Seismic imaging of vertical array data acquired using smart DAS uphole acquisition system

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Summary

A novel acquisition scheme using distributed acoustic sensing (DAS) technology, which enables simultaneous near-surface characterization and deep reflection imaging, is proposed. At the heart of the system are the smart DAS upholes, a series of shallow wells instrumented by a continuous fiber-optic cable. Accurate long-wavelength statics captured from direct uphole measurements reduce interpretation uncertainty, while much of the surface wave noise that contaminates conventional surface acquisition is avoided when recording using buried vertical arrays. Here the first field tests conducted in Saudi Arabia are presented, focusing on the imaging results produced from data acquired from the vertical portions of the fiber. Both time and depth seismic images show excellent results despite large well spacing. Comparison of DAS data with legacy seismic revealed good agreement between them. The smart DAS uphole system is a paradigm shift in seismic acquisition that can overcome some of the major challenges caused by complex near surface conditions, resulting in improved data quality and reduction in exploration risk.

Introduction

Exploration efforts are increasingly moving toward the delineation of low-relief structures (vertical closure of less than 60 m or ~30 ms), putting ever more stringent requirements on the fidelity of seismic data. This is a major issue in the arid environment of the Middle East, where a highly variable and complex near surface significantly inhibits conventional seismic imaging. Sand dunes of variable thickness, karsts (dissolution features) and wadis (dry river channels) lead to large lateral velocity changes in the near surface that can distort the target of interest if not properly accounted for during processing (Keho and Kelamis, 2012). This requires accurate near-surface velocity models to remove mid-to-long wavelength statics, which may not be achieved by conventional indirect methods such as refraction tomography. In addition, surface acquisition results in high levels of surface-related noise that completely mask the reflections of interest. For some time, the industry has approached this challenge through an exponential increase in channel count to better sample the seismic wavefield. Despite the use of 100,000 channel systems and a trace density of 100 million traces/km^2, we are still a long way from reaching a density that could drastically reduce near-surface noise and significantly reduce uncertainty caused by variable near surface velocities.

We believe that a completely new approach may be required to improve land data quality and produce accurate near surface models. A promising solution is the use of vertical seismic arrays (Ikele and Wilson, 1999), which have the potential to overcome traditional land data quality issues by avoiding much of the near-surface, significantly reducing recorded surface-wave energy and placing the receivers below some of the near-surface heterogeneity. Bakulin et al. (2012, 2015) showed vastly superior data acquired by buried receivers compared to surface sensors at the same location. In addition, direct velocity measurements of the near-surface can be made using near zero-offset sources and picking first arrival times to the buried receivers. Instrumenting entire wells with conventional geophones would be extremely expensive. A more efficient and economic use of the available real estate provided by shallow wells is to instrument them with cheap fiber-optic cable, which is turned into a continuous seismic sensor through distributed acoustic sensing (DAS) technology (Miller et al., 2012). Since DAS is predominantly sensitive to axial strain along the length of the fiber, it is ideally suited for recording near-vertically propagating reflections in the shallow wells. In this work, we present the concept and imaging results produced from the first field tests of the smart DAS uphole acquisition system.

Vertical array data acquired with smart DAS upholes

A smart DAS uphole (Bakulin et al., 2017) is a shallow well equipped with standard fiber-optic cable similar to the one used in the telecommunications industry and connected to a DAS interrogator. The cable is lowered into the well, which is then backfilled to provide good coupling with the formation. A grid of these upholes is installed over a prospect area using a continuous fiber which is trenched between wells (Figure 1). A dense carpet of surface shots provides suitable coverage for deep reflection imaging. The illumination provided by this acquisition system largely

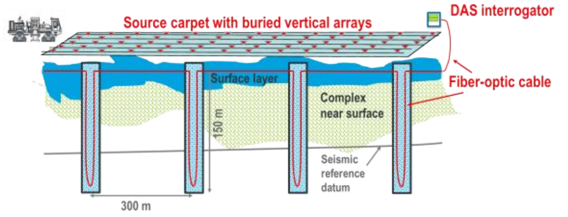

Figure 1: Acquisition system with smart DAS upholes connected using single continuous fiber cable

depends on the hole spacing and depth, which can be adjusted to be comparable to surface seismic (Ikele and Wilson, 1999). The fiber is cost-effective, costing from $1 per meter, meaning that DAS measurements are significantly cheaper in comparison to buried conventional geophones or hydrophones. DAS outputs seismic signal at virtually any point along the cable, resulting in high receiver density, while recorded data has wider frequency bandwidth compared to geophones.

