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Smart DAS Uphole Acquisition System for Near-Surface Model Building: Results from the First Successful Field Tests

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Abstract

Accurate near-surface velocity models are required to correct for shallow velocity heterogeneities that can otherwise lead to the misinterpretation of seismic data, particularly in the case of low-relief structures. Here we show how a novel uphole acquisition system utilizing distributed acoustic sensing (DAS) technology can be used in a number of different ways to generate near-surface models.

The novel smart DAS uphole system connects multiple shallow wells with one continuous optical fiber. The horizontal and vertical segments of the fiber allow several techniques for near-surface model building to be tested using the same system. Uphole surveys use the vertical fiber segments to make accurate, localized velocity measurements, while the directivity of the DAS fiber enables horizontal sections to be used for refraction tomography and surface-wave inversion.

The smart DAS uphole acquisition system, which enables the collection of data for deep reflection imaging and near-surface characterization simultaneously, has been successfully tested for the first time. Data acquired from ten smart DAS upholes produced excellent early arrival waveform quality for picking and subsequent velocity model building. This direct velocity measurement of the near-surface can reduce uncertainty in the seismic interpretation. In addition, replacing the shallow part of the depth velocity model with the DAS uphole model resulted in significant improvements in the final depth image from topography.

The directivity of DAS enables the recording of refracted events on horizontal fiber sections which have been picked as input to refraction tomography. This produces an alternative near-surface model that captures a larger volume of the subsurface. Ultimately, while the uphole velocity model is only suitable for removing long-wavelength components of near-surface variation, the refraction velocity model may allow for the correction of small-to-medium wavelength statics.

Introduction

As oil and gas exploration increasingly moves toward the delineation of low-relief structures and stratigraphic traps, the importance of acquiring an accurate near-surface model grows: low-relief structures are defined here as having vertical closure of less than 60 m (approximately 30 ms). Nonetheless, surface seismic is significantly affected by the near-surface geology which can distort the true subsurface structure, leading to incorrect interpretation of the data if not correctly accounted for during processing. The cartoon shown in Figure 1 illustrates some of the challenges faced. Figure 1a shows the ideal case of a simple layered earth model with laterally homogeneous formations stacked on top of each other. In this case, it should be relatively simple to reveal the true subsurface of structure from the seismic image; however, the simple case shown in Figure 1a is usually far from reality. Variable surface topography, lateral velocity variations, low-velocity zones, and sand dunes are commonly encountered and can significantly distort the seismic image (Figure 1b). This is typical of the conditions encountered in the Middle East where the arid environments not only distort the seismic image, but also degrade data quality (Keho and Kelamis, 2012).

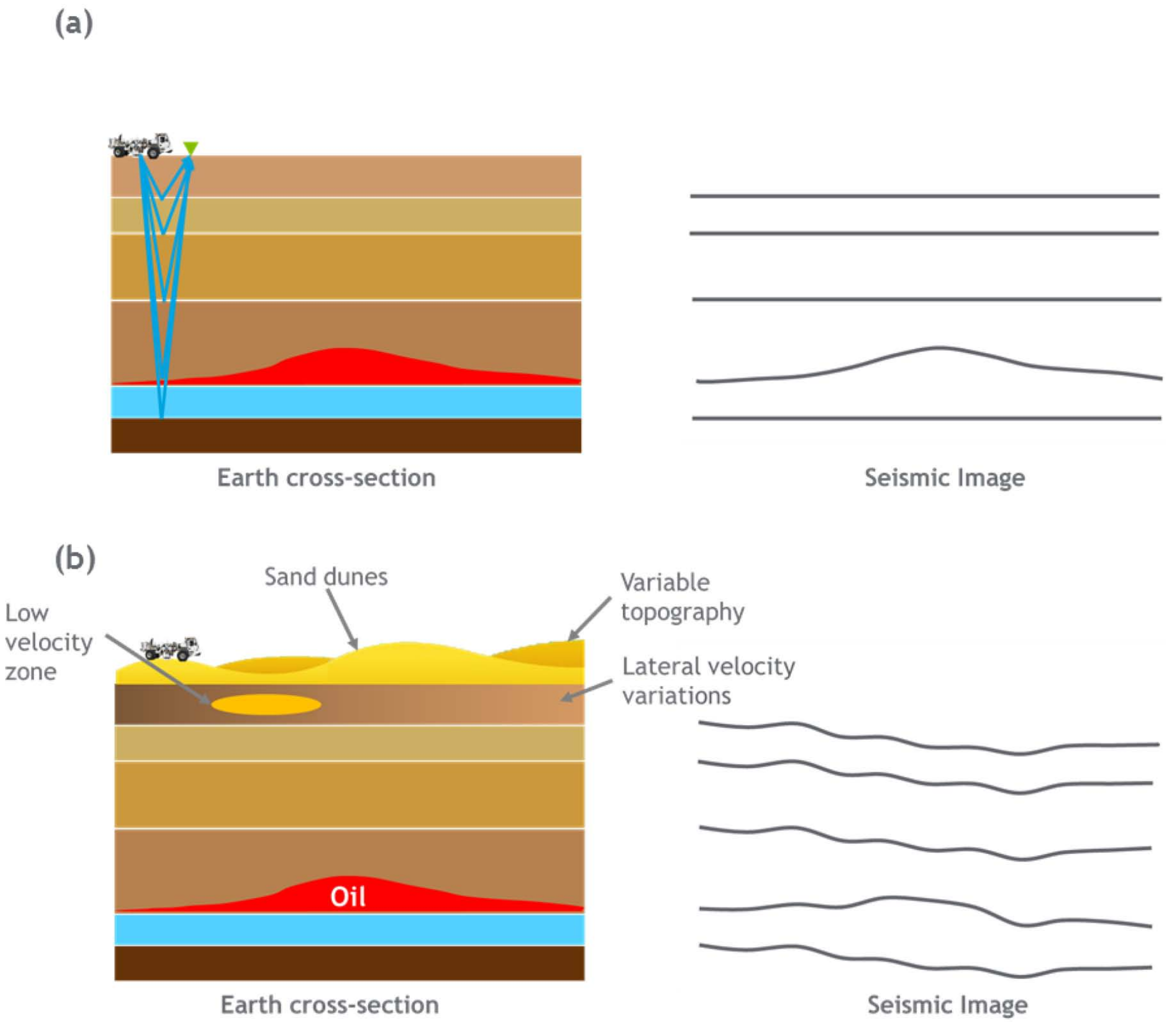

Figure 1—Cartoon illustrating the potential effects of the near surface on the final seismic image. In the case of a simple layered earth model (a), the seismic image should represent the subsurface structure. In the presence of near-surface complexity (b), the seismic image is distorted and no longer represents the true structure. This effect needs to be corrected for during seismic processing. Note that this cartoon is for illustration only.

