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Advances in near-surface characterization and deep imaging with smart DAS upholes

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Summary

A smart distributed acoustic sensing (DAS) uphole system is proposed that utilizes a cost effective, permanently installed fiber as a seismic sensor embedded in the shallow subsurface. Using this system, uphole velocity surveys for near-surface characterization can be acquired with a single shot by recording all depth levels simultaneously. Dense grids of on-demand smart DAS upholes produce more accurate long-wavelength statics than conventional approaches, reducing uncertainty in the interpretation of low-relief structures. Connecting multiple upholes with a single fiber enables seismic surveys to be acquired with buried vertical arrays. These can provide robust images of the deeper subsurface like surface seismic, but with much improved accuracy due to the elimination of most of the near-surface complexities. The system comprising a carpet of surface shots and a dense grid of smart DAS upholes provides a complete dataset for near-surface characterization as well as imaging for oil and gas exploration of low-relief structures.

The proposed smart DAS uphole acquisition scheme was successfully tested on an onshore field in Saudi Arabia. The field test demonstrates the validity of the components and the entire system. Smart DAS uphole data was found to be of excellent quality, while recorded seismic data with buried vertical arrays showed clear reflection signals and produced images of the deeper subsurface.

This paper presents the smart DAS uphole system for near-surface characterization and deep imaging, including a discussion of the processing results from the data acquired during the field tests. We show how the novel acquisition system can be used in the petroleum industry to decrease the risks associated with the exploration of low-relief structures.

Introduction

For many years, reflection seismology using surface acquisition has been the conventional tool for exploration, development and monitoring of oil and gas reservoirs. Despite numerous advances and developments in surface seismic acquisition and processing that have significantly improved data quality, many challenges remain unresolved, which leads to critical uncertainty in the resulting seismic image. In arid regions such as the Middle East, complex near-surface conditions are the source of most of these issues, with sand dunes, dry river beds, karsted areas and complex topography significantly corrupting surface seismic data (Keho and Kelamis, 2012). Low-velocity anomalies, strong surface-related noise and backscattered seismic events caused by these complexities deteriorate target reflections, making seismic imaging and interpretation very challenging. As an example of how the near surface can affect deeper reflections, let us consider a relatively simple, but realistic model shown in Figure 1. The model contains a karst (void) around 300 m below the surface that causes a low-velocity anomaly in the velocity model. If this anomaly is not accounted for correctly during seismic processing, it will significantly distort reflectors in the deeper part of the seismic image (Figure 1). Such distortion makes the interpretation of the seismic image very challenging and can significantly increase exploration risk. A common solution to treat the near-surface complexities is to apply static corrections or time-shifts to the acquired seismic data (Cox, 1999). These vertical time corrections are applied to eliminate the influence of the near-surface and to shift the data to some reference level more suitable for seismic imaging. After application of these corrections, the seismic data has a more correct time structure, which is the ultimate goal of seismic time processing. Accurate calculation of statics is difficult in the presence of complex near-surface conditions, and requires application of special geophysical techniques. The most common and widely used approach in the industry are methods based on refracted waves, such as refraction tomography. Unfortunately, these methods have many limitations and are unable to provide reliable results in the areas where velocity inversions occur. At the same time, we need to accept that current exploration targets, such as low-relief structures, which typically have vertical closures of less than 60 m (around 30 ms), require very accurate near-surface models for their successful delineation. Indeed, to achieve this goal, near-surface velocity models and long-wavelength static corrections must be estimated with an accuracy that should be 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 (Figure 2). A true low-relief structure with a closure of 30 ms is shown on the left. An uncertainty in the statics model of 20 ms, which is smaller than the vertical closure of the structure, affects its delineation, but still allows us to map the target correctly. The large uncertainty of 50 ms completely deteriorates the map, making the structure interpretation unreliable.

The most robust and accurate results for near-surface characterization are produced by direct measurements of vertical seismic travel-times in shallow holes, known as upholes. Although a very popular and widely used method in the past, currently it is often underutilized due to economic and logistical reasons. To show how a dense grid of upholes can provide an accurate statics/velocity model we make a simple but realistic synthetic example using the SEAM Arid model (Oristaglio, 2015). Its upper part replicates near-surface complexities typical of arid environments. These complexities are introduced into a top layer of the model with a thickness of 500 m and are visible in Figure 3 (left). A horizontal slice at a seismic reference datum located at 100 m depth (Figure 3b) shows strong heterogeneity and complexity inside this zone. The true statics calculated down to the seismic datum (Figure 4, left) show rapid vertical travel-time variations in the near surface. However the most important, and usually unresolved time-shifts, are long-wavelength static variations (Figure 4, middle) which can be obtained by smoothing the full static. These variations significantly affect the structural interpretation and should be estimated with great care. Let us assume two structures in the model having 10 ms and 20 ms vertical closures as shown in Figure 4 (right). If upholes spacing is sparse, then inaccurate long-wavelength statics is estimated and low-relief structures of interest may become poorly resolved (Figure 5a and 5c), with the large structure significantly smeared and the apex of the small one shifted laterally. An example of how such 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. In contrast, a dense uphole grid (1x1 km) allows us to delineate the same structures with high accuracy (Figure 5b and 5d).

