Smart DAS upholes for simultaneous land near-surface characterization and subsurface imaging

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Abstract

A novel integrated land seismic imaging system that uses distributed acoustic sensing (DAS) in a grid of shallow upholes is proposed. This system allows simultaneous land near-surface characterization and subsurface imaging in a cost-efficient manner. Using this fiber-optic system, uphole velocity surveys can be acquired at any time with a single shot, since all depth levels are recorded simultaneously. Dense grids of smart DAS upholes accurately characterize long-wavelength statics and reduce uncertainty in exploration for low-relief structures. In addition, connecting multiple upholes with a single fiber enables efficient acquisition of seismic surveys with buried vertical arrays, which can provide superior images of the deeper subsurface than surface seismic, but with improved accuracy, since they bypass most of the near-surface complexities. The smart DAS upholes can deliver on-demand surveys that simultaneously characterize the near surface and perform deep reflection imaging of oil and gas targets for exploration, development, or reservoir monitoring. We have performed successful field testing of the smart DAS system on an onshore field in Saudi Arabia. Such a system is long overdue for land regions that have complex near-surface conditions.

Introduction

Surface seismic remains the leading technique to explore, develop, and monitor oil and gas reservoirs. In recent decades, land seismic improvements were largely associated with a channel count race to better sample surface-related noise so it can be effectively filtered in processing. Greatly increasing the channel count comes at considerable additional expense with diminishing returns and has done little to address unresolved near-surface complexity that typically plagues onshore seismic imaging in the Middle East. Accurately accounting for lateral velocity heterogeneity in the near surface is particularly important for the delineation of low-relief structures, which typically have vertical closures of less than 60 m (around 30 ms). To achieve this goal, near-surface velocity models and long-wavelength static corrections must be estimated with an accuracy that is only a small fraction of the overall structural closure. Otherwise, the static errors could introduce vertical shifts into the final seismic volume that might obscure the actual structure. An example of how these errors significantly affect the reservoir volumetric estimation is presented by Nosjean et al. (2017), where calculated volumes based on processing with different near-surface models vary by a factor of three.

We propose an alternative acquisition scheme, with far fewer channels than surface seismic, that addresses both data quality and near-surface challenges by burying sensors in the subsurface. The main component of the system is the smart distributed acoustic sensing (DAS) uphole shown in Figure 1a, a shallow hole (50–500 m deep) instrumented with cost-effective optical DAS fiber acting as a seismic sensor.

Smart DAS upholes provide direct measurements of shallow velocity variations and reduce the creation of false structures caused by a poorly characterized near-surface model arising from indirect methods such as refraction tomography. Using a network of smart DAS upholes connected by a single fiber (Figure 2a) allows the proposed fiber-optic system to perform new seismic acquisition with buried vertical DAS arrays. Such acquisition is achieved with relatively small incremental cost by running connecting fiber cables between DAS upholes as shown in Figure 2a. The trenched connecting cables also record useful surface seismic data, similar to that recorded by conventional horizontal geophones. If we were to use omnidirectional DAS cable, we would record seismic data similar to that detected by conventional vertical geophones.

The resulting geophysical surveys can be used for exploration of low-relief structures, detailed reservoir geophysics, or permanent monitoring.

Bridging the gap between uphole acquisition and seismic

Direct measurements can provide more reliable and accurate characterization of near-surface properties. In the past, shallow holes (known as upholes) were widely used to produce near-surface velocity profiles to calculate the static corrections needed to reduce the influence of the near surface on seismic depth images (Cox, 1999; Ley et al., 2003). Conventional seismic upholes require moving a single geophone up the hole and using a hammer or weight drop source to obtain first breaks. Data quality is usually questionable for several reasons. First, the data are acquired using a wall-lock geophone in an open hole that results in variable receiver coupling. The need to repeat the shot at each receiver level also results in variable source signatures. It is difficult to achieve accurate depth control due to manual operations and at large depths; multiple excitations of the weak source are required to achieve good first breaks. Operationally, the uphole crew must be continuously on site during drilling, to enter the hole and perform the survey as soon as it is completed to avoid potential borehole collapse. This makes uphole measurements difficult and expensive, limiting their usage.

The proposed smart DAS uphole setup is a novel method to acquire upholes using inexpensive fiber-optic DAS cables. The DAS cable is deployed in the hole immediately after drilling and can be permanently left in place due to its low cost. Every meter of DAS cable acts as a seismic sensor (Miller et al., 2012), enabling a multilevel array covering the entire length of the uphole from top to bottom. A grid of low-cost upholes allows us to directly estimate long-wavelength statics corrections required for reliable imaging of low-relief structures.

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Using disposable DAS sensors opens up another opportunity, namely to record higher quality seismic reflection data with buried receivers. Bakulin et al. (2012, 2015) compared seismic imaging obtained using surface and buried geophones, which showed superiority of the buried data. In the case of smart DAS upholes, we obtain reflection records with the entire vertical antenna similar to seismic offshore surveys (Ikelle and Wilson, 1998; Asakawa et al., 2012). While holes are sparse in the horizontal direction, the vertical antennas make up for this spatial sparseness by capturing significant additional reflection angles. Indeed, by comparing angle illumination and coverage (Ikelle and Wilson, 1998), one can conclude that surveys with buried vertical arrays may be equivalent to surface seismic. Thus, the novel smart DAS uphole concept allows for both near-surface characterization and targeted deep imaging simultaneously.

