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Reflection Seismic Imaging Using Smart DAS Upholes

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Summary

We invent and test a new system to acquire seismic data using continuous fiber-optic DAS cable deployed in a grid of shallow vertical holes. This system allows simultaneous land near-surface characterization and subsurface imaging in a cost-efficient manner. With smart DAS upholes we achieve perfect calibration of near-surface complexities and record cleaner seismic data. Connecting multiple upholes with a single fiber enables efficient acquisition of seismic surveys with buried vertical arrays, which can provide images of the deeper subsurface similar to surface seismic, but with improved structural control, since they bypass most of the near-surface complexities. We have performed successful 2D field testing of such a system on one of the onshore fields in Saudi Arabia. The new system can deliver an on-demand standalone survey that simultaneously characterizes the near surface, performs deep reflection imaging of oil and gas targets for exploration, and can be used for development or reservoir monitoring. Such a system is long overdue for land regions that have complex near-surface conditions.

Introduction

Land surface seismic remains the key technique to explore, develop and monitor oil and gas reservoirs. In the past decades, improvements land seismic were associated with increasing channel counts aimed to better sample surface-related noise so it can be removed during imaging. This route comes at a considerable additional expense with limited returns and also does not directly resolve near-surface complexity that typically plagues land 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 should be only a small fraction of the overall structural closure. If not properly accounted for, the static errors could introduce vertical shifts into the final seismic volume that might obscure the actual structure and significantly affect estimates of the potential reservoir volume. This was illustrated 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 innovative acquisition scheme with much fewer channels, that addresses both data quality and near-surface challenges at once by burying sensors in the subsurface. The main component of the system is a "smart DAS uphole" that is a shallow hole 100-500 m deep instrumented with cost-effective optical fiber acting as a seismic sensor and interrogated using Distributed Acoustic Sensing technology (Miller et al., 2012). Smart DAS upholes provide direct measurements of shallow velocity and eliminate false non-geological imprints on seismic structure caused by poorly characterized near-surface velocity variations typical of arid environments. In this study we show that dense grids of upholes can be connected with a single fiber and enable efficient acquisition of targeted reflection seismic surveys with buried vertical arrays. Such surveys can provide an alternative approach to imaging smaller prospect areas and serve as efficient surrogates for localized seismic surveys. Grids of smart DAS upholes represent a new paradigm that can characterize the near surface as well as produce reliable images of low-relief structures at depth.

Synthetic test of imaging with buried vertical arrays

A 2D grid of connected smart DAS upholes (Figure 1) comprises an acquisition system with vertical arrays and surface sources for subsurface imaging. While upholes are sparse in the horizontal direction, this is compensated for by recording vertical antennas that provide significant additional illumination angles enabling reflection records with coverage similar to the surface seismic (Ikelle and Wilson, 1998). Derivation of an accurate near-surface model from a grid of upholes is covered in another study, whereas here we focus on subsurface reflection imaging with vertical arrays.

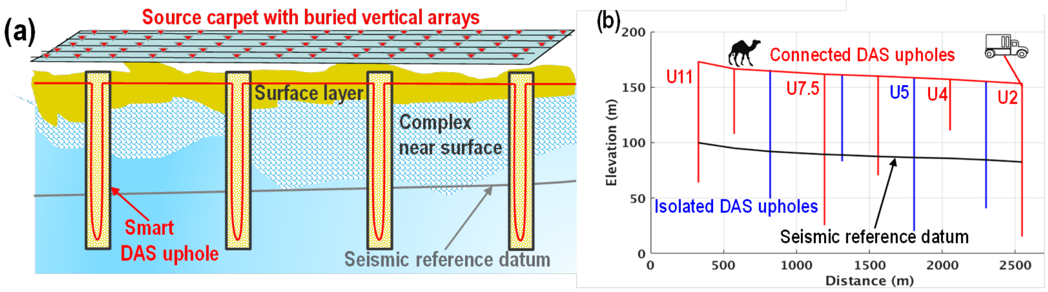

Figure 1 *(a) Schematic representation of field geometry of simultaneous DAS recordings in multiple wells acquired with a carpet of sources. (b) Field acquisition contains six vertical arrays on a single fiber with average hole spacing of 400 m and average depth of 100 m.*

Figure 2a shows a subsurface image obtained using synthetic acoustic data with an acquisition geometry similar to that of the field data described later. Vertical geophones are located along 10 upholes each with a depth of 200 m and spaced 400 m apart. A source line is shot above the vertical arrays with spacing of 10 m and maximum offset of 5 km. While shallow horizons suffer from limited illumination when migrated with primaries only, the target low-relief structure at a depth of 1200 m is well imaged despite a closure of just 25 m.