In addition, by directly measuring vertical traveltimes from the surface to each depth level, this system provides accurate estimation of near-surface velocities at the uphole locations (Bakulin et al., 2017). By interpolating these values between the adjacent upholes, accurate long-wavelength statics are obtained, decreasing uncertainty in the interpretation of subtle reservoir structures. Smart DAS upholes have a number of advantages over the conventional uphole approach (discussed in a separate work), making them an efficient and low-cost solution for detailed near-surface characterization. In that sense, a grid of DAS arrays can be considered as a self-sufficient acquisition system that provides detailed characterization of the near-surface and reliable imaging of deeper target horizons.

Synthetic imaging results

To study the value of acquisition using a grid of smart DAS upholes for deep reflection imaging, a synthetic feasibility study was conducted. The simplified ray scheme, calculated using a homogeneous velocity model for a single reflector, shows that angle coverage sufficient for imaging can be obtained when an appropriate well depth and spacing is chosen. For example, well depth of 200 m and spacing of 200 m provides sufficient angle coverage for the reflector at 1,200 m depth (Figure 2). Unlike surface seismic, the illumination distribution for vertical arrays is not uniform and each case should be considered with care. In particular, the image is expected to deteriorate in the shallow part in comparison to the deeper section due to reduced fold.

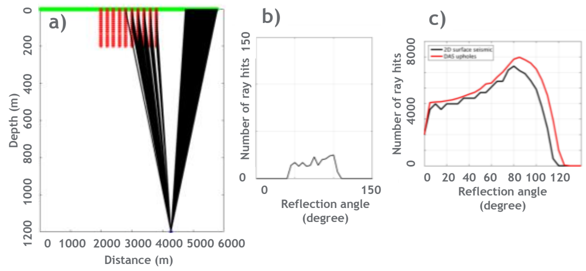

Figure 2: (a) A simplified ray scheme is shown for imaging a reflector at 1,200 m depth with the system of 10 DAS upholes at 200 m depth and spaced at 200 m; (b) angle coverage for a specific point on a reflector; (c) the average angle coverage for the entire reflector is comparable to surface seismic with source and receiver sampling of 10 m.

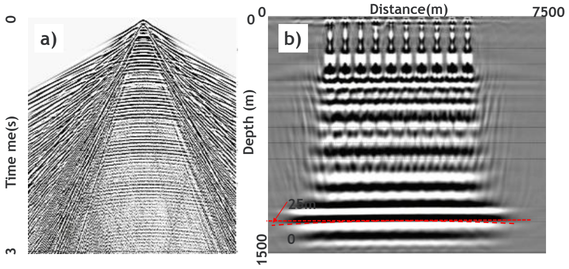

Figure 3: (a) Synthetic common-receiver gather at a depth of 156 m calculated using elastic modelling; b) Acoustic reverse-time migration of the elastic synthetic data with only 10 vertical arrays after basic pre-processing. Small low-relief structure with closure of 25 m is correctly imaged at a depth of 1,200 m.

Synthetic elastic data were generated using a realistic velocity model constructed from well logs from the test site (next section). An example of a common-receiver gather calculated at 156 m depth is presented in Figure 3a. After basic noise attenuation, the reverse-time migration (RTM) algorithm was applied to the synthetic data (Figure 3b). The resulting image shows good illumination of the target reflector at 1,200 m depth and correctly delineates the low-relief structure of interest. The image in the upper part of the section is distorted due to low illumination as predicted by the initial ray-based analysis. The synthetic study illustrates the possibility to use vertical arrays for deep imaging of target horizons.

Field test in Saudi Arabia

To prove the concept of smart DAS upholes, an onshore field experiment was conducted in Saudi Arabia. The test covered both near-surface characterization and deeper subsurface imaging capabilities of the system, but here we focus only the deep imaging part. Ten wells were drilled as shown in Figure 4. Six of them were connected by a single continuous fiber (red line) trenched at 1 m depth at the surface, while four others were used only for near surface

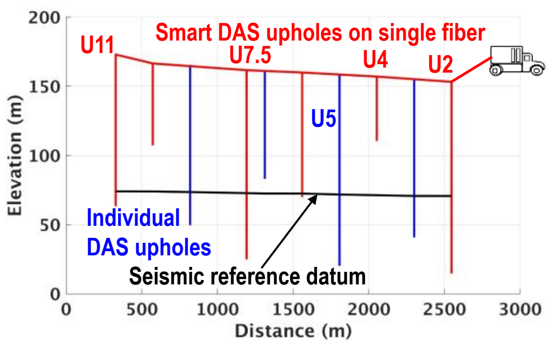

Figure 4. Field experiment layout.