To test this new concept, a field experiment has been conducted in Saudi Arabia. We installed a smart DAS uphole array comprising a 2D line of upholes recording a reflection survey using a single continuous fiber cable running through multiple wells. Next, the data quality of DAS upholes was assessed and compared with a standard uphole acquisition using conventional clamped geophones. We then demonstrate that a 2D survey with vertical DAS arrays can deliver robust seismic data for subsurface imaging. We present a direct comparison of prestack data and images obtained using the DAS system and legacy surface seismic with geophones. This is followed by a discussion of the main advantages of this technology and potential future applications in exploration and monitoring.

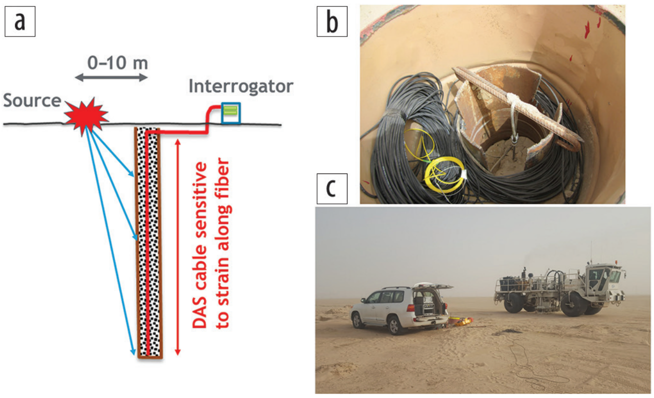

Figure 1. Smart DAS uphole: (a) schematic diagram; (b) wellhead before installing the protection cover; (c) recording DAS uphole survey with a mobile unit and a vibrator. A single sweep is sufficient since receivers cover the entire hole.

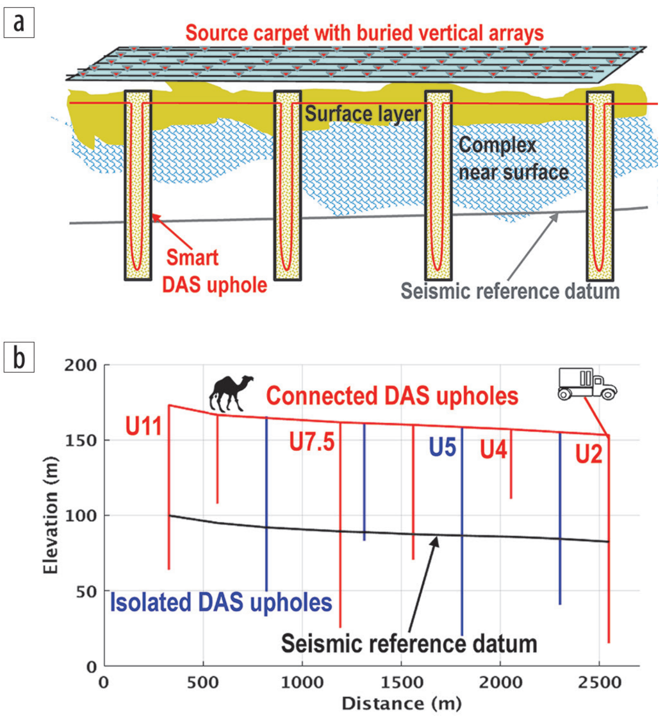

Figure 2. (a) Schematic and (b) actual field geometry of simultaneous DAS recordings in multiple wells acquired with a carpet of sources. Field acquisition contains six vertical arrays on a single fiber with average hole spacing of 400 m and average depth of 100 m.

Field acquisition

A field test was conducted to validate both near-surface characterization and deeper subsurface imaging in an onshore area in Saudi Arabia. The first component of the field test was the uphole acquisition shown schematically in Figure 1a. A tactical tight-buffered DAS fiber cable was installed in the open hole and then backfilled with an appropriate material providing good coupling between the fiber and formation. To map DAS channels to their respective surface and borehole locations, a process called distance calibration was used which compares points of known physical location and measured optical distance along the fiber. Figure 1b shows the wellhead of a completed smart DAS uphole after backfilling. The fiber is connected to the mobile interrogator unit and the seismic source is placed at the surface close to the well (Figure 1c). Several sources were used for testing, including an accelerated weight drop (AWD), vibrator pulse, and a conventional vibrator sweep. Together with DAS acquisition, conventional uphole measurements with a single-receiver geophone instrument were also performed in several wells for comparison and verification purposes.