Smart DAS upholes

As an alternative to conventional upholes, a new seismic acquisition method is proposed in which the upholes are equiped with optical fiber cable (Bakulin et al., 2017). Distributed acoustic sensing (DAS) is a recent and rapidly evolving technology for seismic data measurements that turns the entire cable into a seismic sensor (Miller et al., 2012). It consists of a standard fiber optic cable such as used in the telecommunications industry and a special interrogation and recording unit. A series of laser pulses is introduced into the fiber and energy from Rayleigh backscattering due to tiny imperfections in the cable is recorded. Seismic waves deform the cable and cause phase and amplitude changes in the recorded light signals. These changes are transformed into localized measurements of changes in strain along the cable, averaged over some distance, and are output as the seismic signal at any point along the cable. This provides seismic data with very dense receiver spacing and wide frequency range. The fiber is cost-effective compared to geophone sensors, costing from $1 per meter, meaning that DAS measurements can become significantly cheaper in comparison to typical seismic acquisition.

In smart DAS upholes, the fiber is installed into a shallow well (Figure 6, left) and connected to the interrogator at the surface. Vibroseis, or another seismic source, is excited at the surface near the well head and the signal is recorded by the DAS unit. In comparison to conventional upholes, this system has several advantages. In the conventional approach, a recording instrument measures the signal at one depth level at a time and may require multiple excitations of the shot at single location. This results in variations of the recorded waveforms at different depth levels due to different source signatures and different receiver coupling and requires a lot of time to acquire. In contrast, smart DAS upholes record the signal simultaneously from top to bottom using a single source excitation, leading to stable waveforms and very fast acquisition. Operating with the seismic tool in an open hole during conventional uphole surveys can also lead to collapsing of the well, losing the tool and delaying acquisition. In DAS surveys, the cable is installed directly after the drilling and the hole is backfield with an appropriate material. This minimizes the risk of collapse and allows to decouple the acquisition from the drilling and installation phase allowing to optimize both operations individually. In addition, due to the low fiber cost, it can be placed in the uphole permanently and the acquisition can be repeated again if necessary.

Several smart DAS upholes can be connected using a single cable as shown in Figure 6 (right). In this case, the recording unit measures the seismic signal in all upholes simultaneously. In addition, connected uphole grids can be considered as a deep imaging system using vertical seismic arrays (Ikelle and Wilson, 1998), which can provide data suitable for seismic imaging of reservoirs. In that sense, a grid of DAS arrays can be considered as a flexible acquisition scheme that provides very detailed characterization of the near-surface and seismic imaging of deeper target horizons. Due to an accurate near-surface model obtained from DAS upholes, we can expect significant reduction in structural uncertainty of seismic images and as a result more reliable delineation of subtle reservoir structures.

Field experiment

Acquisition

To prove the concept of smart DAS upholes, a field experiment was conducted in an onshore area in Saudi Arabia. Ten boreholes were drilled as shown in Figure 7, with an average spacing of 400 m and an average depth of 100 m. Six of them were connected by a single continuous fiber, while four others were used individually. An example of drilling operations is presented in Figure 8 (left) showing a mobile rig used in the experiment. The surface part of the cable was trenched at 1 m depth as shown in Figure 8 (middle and right). The fiber was then lowered into the well (Figure 9, left), using an attached weighted mass. The wellhead of the smart DAS uphole after cable installation is shown in Figure 9 (right). Figure 10 shows an example of data acquisition using the installed smart DAS upholes. In this case, a seismic vibrator is used as a source. The interrogator unit was installed inside a vehicle and was controlled by one operator.

Data from smart DAS upholes

An example of data recorded from a smart DAS uphole is shown in Figure 11 (right). The early arrival waveforms were acquired by stacking 10 source sweeps to increase signal-to-noise ratio. We see that direct arrivals are clearly identified and can be easily picked. The waveforms are stable at all depths and are suitable for picking. For comparison, we also recorded a conventional uphole in a different well using a single geophone (Figure 11, left). At each depth level the source is repeated 10 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. Overall, the DAS waveforms are generally of similar or better quality compared to the conventional uphole. Travel-time curves are compared in Figure 12 for conventional and DAS picks from the same well. A geometric correction has been applied to convert the picks to equivalent vertical travel-times considering the actual source offset with respect to the uphole. The travel-time picks show good agreement and provide the same velocity estimation in the near-surface.

By interpreting the travel-time picks from all the upholes, we construct a multi-layered near-surface model as shown in Figure 13 (left). The model shows variability of seismic velocities with depth and pinching out of the third layer on one side of the survey. Using this model, statics to the seismic reference datum were calculated (Figure 13, right). We observe variations of the static corrections along the survey line over both medium and long spatial wavelengths. Accurate determination of such variations is extremely important for correct delineation of low-relief structures.

Imaging with vertical DAS arrays

In addition to picking vertical travel-times similar to conventional upholes, a grid of smart DAS upholes offers a unique opportunity to image deep reflectors. Seismic data acquired in arid environments is often contaminated by very strong noise caused by multiple scattering in the near surface, mode conversions and surface wave noise. Buried receivers can partially overcome this problem and can provide better quality data than conventional surface seismic (Bakulin et al., 2012, 2015) due to significant reductions in surface wave energy recorded. Smart DAS upholes record the data below the surface and in this way have similar properties to the data acquired with buried geophones. Since conventional fiber cable is sensitive mostly to the longitudinal strain along the axial direction, vertical DAS arrays are able to record reflected P-waves propagating near-vertically which can be used for deep imaging. An example of a raw seismogram recorded at a fixed downhole location at a depth of 125 meters for all shots at the surface is shown in Figure 14 (left). The data is of good quality and shows several strong reflections, though the weak ones are hidden below high-amplitude surface-related arrivals. After attenuation of surface random noise, we observe a clear seismogram showing refracted waves, ground-roll and reflected events (Figure 14, middle). To highlight reflections and suppress other unwanted events, we apply linear noise attenuation as shown in Figure 14 (right). The data clearly indicate the presence of strong reflected energy suitable for imaging. To construct seismic images, we first datum/time shift the downhole data to the surface and then apply conventional processing steps such as velocity analysis, deconvolution, residual static corrections and CDP stacking. An example of seismic stack sections before and after applying surface-consistent deconvolution is shown in Figure 15. The spectrum of the deconvolved image is flatter and shows higher frequency content. This suggests that a conventional processing flow can be adapted to process shallow DAS seismic data acquired with vertical arrays.

