data mainly due to the large geophone spacing. Therefore, high-resolution subsurface geologic models can potentially be obtained from DAS VSP measurements,

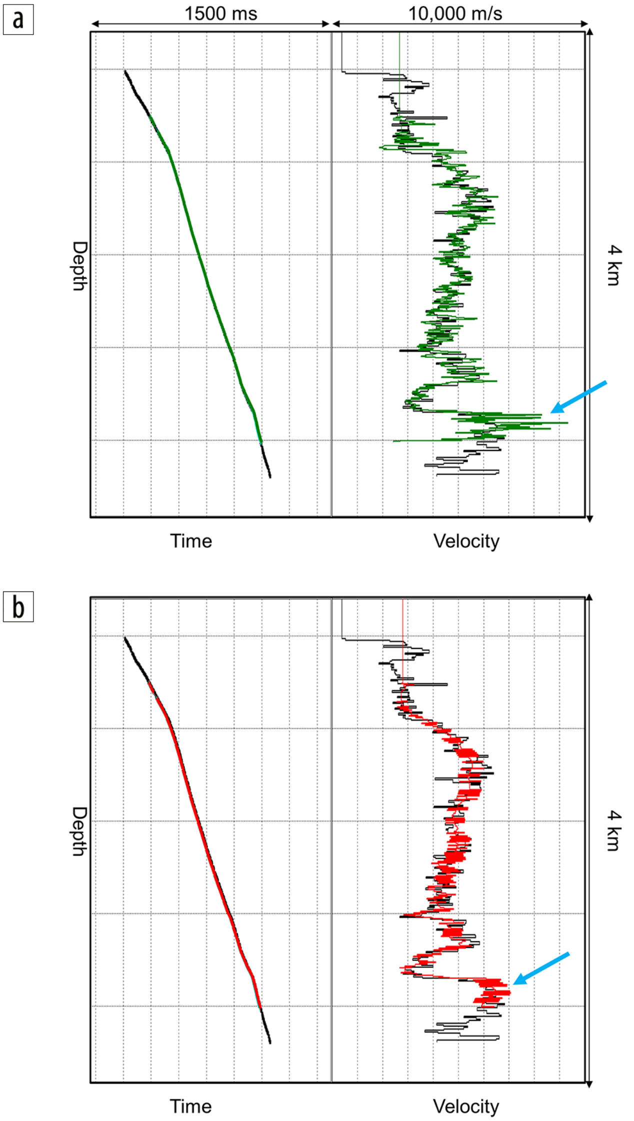

Figure 5. Comparing time-depth curves and inverted velocity profiles obtained with DAS and geophone VSP. (a) The DAS ZVSP velocity profile and time-depth curve in well A (green curve and picks) agrees with the geophone data (black curve and picks) at nearby well B. However, velocity exhibits oscillatory behavior in the deviated section (blue arrow). (b) Tomographic multioffset DAS inversion with lateral homogeneity constraint uses large ensembles of traveltime picks and yields a less oscillatory and more closely matching profile and a time-depth curve, especially in the deviated section denoted by the blue arrow.

showing the power of DAS technology to reveal deep subsurface information with high resolution.

Similarly, Figure 5a shows the P-wave velocity profiles using ZVSP DAS at well A (green curve) and the legacy geophone velocity profile in nearby well B (black curve) with the associated time-to-depth curves. The remarkable agreement between the two velocity profiles indicates the robustness of the DAS first-arrival picks for this well. However, as well deviation of the deeper section increases, sensitivity of the DAS measurement to the direct arrival from the ZVSP shot degrades. Hence, the quality of the traveltime picks worsens. As a result, the obtained velocity profile in this bottom section of the well diverges from the stable geophone profile, as denoted by the blue arrow in Figure 5a.