The second phase of the field test was to acquire a reflection survey using the same smart DAS upholes. While placing a separate DAS fiber in each hole is suitable for a dedicated uphole survey, it would require multiple interrogators for reflection surveys which is currently expensive and impractical. To improve efficiency, multiple upholes were connected using a single continuous fiber (as shown in Figure 2a), which requires running fiber up and down each hole with a loop at the bottom. Surface sections of the cable are trenched at 1 m depth. By installing a continuous fiber in the holes and trenches (Figure 2a), we enable simultaneous acquisition of all DAS channels with a single interrogator unit. Several 2D shot lines were acquired using vibrators over the area of interest with a 10 m inline and crossline spacing. This resulted in 2850 source locations and around 1200 DAS channels (using 4 m sampling), a quarter of which are downhole. Actual receiver geometry is shown in Figure 2b where red indicates the connected DAS upholes used for imaging and blue shows the isolated ones. Since the fiber is predominantly sensitive to the strain along the axial direction (Figure 1a), downhole channels are best suited for recording reflected, near-vertically propagating P-waves which we used for imaging.

Surface channels are less sensitive to reflections, but record well-sampled groundroll for surface-wave inversion, and capture strong refracted arrivals required for tomography.

The fiber remains installed at the site allowing repeated uphole measurements and/or reflection surveys to be acquired in the future to address seasonal variations or for seismic monitoring.

Smart DAS uphole data

One goal of the new acquisition system is to better characterize the near surface for more accurate imaging. First we compare the data obtained using conventional and smart DAS upholes for direct near-surface velocity measurement. A conventional uphole gather acquired using an AWD source and wall-lock geophone is provided in Figure 3a. At each depth the source is repeated several times and data stacked to produce the output shown. This may partly explain some of the early arrival waveform and first-break pick variations observed in the data. Beyond 100 m depth, a substantial change in frequency content and apparent velocity of the first arrivals is observed, which is most likely caused by changing lithology.

Smart DAS uphole gathers are shown in Figures 3b and 3c for comparison. The early arrival waveforms shown in Figure 3b were also acquired by stacking 10 repetitions of an AWD source. Since all depth levels can be recorded simultaneously by the DAS fiber, the acquisition is much faster and the resulting waveforms more consistent between channels, with high-quality waveforms observed from the surface to a total depth of 110 m. Note that the gathers shown in Figures 3a and 3b are from different locations so a direct comparison of the picked times can't be made. However, DAS waveforms are generally of similar or better quality compared to the conventional uphole.

The DAS uphole shown in Figure 3c was acquired in an adjacent well (around 300 m away) to the conventional uphole (Figure 3a) using 10 vibroseis sweeps (8–80 Hz). As in Figure 3b, we generally observe consistent early arrival waveforms that are suitable for picking. Traveltime curves are compared in Figure 4a for conventional and DAS picks from these adjacent wells. A geometric correction has been applied to convert the picks to equivalent vertical traveltimes,

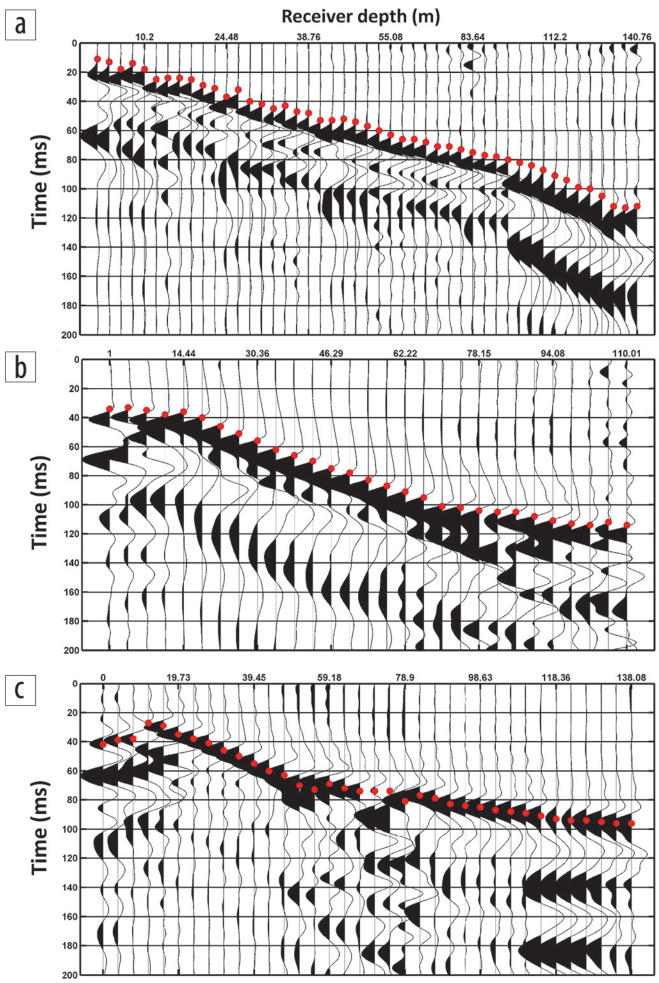

Figure 3. Waveforms recorded for different upholes: (a) conventional uphole U4 using geophone and AWD (stack of 10 sources at each depth location). A channel spacing of 2 m is used above 50 m depth and 4 m below. Source offset is 5 m. (b) DAS uphole waveforms for U11 using AWD source (stack of 10 shots). Channel spacing is 4 m and source offset is 5 m. (c) Waveforms recorded for DAS uphole U5 with vibroseis source (stack of 10 sweeps), located ~300 m from U4 in Figure 2b. Here all channels are spaced at 4 m. Source offset is 10 m.