The imprint of the near-surface on the seismic image needs to be accounted for during processing to allow an accurate interpretation of the subsurface structure to be made. These distortions are often considered to be variable travel-time delays caused by the varying distance and velocities that different raypaths encounter through the shallow portion of the earth. The most common approach to correct these effects is to redatum the data as if it were acquired from beneath this complex near-surface layer. Here, a model of the near-surface velocity is first constructed and the two-way travel-time to the new datum is then computed assuming vertical propagation of the wavefield. These timeshifts, known as static corrections, are then applied to the seismic data. This assumption of surface consistency, where the same correction is applied to all traces at the same location, does not capture the true physics, but performs sufficiently well in many cases. Other methods that more accurately represent the wavefield propagation, such as wave-equation redatuming, still rely on an accurate model of the near-surface velocity

Numerous techniques have been developed to generate the shallow velocity model from geophysical data, but the most widely used is refraction tomography. Although it captures information from a large volume of the subsurface, it suffers from several limitations such as the need for reliable first-break picks and lack of accuracy for capturing the long-wavelength trends in the data. To delineate low-relief structures, the accuracy of the long wavelength static corrections (derived from the near-surface velocity model) should be a small fraction of the structural closure that we are trying to measure (i.e. much less than 30 ms). Nosjean et al. (2017) studied the sensitivity of the estimated reservoir volume to errors in the near-surface models and found that the resulting volume varied by a factor of three. More dependable velocity measurements can be made directly in shallow holes (known as upholes), where the first-break time from a surface source to a downhole sensor is measured. The conventional uphole approach also suffers from some drawbacks. First-break variability can result from inconsistent geophone coupling and source signature differences; in addition, the borehole may collapse before completion of the survey, leading to loss of equipment and time.

In this paper we propose a new type of uphole measurement using distributed acoustic sensing (DAS), which overcomes some of the issues with conventional measurements using a fiber-optic cable in place of a geophone sensor. Moreover, numerous additional benefits are realized when multiple shallow wells are connected. One such example is the potential to integrate other near-surface modeling techniques, and the ability to simultaneously acquire data for deep reflection imaging. In this paper we describe this novel acquisition system and results from the first field tests.

Smart DAS uphole system

In the past, the drilling of shallow holes was commonly performed to accurately measure the long-wavelength component of the near-surface velocity (Cox, 1999). The conventional uphole method (Figure 2a) involves lowering a wall-lock geophone into a shallow well (typically 50 to several hundred meters deep) and measuring the travel time from a surface source to the sensor. Once the measurement has been made at one depth level, the geophone is raised to the next sampling point and the process repeated. This acquisition, where the receiver is in an open hole and the repetition of the source is required for each depth level, can result in variable coupling and source signatures. Some jitter is observed in the first-break picks of the example conventional uphole data provided in Figure 2b. More importantly, the hole needs to remain open until the data has been acquired, which bares the risk of borehole collapse and loss of equipment.

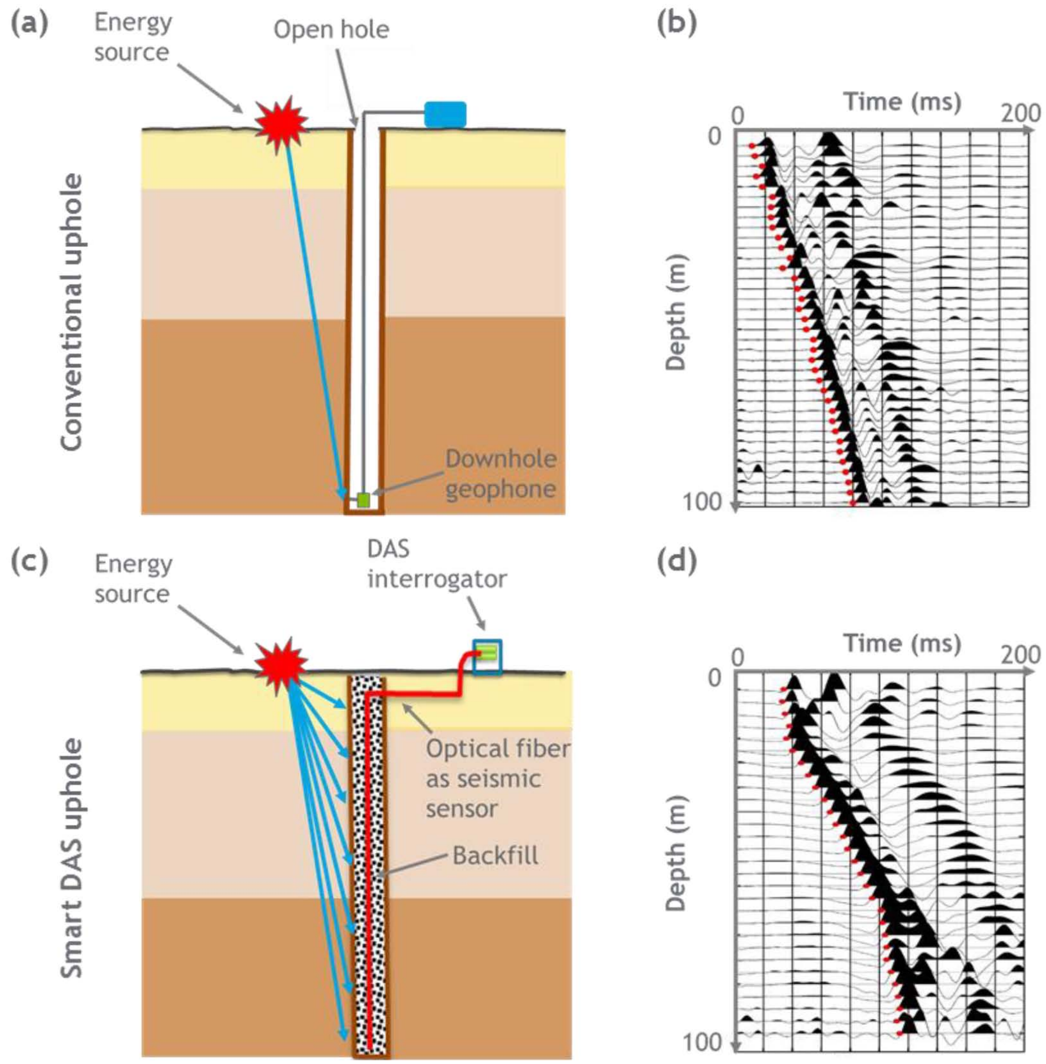

Figure 2—Comparison of (a,b) conventional and (c,d) smart DAS uphole systems and example data

Distributed Acoustic Sensing (DAS) can be used to provide the direct near-surface velocity measurement while overcoming some of the limitations of the conventional uphole approach. DAS effectively turns a standard fiber-optic cable into a continuous acoustic sensor for recording seismic data. This technology, which is rapidly increasing in popularity, uses an interrogator unit to emit a pulse of light through the cable and measures backscattered energy resulting from tiny imperfections in the fiber (Miller, 2012). Passing seismic waves causes stretching and contraction of the fiber, resulting in small phase shifts in the returned signal. This results in DAS being predominantly sensitive to strain along the length of the fiber. DAS has been used for a wide variety of applications in different fields such as rail track surveillance, power cable monitoring systems, and acquisition of VSP data (e.g. Miller et al., 2012) in the oil and gas industry.