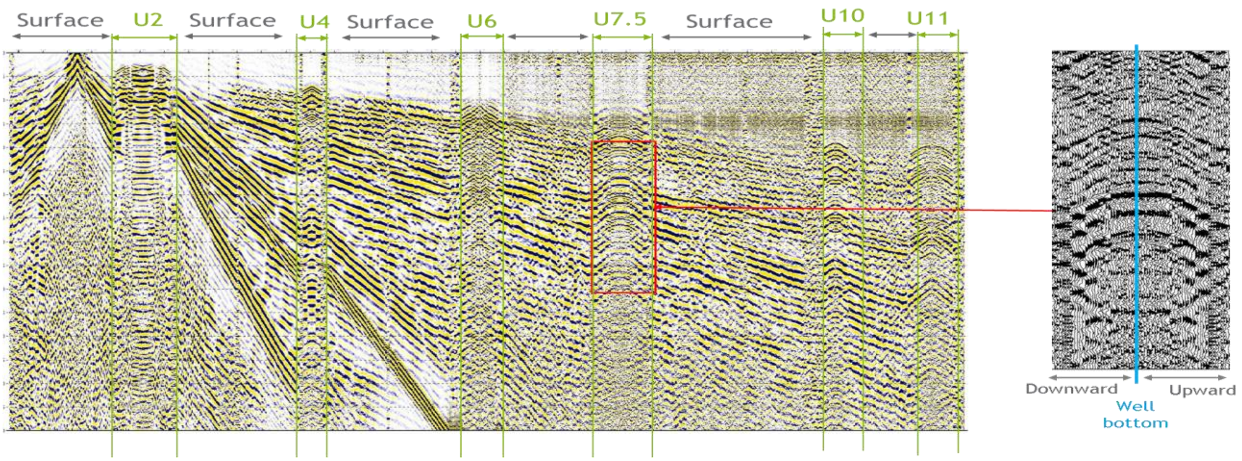

Figure 5. Raw common-shot gather acquired using the smart DAS uphole acquisition system. The gather consists of surface and downhole parts recorded simultaneously. The downhole part has both upgoing and downgoing legs as shown on the right.

model building. For seismic imaging we used the six wells with continuous fiber that have an average spacing of 400 m and average depth of 100 m. Several lines of Vibroseis shots were acquired with an inline interval of 10 m.

An example common-shot gather acquired using the six connected smart DAS upholes is shown in Figure 5. This gather shows the entire fiber line (surface and downhole parts) using 4 m channel spacing. We observe excellent data quality, with different elastic waves recorded simultaneously by different portions of the fiber. The surface part contains refracted events and strong, unaliased groundroll. Reflection events are not recorded by the surface cable due to the directivity of DAS measurements In contrast, the downhole parts of the cable clearly show downgoing and upgoing events that can be used for deep seismic imaging. It is worth mentioning that each uphole contains an upgoing and downgoing leg of the fiber as shown in Figure 5 (right), forming a symmetric gather. In the following imaging examples we use both downgoing and upgoing parts to increase signal-to-noise ratio in the final result. In this work, we do not consider the surface part of the DAS cable and use only the data recorded in upholes for deep imaging. The surface data is valuable information that can be used for near-surface related studies such as refraction tomography or surface wave inversion.

Data processing and imaging

Conventional processing tools, with some modifications and approximations, are used to process vertical array data acquired using the smart DAS uphole acquisition system. Cross-line stacking of the three shot lines improves the signal-to-noise ratio by suppressing cross-line noise while enhancing inline propagating events. For time processing, the data is then projected from the downhole locations to the surface. This can be achieved by different methods, including the use of direct arrival traveltimes (Fuller and Sterling, 2010), via wave-equation redatuming (Al-Ali and Verschuur, 2006) or by interferometric approaches (Schuster, 2009). After a number of numerical tests, we conclude that conventional static time-shifts work well for this particular site due to very slow velocities in the near-surface. To estimate the shifts for each depth level, we use the smart DAS uphole data acquired using the sources located very close to the wellheads. Picking of first arrivals provides time-depth curves similar to conventional upholes. By applying the picked traveltimes to the data, we shift the receivers to the surface and flatten the reflection events at each uphole location. Other major time-processing steps include random and linear noise attenuation, velocity analysis, surface-consistent deconvolution and residual statics, and finally CDP stacking.

An example common-receiver gather recorded at a fixed downhole location (depth of 125 m) after cross-line shot summation is shown in Figure 6a. The data is of good quality and shows refracted waves, ground-roll and several strong reflections. The common-receiver domain has good spatial sampling due to the dense distribution of shots at the surface, so is suitable for efficient noise removal. After random and linear noise attenuation, we observe clear reflection events suitable for deep imaging (Figure 6b).

The stack section obtained using DAS data after noise attenuation is shown in Figure 7a. The image is of excellent quality and allows us to clearly identify the target horizon. When compared to the legacy 2D surface seismic data (Figure 7b), processed with the same legacy velocity and no statics, we observe very good agreement between the two stacks throughout the section. Note that we do not apply linear noise removal to the legacy data since field arrays suppressed much of the noise. The two sections are 45 degrees with respect to each other, but at the intersection (red line) we observe excellent tie between the reflectors.