Finally, we compare the results obtained from the DAS arrays with legacy conventional surface data acquired in the same area. 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 datasets and used the same legacy velocity model 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 geophone data. The stack sections obtained for both datasets are shown in Figure 16. We observe very good agreement between the two images all the way from shallow to deep. The two sections are at 45^o azimuths with respect to each other and their intersection is shown by the vertical red line. Detailed comparison at the intersection point shows an excellent tie between the reflectors on both images. This confirms the high sensitivity of DAS vertical arrays to reflection energy, and the ability to obtain equivalent images to surface seismic, despite large spacing between shallow holes.

Conclusion

Smart DAS upholes are proposed as an alternative way of acquiring seismic uphole surveys. Cost-effective DAS fiber-optic cable is installed in smart upholes and connected to a recording unit at the surface. This allows us to record the seismic signal from ground level to total depth with a single source position, making the acquisition very fast and efficient. This results in an identical source signature for all receivers providing superior waveform quality compared to conventional upholes. Since the uphole can be equipped with a fiber cable and backfilled directly after drilling, the operational risks related to hole collapses and downhole tool loss are significantly decreased.

Connecting several DAS upholes with a single fiber cable enables efficient acquisition of grids of on-demand smart DAS upholes over prospects suffering from near-surface challenges. As we have shown, dense areal grids with a spacing of 1x1 km can resolve long-wavelength statics with sufficient accuracy to explore and delineate low-relief structures. The near-surface velocity model derived from the DAS uphole data has high level of detail providing good estimates of both long- and medium-wavelength static corrections.

Grids of DAS upholes enable efficient acquisition of reflection seismic data with buried vertical arrays. The resulting seismic image has excellent quality and is comparable to legacy seismic data despite more limited spatial sampling horizontally. Such surveys can provide an alternative approach to imaging small prospect areas and serve as an efficient method for localized seismic surveys.

We have presented a 2D field experiment showing the feasibility of the entire system. We believe that smart DAS upholes represent a new paradigm in seismic acquisition that can accurately characterize the near surface and produce reliable seismic images in depth.

Acknowledgments

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Figures

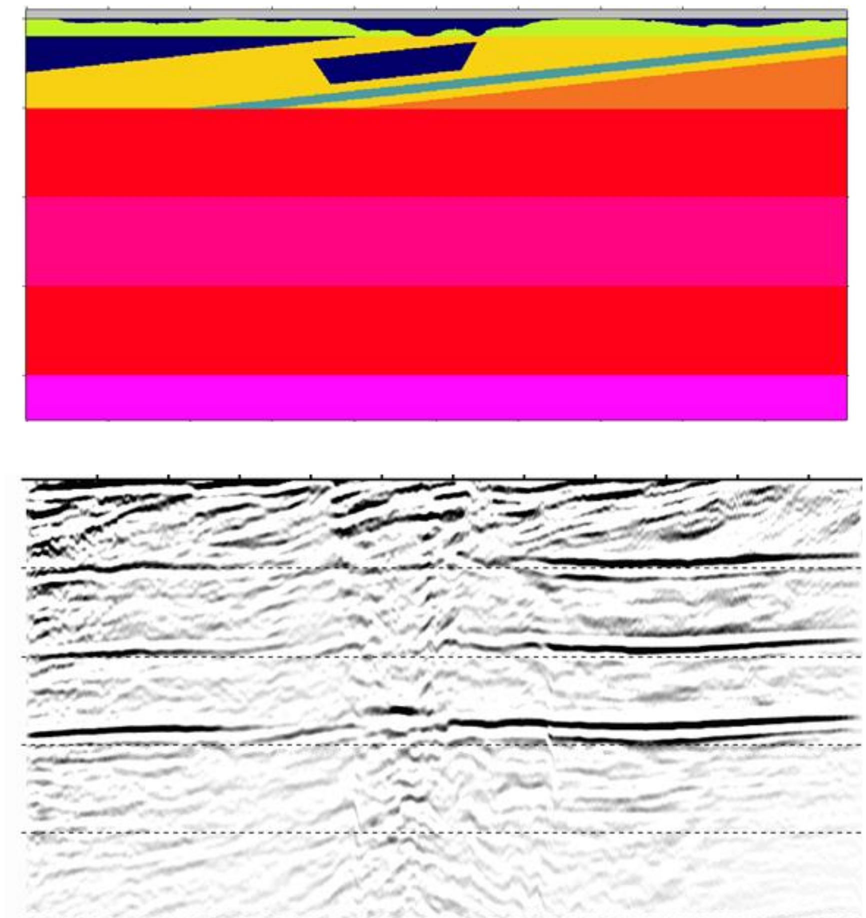

Fig. 1—A synthetic example of how complex near-surface conditions can deteriorate the seismic image. The velocity model (top) contains a low velocity anomaly 300m below the surface. The seismic image of deeper interfaces is significantly corrupted by the anomaly making interpretation challenging (bottom).