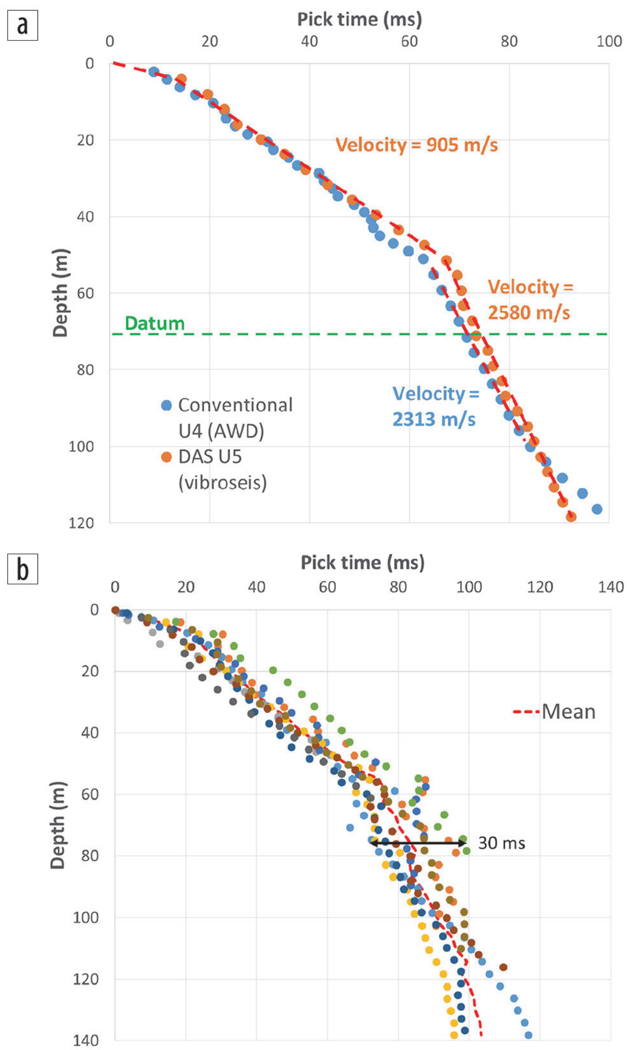

Figure 4. Comparison of first-break picks from various upholes: (a) adjacent wells (~300 m) using conventional (blue) and DAS fiber (orange) receivers; (b) all 10 DAS upholes acquired using a vibroseis (stack of 10 sweeps).

considering the actual source location with respect to the uphole (Cox, 1999). In general, the picks show good agreement although there is a slight deviation in the observed velocities below 40 m, which is not unreasonable given the nature of the near surface in arid environments.

All first-break picks for the 10 DAS upholes acquired using vibroseis sweep data are plotted in Figure 4b. While the general trend of the picks is similar between wells, clear lateral velocity variations are apparent even over such a small scale of a few kilometers. For example, at a depth of around 80 m we observe variations of 30 ms in one-way traveltimes. These variations represent mid- to long-wavelength statics that need to be accurately estimated to reliably image low-relief hydrocarbon structures.

The first smart DAS uphole seismic experiment demonstrated that excellent data quality, comparable if not better than those obtained using conventional methods, can be obtained for detailed near-surface estimation. While conventional uphole acquisition requires multiple source excitations at the surface and repositioning of the geophones, the smart DAS uphole survey can be acquired with a single shot, resulting in more efficient acquisition and stable waveforms. This offers a great opportunity to reduce cost or use the time to acquire multioffset upholes for better near-surface characterization. Besides the improved data quality, DAS upholes present several other advantages over conventional methods. During acquisition of conventional uphole data, any collapse of the borehole may lead to the loss of the tool, resulting in delays. For DAS upholes, the risk is greatly reduced since the fiber is installed and backfilled right away. Entering most upholes with DAS cables immediately after drilling has proven straightforward, and fluid or solid backfill, cementation, or bentonite packing represent practical solutions providing good acoustic coupling. In addition, the uphole survey can be repeated in the future and can also be incorporated as part of a seismic reflection survey using multiple upholes.

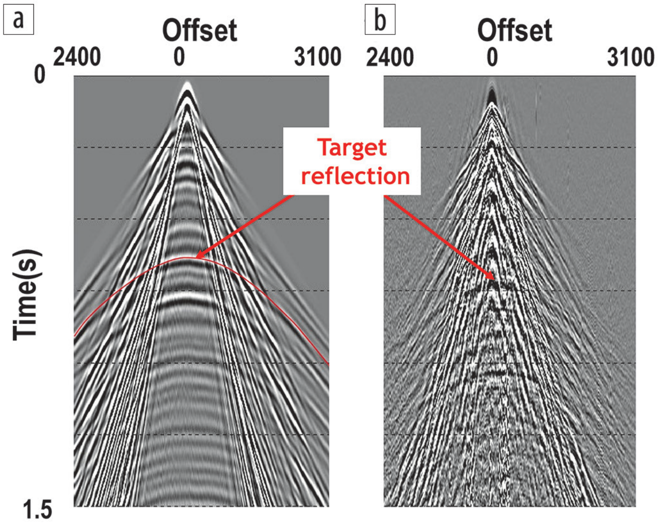

Figure 5. Comparison of (a) synthetic and (b) real common-receiver gathers. Sensor depth is 130 m from U7.5. Target reflection event calculated using ray tracing in true model is overlaid over synthetic data.