In this study, a new system for acquiring upholes, the smart DAS uphole system, was tested using DAS technology (Figure 2c). Once the shallow well has been drilled, the fiber-optic cable is lowered into position and then immediately backfilled. This system removes the risk of hole collapse and loss of equipment encountered in conventional surveys, while also enabling the uphole survey to be performed anytime effectively decoupling installation from acquisition. Since the fiber-optic cable acts like a continuous sensor, the entire length of the uphole can be acquired with a single shot, resulting in less variation in the early arrival waveforms (Figure 2d). This novel application of DAS for the acquisition of uphole data also has numerous other advantages: simplified installation, economic equitability due to the cheap cost of the fiber, and uphole achievability and easy repetition if necessary since the fiber is installed and left in place. For instance, in desert environments, sand dune migrations are known to result in significant changes to surface topography even over periods of months and years (Bakulin et al., 2018b). The ability to acquire uphole data at the time of seismic acquisition gives greater confidence in the derived near-surface model.

Additionally, if multiple upholes are connected (as depicted in Figure 3), the smart DAS uphole system can be used to simultaneously characterize the near-surface and image the deeper subsurface structure. Since the DAS fiber is primarily sensitive to strain rate along the length of the fiber, it is well suited to measuring P-wave reflection events from the deeper subsurface (Figure 3b). Note that in theory reflection imaging can be achieved by acquiring data from multiple isolated DAS upholes. This would be an inefficient use of the more expensive DAS interrogators so it is therefore infeasible in practice.

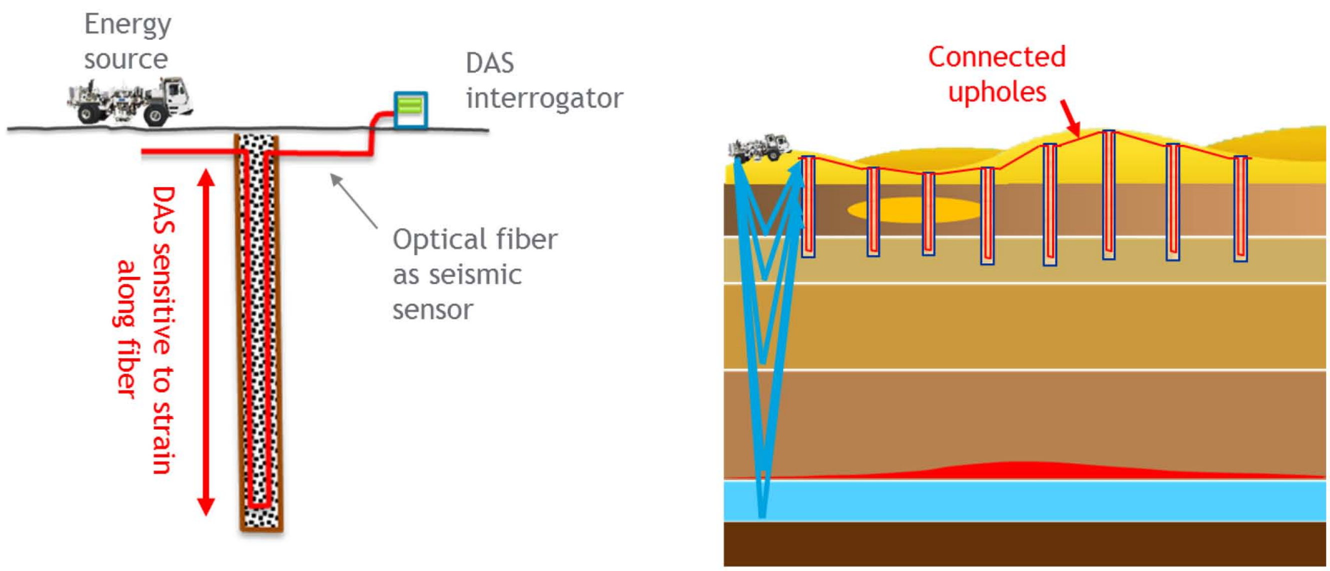

Figure 3—Smart DAS uphole acquisition system for near-surface characterization and deep subsurface imaging.

Placing the sensors beneath some of the near-surface heterogeneity can also lead to improved data quality (Bakulin et al., 2012), particularly when placed below sand dunes which cause a number of issues for seismic imaging. Furthermore, the horizontal sections of fiber connecting the wells also open up the possibility of using different near-surface characterization methods and potentially combining them to capture the benefits of the different approaches. This is discussed further in the next section.

Near-surface characterization with smart DAS uphole system

As described in the previous section, conventional and widely used DAS cables predominantly sensitive to strain, parallel to the length of the fiber. In the case where we have multiple connected upholes (e.g. Figure 3), we have both vertical and horizontal segments of fiber. This potentially enables different near-surface modelling techniques to be performed on data acquired from the same system (Figure 4). The vertical segments of fiber are used for uphole surveys, with the DAS fiber well suited to measure the almost vertically propagating wavefield from the near-offset source (Figure 4a). Data recorded with horizontal fibers placed in shallow trenches at the surface can be used for other alternative near-surface characterization methods. The directivity of DAS here is sensitive to the more horizontal propagation of the refracted (Figure 4b) and surface-wave (Figure 4c) energy, which can be used for refraction tomography and surface-wave inversion respectively. Specialized omnidirectional fiber cable designs can enable multicomponent measurements with DAS (Bakulin et al., 2018c). This opens the possibility for a so-called weathering reflection seismic (WRS) method to be applied to the DAS data that requires very dense source and receiver sampling in order to pick zero-offset times and moveout velocities for the shallowest near-surface reflectors (Martin et el., 2009).