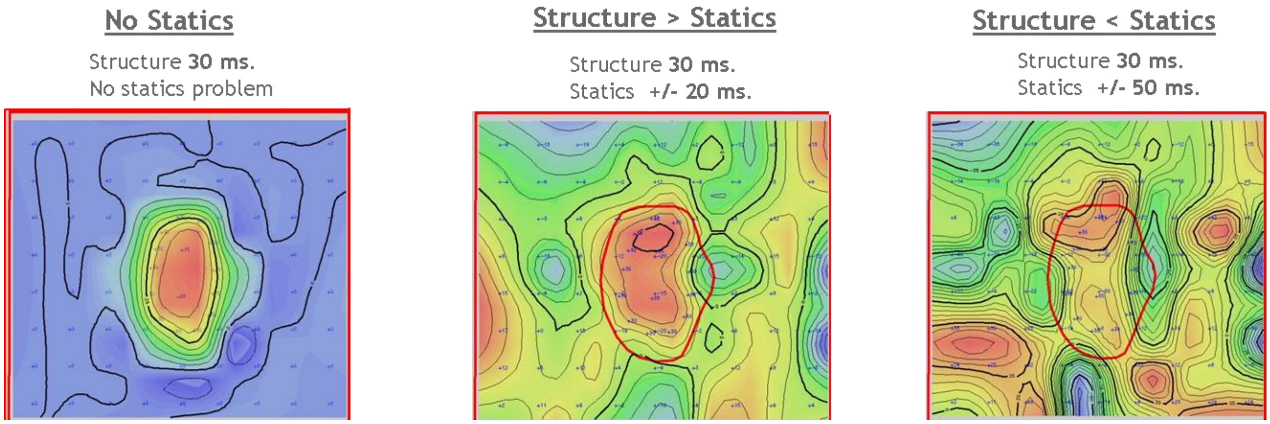

Fig. 2— Example of delineation of a low-relief structure with uncertainty in the static model. The true low-relief structure has a closure of 30ms (left). Uncertainty of 20 ms in the static model still allows us to interpret the horizon correctly (middle). Large uncertainty (50 ms) significantly deteriorates the map and corrupts the interpretation result (right) (courtesy of Riyadh Saad, Geophysical Data Processing Division, Saudi Aramco).

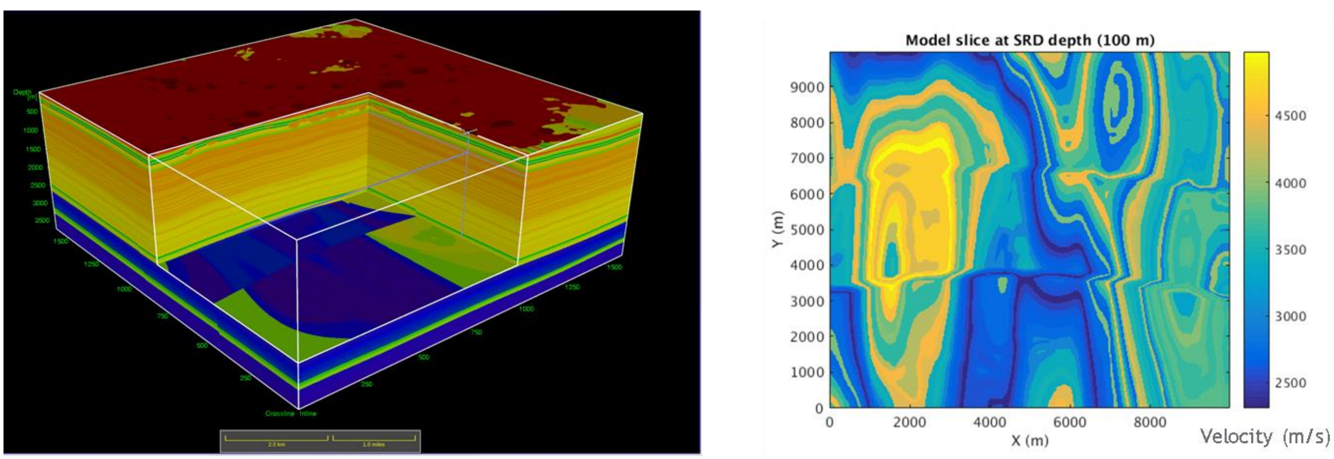

Fig. 3— A realistic synthetic SEAM Arid velocity model with near-surface complexities typical of arid environments (left). A horizontal slice through the model at 100m depth shows strong inhomogeneity in the near-surface (right).