Imaging with buried vertical DAS arrays and comparison with legacy seismic data

Field reflection data versus modeled response. Reflection imaging of the deeper subsurface is another opportunity enabled by the smart DAS uphole concept. Seismic data acquired in arid environments are often contaminated by very strong noise caused by multiple scattering in the near surface and surface waves. Buried receivers can partially overcome this problem and can provide better quality data than conventional surface seismic (Bakulin et al., 2012, 2015). Similar findings are made with the buried DAS data, where with increasing sensor depth we observe more and more reflection signals, and less contamination by horizontally propagating energy in the near surface. Synthetic and real data at a depth of 130 m are compared in Figure 5 showing that the field data are of sufficient quality to allow us to observe the target reflection signal on the raw gather.

Comparison of prestack DAS and legacy seismic data. It is of interest to benchmark the DAS data against the legacy 3D seismic. Figure 6 shows common-receiver gathers obtained using a single DAS channel in a shallow hole and legacy data using surface geophone arrays. We observe excellent kinematic agreement between reflected signals on both data sets. DAS data show more details because of the finer source sampling of 10 m compared to 60 m for legacy data. The lower levels of linear noise on legacy data are explained by the use of 72 geophone and five vibrator arrays in the field, which efficiently suppress groundroll and other arrivals with low apparent velocity. After we apply linear noise removal to DAS data and decimate to the same spacing, we see closer agreement between DAS and legacy geophone data, especially for shallow reflectors that were heavily obscured by groundroll (Figure 6c). Since a linear 8–80 Hz sweep was used

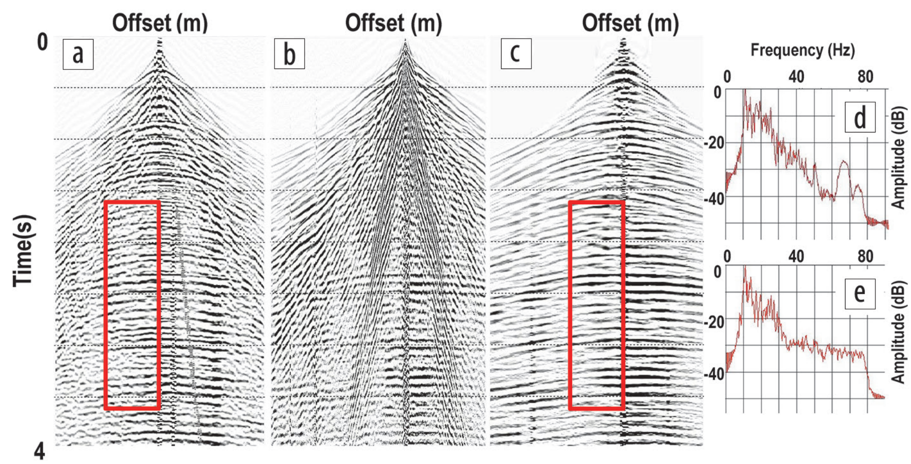

Figure 6. Comparison of prestack common-receiver gathers obtained with surface geophone (legacy 3D seismic) and DAS receiver at 15 m depth: (a) raw legacy seismic gather with 60 m source spacing, (b) raw DAS gather with source spacing of 10 m, and (c) same DAS gather after linear noise removal and decimation to 60 m source spacing. Spectra of legacy geophone (d) and DAS data (e) after noise removal show similar behavior.

for both acquisitions, we can also directly compare spectra of the DAS and geophone gathers (Figures 6d and 6e). They appear quite similar confirming the broadband nature of the DAS receivers and general equivalence with geophones.

Image comparison between DAS and legacy seismic data. While the DAS field data set contains only six vertical arrays with irregular and large spacing (Figure 2b), we obtain a robust 2D image that can be compared with the legacy surface seismic image. To make the comparison fair, we have selected an equivalent 2D subset from the legacy 3D data, containing one receiver line and one parallel high-density shot line with spacing of 60 m for both. We have applied the same time processing to both data sets and used the same legacy velocity and no statics. To compensate for the lack of source/receiver arrays during DAS acquisition, we have applied linear noise removal to the fiber-optic data whereas we relied on field arrays for legacy data. One major nonstandard step for DAS data processing was bringing all the receivers to the same depth level for time processing and stacking. This can be done in several ways, including using direct arrival traveltimes (Fuller and Sterling, 2010), via wave-equation redatuming (Al-Ali and Verschuur, 2006) or by interferometric approaches (Schuster, 2009). In this work, we use vertical traveltimes picked on the uphole data and redatum all traces to the surface using the resulting statics. With this approach, all depth levels can be merged to form a final stack with significantly improved signal-to-noise ratio compared to individual stacks from a single depth.