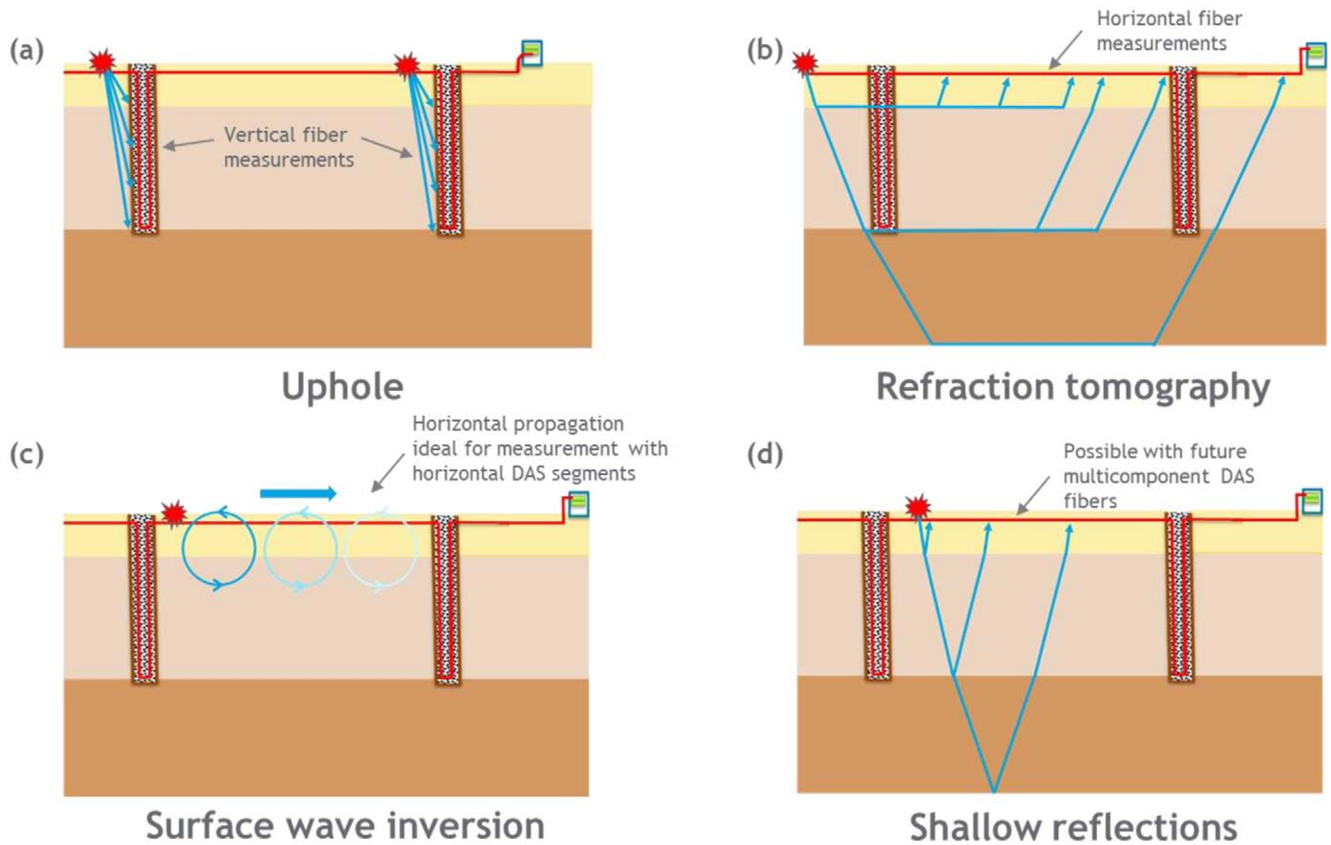

Figure 4—Potential near-surface modelling options using the smart DAS uphole acquisition system.

Some of the advantages and disadvantages of these near-surface modelling techniques for the DAS system are captured in Table 1 and discussed in the following sections. Since all these approaches can be captured at the same time using a common acquisition system, it may be possible in the future to combine different techniques to take advantage of the benefits that each bring (e.g. using upholes as a constraint in refraction tomography to combine medium- and long-wavelength components).

Table 1—Comparison of different near-surface modelling techniques that are possible with the smart DAS uphole system

	Advantages	Disadvantages
Upholes	• Direct velocity measurement • Capture long-wavelength velocity trends • Velocity inversions can be captured • Measure vertical velocity	• Local measurement next to borehole • Restricted to maximum depth of upholes • Possible issues for shallow measurements
Refraction tomography	• Sensitive to large volume of the subsurface • Can obtain deeper information than possible with upholes	• Cannot resolve velocity inversions • Dependent on quality of data and first-break picks • Non-uniqueness of inversion • Measures near-horizontal velocity • Long-wavelength less certain
Surface wave inversion	• High sensitivity to very shallow part • Shear velocity estimation	• Not sensitive to deeper part • Needs picking of higher modes for P-wave velocity inversion • Usually inversion is done in 1D approximation
Shallow reflections	• Measures near-vertical propagation velocities • Consistent with imaging	• Requires very dense acquisition

Upholes

This is the only technique that allows a direct measurement of the near-surface velocity. For this reason, and the typically good signal-to-noise ratio of the data, they are considered the most accurate velocity measurements. With sufficient spatial sampling, these upholes can accurately capture the long-wavelength component of the static corrections required to correct our seismic data. Due to the almost vertical propagation (Figure 4a) of the measured energy due to the near-offset source (typically 0-10 meters), upholes are a localized velocity measurement around the well. If this happens to be placed in a local anomaly, then it may not reflect the global velocity trend. Due to the directivity of the DAS sensor, accurately measuring the very shallow velocity may be a challenge since the direct energy is perpendicular to the fiber. This is discussed further in the results section.

Refraction tomography

Unlike the uphole method, refraction tomography uses data that has been affected by a large volume of the subsurface between the wells. Therefore, it is capable of capturing the shorter wavelength details of the near-surface than is typically possible with upholes. Refraction tomography also has the potential for deeper subsurface characterization than upholes (Figure 4b) if sufficient offsets are acquired.

Refractions do not provide direct velocity measurements however, they must be inferred through an inversion process. This relies on accurate picking of the first-break arrival times, which can often be challenging due to poor data quality in desert environment. In addition, refraction tomography cannot reveal velocity inversions (where a high-velocity layer overlies a slower layer) in the shallow geology. Finally, this method is sensitive to the horizontal velocity of each layer, whereas the reflection seismic data that we wish to correct is assumed to travel vertically through the near-surface.

Surface wave inversion

Surface waves are usually strongest and clearest events on seismic records. Often they are treated as noise in seismic processing and are removed by special noise attenuation techniques; however, these waves are sensitive to velocity variations in the very near-surface and therefore can be used to retrieve them. The standard technique for this is dispersion curve inversion that requires picking of phase velocities on a velocity-frequency panels and then their inversion using local 1D approximation. Picking and inversion of fundamental mode only, provides good estimation of S-wave velocity. This velocity can be used directly for building near-surface models for multicomponent processing and elastic imaging, or can be transformed to P-wave velocities using some empiric relations. Picking and inversion of additional higher modes allows simultaneous inversion for of P- and S-wave velocities.