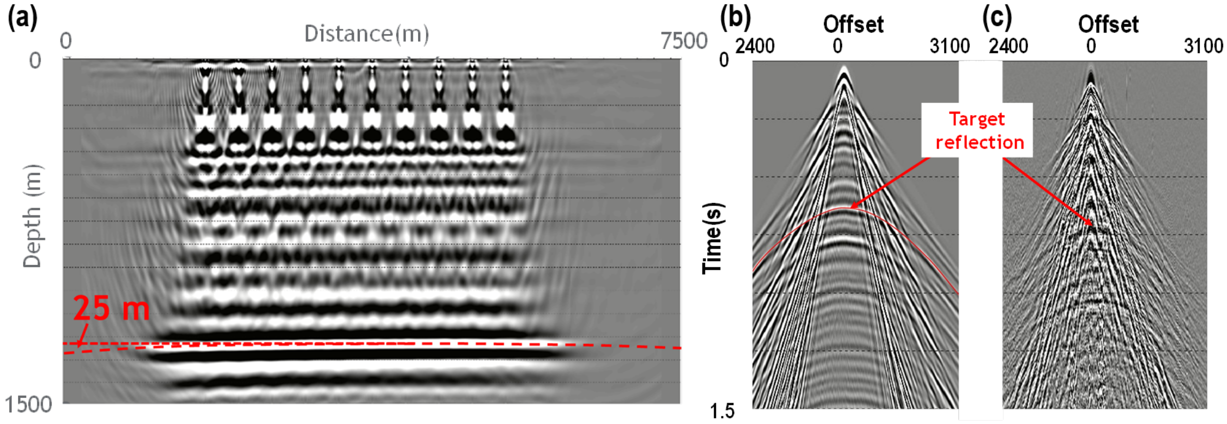

Figure 2 *Synthetic example showing (a) reverse-time migration (RTM) image of data with 10 vertical arrays, (b) typical common-receiver gather and (c) a field data gather for a sensor at 130m depth. The target reflector is clearly identifiable on both gathers.*

Field test with connected smart DAS upholes

To test this new concept, a field experiment was conducted in Saudi Arabia. This comprised installation of a smart DAS uphole array to record a reflection survey using a single continuous fiber cable running through multiple wells. While it is possible to record vertical array data using multiple DAS interrogators at each hole, it is currently expensive and not practical. To improve productivity, a single fiber was installed that connected multiple wells running fiber up and down in each well with a loop at the bottom. Between the holes, fiber optic cable is trenched at 1 m depth. Simple fiber in vertical wells provides a response similar to a vertical geophone, whereas horizontal sections are analogous to inline geophones and therefore are not used for reflection imaging in this study. While the actual acquisition geometry is irregular and limited (Figure 1b), we will demonstrate that it can deliver a good quality image. Laser interrogation of the single fiber results in 300 DAS channels in vertical arrays at a 4 m spacing. The average depth of the upholes is around 100 m and average spacing is around 400 m. A 2D array of vibroseis source locations was acquires over 950 locations with a 10 m spacing.

Figure 2a and b compares common-receiver gathers obtained using elastic synthetic modelling and field data experiment with a receiver at 130 m depth. Both records shows clear reflectors including the target event at around 1200 m depth. It validates that placing receivers in the subsurface can greatly improve seismic data quality as suggested in previous studies (Bakulin et al., 2012; 2015). Modelling suggests that increasing sensor depth should reduce near-surface scattering and horizontally propagating energy, while increasing the visibility of reflection signals (Figure 3a). Though not as clear as synthetic data, the field data shows a similar trend (Figure 3b).

To benchmark the DAS data against legacy 3D seismic data we selected an equivalent 2D subset from the legacy 3D data, containing one receiver line and one parallel shot line with spacing of 60 m for both. The same time processing was applied to both datasets using the same legacy velocities with no statics. To compensate for the lack of large 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 seismic. One major non-standard step for DAS data processing was bringing all the receivers to the same depth level for time-processing and stacking. This can be done using different methods, including using direct arrival travel-times (Fuller and Sterling, 2010), via wave-equation redatuming (Al-Ali and Verschuur, 2006) or by interferometric approaches (Schuster, 2009). In this study, we use vertical travel-times picked along vertical arrays, and datum all traces to the surface using the resulting statics. As a result, all depth levels are merged to form a final stack with significantly improved signal-to-noise ratio compared to individual stacks from a single depth.