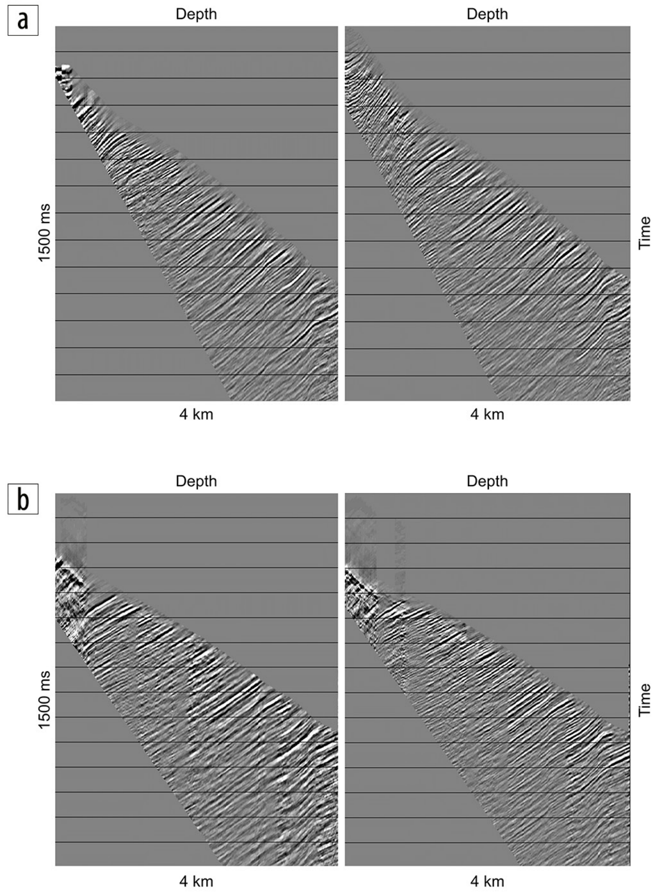

Figure 6. Typical processed gathers after wavefield separation and before migration at (a) well A and (b) well B show clear and consistent upgoing reflection response.

To rectify this oscillatory effect of the velocity profile in the deviated section of well A, we use the large ensemble of offset first-arrival traveltimes from 293 shots and 639 receivers. More than 140,000 picks were used for a 1D (i.e., laterally invariant) traveltime inversion. We used a starting velocity model consisting of five layers. Figure 5b compares the inverted velocity profiles and their associated time-depth curves. Inversion of offset traveltimes results in the velocity profile closely matching the geophone one in the highly deviated section of well A. This result demonstrates that multioffset inversion of the walkaway traveltime picks can yield a robust velocity profile, despite reduced data quality in the deviated section of the well.

Dual-well VSP migration

A key objective of this experiment is to obtain a detailed subsurface image in the vicinity of the two wells using the simultaneously acquired DAS VSP data set. An accurate velocity model and a robust reflection response from the densely sampled DAS data are the main ingredients for a successful migration exercise. The previous section showed how the tomographic inversion could yield a highly resolved laterally invariant velocity model. Next, the recorded DAS VSP wavefields from all shots at wells A and B were separated using median filtering flattened on first-arrival times to suppress the downgoing energy. Then, we applied a dip-median filter to the residual gathers to enhance upgoing