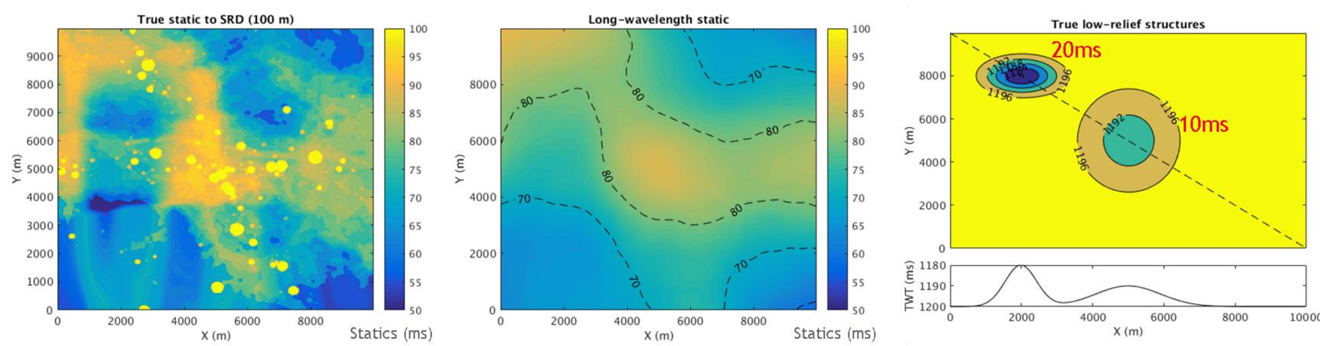

Fig. 4—True static corrections calculated for a seismic reference datum at 100 m depth in the Arid model (left). Long-wavelength statics obtained by smoothing of full statics following conventional processing flow (middle). Synthetic low-relief structure shown without any distortions assuming perfectly correct statics is estimated (right).

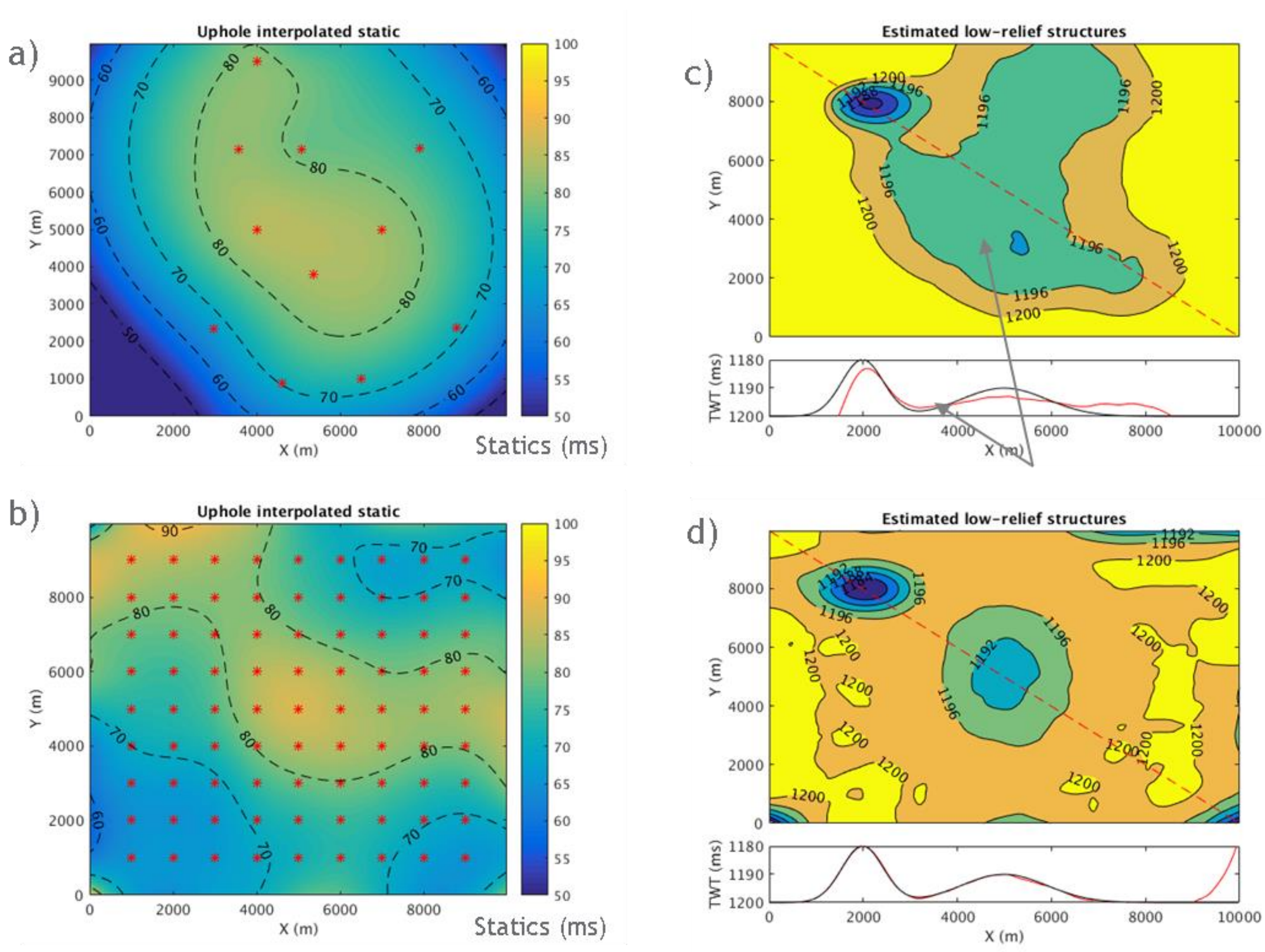

Fig. 5—Left column: Estimated long-wavelength statics using interpolation from upholes (red dots) including (a) coarsely sampled upholes located according to true field geometry and (b) densely sampled upholes on a regular grid 1 x 1 km. Right column: corresponding maps of estimated low-relief structures obtained using actual static corrections.