Figure 7 compares brute seismic stacks obtained with DAS and legacy geophone data. Both shallow and deep reflectors are robustly imaged on the DAS data similar to surface seismic. DAS and legacy lines intersect at 45°, so the DAS image is shown on one side and the legacy image on the other. An excellent tie of both images is seen at the intersection point, both for the target reflector as well as other reflectors, all the way to 3 s. This confirms the excellent sensitivity of DAS vertical arrays to reflection energy, and the ability to obtain equivalent images to surface seismic, despite large spacing between shallow holes. Further processing and refinement of the velocity model should improve the image. Likewise, depth imaging can be performed using a model that has calibrated near-surface velocities obtained with the DAS upholes.

Applications to exploration

The smart DAS uphole concept provides many more opportunities in terms of oil and gas exploration of complex prospects, such as low-relief structures. If there is significant uncertainty in the near-surface model that may impact exploration, then acquisition of new on-demand smart DAS upholes can be requested. The drilling crew predrills all the upholes and installs the DAS fiber. Then the recording crew comes and records all uphole surveys with a single shot/sweep per uphole (or several shots for stacking). Decoupling the drilling/deployment phase from the uphole acquisition can minimize risk, cost, and acquisition time. Efficient acquisition using a strong energy source such as vibroseis will allow complete acquisition of an uphole with a single sweep. This may deliver additional benefits, such as acquisition of shallow VSPs, to help identify multiple generators in the near surface that are typically missed by conventional VSP surveys, due to poor shallow data quality. If the on-demand concept is adopted, then it becomes practical to perform regular grids of upholes over prospects of interest. Such uphole surveys can be fit-for-purpose solutions in areas with near-surface challenges. The reasons include:

- A grid of smart DAS upholes can completely resolve long-wavelength statics and deliver a near-surface model with the accuracy needed for low-relief structures.
- Buried data are of higher signal-to-noise ratio compared to surface reflection data and can provide angle coverage and images comparable to surface seismic.
- Combined smart DAS upholes and surface seismic survey (i.e., using the same sources) offers a unique apparatus for characterizing the near surface through one-way tomographic inversion.
- The combined survey is a self-contained package that can derisk prospects of interest.

To illustrate how the grid of upholes can assist seismic exploration by resolving long-wavelength statics and deliver an accurate near-surface model, we simulate a synthetic example using the SEAM II Arid model (Oristaglio, 2015). Consider two low-relief structures in an area of interest of 10 × 10 km (Figure 8a). Figure 8b shows true long-wavelength statics computed using the SEAM Arid velocity model assuming a seismic datum at 100 m depth. The largest structural uncertainty comes from errors in long-wavelength statics that distort the geometry and volume of the explored structures. Acquiring a patch of upholes on a 1 × 1 km grid requires 81 wells (Figure 8d). Assuming that short-wavelength statics can be estimated from seismic, we can simply interpolate long-wavelength statics from upholes into the entire volume and obtain reliable statics for the entire survey. Figure 8c confirms reliable mapping of both 10 and 20 ms low-relief structures with uphole-based statics. Considering the larger exploration risks associated with low-relief structures, and the significant cost of drilling exploration wells, such targeted grids of upholes could become a useful tool in our geophysical toolbox. DAS-based upholes can provide direct and reliable static estimates not only for time imaging, but also depth imaging to avoid depth mis-ties often encountered in areas with complex near-surface conditions.

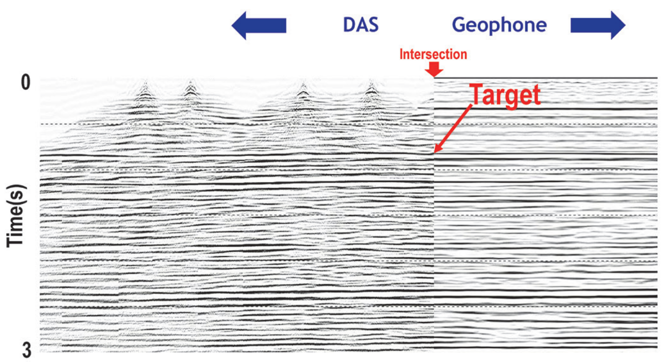

Figure 7. Comparison of 2D images obtained with vertical DAS arrays (left) and surface legacy seismic (right). The vertical arrow marks where both lines intersect each other at 45°. Observe the excellent tie between main reflectors.

Fiber trenched along the surface appears to record excellent data that could be readily compared to modeled elastic responses (Figure 9). As expected, the mostly axial directivity of the fiber suggests it is more similar to horizontal geophones. Unlike vertical geophones, both DAS and horizontal geophones show little evidence of reflections. Well-sampled refraction arrivals and groundroll can be readily used for refraction tomography and surface-wave inversion (Silvestrov et al., 2015). The excellent quality of shallow trenched DAS data suggests that P-wave surface seismic imaging can be within reach, provided omnidirectional DAS cables are used.