Shallow reflections

Dense acquisition typical to DAS allow the recording of reflections from very shallow reflectors located at the first hundreds or even tens meters in the subsurface. With conventional seismic, such events are not discernible on seismograms due to the sparse sampling of sources and receivers, which is targeting much deeper horizons. These shallow reflections can be processed using the same methods as in conventional seismic and provide shallow images and corresponding seismic velocities (Martin et el., 2009). This gives very accurate information about near-surface and can be used both for statics calculation and for creating near-surface models for redatuming and migration (Yilmaz, 2013). In contrast to refraction tomography or surface waves inversion, this method estimates near-vertical velocities and in this sense is more consistent and suitable for statics corrections of reflection imaging data, not suffering from anisotropic effects.

Field tests

The first field test of the smart DAS uphole acquisition system has been conducted in an arid environment. The objective of these tests was to confirm that the system can be used to characterize the near-surface velocity and also assess the potential for it to be used for recording reflection events for imaging of the deeper subsurface.

Test configuration

A 2D DAS receiver line was installed over approximately 3 km, which consisted of ten smart DAS upholes (Figure 5). Holes shown in red were connected, while those in blue were standalone upholes. All ten wells were used for characterizing the near-surface using uphole data, while only connected wells allow for efficient acquisition of vertical array data for deep reflection imaging.

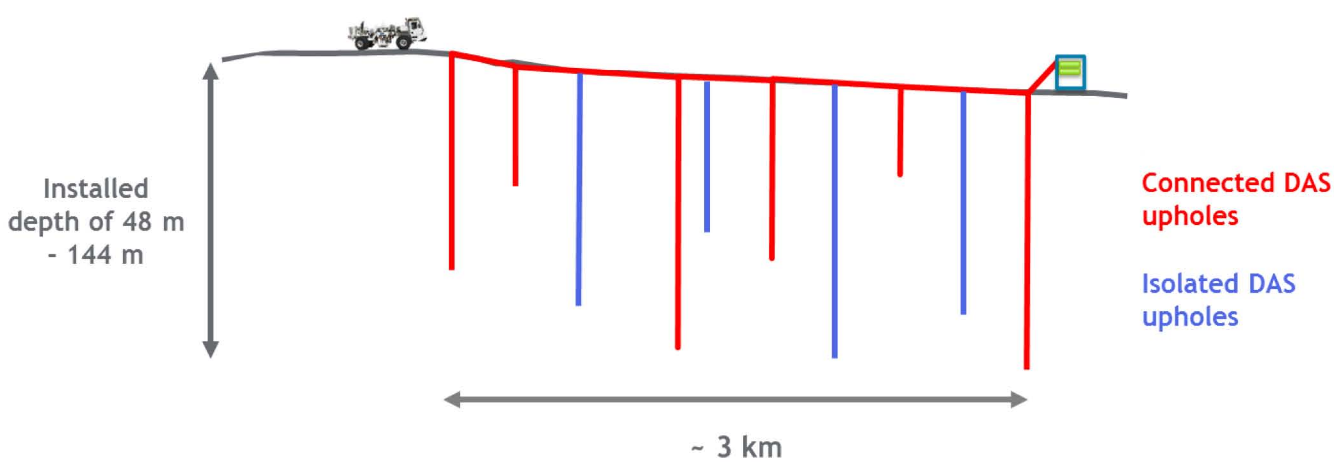

Figure 5—Configuration of smart DAS uphole system used for this study.

The tests were conducted in two phases, the first of which was the uphole acquisition. These tests involved assessing various sources including: accelerated weight drop, vibroseis pulse and vibroseis sweep. The vibroseis sweep however was found to perform best (Bakulin et al., 2017a), particularly for the deeper parts of the fiber. The results in this paper only focus on data acquired using a conventional sweep. Here the vibroseis source was positioned ten meters from each uphole and a single linear sweep (8-80 Hz) was used to acquire the data.

The second phase was the acquisition of data for deep reflection imaging using the six connected upholes with a single interrogator unit. Three shot lines were used for processing of the data, with inline and crossline spacing of 10 m between shot points. Using 4 m sampling of the DAS fiber resulted in approximately 300 DAS channels in the vertical segments of the fiber.

Near-surface modelling

In this section, the results of near-surface modelling using upholes and refraction tomography are discussed, along with a brief summary of the potential of surface wave inversion.

Upholes. In general, improved data quality was obtained through the use of the smart DAS uphole system (Bakulin et al., 2017a). Consistent early arrivals due to the use of one source and consistent sensor coupling enabled easy picking of first break travel-times (Figure 6a). However, one area of uncertainty is the effect of very shallow, low velocity layers on DAS measurements. As shown in Figure 6b, we often observe a reversal of travel times for the shallow channels (typically first 10-15 meters). This may be partly explained by the insensitivity of the DAS fiber to strain perpendicular to the length of the fiber. As a result of the offset between source and uphole (10 m in this case), the direct arrival will be travelling horizontally as opposed to the deeper portions of the fiber where the propagation is almost vertical. DAS may not be sensitive to these horizontally propagating P-waves. Another possible explanation is the effect of gauge length (the distance over which strains are measured to produce an output at one channel), used for the DAS surveys. As described by Bakulin et al. (2018c), frequencies above 40 Hz are becoming filtered out with a DAS system using a gauge length of 7.5 m when the near-surface velocity is around 300 m/s. To obtain the highest resolution for the shallow part of the near-surface, smaller gauge lengths may be required (e.g. 2 m).