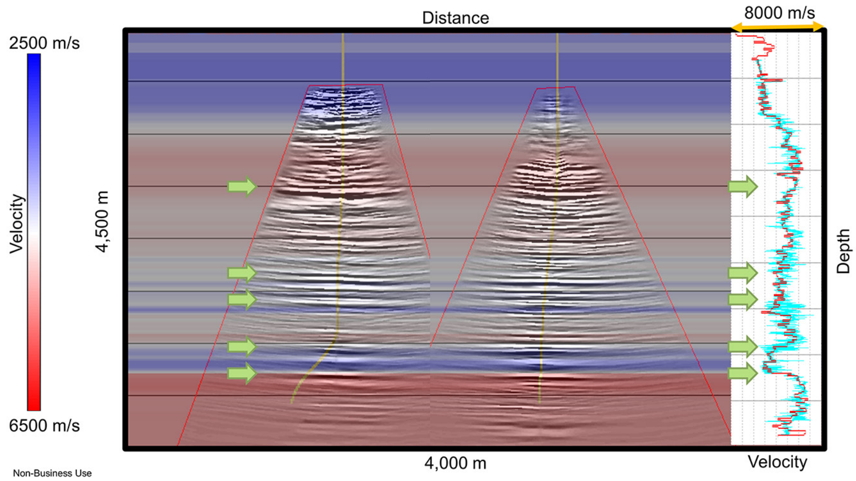

Figure 7. Depth-migrated section with a background of the inverted tomographic velocity model. The high-resolution subsurface image around the wells matches key markers noted in the 1D geophone checkshot profile and sonic log at well B, marked by the green arrows.

reflections. Our filtering procedures were limited to median and dip-median filters. This constraint arises due to the single-component strain measurement provided by DAS acquisition. It is worth mentioning that median filtering is the favored technique in this region, even when dealing with 3C geophone data. Following the wavefield separation, a predictive deconvolution is applied to suppress the multiples and enhance single-scattering (i.e., primary) reflections. Finally, a mute around the reflection response is applied to all the gathers to mitigate the effects of the tube waves.

Figures 6a and 6b show typical processed gathers after wavefield separation recorded at wells A and B, respectively. The Kirchhoff migrated section using the dual-well DAS VSP data set and the smoothed velocity model is presented in Figure 7. It shows a remarkable tie between the two wells, with the green arrows pointing to the key markers. The image overlays the velocity model and displays key reflection events at significant velocity contrasts. The geophone checkshot profile (red curve) at well B and the sonic log (light blue curve) are shown on the right to validate the results further, revealing the main makers' correspondence with significant velocity contrasts. The dominant wavelength of the image is estimated to be about 60 m, depending on the frequency content and the thin bed seismic velocities (Chopra et al., 2006), which yields a vertical seismic resolution of about 15 m of the thin beds in the migrated section. The image shows the power of the dual-well simultaneous recording to obtain a highly resolved image at two wells efficiently and cost effectively while saving operational time for the acquisition.

Conclusions

We present the analysis of a simultaneous dual-well DAS acquisition using preinstalled on-tubing fibers in two adjacent deep wells in a desert environment. The dual-fiber interrogator enables efficient centralized acquisition with real-time data quality control. A selected gauge length of 24 m acts as a built-in receiver array, improving signal clarity. Additionally, employing 16 sweeps per shotpoint further enhances S/N. Consequently, the obtained DAS VSP data using these acquisition parameters and on-tubing fibers possess high quality down to 4 km depth. The S/N of the records at well B shows a drop of about 5 dB compared to well A. This drop is due to a 3 km extension fiber and a strong optical reflector near wellhead B that cannot be rectified in the field. During processing, we apply low-pass filtering to enhance the data and enable robust first-break picking as shallow as 500 m. The obtained DAS corridor stacks at the two wells tie closely with the surface seismic images and the legacy geophone VSP corridor stack. The DAS velocity profile at well B clearly demonstrates the ability to reconstruct a high-resolution P-wave velocity model consistent with the sonic log. We further showcase the power of the multioffset laterally invariant inversion at well A to deliver a robust and stable velocity profile from a large ensemble of DAS walkaway traveltime picks, despite lower DAS sensitivity in the deviated section of the well. The processed upgoing reflected events at both wells were migrated with a smooth version of the inverted velocity model to obtain a high-resolution subsurface image around the wells. The image extends several hundred meters away from each well, with an excellent vertical seismic resolution of 15 m. The strongest events on the migrated image correspond well to the key subsurface markers, enabling a more robust interpretation of the subsurface geology. In addition, we demonstrate how a novel acquisition using a dual-fiber interrogator enables simultaneous recording of dual-well DAS VSP to characterize crosswell space and enhance the resolution limit in two adjacent onshore deep wells. TLE

Data and materials availability

Data associated with this research are confidential and cannot be released.

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