Applications to monitoring

The outlined DAS system can become the next tool of choice for permanent reservoir monitoring. Bakulin et al. (2013, 2015) and Bakulin and Jervis (2017) demonstrated successful permanent seismic monitoring with buried sensors during Saudi Aramco's first CO2-EOR demonstration project. Here, because of the high cost of conventional sensors, a single multicomponent geophone was installed in each 70 m hole. While DAS cables for deep wells may require expensive protection and cost US$20–30 per meter, for shallow near-surface applications much less protection is required and may cost in the range of US$1–5 per meter. With such cost-effective DAS sensing, we can now instrument the entire hole from surface with sensors every few meters at a small fraction of the cost of a conventional single geophone. Having multiple sensors in each well will lead to higher fold and more repeatable time-lapse images, compared to what is available with conventional sensors. When the entire hole is instrumented, we can further increase the spacing between shallow holes, thus making the monitoring systems more cost effective, suggesting the proposed fiber-optic DAS system can have high impact for land seismic acquisition and monitoring.

Summary and outlook

Geophysical methods must deliver higher accuracy and fidelity to be used for exploration of low-relief structures, reservoir geophysics, and monitoring in challenging arid regions. While improving surface seismic through increasing channel count is the approach taken by most companies, we have chosen a novel approach of utilizing shallow boreholes instrumented with DAS fiber-optic cables as seismic sensors. Cost-effective sensors via DAS cables in shallow holes, allow direct estimation of near-surface velocities, thereby eliminating a major source of structural uncertainty when delineating low-relief structures that are

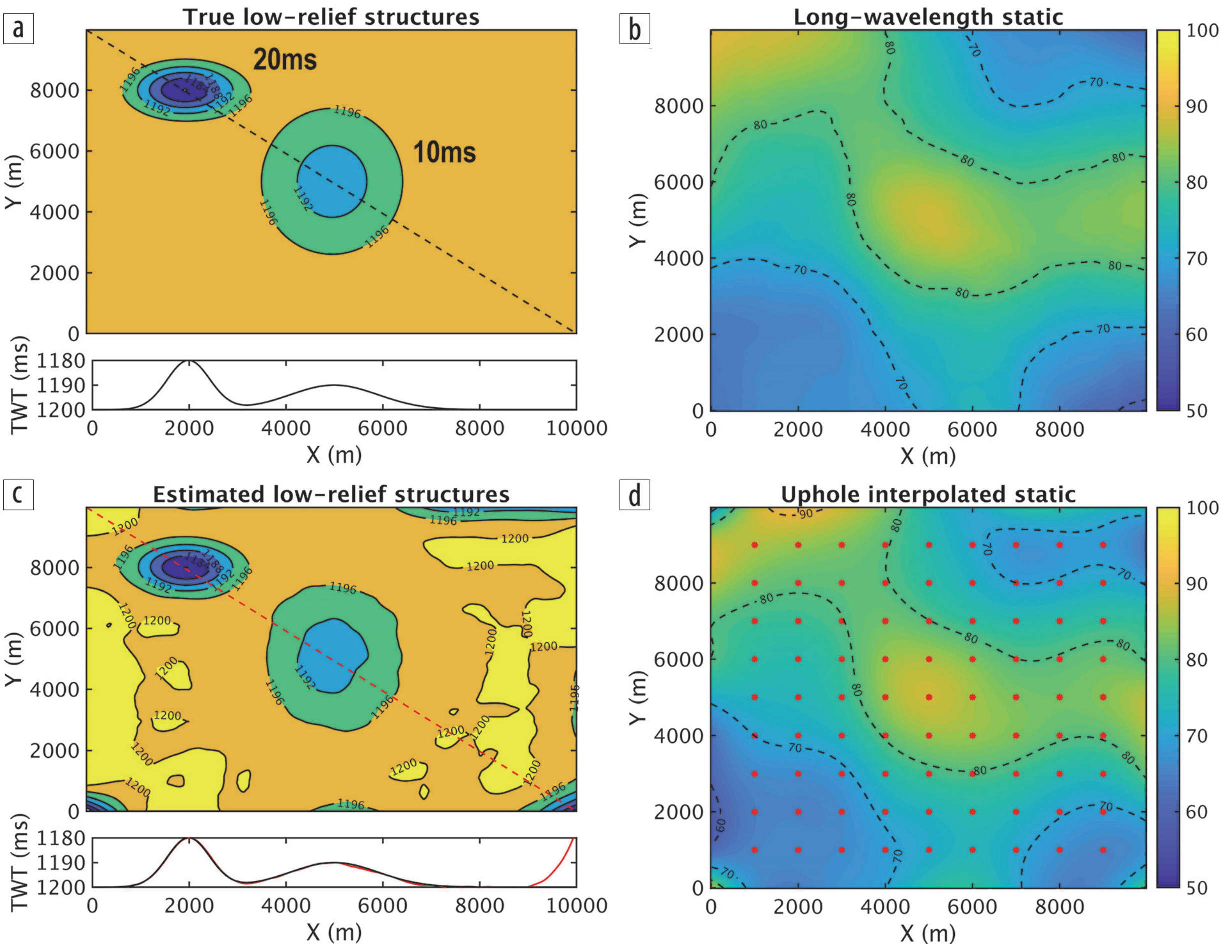

Figure 8. Mapping of low-relief structures using uphole-based near-surface models: (a) synthetic low-relief structures and (b) long-wavelength static time shifts derived from the near-surface part of SEAM II Arid model; (c) reconstructed structural map and (d) long-wavelength static values derived from interpolating uphole grid drilled at 1 × 1 km. Note the good estimation of near-surface statics and consequently reliable reconstruction of target low-relief structures in (c).