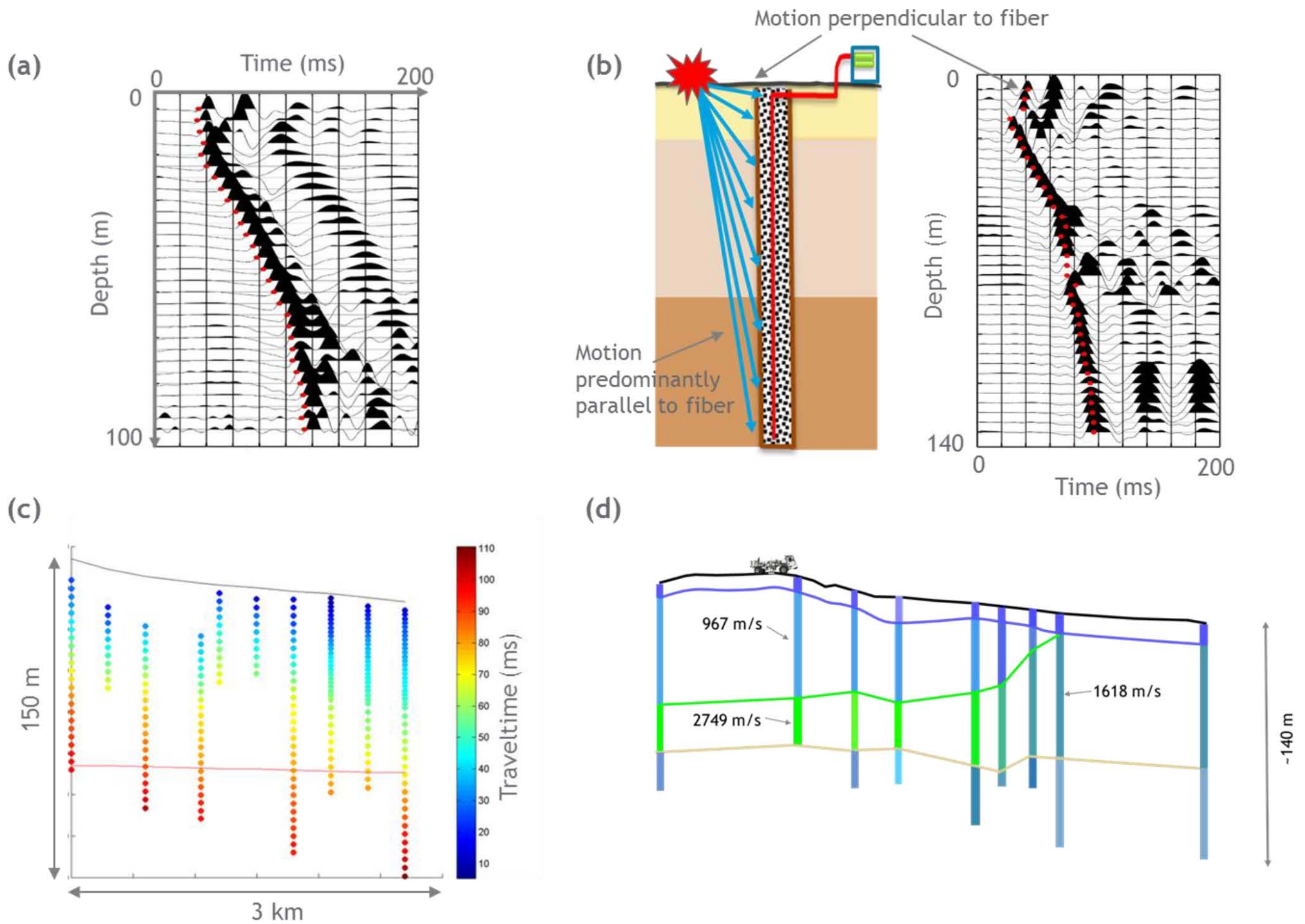

Figure 6—Results from near-surface velocity model building using smart DAS uphole data.

The first-break pick times are displayed in Figure 6c for the ten wells. The issue of the shallow picks is evident here on the left side of the line where there are missing values: the data from several conventional upholes was used on the right side of the line due to installation issues. The near-surface velocity model constructed from the uphole data is shown in Figure 6d. Note here that the two shallow wells in the middle of the line were not used in the model building process since they did not extend to sufficient depth.

Tomography. Using the horizontal segments of the DAS fiber, it is possible to identify and pick first-break arrivals resulting from refracted events (Figure 7a) Note that pre-processing of the data using supergrouping (Bakulin et al., 2018a) was required in order to enhance these events for first-break picking. The traveltime picks for all gathers are displayed in Figure 7b as a function of offset. It is apparent here that there is little variation in the pick times. These numbers are then used to generate the three-layer initial model shown in Figure 7c. The final result after refraction tomography is shown in Figure 7d. Little change is shown from the initial model, except from smoothing of edges since the picks vary little across the line. The reasons for differences between the uphole and refraction tomography models is unclear at present. Future tests are planned with multicomponent DAS fiber that may help to reduce uncertainties in the measurement.

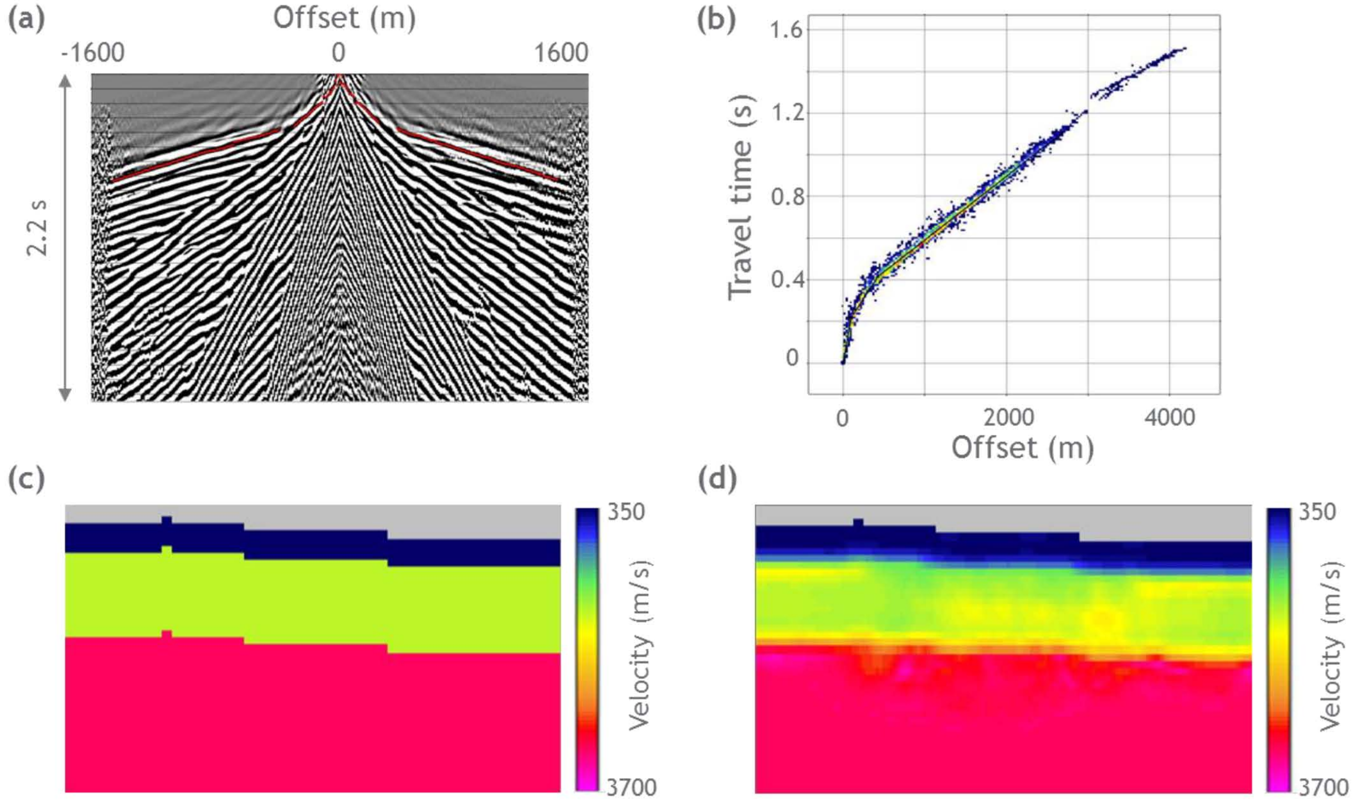

Figure 7—Near-surface tomography model building using smart DAS uphole system: (a) data from horizontal segments of fiber after picking of first-breaks (red dots), which are collected for all gathers (b) and plotted as a function of time and offset. This is used to generate the (c) initial model and (d) final velocity model after running tomography.