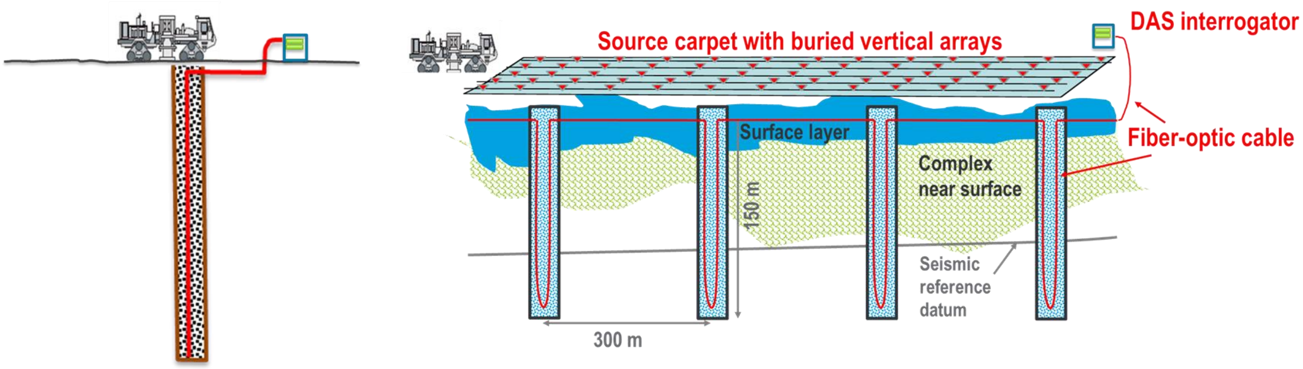

Fig. 6—Smart DAS uphole (left) and a smart DAS uphole acquisition system consisting of connected upholes with a carpet of seismic shots located at the surface (right).

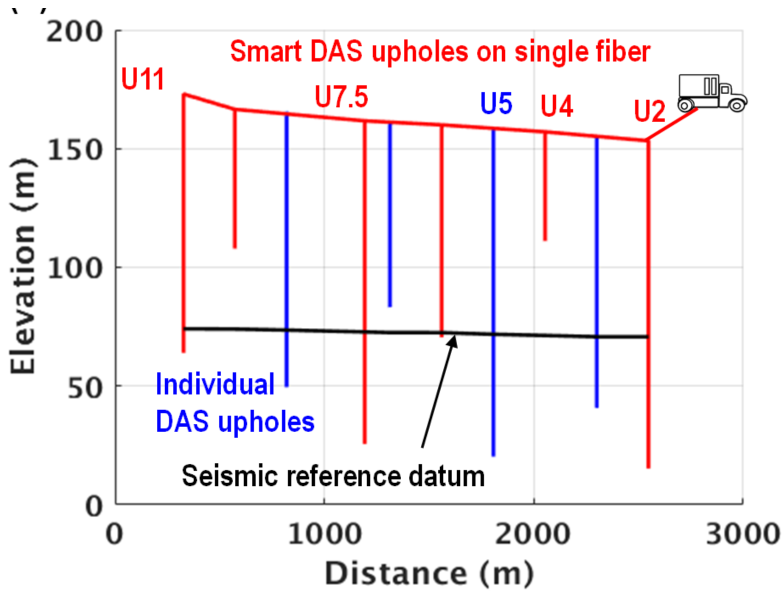

Fig. 7— Actual layout of the field experiment using smart DAS upholes.

Fig. 8—DAS Uphole drilling and trenching.

Fig. 9—DAS fiber installation and completion.

Fig. 10—Acquisition of DAS uphole data.

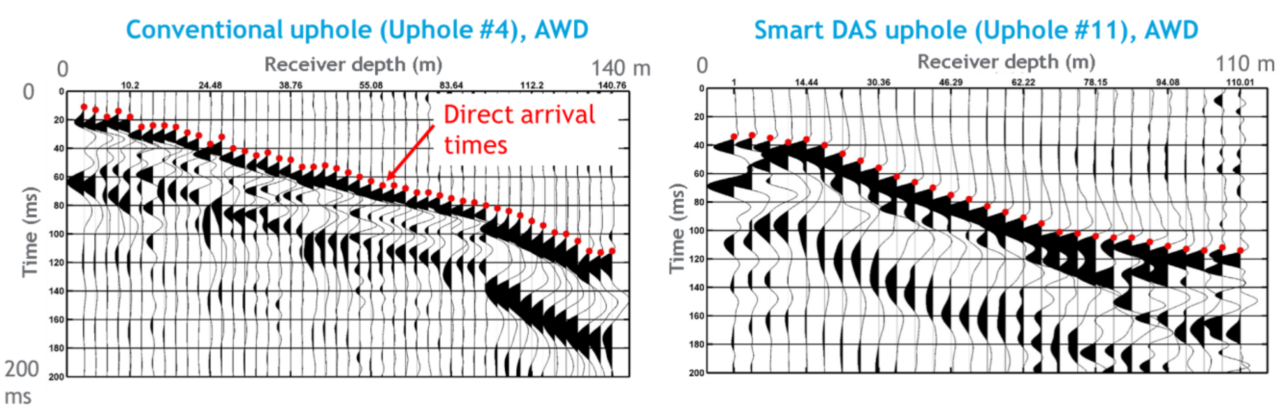

Fig. 11—Comparison of conventional (left) and DAS uphole data (right). Note that the recordings are from different upholes.