important exploration targets. In development and production, such buried systems can deliver new high-fidelity reservoir characterization and enable cost-effective reservoir monitoring leading to increased recovery. This is a paradigm change in land seismic, where instead of putting more channels on the surface with diminishing returns, we can achieve more significant data quality improvement using far fewer and higher quality channels in buried shallow holes.

We have presented a 2D field experiment demonstrating the validity of the components and the entire system. Smart DAS upholes, which enable simpler, safer, and more cost-efficient operation, were found to produce excellent data quality for near-surface characterization. With sensors present from ground level to total depth, a single source excitation is required resulting in identical source signature for all receivers providing superior waveform quality compared to conventional upholes.

The connection of these upholes with a single fiber enabled the efficient acquisition of a targeted reflection survey using a buried vertical array. This has the potential to significantly reduce the cost of acquiring land seismic data, by removing the huge burden imposed by the hundreds of thousands of geophones and cables typically used. Buried DAS arrays can provide an alternative approach to imaging smaller prospect areas, and can serve as efficient surrogates for localized seismic surveys. Comparison of the acquired DAS data with legacy seismic revealed good agreement between DAS and geophone data both on prestack gathers, amplitude spectra, and final stack. This is a remarkable achievement, as it paves the way for developing an integrated surface seismic acquisition system that uses DAS to replace conventional geophones. TLE

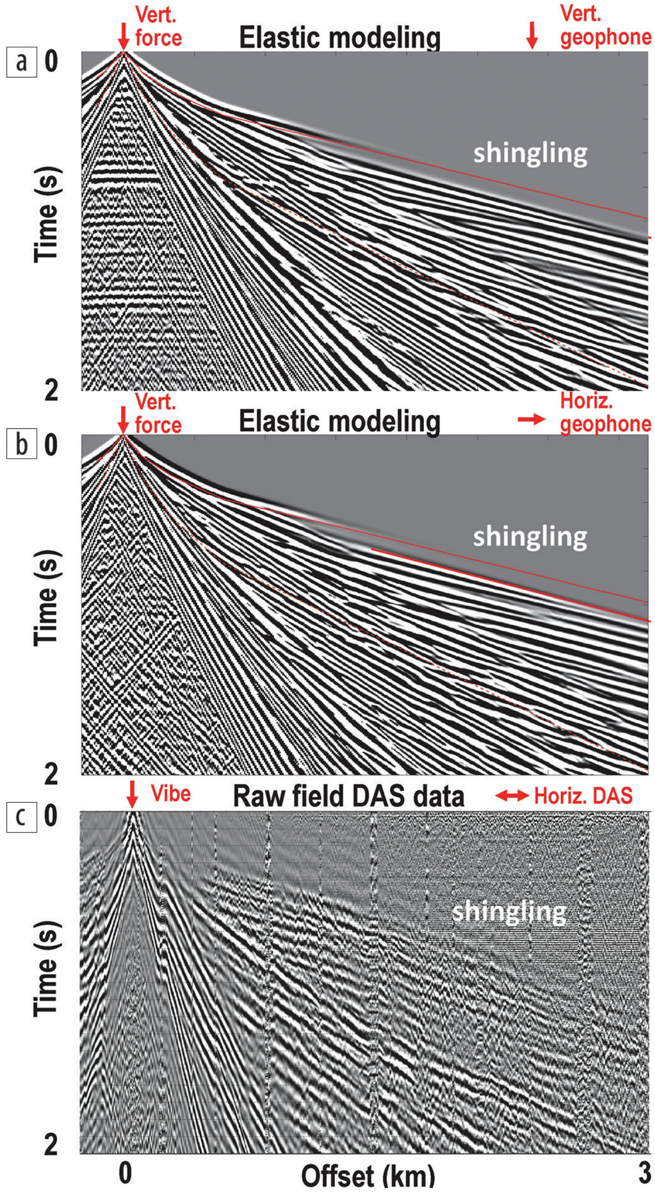

Figure 9. Synthetic versus field data including (a) elastic modeled vertical component, (b) horizontal component, and (c) a field gather obtained with horizontal DAS cable trenched at 1 m depth. Observe the excellent quality of the field gather and general agreement with modeled response of horizontal as opposed to vertical geophones. Shingled refraction arrivals (associated with velocity inversion) are visible. Groundroll arrivals are well sampled without aliasing and are suitable for surface-wave inversion.

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