Surface-wave inversion. Surface waves propagate at a relatively low speed and a very dense source/receiver sampling (<5 m) is required to record them without aliasing. Such sampling is not achievable during full-size conventional seismic acquisition due to economic reasons. Moreover, the sources and receivers are usually grouped into special arrays that are designed to attenuate surface waves at the time of the recording; therefore, conventional seismic data is often not suitable for inversion of surface waves. In contrast, the DAS system allows to get data at a very fine sampling with any desirable grouping of the channels that can provide very high-quality recordings for such inversion. As can be seen in Figure 7a, a very strong and clear surface wave is presented on a horizontal part of the trenched DAS cable recorded at a 1m depth. The signal is not aliased due to 4 m sampling as can be seen in the frequency domain in Figure 8, which allows us to reliably pick fundamental and higher-order dispersion curves. The inversion result is presented in Figure 8 confirming the ability of the method to update very shallow and low-velocity zones that are hardly inverted using the tomographic approach.

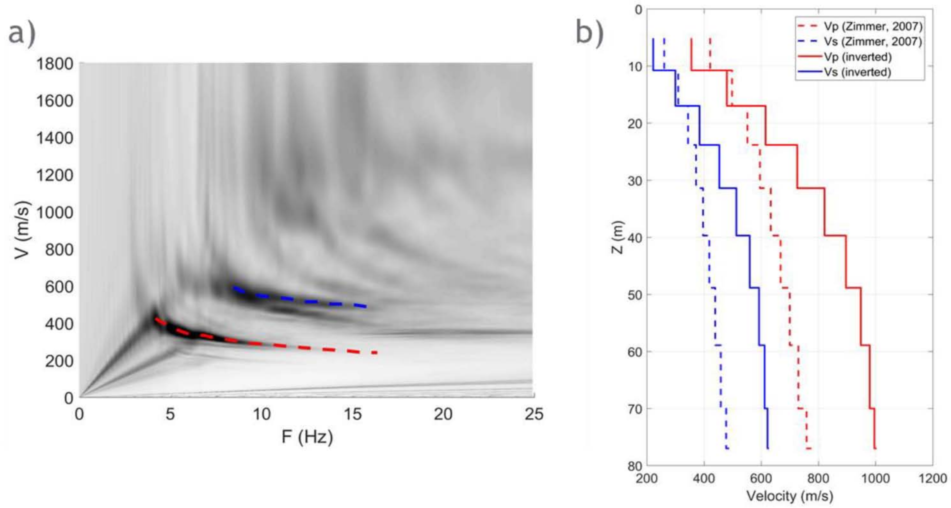

Figure 8—Surface waves inversion using DAS data. (a) Picking of dispersion curves on phase-velocity panel. (b) Inversion result.

Shallow reflections. In the current experiment, we used conventional fiber that is mostly sensitive to longitudinal deformations and has theoretical directivity pattern diminishing to zero for P-waves propagated orthogonal to it. As a result, the horizontal part of the cable does not provide reliable reflected events as can be seen in Figure 7a. A solution to this is using of special omnidirectional fiber cables that allows to make P-wave recordings with DAS (Yavuz et al, 2016). Nevertheless, to illustrate the shallow reflections method in the current experiment, we use a common-receiver gather recorded in one of the upholes at a shallow depth of 7 m from the surface. The gather before and after noise attenuation is shown in Figure 9. Due to fine source sampling of 10 m, the ground-roll was perfectly removed revealing strong shallow-reflection events. Conventional velocity analysis and stacking can be used to estimate NMO velocities of this event and to get stack of the shallow section. In the current experiment this provides only local velocity measurement around each uphole as shown in Figure 9c.

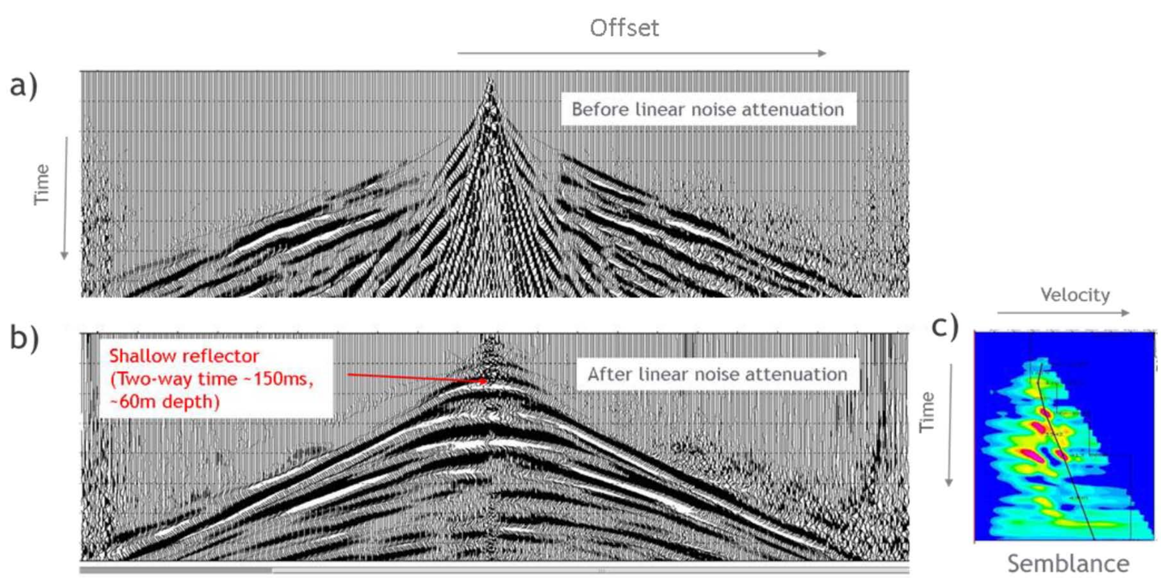

Figure 9—Revealing shallow reflections from DAS data: a common-receiver gather recorded by shallow DAS channel at 7 m depth inside the uphole before (a) and after noise attenuation (b); (c) semblance panel used to pick NMO velocities for shallow reflectors.