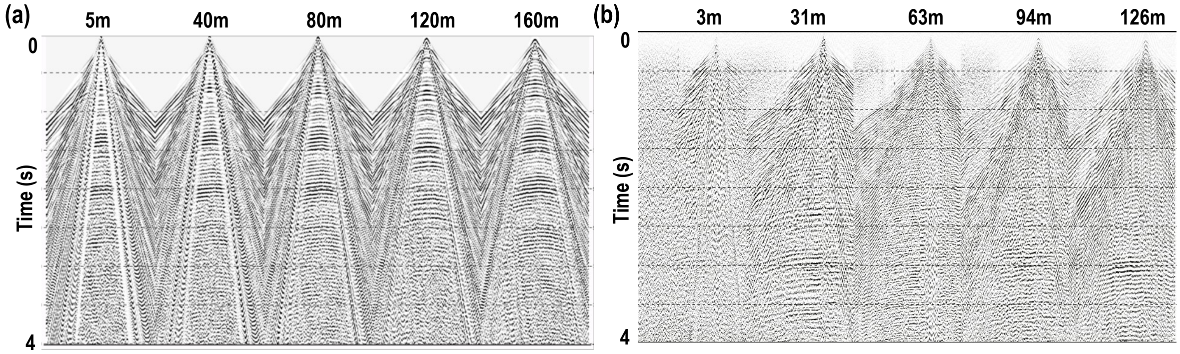

Figure 3 *Effect of receiver depth on data quality demonstrated using (a) synthetic elastic data compared to (b) real field data. Generally cleaner reflection data is observed at larger depths.*

Figure 4a compares brute stacks obtained with DAS vertical arrays and legacy vertical geophone seismic data. Both shallow and deep reflectors are clearly imaged on the DAS data similar to surface seismic. DAS and legacy lines intersect at 45 degrees, so the DAS image is shown on one side and the legacy image on the other side. An excellent tie of both images is seen at the intersection point, both for the target reflector as well as other reflectors. This validates 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. Figure 4b compares reflection ray coverage for reflector at 1000 m depth for the case of a simple homogeneous model for dense surface seismic acquisition and smart DAS upholes. The maximum offset, and source and receiver sampling is identical for both scenarios. One can see that DAS upholes can deliver similar ray coverage when uphole depths are approximately equal to the borehole separation distance. Depth imaging can be performed using a model that has calibrated near-surface velocities obtained with the DAS upholes.

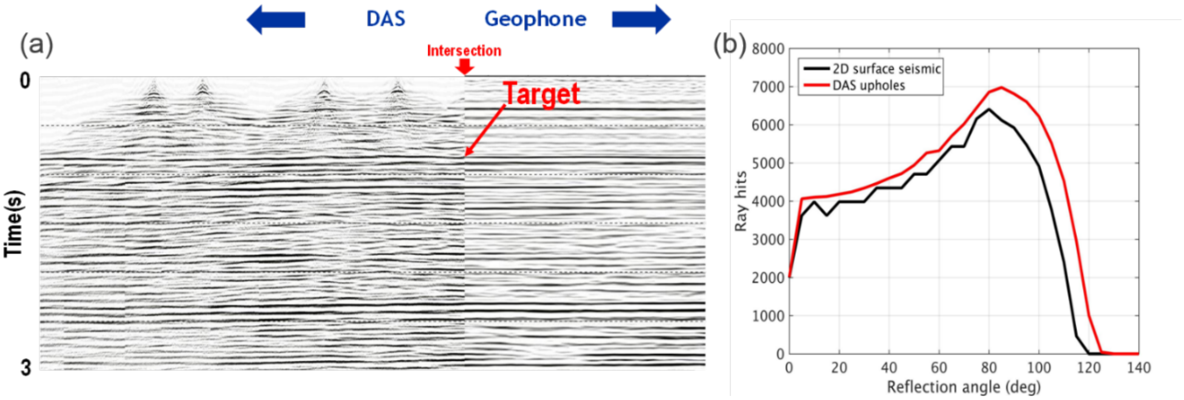

Figure 4 *Field data comparison including (a) 2D images obtained with vertical DAS arrays (left) and surface legacy seismic (right), and (b) ray coverage density versus reflection angle for a reflector at 1000 m depth. The vertical arrow marks where both lines intersect each other at 45 degrees. Source sampling is 10 m along the line for both acquisition scenarios.*

Conclusions

We presented a novel fiber-optic land acquisition concept along with a 2D field test consisting of smart DAS upholes connected by single fiber. Instrumented from top to bottom with cost-effective optical fiber, smart DAS upholes provide a large number of seismic channels at dense vertical spacing. Simultaneous recording of all vertical arrays enables angular coverage of reflected events that is similar to surface seismic even when spacing between holes is rather sparse. Synthetic and field data examples prove that such a system can produce good quality subsurface images similar to surface seismic. An added benefit of using vertical arrays on land is the ability to directly measure near-surface velocity. For time imaging this results in a more accurate description of long-wavelength statics that is crucial for delineating challenging exploration targets such as low-relief structures. For depth imaging, one can directly build a calibrated depth model from topography. The ability to simultaneously resolve the near-surface and image deeper subsurface make such a fiber-optic system uniquely suitable for seismic imaging in arid desert environments and other land areas with a complex near surface. In such situations, reflection data recorded by buried sensors is usually cleaner than surface seismic data and allows obtaining equivalent images with many fewer channels. Such a DAS system has the potential to become the next tool of choice for delineation of low-relief structures, targeted reservoir characterization and monitoring. With omnidirectional DAS cables, we can also include surface DAS channels into the mix to improve velocity model building and imaging. We aim to report such experiments in future work.

Acknowledgements

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