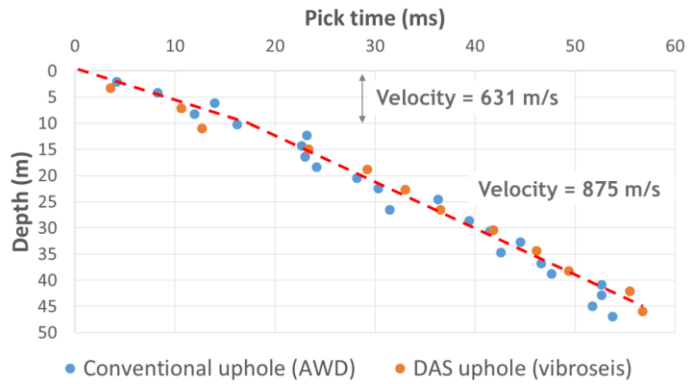

Fig. 12—Comparison of DAS and conventional uphole picks shows less variation in the DAS traveltime picks. A similar velocity would be derived from both sets of picks.

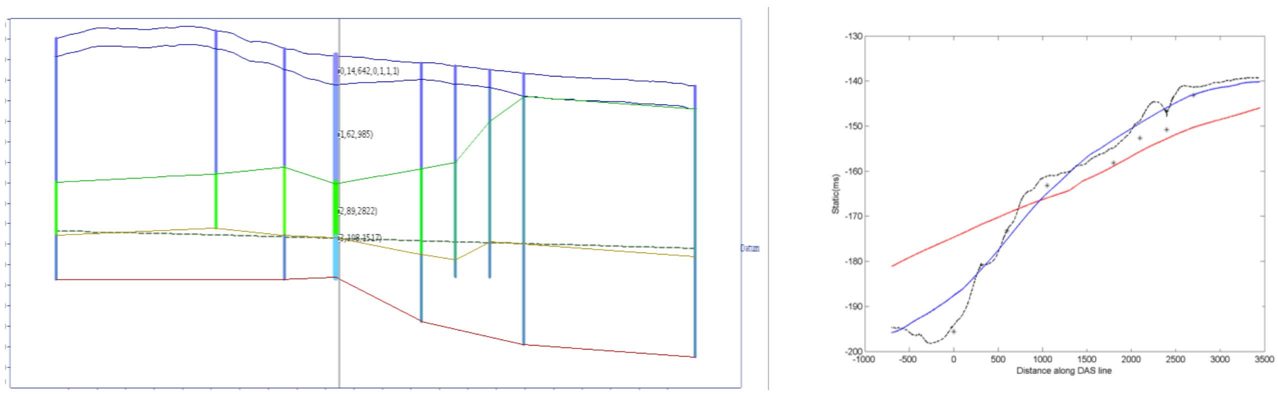

Fig. 13—Multi-layered near-surface model (left) obtained using travel-time picks from DAS upholes, and calculated static corrections (right). Original statics (black line) were smoothed with 800 m (blue line) and 2000 m (red line) windows to reveal features at different spatial wavelengths.

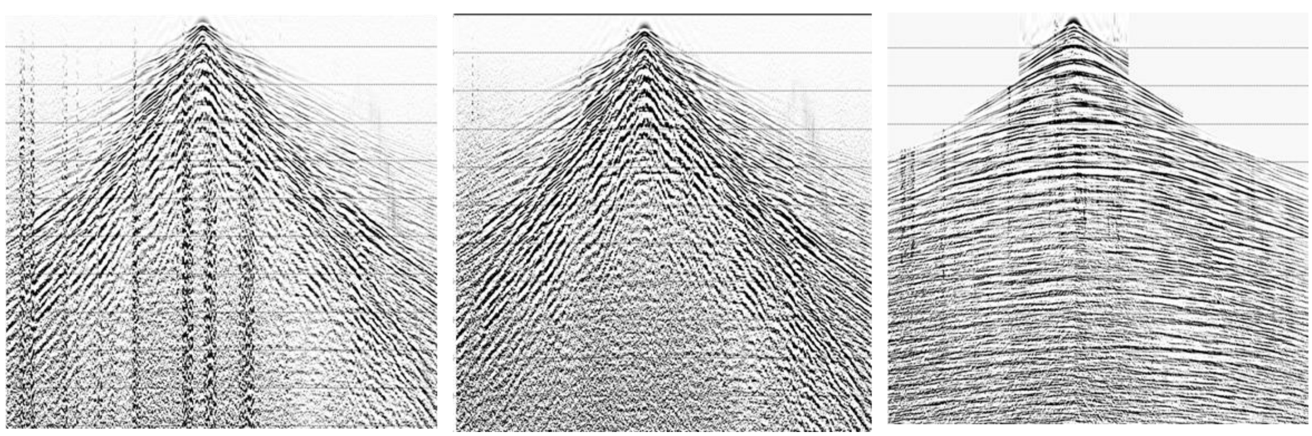

Fig. 14— A common-receiver gather recorded with a single DAS channel at 125 m depth: (left) raw gather, (middle) after random noise attenuation, and (right) after linear noise attenuation.