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Additional velocity analysis based on CMP gathers obtained from the DAS data allows us to improve the stacking velocities, resulting in a more coherent stack section. Surface-consistent deconvolution improves resolution by recovering higher frequencies. Finally, surface-consistent residual static corrections were applied to compensate for high-frequency static anomalies in the CMP gathers. We conclude that conventional time-processing tools can be successfully applied to the vertical array data.

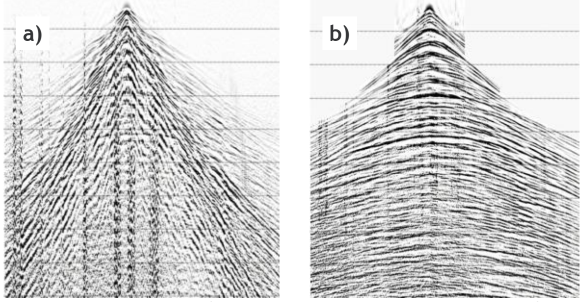

Figure 6: An example of common-receiver gather at a depth of 125 m from DAS data (a) before and (b) after noise attenuation.

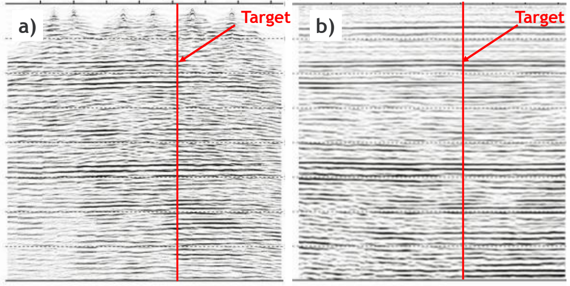

Figure 7: Stack section obtained using data from (a) DAS vertical arrays and (b) from legacy 2D conventional surface seismic. The vertical red line shows intersection of two stacks.

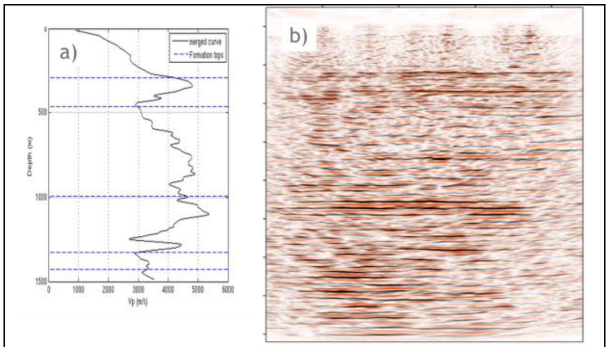

Figure 8: (a) Upper part of the velocity model used for depth imaging. (b) RTM result using vertical array DAS data.

Successful depth imaging has also been applied to the DAS data. A rough estimate of the depth velocity model extracted from a deep well located close to the test site was used. The top part of the migration velocity profile is shown in Figure 8a. In contrast to time processing, here we use the true receiver locations in depth and do not shift the data to the surface. The RTM result (Figure 8b) shows outstanding image quality, comparable to the stack section from time processing. We do not expect significant differences between time and depth images due to the relatively flat geology. A more detailed comparison of the stack section and depth image after depth-to-time conversion shows very good correspondence (Figure 9). The dip-angle common image gathers from RTM look acceptable and should allow further updates to the velocity and refinement of the image.

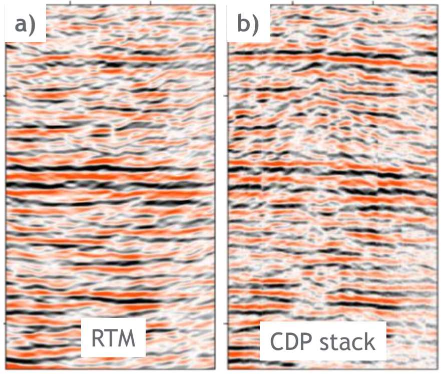

Figure 9: Comparison of (a) depth and (b) time images shows good agreement. RTM image is converted to time for comparison.

Conclusions

Field tests of a smart DAS uphole acquisition system for simultaneous near surface characterization and deep reflection imaging have been conducted in Saudi Arabia. Vertical arrays of DAS fiber show excellent sensitivity to reflection energy, resulting in equivalent time images to surface seismic, despite the large spacing between shallow holes. Depth imaging of the DAS data produces excellent results using only an approximate migration velocity model. The near-surface part of the model can be updated further using the velocities measured in the upholes, while the deeper section can be improved using migration velocity analysis. Such uphole surveys can be used as fit-for-purpose solutions in areas with challenging near surface conditions. We believe that this represents a new paradigm in seismic acquisition that can accurately characterize the near surface and produce reliable seismic images of the subsurface.

Acknowledgments

We thank Saudi Aramco for permission to publish this work.

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