Imaging

The stacked DAS data after basic processing is compared to legacy geophone data in Figure 8. Details on the processing applied to the data can be found in Bakulin et al. (2018d). The results show that excellent image quality is possible using DAS data, which clearly allow identification of the target structure. As can be seen in Figure 10, the main reflections from the stacked DAS data generally tie well with the legacy geophone data at the intersection point. Differences in the deeper part of the section are likely related to different acquisition geometries, where the main objective of the DAS survey was for the shallower reflectors.

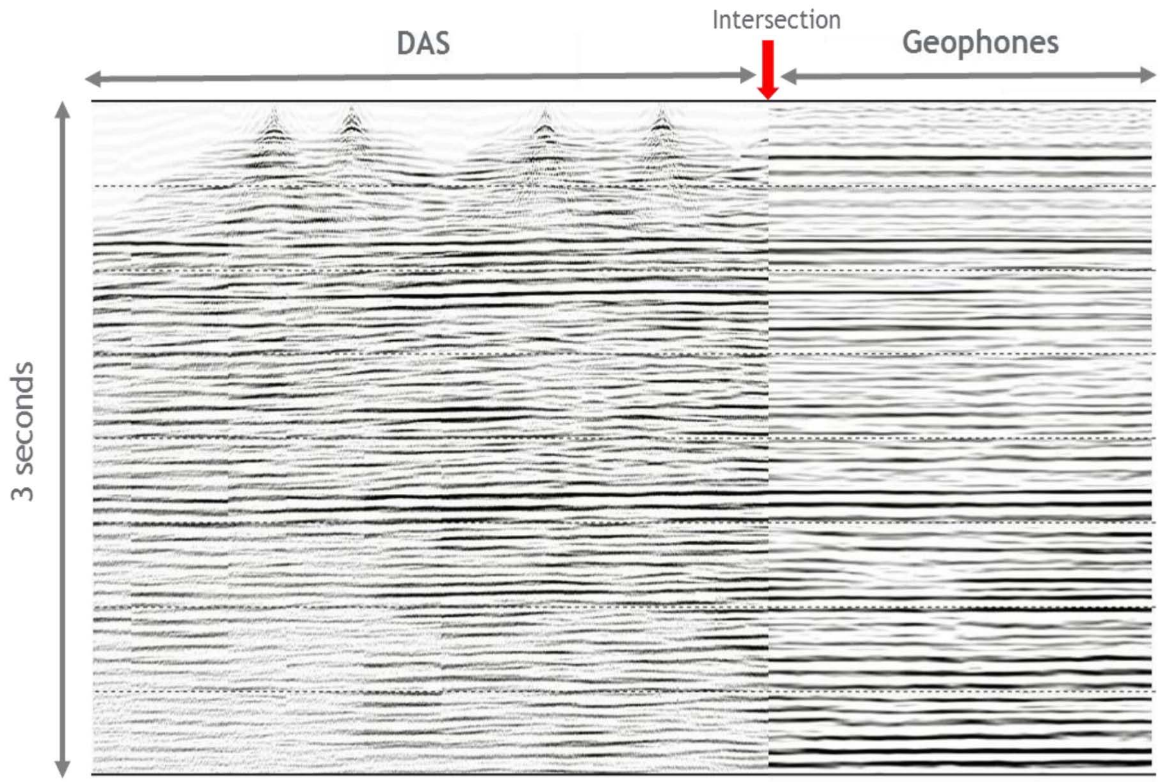

Figure 10—Comparison of images obtained using smart DAS uphole acquisition system (left) and conventional 2D surface seismic with geophones (right).

To test the impact of the near-surface velocity measured using the smart DAS uphole acquisition system, pre-stack depth migration from the surface was run using the legacy and updated uphole models (Figure 11a). The legacy uphole was located at around one km from the DAS line, which is usually considered a small distance between adjacent upholes in near-surface surveys. Nevertheless, as seen in Figure 11a, the new DAS uphole, located exactly at the site of investigation, provides velocity that is almost two times smaller than the legacy one. Both Figures 11b and 11c were produced using the same reflection data from vertical DAS arrays, the only difference being the velocity used for the upper 150 meters of the model. Though the thickness of this near-surface layer is very small compared to the depth of the target (around 1500m), it leads to significant differences in the images due to the very low propagation velocities inside it. The improvements in the image using the updated smart DAS uphole measurement (Figure 11c) are significant: events display much better lateral continuity compared to the image produced using the legacy uphole velocity information (Figure 11b).

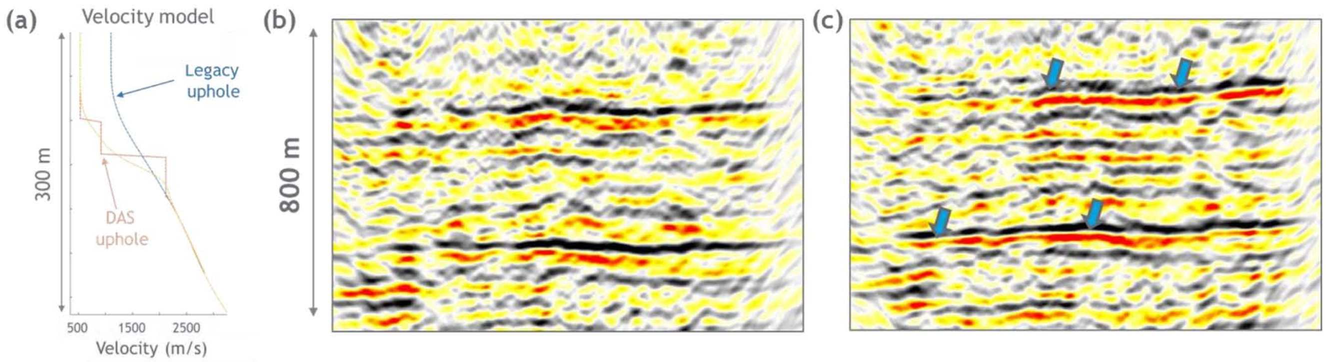

Figure 11—Depth migrated images from topgraphy produced using (b) legacy and (c) smart DAS uphole near-surface velocity models.

Conclusions

The first successful field trials using the smart DAS uphole system have been completed, producing excellent results. First break waveforms are generally as good, if not better, than those produced by conventional uphole methods. This is achieved with a simplified and safer operation using a cheaper sensor and the ability to perform or repeat the uphole survey as required. These first breaks can be used to build a near-surface model to reduce uncertainty in exploration for low-relief structures. We envision smart DAS upholes to enable acquisition of on-demand prospect-oriented dense uphole grids over specific low-relief structures plagued by poorly characterized near-surface velocity variations.

It has also been shown that horizontal segments of fiber connecting multiple upholes can record data for refraction tomography and surface wave inversion. Omnidirectional fiber cables will allow recording of shallow reflection surveys with the same system. In the future, the combination of all these datasets will help to better resolve the near-surface variations and anomalies by using all the available information and different wavelengths from these methods.

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