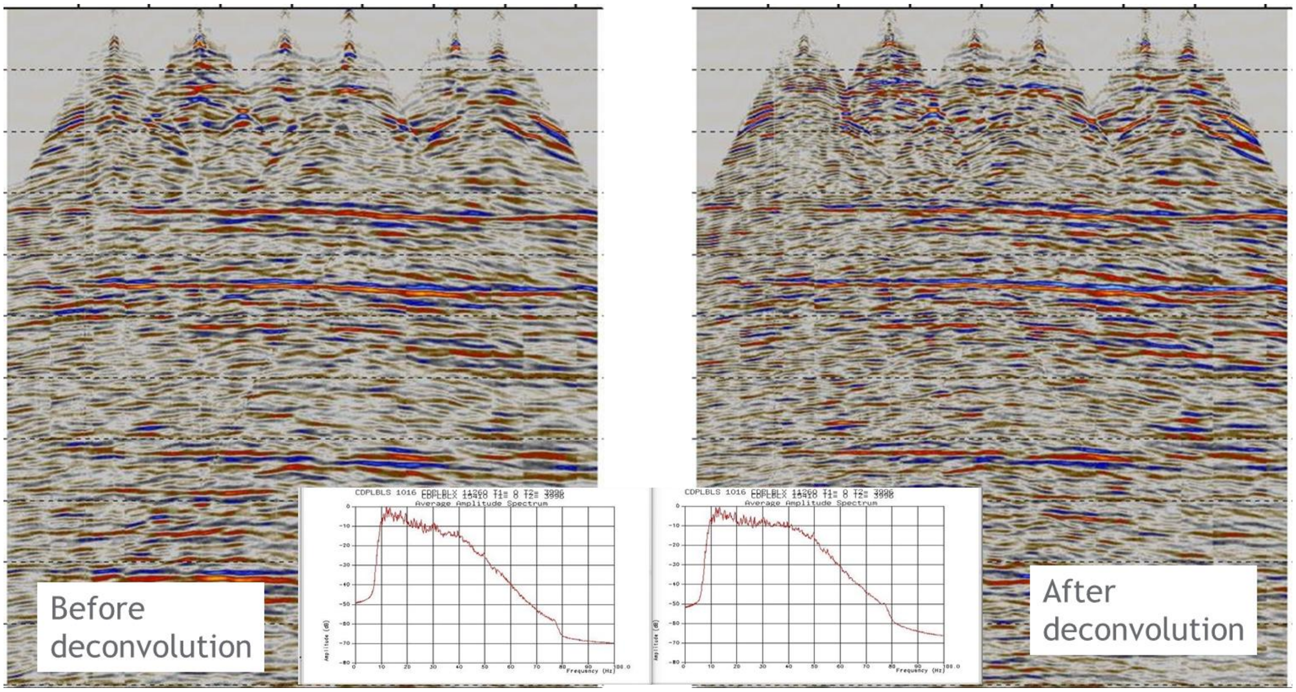

Fig. 15—Processing of DAS data using surface-consistent deconvolution. Stack sections and average amplitude spectrums before surface-consistent deconvolution (left) and after deconvolution (right).

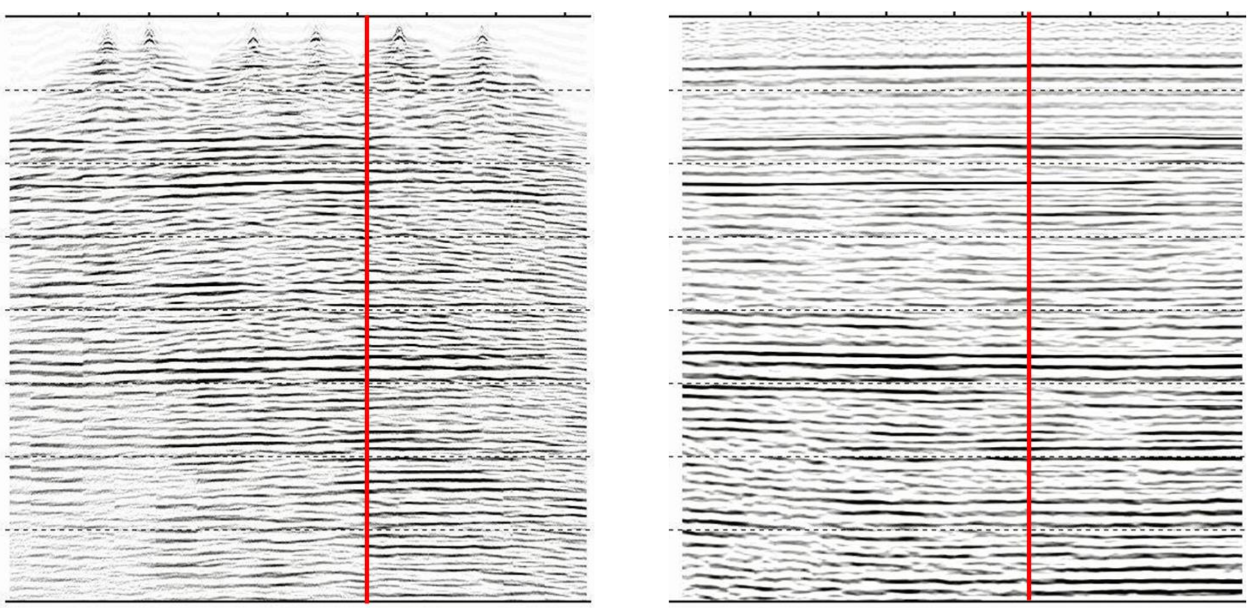

Fig. 16—A comparison of time images obtained using vertical DAS arrays (left) and legacy 2D surface seismic data (right).